CONTEXTUALIZING AND COMMUNICATING THE ANCILLARY BENEFITS OF GREEN STORMWATER INFRASTRUCTURE

by

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ABSTRACT

As we move into an era of increased urbanization, stormwater practitioners are charged with creating multi-functional solutions through the installation of stormwater control measures (SCMs). Green stormwater infrastructure (GSI) mirrors natural hydrologic processes and can be used as an alternative or complement to traditional grey infrastructure. To encourage greener interventions, practitioners promote co-benefits (ancillary social, ecological and environmental outcomes). Co-benefits are difficult to quantify because they span a diverse set of categories that cannot be easily measured with a single metric. This dissertation advances the science of co-benefits by querying (1) the impact greening programs have on vegetation in cities, (2) the public's preference for GSI and co-benefits, and (3) the feasibility of incorporating co-benefits into the planning process.

First, a ten-city greenness study found that robust GSI programs did not always correspond with increased city-wide greenness. In Philadelphia, the installation of non-vegetated SCMs contributed to decreased urban greenness. Second, a survey administered in three cities found that respondents preferred new GSI installations and had less confidence in GSI to handle storms. The co-benefits surveyed were favorable to most respondents, but a clear divide was identified between environmental and socio-economic related benefits. Finally, a critical review of the literature informed a SCM/benefit attribution matrix that was then applied to a case study in the Berkeley neighborhood of Denver, CO. We found that hydrologic benefits related to SCMs can be quantified using stormwater modeling. To assess vegetated benefits related to SCMs, we created the framework of the 4 C's (community, context, connectivity and canopy) to leverage surrounding urban green infrastructure (like parks) because the modeled solution would add only 1% to the neighborhood's vegetated area. To incorporate the results of this dissertation into stormwater planning, we advocate that municipalities adopt multi-department integrated vegetation goals to optimize the benefits of all types of urban green infrastructure.

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CHAPTER 1

INTRODUCTION

1.1 Background

Urban areas in the United States and around the world are experiencing rapid population growth. By 2050, the United Nations projects that 89% of the population in the US will live in cities (United Nations, Department of Economic and Social Affairs, 2019). To accommodate this growth, cities are growing up and out (i.e. expanding suburbs and infill development). Increased urbanization results in increased impervious surfaces that generate more stormwater runoff.

The quantity and quality of urban stormwater has historically been managed by grey infrastructure, which is characterized by concrete and pipe-based systems that convey water through neighborhoods and discharge into natural water bodies. In older US cities, stormwater and wastewater flows are intermingled in combined sewer systems (CSS) and routed to wastewater treatment plants. During large storm events, flows in CSS systems can exceed the treatment capacity at plants and result in the discharge of untreated sewage into natural systems.

To help reduce the flows into CSS systems during storm events, green stormwater infrastructure (GSI), which utilizes vegetation and/or promotes natural hydrologic processes, is utilized to intercept flows (USEPA, 2019a). Municipal separate storm sewer systems (MS4) systems, which convey only stormwater, also benefit from the installation of GSI (USEPA, 2019c). According to the USEPA, GSI "reduces and treats stormwater at its source while delivering environmental, social, and economic benefits" (USEPA, 2019c).

Practitioners are often most comfortable with grey infrastructure design, cost, maintenance, and performance. For cities looking to adopt GSI, ancillary social, environmental, and ecological benefits, also called "co-benefits", are cited to bridge the uncertainty and inexperience gaps (Bell et al., 2019). In addition to providing additional positive outcomes to stormwater interventions, co-benefits are used to garner public support for GSI programs. Co-benefits stem from the body of ecosystem services literature in which green spaces provide secondary and tertiary levels of benefits to surrounding communities and wildlife.

Co-benefits span a broad range of topics. Some co-benefits, like flood control and water flow regulation are often primary design objectives of individual stormwater control measures (SCMs) but when placed strategically on a neighborhood scale can bolster a city's resiliency to larger storm events (Eckart, McPhee, & Bolisetti, 2017). Social co-benefits range from economic outcomes related to proximity to green spaces to positive impacts on a neighborhood's public health through access to recreational opportunities. Some co-benefits can have secondary impacts on a neighborhood; for example, the environmental co-benefits of urban heat island mitigation and improved air quality have secondary social co-benefits related to improved public health. A complete list of co-benefits considered at the outset of this dissertation can be found in Appendix A. This literature review was performed by the author and was incorporated into the co-benefit section of Bell et al.,(2019).

In practice, most stormwater systems that incorporate GSI operate on a green to grey continuum, where greener SCMs like bioretention cells (i.e. rain gardens) are placed in the same sewersheds as greyer SCMs like underground detention structures (Bell et al., 2019). When stormwater planners look to design interventions to mitigate the impacts of land use changes, they would like to know the tradeoffs between greener and greyer interventions (Bell et al., 2019). In response to this need, a planning-level integrated decision support tool (i-DST) is being created that couples hydrologic modeling with life cycle costing and a benefit assessment to provide optimized SCM solutions. The i-DST utilizes a modified version of EPA's System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN) for hydrologic modelling and optimization of SCMs on the green to grey continuum.

Note: This dissertation uses "co-benefits" and "benefits" interchangeably. For a planning level assessment, like in the i-DST, "benefit" is preferred as it is considered decision-making factor and not ancillary.

The incorporation of benefits into a stormwater planning tool requires that we address three knowledge gaps in the literature. These gaps include the impacts of system-level development trends, the public's preference for stormwater infrastructure and benefits and the potential for SCMs to accrue benefits. This dissertation will work on filling these gaps and will be used to inform a benefit assessment module in the i-DST. A quick overview of each knowledge gap is discussed in the following sections; a more detailed review of the current state of the literature is presented with each chapter.

1.1.1 Systems-level Trends in Urban Vegetation

While the literature is clear on the presumed benefits of installing GSI, little work has been performed to evaluate current implementation of GSI on a city-wide or national scale. Understanding the scale at which GSI is being installed compared to the scale at which impervious surface is being installed can help practitioners strategically plan future interventions that optimize desired benefits. Many cities use geographic information systems (GIS) mapping to inventory their SCMs, but datasets are often incomplete and lacking adequate spatial and temporal resolution. Data quality could be improved by leveraging remote sensing techniques. In the field of ecosystem services, the normalized difference vegetation index (NDVI) is used to track the quality and quantity of urban green spaces. NDVI uses spectral signals from satellite imagery to quantify vegetation on a scale of -1 (pavement) to 1 (very healthy plant). In the literature, NDVI has been used to quantify the temporal and spatial spread of urban green spaces (Calderón-Contreras & Quiroz-Rosas, 2017; Gascon et al., 2016; Kim, Kim, Li, Yang, & Cao, 2017), but no published studies focus on the impact of GSI and other greening programs.

1.1.2 Variability of Public Preference for GSI and Benefits

Cities implementing GSI have started to shift their planning approaches from traditional centralized (grey) interventions towards collaborative, multi-department, distributed (green) efforts (Lennon, 2015). A more collaborative approach requires stakeholder input, especially during the planning phase. More distributed interventions can have multiple impacts on the residents of neighborhoods where SCMs are installed. Community members can experience rate increases, be engaged to install SCMs on their private property, and can assume maintenance of public and private SCMs (Keeley et al., 2013; Thurston, Taylor, Shuster, Roy, & Morrison, 2010). Neighborhood residents are also the primary benefactors of any positive outcomes associated with SCM installation.

For GSI programs to be successful, community buy-in is critical. The existing body of literature offers little insight into the public’s perception of using GSI. Keeley et al. quoted a stormwater practitioner from Cleveland stating that “… [GSI] is essential to selling rate hikes.

People have to see a surface manifestation of their tax money" (Keeley et al., 2013). While this perspective offers some insight into how practitioners view their relationship with the public, how people perceive GSI is still unclear. In a limited study on a small watershed in the Midwest, Thurston et al. found that when residents were asked how much they would like to be paid to install a green SCM on their property, the majority of respondents did not require a subsidy (Thurston et al., 2010). While these results are promising, especially in the context of private land interventions, assuming a population has consensus on societal objectives, defined as "objectives with which a majority of people would agree", is inappropriate "because people have high diversity of perspectives" (Reichert, Langhans, Lienert, & Schuwirth, 2015).

1.1.3 The Potential for SCMs to Accrue Benefits

Two main drivers for the accrual of co-benefits from SCMs are decentralized management of flows and added vegetation. Hydrologic benefits are typically quantified using stormwater modeling and are well-studied (Eckart et al., 2017; Jefferson et al., 2017). Vegetated benefits are often linked to larger urban green infrastructure installations, like parks, and their attribution to smaller installations like SCMs is assumed but not verified. Many of the vegetated benefits, like improved air quality and urban heat island mitigation, are derived from literature on the impacts of urban trees (Berland et al., 2017; D. J. Nowak, Crane, & Stevens, 2006), but their transferability to SCMs along the grey-green continuum has not been proven. In the existing literature, more effort has been dedicated to identifying potential benefits and creating metrics for their incorporation (GIVaN, 2010; Guo & Correa, 2013; McGarity et al., 2015). The boundary conditions on these assessments are often limited to the SCMs to be installed and little to no consideration is given to leveraging the existing larger urban green infrastructure system.

1.2 Research Objectives

This dissertation fills some the knowledge gaps detailed and add specificity to inform the creation of a benefit assessment module that can be integrated into watershed-scale planning tools. First, we evaluated the efficacy of greening programs to offset urban densification. Next, public preference of GSI and its ancillary benefits were queried so that decision makers have a better understanding of how residents feel about existing and future stormwater infrastructure interventions. Finally, the potential for SCMs to realize benefits was explored so that decision makers have a complete understanding of the impacts of their infrastructure decisions. By linking benefits to design components of infrastructure a more holistic and transparent environmental decision making framework can be created that links “scientific prediction” with “societal valuation” (Reichert, et al. 2015).

1.2.0 Research Questions

The goal of this research is to obtain a better understanding of benefits related to stormwater management on a national scale. The following objectives and their corresponding science questions and hypotheses highlight the knowledge gaps addressed by this dissertation.

1.2.0.1 Objective 1: National Study of Urban Greenness

Question 1.1 How is greenness trending in cities that continue to develop and have signature greening programs?

> *Hypothesis 1.1* Greenness (as measured by the normalized difference vegetation index (NDVI) and corrected for climate signals) will be decreasing over city boundaries because cities do not implement signature greening programs at scales that offset development-related increases in impervious surfaces.

Question 1.2 How do vegetated or non-vegetated stormwater control measures (SCMs) contribute to greenness trends?

> *Hypothesis 1.2* The installation of non-vegetated SCMs in Philadelphia has contributed to decreased city-wide greenness.

Question 1.3 How does surrounding urban green infrastructure (UGI) impact zip-code level greenness trends?

> *Hypothesis 1.3.* If the SCMs installed are smaller than the 30 by 30 meter Landsat pixel size, then the surrounding UGI exerts as much or more influence on a zip-code level greenness trends in Philadelphia.

1.2.0.2 Objective 2: Public Perception of Stormwater Infrastructure and Public Preference for Benefits

Question 2.1 What impacts do demographics (i.e. race, age, gender, population density, financial security, educational attainment and housing tenue) and city of residence (Philadelphia, PA; Denver, CO; Seattle, WA) have on a resident's preference for grey/green infrastructure?

> *Hypothesis 2.1* Preference for green/grey infrastructure will be consistent across all demographic characteristics and in the cities studied.

Question 2.2 How does preference for grey/green infrastructure change when asked about ability of existing infrastructure to handle storms vs. the type of new installations preferred?

> *Hypothesis 2.2* Respondents will have a higher preference for grey infrastructure to handle storms and a higher preference for new installations of green infrastructure.

Question 2.3 How are preferences for benefits influenced by demographic characteristics and city of residence?

> *Hypothesis 2.3.* Preference for all benefits will be consistent across all demographic characteristics and in the cities studied.

1.2.0.3 Objective 3: Incorporating Benefits in a Stormwater Planning Tool

Question 3.1 Based on physical form and feasibility, which stormwater control measures (SCMs) included in i-DST SUSTAIN have the potential to accrue hydrologic process- and vegetation-based benefits?

> *Hypothesis 3.1* SCMs on the greyer end of the continuum will accrue hydrologic-based benefits but not vegetation-based benefits. SCMs on the greener end of the continuum will accrue both hydrologic and vegetation-based benefits.

Question 3.2 Spatially, what is the contribution of SCMs to urban green infrastructure (UGI) in the Berkeley neighborhood and across all of Denver, CO?

> *Hypothesis 3.2* If the spatial extent of SCMs is less than other types of UGI then a benefit analysis cannot be decoupled from UGI.

Question 3.3 Given that vegetation-based benefits are dependent on trees, how does tree canopy vary with SCM type in Denver?

> *Hypothesis 3.3* If SCMs are larger and more pond-like then they will have trees around their perimeter and their tree canopy will be low. If SCMs are smaller then they will have more trees planted directly into their spatial extent so they will have a higher tree canopy.

1.3 Dissertation Overview

Chapters 2 through 4 of this dissertation address the science questions and hypotheses outlined in the previous section. Chapter 2 uses remote sensing and a spatial inventory to address the questions and hypotheses associated with Objective 1. Chapter 3 uses results from a public perception survey to explore nuance within the questions and hypotheses associated with Objective 2. Chapter 4 provides a critical review of the literature from the lens of stormwater management and uses stormwater modelling and an analysis of urban green infrastructure to answer the questions and hypotheses associated with Objective 3. Finally, Chapter 5 concludes the dissertation by tracking how the work performed in Chapters 2 through 4 answered each science question and proved or disproved each hypothesis. Chapter 5 also details the broader impacts of this work and areas for future study.

CHAPTER 2

GREENING UP STORMWATER INFRASTRUCTURE: MEASURING VEGETATION TO ESTABLISH CONTEXT AND PROMOTE COBENEFITS IN A DIVERSE SET OF US CITIES

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2.1 Abstract

Urban greening practices are often adopted to mitigate the negative impacts of increasing impervious surfaces in urban areas. In the United States, green approaches are prevalent in the field of stormwater management as some cities are required to install green stormwater infrastructure (GSI) to meet regulatory requirements. While the primary function of GSI is to address stormwater quality and quantity issues, stormwater managers often tout the ancillary social and environmental benefits, or co-benefits, when promoting their green approach. Co-benefits are difficult to quantify because they span a diverse set of categories and cannot be easily measured using any single metric. Drawing from existing techniques in the field of ecosystem services, this study uses the normalized difference vegetation index (NDVI) to establish trends in ecosystem services in ten US cities with GSI programs and to evaluate the impacts of GSI interventions on urban greenness. Results show that only two of the ten study cities (Seattle, WA and Milwaukee, WI) are getting greener, likely due to maturing vegetation. A case study for one of the 10 cities, Philadelphia, utilizes a stormwater control measure (SCM) inventory of GSI installations, and shows decreasing greenness at the city-wide scale. This case study demonstrates that 62% of GSI project area is composed of non-vegetated SCMs. High-resolution imagery and spatial GSI data identify densification trends in Philadelphia where non-vegetated SCMs are installed to control post-development stormwater, resulting in a decrease in NDVI. Smaller, vegetated SCMs contribute to greenness and related co-benefits when installed in series, especially when near larger vegetated vacant lots. Moving forward, decision makers are

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encouraged to incorporate NDVI into their planning processes to move beyond water quality and quantity control measures and directly incorporate and incentivize co-benefits into GSI goals.

2.2 Introduction

As cities in the United States continue to iterate on development approaches, the concept of urban greening has emerged as a ubiquitous way to address the negative impacts of urban growth and densification. Traditionally most development, spanning from infill in the urban core to sprawl along the urban perimeter, results in an increase in impervious area and a decrease in pervious land. Urban greenness mitigates a broad range of post-development issues, from reducing the urban heat island effect associated with increased pavement to improving recreational access in crowded urban centers (Gómez-Baggethun & Barton, 2013). In the context of urban water management, green stormwater infrastructure (GSI) is being employed to help reclaim the natural hydrologic cycle and improve the water quality of receiving bodies. GSI can be considered a piece of the urban green infrastructure puzzle; while other green infrastructure may provide stormwater management services, GSI is primarily used to capture and treat water from impervious surfaces.

Stormwater infrastructure exists on a grey to green continuum, with greyer infrastructure characterized by traditional centralized systems made of pipes and concrete structures and greener infrastructure characterized by typically (but not always) distributed, often vegetated systems that mimic natural hydrologic processes (Bell et al., 2019). Stormwater control measures (SCMs), or single units of infrastructure, on the greener end of the continuum are not always vegetated, as in the case of pervious or porous pavement. The SCMs considered to be GSI can vary by city, but the dominant hydrologic processes shift from detention and evaporation to infiltration and transpiration as SCMs move towards the greener and more vegetated space on the continuum (Bell et al., 2019).

In the US, stormwater managers' primary motivation during the infrastructure planning process is compliance (Bell et al., 2019). Urban stormwater management falls under the USEPA's National Pollutant Discharge Elimination System (NPDES), either under the Municipal Separate Storm Sewer System (MS4) for separate sewer systems or under the city's wastewater NPDES permit in the form of Combined Sewer Overflow (CSO) allowances. Starting in 2004, USEPA consent decrees required many cities and counties with CSOs to implement GSI programs to create targeted interventions that complement their existing grey infrastructure to obtain compliance with their permit (Meng, Hsu, & Wadzuk, 2017; USEPA, 2019a). Because green SCMs are installed on a distributed basis and manage water locally, installing GSI reduces storm flows into existing pipes. In areas that drain to combined sewers, less stormwater in pipes results in reduction or absence of CSO events that are characterized by the discharge of untreated sewage into natural waterways.

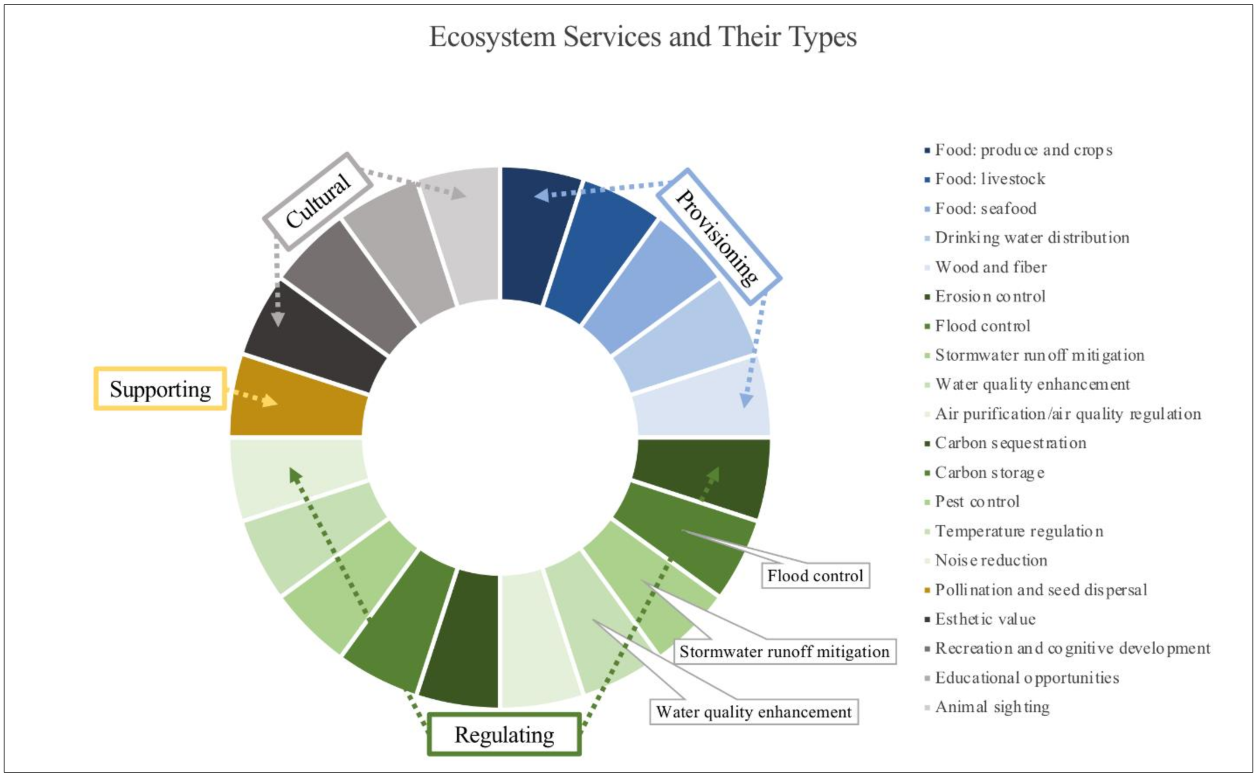


Figure 2.1: Ecosystem services adapted from Andersson et al., (2015) categorized by the functions they provide to communities and the surrounding environment. The three ecosystem services highlighted (flood control, stormwater runoff mitigation, and water quality enhancement) are the primary functions of stormwater management infrastructure.

In addition to reducing storm flows, the USEPA promotes GSI as a means to deliver “environmental social and economic benefits” to communities (USEPA, 2019c). These ancillary ecological, environmental, and social benefits are often called co-benefits and can be evaluated through an ecosystem services framework (Bell et al., 2019). Urban ecosystem services span a broad range of categories, from food production in community gardens to noise reduction from trees (Andersson et al., 2015). Figure 2.1 provides a comprehensive list of ecosystem services broken down by functional type (i.e. provisioning, regulating, supporting and cultural) (Andersson et al., 2015). Three of the 20 services listed (i.e. flood control, stormwater runoff mitigation, and water quality enhancement) are seen as the primary functions of stormwater management infrastructure. In relation to ecosystem services, co-benefits can be defined as how the three stormwater management services interact synergistically with the other ecosystem services.

While co-benefits are often mentioned in GSI program planning documents, cities have yet to adopt approaches that explicitly use multiple co-benefits as decision-making criteria (Alves, Patiño Gómez, Vojinovic, Sánchez, & Weesakul, 2018; Meerow & Newell, 2017). One potential hurdle to incorporating co-benefits into the planning process is the regulatory incentive structure; compliance is tracked through water quantity and quality metrics. Additionally, co-benefits are difficult to measure and attribute, especially without knowledge of the context in which GSI is being installed (Keeler et al., 2019). The first step towards quantifying co-benefits is to develop metrics that are easy to compute, incorporate information about nearby conditions, and are correlated to actual measurable ecosystem services.

Vegetation is one of the main sources of urban ecosystem services and increased vegetation is correlated to increased environmental and ecological co-benefits such as habitat enhancement, bird species richness and increased riparian flow (Jarchow & Glenn, 2017; Leveau, Isla, & Bellocq, 2018; Nieto, Flombaum, & Garbulsky, 2015; Pettorelli et al., 2005; Stathopoulou & Cartalis, 2007; Travaini et al., 2007; Turner et al., 2003). Fourteen of the 20 services in Figure 2.1 have positive correlations with vegetation. Social co-benefits, while likely positively correlated with vegetated areas, require stakeholder engagement to fully prioritize and track SCMs and their intended outcomes (Alves et al., 2018; Calderón-Contreras & Quiroz-Rosas, 2017; Gascon et al., 2016) .

In the current study, the normalized difference vegetation index (NDVI) is used as a metric for establishing trends in vegetation and spatially tracking the installation of GSI. NDVI measures the quality and quantity of vegetation through the spectral band math of remotely sensed images and is one of the most popular ways to measure aggregate urban greenness and ecosystem services benefits (Azmy, Hosaka, & Numata, 2016; Calderón-Contreras & Quiroz-Rosas, 2017; de la Barrera & Henríquez, 2017; Krishnaswamy, Bawa, Ganeshaiah, & Kiran, 2009; Martínez-Harms & Balvanera, 2012; Verón, Blanco, Texeira, Irisarri, & Paruelo, 2018). In relation to monitoring urban water quality and quantity, NDVI is an overlapping and complementary measure. For example, higher NDVI values are related to increased ability to capture and treat stormwater volumes by urban green spaces but can also be related to increases in other co-benefits like urban cooling that cannot be measured using water quality or quantity metrics (Kim et al., 2017).

This study aims to demonstrate how NDVI can be used to (1) establish existing conditions of ecosystem services trends within cities, and (2) evaluate the contribution of GSI programs to urban greenness using a case study to provide context for future planning efforts. We first evaluate greenness trends in a diverse set of ten cities in the US with GSI programs. A methodology is developed to correct for increases in greenness due to climate so that non-climate related (anthropogenic) greenness trends can be evaluated. A truncated greenness trending analysis is also included to see if the impacts of GSI programs can be seen on a city-wide scale. We then utilize a GSI inventory coupled with high-resolution NDVI analysis to evaluate the interface of development, GSI interventions, and ecosystem services trends in Philadelphia, PA. Our ultimate goal is to exhibit ways that co-benefits can be evaluated and incorporated into GSI planning and tracking processes.

2.3 Methods

2.3.1 Greenness Tracking Over City Boundaries

2.3.1.1 Selection of the Study Cities and the Study Period

The ten cities selected for this study are distributed throughout the contiguous United States and are located in a range of hydro-climatic regions (Table 2.1). The cities were selected due to their geographic, hydrologic and climatological diversity, availability of data, and the authors' institutional knowledge of the cities. Each city's stormwater infrastructure is described in Table 2.1. The selected cities have GSI programs and all the cities with combined sewer systems (5 of 10) have consent decree agreements with the USEPA that require the use of GSI to achieve compliance (USEPA, 2019a). Table 2.1 also identifies each city's signature greening program or plan that includes GSI goals and the year that effort began (City and County of Denver, 2013; City of Austin, 2012; City of Charlotte, 2019; City of Los Angeles, 2019; City of Milwaukee, 2015; District of Columbia, 2019; Philly Watersheds, 2018a; Seattle Public Utilities, 2015; The University of Arizona, 2015; USEPA, 2018). In addition to the cities being geographically diverse, the programs and/or goals that promote GSI are varied. Cities like Austin, Denver, Los Angeles, and Washington DC have included GSI in their multi-department sustainability plans while cities like Philadelphia have stormwater specific programs that collaborate with other city departments (City and County of Denver, 2013; City of Austin, 2012; City of Los Angeles, 2019; District of Columbia, 2019; Philly Watersheds, 2018a). All cities discuss co-benefits as priorities within their plans, either explicitly or as ancillary benefits they expect to accrue with GSI installation. Milwaukee plans to "[pursue] site-specific combinations of both grey and green infrastructure to maximize stormwater management and the co-benefits associated with increased green space" (City of Milwaukee, 2019).

To track the installation of GSI, cities have tree canopy goals (Charlotte and Washington DC) or volumetric management goals (Philadelphia and Seattle) (City of Charlotte, 2019; District of Columbia, 2019; Philly Watersheds, 2018a; Seattle Public Utilities, 2015). Philadelphia's "greened acres" goal relates to GSI management of "at least the first inch of rainfall over an acre of hard surfaces" (Philly Watersheds, 2018a). Seattle's Integrated Plan, which was created in response to a USEPA Consent Decree, aims to manage 700 million gallons of stormwater per year using GSI by 2025 (Seattle Public Utilities, 2015). None of the cities in this analysis use a vegetation index to track GSI implementation.

As shown in Table 2.1, most of the signature greening programs or plans have start dates after 2010. While GSI was installed within each city in the proceeding decades, the programs or plans selected outline meaningful commitments that should result in the installation of city-wide green SCMs. The study period used in the current analysis is 1990 to 2016. The start of the study period coincides with the impetus of Phase 1 MS4 permitting, which is used as a proxy to the establishment of stormwater agencies in all of the study cities (USEPA, 2019b).

Table 2.1: Selected characteristics of the ten study cities (Trust for Public Lands, 2019).

City	Total Population (2017 forecast)	City Land Area (km^2)	Population Density (10^3 people/ km^2)	Type of Stormwater Infrastructure	Tree Cover (%)	Signature Greening Program/Plan with GSI Goals	Program / Plan Effective Year	Source
Austin, TX	935,606	756.4	1.2	SS	26.7	Imagine Austin	2012	(City of Austin, 2012)
Charlotte, NC	1,063,054	1,344.80	0.8	SS	49.8	Trees Charlotte	2011	(City of Charlotte, 2019)
Chicago, IL	2,781,116	553.6	5	CSS and SS	31.3	USEPA Consent Decree	2014	(USEPA, 2018)
Denver, CO	699,521	302.7	2.3	SS	17.6	2020 Sustainability Goals	2013	(City and County of Denver, 2013)
Los Angeles, CA	3,986,443	1,193.90	3.3	SS	31.5	Sustainable City pLAn	2015	(City of Los Angeles, 2019)
Mesa, AZ	493,089	338.2	1.5	SS	26.1	LID Toolkit	2015	(The University of Arizona, 2015)
Milwaukee, WI	591,865	239.3	2.5	CSS and SS	46.4	GI Baseline Inventory	2015	(City of Milwaukee, 2015)
Philadelphia, PA	1,587,761	335.5	4.7	CSS and SS	40.7	Green City, Clean Waters	2011	(Philly Watersheds, 2018a)
Seattle, WA	687,870	213.5	3.2	CSS and SS	35.1	Integrated Plan	2015	(Seattle Public Utilities, 2015)
Washington DC	674,875	157.6	4.3	CSS and SS	33.9	Sustainable DC Plan	2013	(District of Columbia, 2019)

SS= Separate sewer system; CSS = Combined sewer system

The study period is meant to establish trends in vegetation within cities before major GSI efforts began. Most of the cities started their signature greening programs post-2010, so a truncated 2010 to 2016 analysis was also performed as an initial screening for the impacts of recent GSI installations on city-wide greenness. The trends in vegetation are used as proxies for environmental and ecological co-benefits; a city found to be losing vegetation is assumed to be losing related co-benefits.

2.3.1.2 Calculating City Greenness Trends and Correcting for Climate Impacts

Annual greenness was calculated for each city and a trend analysis was undertaken for the study period (1990 to 2016). Using Google Earth Engine (GEE), surface reflectance images were processed at a 30 by 30 meter (m) resolution from Landsat 5 Thematic Mapper (TM), Landsat 7 Enhanced Thematic Mapper Plus (ETM+), and Landsat 8 Operational Land Imager (OLI) sensors for years 1990-2011, 2012, and 2013-2016, respectively (Gorelick et al., 2017; Masek et al., 2006; Vermote, Justice, Claverie, & Franch, 2016). NDVI was then calculated from the images by subtracting the red band values (RED) from the near infrared values (NIR) and then dividing the difference by the sum of the red band and near infrared bands (i.e. $NDVI = (NIR - RED)/(NIR + RED)$). NDVI values range from -1 to 1, with -1 to 0 representing dead vegetation, or paved surfaces and 0 to 1 representing different levels of vegetated health.

An initial 30 percent (%) cloud threshold was applied to remove images compromised by cloud cover. Maximum value compositing (MVC) was created "on a pixel-by-pixel basis" where "each NDVI value is examined and only the highest value is retained for each pixel location" (Holben, 1986). The highest value pixels were compiled into a composite image of maximum values for the study period (Holben, 1986). For this study, an MVC was created for each year in the study period (1990 to 2016) over the duration of a calendar year (January 1 to December 31). MVC is a ubiquitous technique in remote sensing that smooths noise found in NDVI data (Pettorelli et al., 2005). The MVC images were then masked for water features using the USGS's National Hydrography Dataset (USGS, 2018) and area-averaged over each city's boundary as defined by 2016 Census TIGER/Line spatial data (United States Census Bureau, 2016). The final product is an annual area-averaged maximum composite NDVI ($NDVI_{aaamc}$) for each year in the study period. Denver required an additional filter to cap NDVI values from the OLI data at 0.95

from 2013 to 2016 due to false highs in ultra-urban areas identified in initial inspections of the mapping component of GEE output.

To correct for any disparities between the three sensors, $NDVI_{aaamc}$ values were calculated for each of the cities for the overlap years between TM and ETM+ (2000-2011) and ETM+ to OLI (2013-2016). TM was continuous for matching years in terms of magnitude with ETM+, but OLI over-predicted NDVI. These results are consistent with existing literature (Flood & Neil, 2014; Li, Jiang, & Feng, 2013; Wilson & Norman, 2018). To correct the OLI data and avoid banding issues from ETM+ data, a regression was performed on the aggregated data (Markham, Storey, Williams, & Irons, 2004). The resulting equation, $ETM+_{10cities} = -0.0557 + (1.011 * OLI)$, was used to transform all data from OLI to ETM+ predicted values for the years 2013 to 2016. Data were transformed to predicted ETM+ values as they proved to be consistent with TM data.

Linear regression was performed between $NDVI_{aaamc}$ values and annual precipitation to determine the impacts of climate on each city's $NDVI_{aaamc}$ time-series, as adopted from a dryland degradation assessment approach (J. Evans & Geerken, 2004). Annual precipitation was obtained from NCDC Climate Data Online for each city's airport, with the exception of Austin whose data was from Camp Mabry (NCEI, 2018). Cities showing significant relationships ($P < 0.05$) between $NDVI_{aaamc}$ and precipitation underwent an additional residuals analysis to remove the climate signal from their $NDVI_{aaamc}$ time series. With the climate signal removed, any trends in the residuals are considered results of anthropogenic interventions (J. Evans & Geerken, 2004).

Mann-Kendall (MK) trending tests were performed using MiniTab (Minitab Inc., 2010) for each city's $NDVI_{aaamc}$ time series and each of the climate-impacted city's residuals time series for the study period from 1990 to 2016. MK downward P-values of less than 0.05 (decreasing) or greater than 0.95 (increasing) are considered significant.

To explore more recent trends and gain insight into potential GSI program impacts, linear regression was performed on the truncated time series from 2010 to 2016 with $NDVI_{aamc}$ as the independent variable and year as the dependent variable. While the start dates of GSI programs in the ten cities (shown in Table 2.1) are after 2010, this time period was selected so that more data could be included in the analysis. Linear regression was employed on this smaller dataset as the sample size is too small for valid MK trend testing. Regression P-values of less than 0.05 are considered significant.

2.3.2 Case Study: GSI Inventory and High-Resolution Greenness Tracking in Philadelphia, PA

A GSI inventory analysis was performed to investigate the spatial spread and greenness contributions of SCMs in Philadelphia during the study period. Philadelphia was selected because of its status as a leader in GSI in the US as evidenced by the $1.2 billion allocated for GSI projects (Gordon, Quesnel, Abs, & Ajami, 2018). Spatial stormwater data was acquired using OpenDataPhilly, the official data repository for the City of Philadelphia (City of Philadelphia., 2018). Of the 5 spatial datasets containing GSI information on OpenDataPhilly, only the "Stormwater Practice Polygons" layer was selected for analysis as it is the only layer that approximates the extent of installed SCMs (City of Philadelphia., 2018). The remaining datasets were in point or line format so their spatial extent was unknown. The SCMs analyzed in this study were installed between 1990 and 2016 and have "active status" (as opposed to proposed). These criteria resulted in the inclusion of 56% of total SCMs in the "Stormwater Practice Polygons" layer and 84% of the active projects in the layer. The majority of the 44% of the remaining projects did not have a date associated with their entry and therefore could not be included in the analysis. Of the projects selected for evaluation, 80% were identified as privately-owned projects.

The spatial GSI inventory was performed by calculating the area of each of the selected SCMs. Average area is calculated for each of the 11 SCM types identified in the layer (e.g. the area of each discrete wetland was calculated and then averaged to give one average area value for wetlands). Greenness was calculated using GEE and OLI data for the year 2016 for each SCM type. Similar to the city greenness approach outlined in Section 2.1, MVC was used on all pixels touching or contained by the spatial extend of each SCM. Maximum pixels were area-averaged by type of SCM, resulting in 2016 average greenness values for each the 11 SCM types (e.g. all the pixels touching the spatial extent of each discrete wetland were averaged resulting in one greenness value for wetlands). Pictures and descriptions of each SCM, as defined by Philly Watersheds, can be found online (Philly Watersheds, 2018b).

Second, to demonstrate the potential for using NDVI to track GSI installation and the larger impacts from all types of development, zip code level $NDVI_{aaamc}$ was calculated for the City of Philadelphia from 1990 to 2016 and tested for trends using MK. Three zip codes of interest were selected for further analysis due to their observed trends and proximity to combined sewer service (CSS) areas. Due to the regulatory requirements discussed in the introduction, the CSS sewershed was hypothesized to be a priority area for GSI interventions. A 30 by 30 m pixel-level composite spatial layer was created by subtracting the maximum greenness value for the years 1990 to 1999 from the maximum greenness values for the years 2013 to 2016. The composite from 2013 to 2016 was adjusted for satellite mission disparities using the regression from the national analysis. The composite years were selected to create a baseline greenness value (1990 to 1999) using TM data to be subtracted from a recent year composite (2013 to 2016) that was created using corrected OLI data to simplify the challenges associated with creating a multi-sensor/ multi-year composite.

The resulting composite spatial layer highlights hot spots of development activity over the study period. Hot spots for this study are defined as pixels with a -0.9 to -0.5 decrease or 0.5 to 0.9 increase in NDVI. Historic satellite imagery from Google Earth Pro and the filtered SCM spatial layer from the GSI inventory were used to evaluate changes in land cover within the three study zip codes using pixels with hot spot values as identifiers of redevelopment.

2.4 Results and Discussion

2.4.1 Climate and Greenness

Removing the effects of precipitation in arid climates is a critical first step in being able to equitably compare greenness patterns across the study cities. With the climate signal removed, anthropogenic interventions characterized by adding greenness (e.g. installing parks or other vegetated areas) or losing greenness (e.g. infill re-development of a single-family lot into multiple condominium units) are assumed to dominate the urban landscape.

Table 2.2: Results of the national study with significant trends highlighted.

City	Regression P-value for $NDVI_{aaamc}$ and Annual Precipitation	P-value of Initial Decreasing Trend	P-value of Residual Decreasing Trend	Trends as Determined by Mann-Kendall
Austin	***0.001***	0.17	0.1	No Trend
Charlotte	0.74	0.23	-	No Trend
Chicago	0.73	***0.02***	-	***Decreasing Greenness***
Denver	***< 0.001***	0.5	0.37	No Trend
Los Angeles	***< 0.001***	0.43	0.93	No Trend
Mesa	***< 0.001***	***0.006***	0.06	***Decreasing Greenness Likely due to Climate***
Milwaukee	0.91	***0.97***	-	***Increasing Greenness***
Philadelphia	0.82	***0.0002***	-	***Decreasing Greenness***
Seattle	0.39	***0.97***	-	***Increasing Greenness***
Washington DC	0.5	***0.004***	-	***Decreasing Greenness***

Four study cities (Austin, TX; Denver, CO; Los Angeles, CA and Mesa, AZ) were found to have strong correlations between precipitation and greenness (Table 2.2). Higher annual precipitation coincided with higher levels of greenness in each of the four cities. Three of these cities (Denver, Los Angeles, and Mesa) have the lowest greenness values out of the ten cities studied, while Austin has the second highest greenness value over the study period (Table 2.2). The three cities with low greenness values are located in the arid west and the positive correlation between greenness and precipitation is consistent with the literature (Burrell, Evans, & Liu, 2017). Austin is located in a dry sub-humid climate (Reeves et al., 2015). The remaining cities that do not show a strong relationship between greenness and annual precipitation are located in more humid climates (Reeves et al., 2015). From analyzing the spatial spread of the aridity index in the US in Reeves et al. (2015), it is evident that cities located in areas classified as humid do not experience the same greenness response to precipitation as cities in non-humid areas. The six cities located in humid areas are not sensitive to inter-annual rainfall and thus most trends in greenness are due to non-climate related reasons, either anthropogenic interventions or maturing vegetation. To screen for anthropogenic interventions in the four precipitation-sensitive cities, the signal related to precipitation is removed using a residuals analysis. None of the residuals of the four precipitation-sensitive cities were found to have a trend over the study period (Table 2.2), suggesting that anthropogenic influences are insignificant and that any initial trends observed before the residuals analysis are due to climate.

2.4.2 City Greenness Trends

Greenness for each of the 10 cities for the 1990 to 2016 study period is shown in Figure 2.2. On average, Charlotte, NC and Austin, TX (mean $NDVI_{aaamc} = 0.65, 0.56$, respectively) are the greenest cites and Mesa, AZ and Los Angeles, CA (mean $NDVI_{aaamc} = 0.28, 0.36$, respectively) are the least green. The results of the trending tests are summarized in Table 2.2. After considering the impact of climate on greenness, only Milwaukee and Seattle show statistically significant increases in greenness over the 26-year period. Conversely, Chicago, Mesa, Philadelphia, and Washington DC experience decreasing greenness. With the precipitation signal removed, Mesa's residuals show no trend which means the initial decreasing trend can likely be attributed to climate. Austin, Charlotte, Denver, and Los Angeles do not show any significant trend. Interestingly, each of the three categories above (increasing, decreasing, and no trend) include cities across the range of greenness.

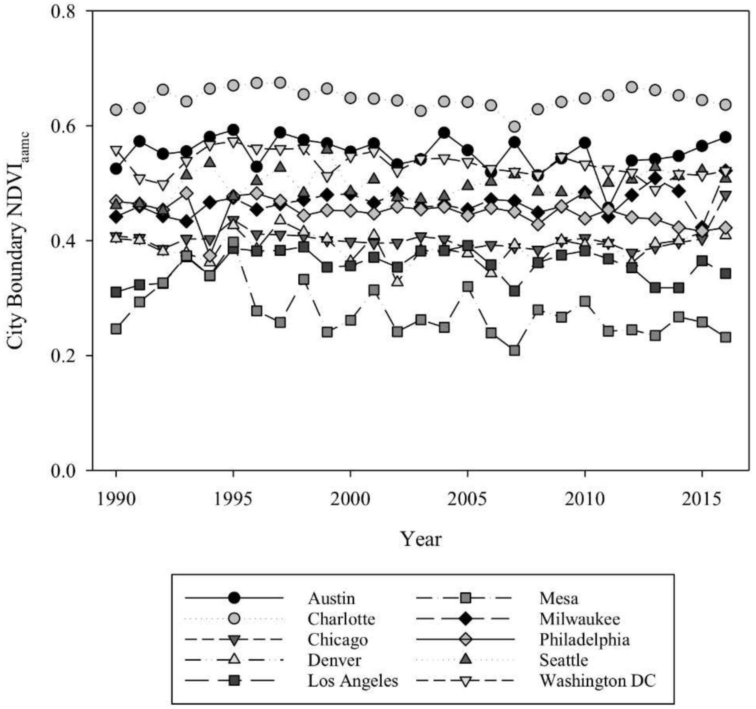


Figure 2.2: Annual maximum greenness trends of the ten study cities from 1990 to 2016.

Adjusting for climate impacts, Chicago, Philadelphia, and Washington DC were found to have decreasing greenness over the study period. While these cities have promoted green infrastructure interventions during the end of the study period, the loss of greenness does not mean that these programs are failing to provide co-benefits. Cities implementing GSI can lose greenness due to rapid development or redevelopment that outpaces the installation of vegetated areas. Population trends since 1990 for each city vary; Philadelphia and Chicago have experienced decreasing/stagnant growth while Washington DC is increasing in population (U.S. Census Bureau, 2016). Increased imperviousness in these cities likely varies by neighborhood and could be tied to redevelopment to increase housing density to make room for more residents or redevelopment as a means of community revitalization to draw people back to the city. In addition, as mentioned in the introduction, not all GSI has a vegetated signal that would be picked up by remote sensing. This relationship is further evaluated in the following case-study. For cities losing greenness, integrated city-wide plans that span beyond stormwater management entities to include joint greenness goals may be the key to gaining vegetation and ecosystem services. A unifying metric like NDVI can be used to track progress in all types of green infrastructure towards city-wide and multi-institutional goals.

The cities with increasing greenness, Milwaukee and Seattle, are likely getting greener due to factors beyond the installation of GSI. Again, population trends since 1990 in both cities vary with Seattle increasing and Milwaukee decreasing in residents (U.S. Census Bureau, 2016). Because NDVI in both cities did not have strong correlations with precipitation, their increased greenness is due to non-climate related variables. Seattle and Milwaukee both have greater than 35% tree cover and over 10% of each cities' areas is covered with parks (Trust for Public Lands, 2019). We hypothesize that the observed increase in greenness trends are likely attributed to preservation and maturing of larger green spaces distributed throughout the city.

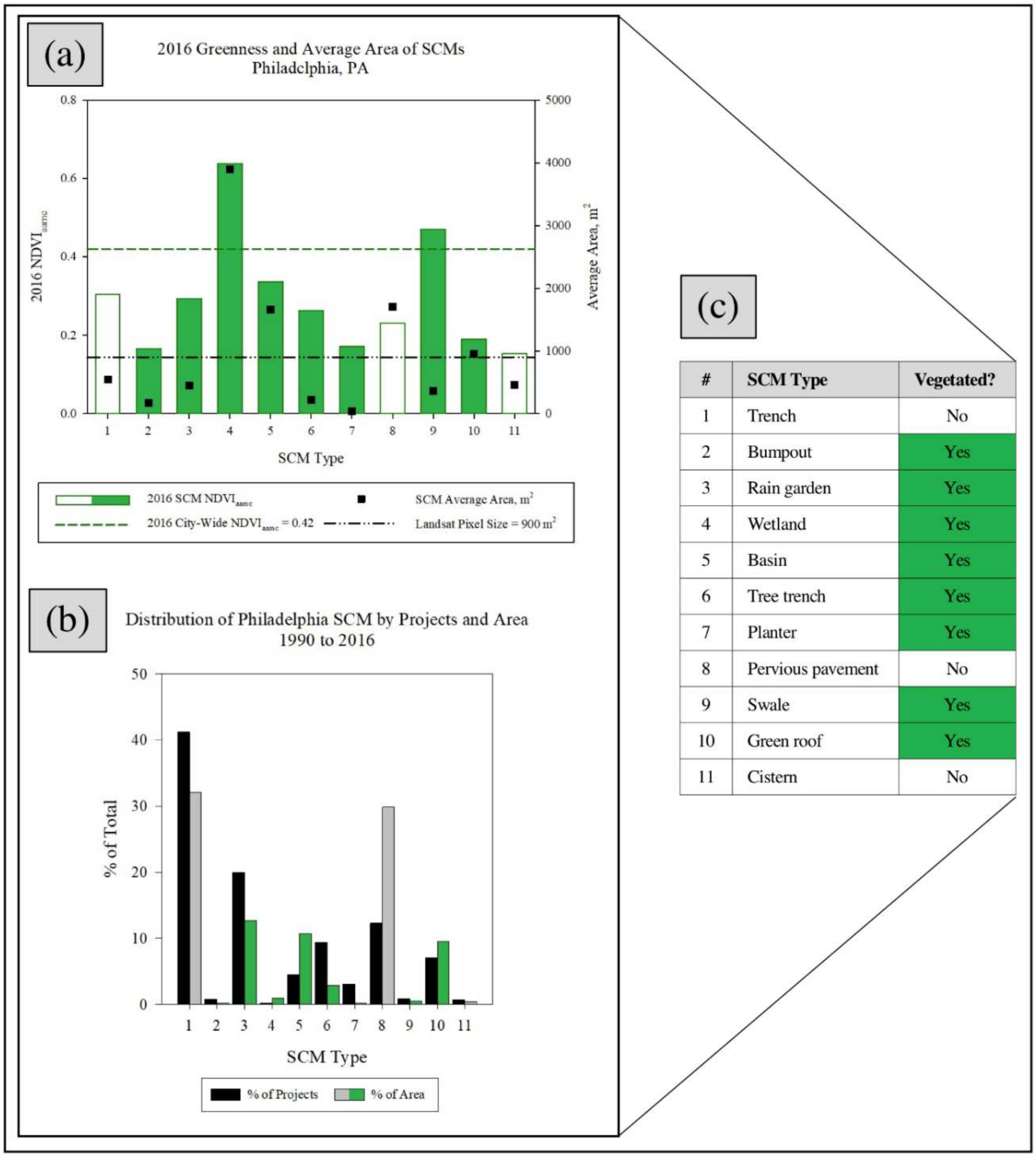
Greenness trends aggregated by city boundary were selected for this study as a national basis of comparison among ten cites. Evaluation of smaller geometries, like zip codes or Census Tracts, may provide more insight into the installation of vegetated GSI and accrual of co-benefits at a neighborhood-level scale. In the context of co-benefits, city-wide greenness tracking can provide insights into systems-level ecosystem services trends within a city and provide context for GSI intervention planning at smaller scales. For example, if greenness is being lost at a city-wide level but gained in certain zip codes, planners can evaluate which interventions are contributing to the increased vegetation and can model future efforts in other zip codes to capitalize on known successes. The linear regressions performed for the 2010 to 2016 period only found one significant trend ($P = 0.02$); a decreasing greenness (slope = -.005) in Philadelphia. Results for all the linear regressions on cities and residuals can be found in Appendix B.

2.4.3 Case Study: GSI Inventory and High-Resolution Greenness Tracking in Philadelphia, PA

2.4.3.1 GSI Inventory

The spatial inventory of the SCMs for the city of Philadelphia is summarized in Figure 2.3. When analyzed for greenness, Figure 2.3(a) shows that only two SCMs, wetlands (SCM Type 4 (4)) and swales (9) have greenness values over the 2016 city-wide value. These two SCMs are likely contributing more to city-wide greenness than other SCMs. When analyzed for average area, Figure 2.3(a) shows that bumpouts (2), tree trenches (6) and planters (7) have the smallest footprint. Wetlands (4), basins (5), pervious pavement (8), and green roofs (10) have larger footprints, and on average span an entire Landsat pixel area (900 m^2).

Figure 2.3(a) shows the relationships between size and greenness for different GSI. For SCM types whose average size is smaller than Landsat pixels, the vegetation in the surrounding area becomes more important. Vegetated SCMs like tree trenches and planters have lower NDVI values because they are often installed adjacent to streets and sidewalks and are not being installed at a scale that can influence overall greenness signal in the pixel. Additionally, not all of the area attributed to tree trenches and planters is vegetated - especially during the first couple years of installation. The type of vegetation is also important to consider, particularly in the case of trees. As SCMs with trees continue to mature, their vegetated area of impact will span beyond the bounds of the SCM footprint. The swales (9) evaluated have smaller footprints but are often installed as part of a larger green infrastructure project so they have a higher greenness signal. While a higher spatial resolution analysis may help better attribute the greenness contributions of smaller SCMs, the Landsat pixel level of resolution is appropriate for this study because co-benefits are more likely to be functionally realized at this scale (Andersson et al., 2015).



#	SCM Type	Vegetated?
1	Trench	No
2	Bumpout	Yes
3	Rain garden	Yes
4	Wetland	Yes
5	Basin	Yes
6	Tree trench	Yes
7	Planter	Yes
8	Pervious pavement	No
9	Swale	Yes
10	Green roof	Yes
11	Cistern	No

Figure 2.3: Figure 2.3(a) shows average greenness for each SCM type (represented by bars) as compared to 2016 city-wide greenness (left vertical axis) and the average SCM size by type (represented by black squares) in relation to the 30 by 30 m Landsat resolution (right vertical axis). The green bars in Figure 2.3(a) and 2.3(b) indicate vegetated SCMs and table 2.3(c) attributes the SCMs types and vegetation to each number in the x-axes in 2.3(a) and 2.3(b).

The green roofs included in this analysis have an underwhelming greenness signal despite being vegetated and larger than Landsat pixels on average. After comparing green roof locations and satellite imagery, it is difficult to see if some of the green roofs identified have been installed. This anomaly may point to challenges GSI installers are having in the construction, vegetation establishment, or on-going maintenance of green roofs in the City and warrants a closer look by members of GSI program staff.

To better understand the impact of larger SCMs and to put the observations made about Figure 2.3(a) into context, Figure 2.3(b) shows a comparison between the percent of GSI projects by SCM and the percent of GSI projects by installed area. Approximately 40% of projects by type are non-vegetated trenches that account for a little over 30% of total SCM area. Pervious pavement, another non-vegetated SCM, also accounts for a large share of total SCM area (nearly 30%). Overall, 62% of the total GSI footprint analyzed is composed of non-vegetated SCMs. Wetlands and swales, the greenest SCMs in Figure 2.3(a), represent a small portion of overall GSI by project number and area.

Consideration of an SCM’s primary function is useful for this analysis. For example, trenches are installed to infiltrate stormwater and treat water quality through filtration and settling, while pervious pavement is installed to infiltrate and detain stormwater volumes and treat water quality through filtration (UDFCD (Urban Drainage and Flood Control District), 2015). Installing trenches and pervious pavement can provide a straightforward path to meet the Philadelphia’s greened acres volume-based goal, but the prevalence of these two SCMs may help explain why the city was found to continue to lose greenness during both periods of greenness trending (1990 to 2016 and 2010 to 2016). Both SCMs provide reliable ways to capture and treat stormwater, and their ubiquity within the evaluated dataset is likely due to institutional experience with those technologies. While volume-based goals help accrue some co-benefits like flood control mitigation and improved water quality, these SCMs do not provide greenness and therefore are not likely to provide any of the 14 co-benefits correlated to vegetation. Referring back to Figure 2.3(b), the basins and green roofs being installed may be projects with larger vegetated area payoffs, as identified by the lower percent project but higher percent area. If GSI planners are looking to shift their focus towards vegetated SCMs, these projects may be good candidates, provided the potential challenges associated with green roofs are resolved.

2.4.3.2 Philadelphia Hot Spot Analysis

To better understand the impacts of GSI on greenness on at the city-block scale, a hot spot analysis was performed. Three zip codes within Philadelphia, 19112, 19139, and 19133 (Figure 2.4), were selected for further analysis due to their increasing greenness trend in CSS area, (19112), decreasing greenness trend in CSS area (19139), and no trend (19133). Each zip code has a different majority land use, with 19112 containing mostly institutional buildings and structures, 19139 containing medium density residential development and 19133 containing a mix of housing densities.

Zip code 19133 exhibited no greenness trend when analyzed over the zip code boundary (Figure 2.5(a)). The hot spot identified in the composite image is a patch of brown pixels (highlighted with a blue box) that signals loss of greenness. Zooming in, this brown patch is overlaid on 2 city blocks. Historic satellite imagery at the hot spot shows a shift from open lots and single-family homes to medium density development. The GSI installed with this redevelopment are outlined with green lines and correspond to non-vegetated trenches installed under the parking lot. In addition, and excluded in the SCM layer analyzed, is a green roof on the building in the May 2016 image (right side). Even with the installed GSI, the net impact of the development resulted in decreased greenness. This observation provides visual evidence of the high rate of installation of non-vegetated SCMs seen in the GSI inventory. Hot spots of added greenness are also occurring within zip code 19133's boundaries. Upon further inspection, many of these pockets of added greenness are from clusters of maturing vegetation like trees.

Zip code 19139, which has an overall decreasing greenness trend, shows another decreasing hot spot (Figure 2.5 (b)). The imagery shows vacant land developed into a juvenile detention facility and trenches to mitigate post-development stormwater. Some of the original green space is retained, but parking lots have also been added. In the context of ecosystem services and co-benefits, even with a loss of greenness, a civic facility is expected to provide more social benefits to the surrounding community than the ecosystem services provided by the vacant lot. The changes in this zip code show that loss of greenness, while correlated with loss of environmental and ecological co-benefits, is not always associated with loss of social co-benefits. Depending on the values of a community, the tradeoffs of decreased greenness for the access to a civic facility may offset the loss of other ecosystem services.

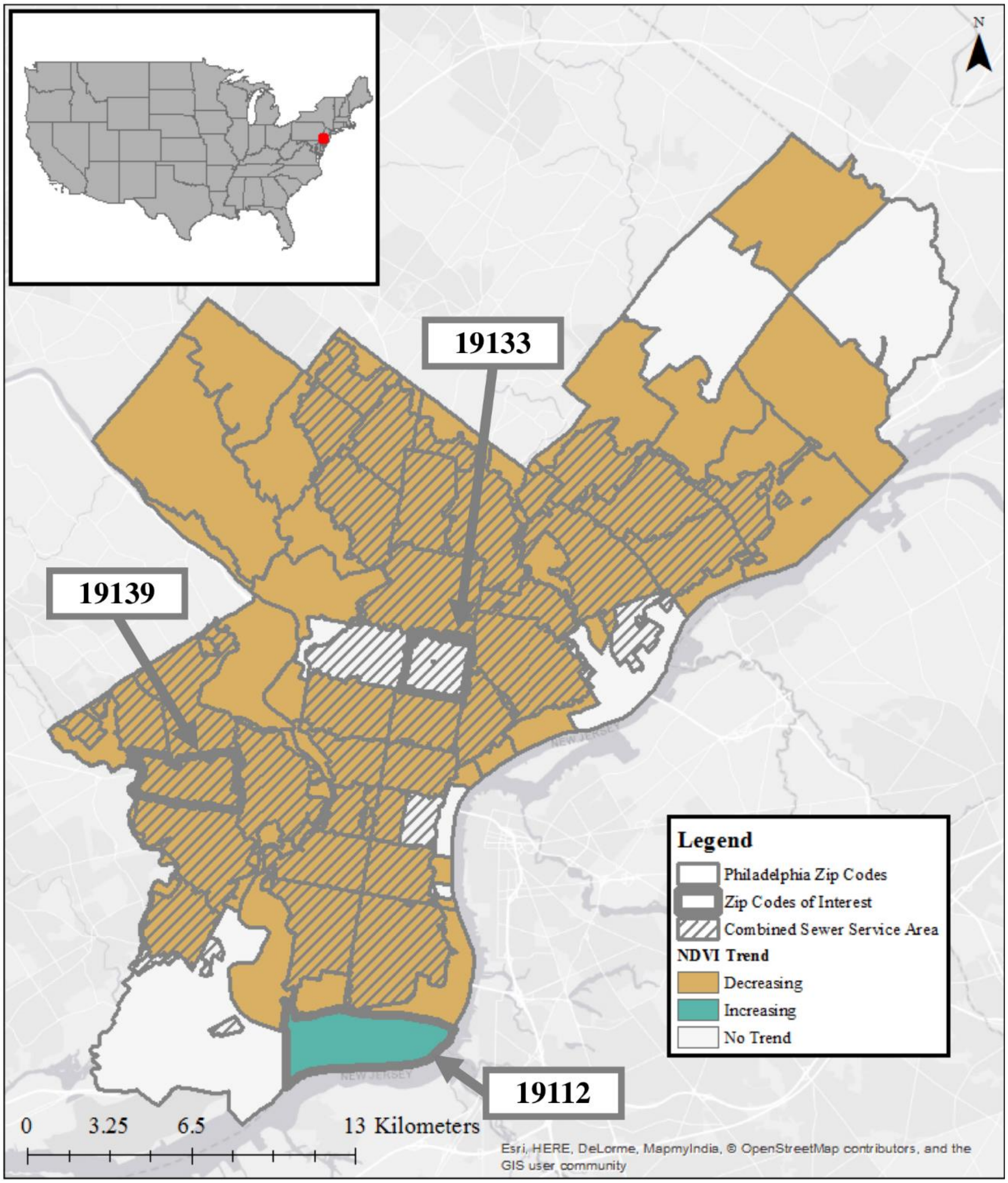


Figure 2.4: Zip codes trends of NDVI in Philadelphia over the study period and their relation to the city's combined sewer service area. The changes in NDVI of the three highlighted zip codes are used for analysis at a higher resolution.

Zip code 19112 was the only zip code in the city found to have increasing greenness during the study period (Figure 2.5 (c)). This zip code is occupied by the Philadelphia Navy Yard and image analysis shows that green space was added, specifically in the form of tree trenches as shown with the green lines at the right in the bottom image. As discussed previously, the greenness signal from SCMs like tree trenches is influenced by the surrounding vegetation. The composite shows that the installation of tree trenches in series contributes to a larger increased greenness hotspot that spans many pixels. Although the installed GSI in this zip code is increasing the greenness signal, the redevelopment of a building in the top right corner to a vacant, vegetated lot appears to have a higher influence on the greenness signal. This reinforces the findings of Rugel et al (2017) who showed that a mixture of sizes and distributions of vegetated areas (i.e. parks and tree canopy) contribute to urban greenness and provides insights into multi-pronged approaches that could help increase greenness in other Philadelphia zip codes (Rugel, Henderson, Carpiano, & Brauer, 2017).

The results of the SCM inventory and hot spot analysis provide detailed insights into the decreasing greenness trends in Philadelphia. The SCM layer, and consequently the discrete SCMs selected for evaluation (those with active status and documented completion year during the study period), contain only a fraction of available spatial data published online by the City of Philadelphia related to green stormwater infrastructure. While future studies could incorporate buffers to counteract the limited spatial spread of the point and line layers not included in this analysis, the selected SCMs provide important insights into GSI installations in Philadelphia and how installations can be studied with high-resolution greenness monitoring. Through the use of high-resolution imagery it becomes clear that the context in which a single SCM is installed is important. The trench is Figure 2.5(a), that spans a Landsat pixel and could potentially have significant impacts on the surrounding area, is non-vegetated and installed with higher-density development resulting in the net loss of greenness despite the addition of GSI. The tree trenches and vacant vegetated lot in Figure 2.5(c) belong to the only zip code in Philadelphia that is getting greener. This analysis suggests that smaller vegetated SCMs installed in series, combined with utilization of larger vacant lots, can induce broader greenness increases.

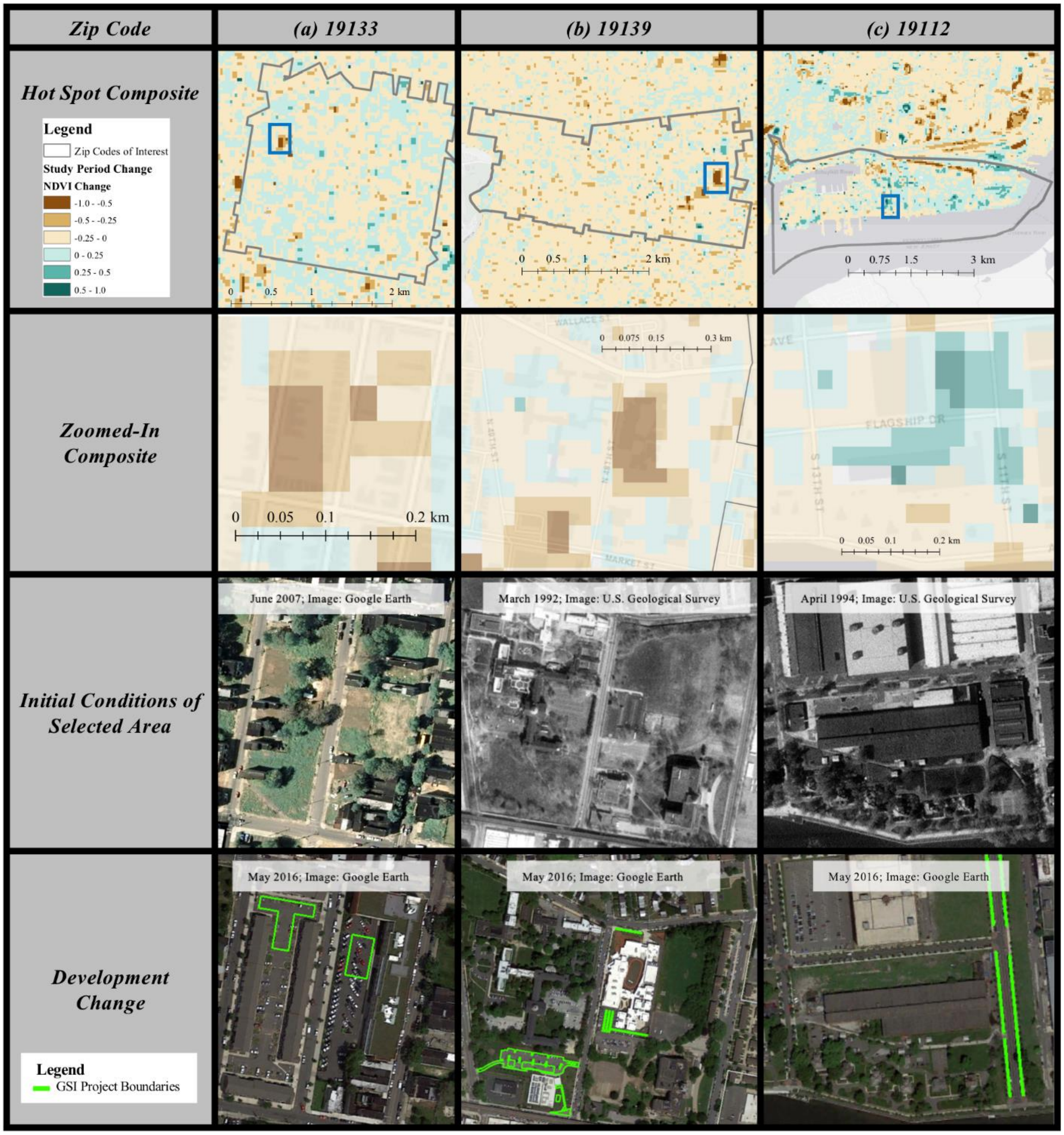


Figure 2.5: Composite imagery from a greenness analysis is shown in relation to historic imagery to show changes in development. Panels (a) and (b) show added non-vegetated GSI accompanying redevelopment while panel (c) shows the impacts of the addition of a series of tree trenches.

2.5 Conclusions

After correcting for climate, only two of the ten study cities (Milwaukee and Seattle) show increased greenness over the 26-year study period. Four cities (Chicago, Mesa, Philadelphia, Washington DC) are losing greenness. The four cities that were more climate sensitive (Austin, Denver, Los Angeles, and Mesa) are located in non-humid areas and have clear greenness responses to precipitation. GSI programs in the study cities were started after 2010 and only overlap the end of the period analyzed; continued greenness tracking can provide more insights into the vegetation impacts of these programs.

In most cases, gains and losses in greenness can be directly linked to gains or losses in environmental and ecological co-benefits. Cites getting greener experience increased ecosystem services due to the maturing of existing green infrastructure dispersed throughout the city in the form of trees and parks. When evaluated over a shorter time period to account for the beginning of city-wide GSI programs or plans, only Philadelphia exhibited a strong (decreasing) greenness trend. These trends may be subject to change as implementation ramps up and the vegetation associated with GSI matures. In the three study cities experiencing decreased greenness, development is outpacing the installation of GSI. Population trends during the study period were found to vary by city and greenness trend suggesting that development/imperviousness is not always increased to accommodate more people but can also be employed as a means to revitalize cities in an attempt to attract more residents.

The GSI inventory of SCMs in Philadelphia found that the greened acres volumetric goal is likely incentivizing SCMs that have a proven track record of infiltration and detention. As a result, 62% of the GSI footprint in the inventory was dedicated to non-vegetated SCMs. Non-vegetated GSI is more similar to traditional grey infrastructure approaches, can be installed in areas traditionally occupied by paved surfaces (i.e. parking lots), and lack the additional burdens associated with maintaining vegetated features. Including non-vegetated SCMs in re-development of lower density lots addresses the changes in stormwater volume due to increased impervious surfaces but results in an aggregate loss of vegetation and loss of most environmental and ecological co-benefits. Loss of vegetation could also result in the accrual of social co-benefit, especially if the land use change provides services to the community.

Moving forward, cities expecting co-benefits from GSI can consider installing more and larger vegetated GSI in conjunction with bolstering other urban green infrastructure projects. As seen in the GSI inventory, the basins and green roofs being installed in Philadelphia provided opportunities for higher greener payoffs than the other SCMs evaluated. Cities can include vegetation monitoring to track the systems-level impacts of increased non-vegetated surfaces. NDVI can be used to set greenness goals so that GSI and other green infrastructure programs can be held accountable for preserving environmental and ecological co-benefits. Evaluating NDVI trends at a finer resolution, like the scale used in this study, can help planners target areas where greenness is being lost and can provide another decision-making variable to be incorporated with engineering design metrics and community preference to create holistic and equitable interventions.

Overall, this study provides a means for decision makers to track bulk ecosystem services and environmental and ecological co-benefits. Future work will attempt to disaggregate and quantify specific co-benefits, including social co-benefits, so that city and stormwater planners can optimize interventions based on community priorities and values.

CHAPTER 3

CONTEXTUALIZING PUBLIC PREFERENCE FOR STORMWATER INFRASTRUCTURE AND ASSOCIATED BENEFITS FOR THREE U.S. CITIES

A paper to be submitted to *Environmental Management*

Katie M. Spahr[1,2], Jessica M. Smith[2], John E. McCray[2], Terri S. Hogue[2]

3.1 Abstract

Green stormwater infrastructure mirrors natural hydrologic processes and is presented as an alternative or complement to traditional grey stormwater infrastructure that uses concrete and pipes to convey flows away from neighborhoods. To encourage greener interventions, practitioners promote co-benefits (ancillary social, ecological and environmental benefits). Co-benefits are accrued at a neighborhood-scale, yet the public is not often asked to weigh in on its preferred outcomes. This study aims at better understanding public preference (by location and demographic) for green infrastructure and co-benefits using an online survey. A representative sample of residents of three US cities (Philadelphia, PA; Denver, CO; and Seattle, WA) were presented informational material and then queried for their preference for different infrastructure types and 16 co-benefits. Results show that most respondents prefer a mix of both green and grey infrastructure to handle stormwater in their neighborhood. Some of this preference shifts to green infrastructure when asked about new neighborhood installations. Black or African American respondents showed a higher preference for grey infrastructure to handle storms while Asian respondents and respondents with a Master's degree or higher showed a higher preference for new green infrastructure installations. Using a lens of importance and consensus, co-benefits generally split into a top three ("Reduced impacts from flooding", "Improved water quality" and "Improved air quality") and a bottom three ("Stress reduction", "Neighborhood cooling" and "Increased property values"). Results of this study can be used as baseline preference data for interventions and can help practitioners select priority benefits in local planning processes.

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3.2 Introduction

As cities around the world develop and redevelop, the amount of impervious surfaces increases, leading to new stormwater quality and quantity challenges. Practitioners have adopted green stormwater infrastructure (GSI) to mirror natural hydrologic processes in the urban environment and disconnect flows from existing grey infrastructure. GSI is typically characterized by vegetated structures that infiltrate and treat stormwater locally while grey infrastructure is typically composed of pipes and drains that capture and convey stormwater to water bodies or wastewater treatment plants. In addition to managing flows and improving water quality, GSI installations can provide communities with ancillary social, ecological and environmental benefits, termed co-benefits (Bell et al., 2019). Co-benefits range from neighborhood beautification from the addition of vegetated GSI to increased local groundwater resources due to the larger volumes of stormwater being locally infiltrated by GSI.

Due to the decentralized nature of GSI installations, agencies that embrace GSI must shift their planning process away from a civil-engineer-centric model and towards an interdisciplinary approach that incorporates input from all relevant stakeholders (Keeley, 2007; Lennon, 2015). While many studies have focused on identifying and engaging stakeholders, such as local community groups and agencies with overlapping interest in GSI planning (Alves et al., 2018; Dhakal & Chevalier, 2017; Feltynowski et al., 2018; Gordon et al., 2018; Heckert & Rosan, 2016; Kati & Jari, 2016; Keeley et al., 2013; Liu & Jensen, 2018; Meerow & Newell, 2017; Nickel et al., 2014; Vandermeulen, Verspecht, Vermeire, Van Huylenbroeck, & Gellynck, 2011), few studies expand their reach to members of the public. The literature that does address public engagement primarily focuses on GSI financing activities, such as willingness to pay for GSI installations on private property (Baptiste, Foley, & Smardon, 2015), and is usually conducted at a case-study level (Derkzen, van Teeffelen, & Verburg, 2017; Madsen, Brown, Elle, & Mikkelsen, 2017; Thurston et al., 2010). Despite the potential significance of co-benefits for residents and growing acknowledgement that public acceptance is a critical component of a successful GSI program (R. R. Brown, 2008; Fitzgerald & Laufer, 2017; Keeley et al., 2013; Nickel et al., 2014), research on the public perception of GSI and co-benefits is very limited. Members of the public hold critical roles as ratepayers experiencing rate increases due to GSI programs, as property owners being asked to install GSI on their private property, and as direct recipients of any co-benefits accrued by GSI in their neighborhood.

The "very high cultural and social heterogeneity" of urban populations (Gómez-Baggethun & Barton, 2013) presents both challenges and opportunities for GSI planning. Many cities focus on community revitalization co-benefits as a key component in their GSI programs (de Graaf & der Brugge, 2010; Haase et al., 2017; Keeley et al., 2013; McGarity et al., 2015; Schilling & Logan, 2008). Analysis of GSI systems in cities attempting to reach underserved populations have found mixed results in regards to actual implementation of GSI in areas of most need (Baker, Brenneman, Chang, McPhillips, & Matsler, 2019; Fitzgerald & Laufer, 2017). Moreover, diverse populations may hold distinct preferences for stormwater infrastructure type and the different co-benefits they offer. Therefore, a diverse subset of a city is important to query to gain insights on perceptions related to spatial and sociodemographic characteristics, and use that data to inform planning efforts.

This study attempts to answer the following questions: (1) how are preferences for GSI influenced by demographic characteristics and city of residence, (2) do residents show a preference for specific co-benefits, and (3) how are preferences for co-benefits influenced by demographic characteristics and city of residence? We investigated these questions using a survey administered to representative population samples of residents of three US cities: Denver, CO; Philadelphia, PA and Seattle, WA. Results from this survey can be used to develop messaging for GSI programs and help inform future finer-scale research on public attitudes towards GSI benefits.

3.3 Methods

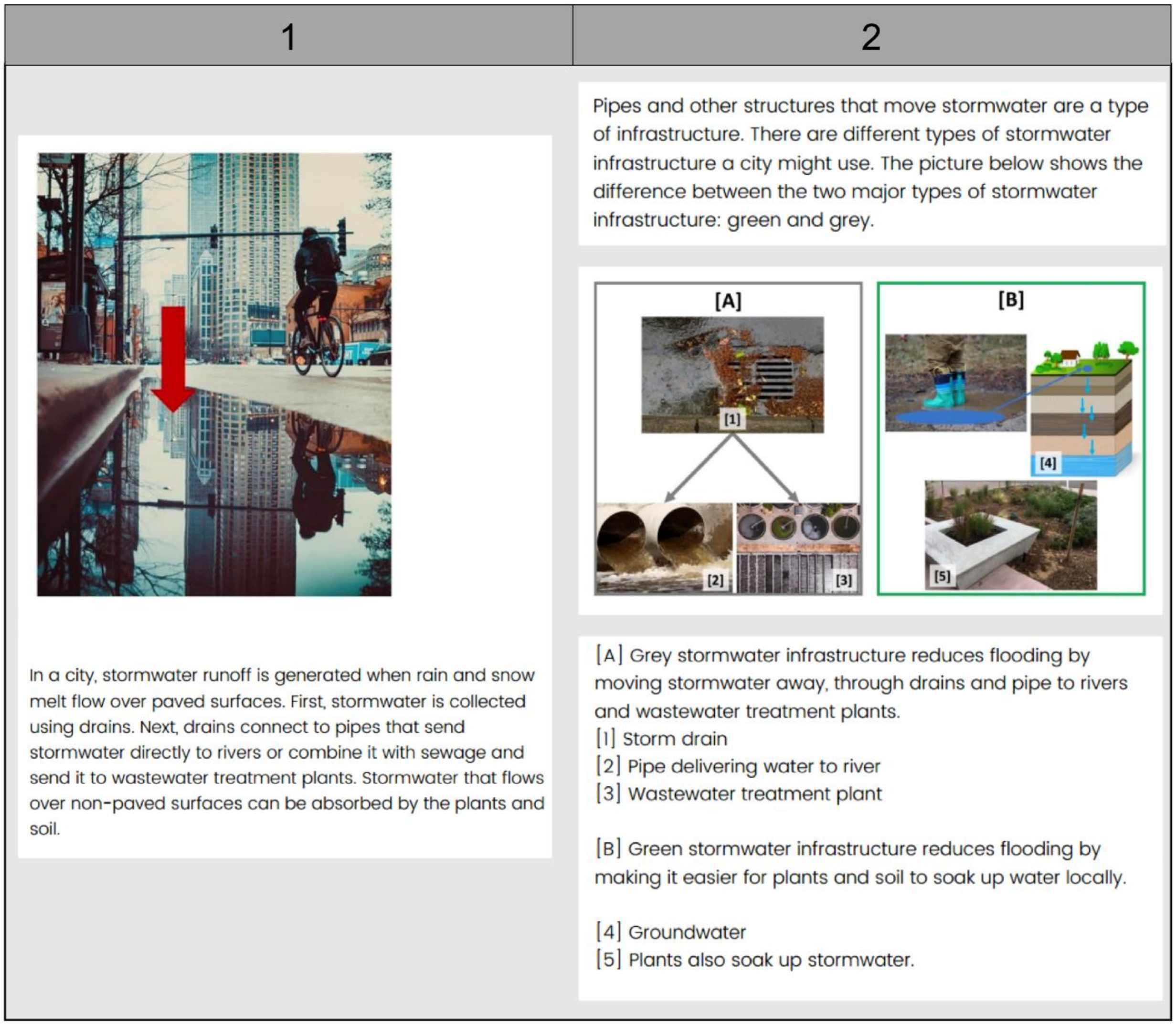
3.3.1 Survey Development

Survey questions were developed to address gaps in scholarly knowledge associated with public preference for green vs. grey stormwater infrastructure and affinity for co-benefits related to stormwater infrastructure. The selected cities (Denver, Philadelphia and Seattle) were chosen based on their diversity in geography, climate, stormwater infrastructure, and policy landscapes.

The survey contained 26 questions accessed after the respondent gave their informed consent. Informed consent was included for compliance with the university's Institutional

Review Board (IRB) exemption for the human subjects work completed. The IRB exemption was initially approved on October 17, 2016 for a broader scope work and approved for a modification that explicitly detailed the work in this chapter on November 7, 2018. The IRB exemption letter can be found in Appendix C.

Survey questions ranged from general questions about stormwater preference to specific preferences about stormwater infrastructure and co-benefits to demographic information. The survey was designed to be administered online and take less than 10 minutes to complete.



In a city, stormwater runoff is generated when rain and snow melt flow over paved surfaces. First, stormwater is collected using drains. Next, drains connect to pipes that send stormwater directly to rivers or combine it with sewage and send it to wastewater treatment plants. Stormwater that flows over non-paved surfaces can be absorbed by the plants and soil.

Pipes and other structures that move stormwater are a type of infrastructure. There are different types of stormwater infrastructure a city might use. The picture below shows the difference between the two major types of stormwater infrastructure: green and grey.

[A] Grey stormwater infrastructure reduces flooding by moving stormwater away, through drains and pipe to rivers and wastewater treatment plants.
[1] Storm drain
[2] Pipe delivering water to river
[3] Wastewater treatment plant

[B] Green stormwater infrastructure reduces flooding by making it easier for plants and soil to soak up water locally.

[4] Groundwater
[5] Plants also soak up stormwater.

Figure 3.1: Infographics were used to ensure all respondents understood how stormwater is generated (1) and the difference between green and grey infrastructure (2).

The survey text included infographics (Figure 3.1) explaining the generation of stormwater, the differences between green and grey infrastructure, and the different scales of green infrastructure to help to ensure that respondents were drawing from a similar knowledgebase when answering the questions. Initial screening was performed using a talk-through approach wherein the researcher walks through the survey with potential respondents and asks for feedback on the questions and infographics. Next, the survey was reviewed by a social science expert on the project team to ensure the wording and structure of questions and graphics are not unduly influencing the respondents. Technical members of the project team then reviewed the survey and infographics for their technical merit. The survey was then piloted online using students from two upper division undergraduate classes at the university.

Once the survey had gone through reviews and iterations, it was translated from English into Spanish and edited by four native Spanish speakers for grammar, wording, and consistency. Both versions of the survey were given to Qualtrics for survey administration. The final survey is included in Appendix D. For each city, spatial and demographic quotas (gender, age, and race) were set to match survey respondent demographics to overall population demographics of each city using data from the 2017 American Community Survey (ACS)(US. Census Bureau, 2017). Spatial quotas were set by creating four zones for each city. Zip codes were allocated to each zone using quantile breaks of population density data calculated from the ACS for each city; for example, high density in Seattle was defined locally and not based on high density in Philadelphia. Spatial aggregation into four zones was performed to anonymize respondents and comply with the university's Institutional Review Board (IRB) exemption associated with this work.

3.3.2 Survey Administration

A soft launch of the survey was administered by Qualtrics from March 26 to 28, 2019 to test the quota logic and quality of results; 40 responses were collected. The soft launch responses helped refine the locational and demographic filters used to screen for qualified respondents. The survey relaunched on March 28 and ran until April 7, 2019. A total of 388 valid responses, including the 40 soft launch respondents, were collected. For all phases of the launch, duplicate and apathetic responses (respondents selecting "I'm not sure" for more than 50% of applicable fields) were filtered out; all other responses were considered valid.

Survey responders received a small incentive from Qualtrics for completing the survey. Upon successful completion of the survey, each respondent was either given Qualtrics points to be redeemed for later incentives or a credit banking for gift cards worth about US $2.60. Qualtrics uses a system of incentives to gather survey responders. The incentive they receive equals 50% the price of the amount the research team paid Qualtrics for each response. The human subjects team that reviewed the research protocol determined that this amount was appropriate. These incentives are standard in human subjects research, but especially crucial for people to allow people with low incomes to spend time involved in research activities (Eubanks, 2011).

3.3.3 Survey Data Analysis

Of the 26 questions asked in the survey, this analysis focuses on responses to the 13 questions relevant to the developed science questions: six that solicited preference for stormwater management and infrastructure and their resulting co-benefits and seven that established the demographic characteristics of the respondent. Analysis of the remaining questions, which include additional demographic information and preference for GSI sizing, will be included in future work. Race was the only demographic category in which the respondent could choose one or more descriptors; all other questions required the respondent to select only one field.

Survey data from the stormwater infrastructure and co-benefit preference questions are reported here by city and demographic breakdowns using percent (%) distribution of answers. Of the 388 responses collected, 149 were from Philadelphia, 122 were from Denver, and 117 were from Seattle. Based on the 2017 ACS population data for each city, the sample sizes have margins of error (at a 95% confidence level) of 8%, 9% and 9%, respectively. To identity any trends, a ± 10% threshold on the aggregate responses was used to identify more or less preference for both stormwater infrastructure and co-benefits by demographic field. For example, if the overall survey respondents showed a 56% preference for a question, outliers were identified at a ≥66% and ≤46%.

Green or grey infrastructure preference was measured using two questions: “Which type of infrastructure do you think could best handle the stormwater in your neighborhood?” and “If your city wanted to put in more stormwater infrastructure in your neighborhood which type would you prefer? Assume your answer has no impact on your stormwater bill or the effectiveness of the system." Through this chapter, the responses to these questions are caveated with language referencing **handling** of stormwater or **new installations**. Because we sought to elicit preference for GSI independent of financial implications, survey questions from this study were framed to remove the monetary component of infrastructure interventions.

To measure co-benefit preference, respondents were first informed that "stormwater infrastructure can have benefits beyond managing the water." GSI vs. grey infrastructure were intentionally not distinguished to not bias the responses. Respondents were then asked to rate their preferences for 16 co-benefits using a 5-point Likert scale of "Very Important" to "Not Important." An "I'm Not Sure" option is also included on the survey as a means to flag respondents' belief in the link between stormwater infrastructure and the specific co-benefit but excluded from analysis because of the small number of respondents that chose the option and its lack of ability to gauge preference. To analyze co-benefit preference, % importance is calculated using the aggregates of the "Very Important" and "Important".

In addition to % importance, the measure of consensus is calculated for each demographic in the co-benefit preference responses (Tastle & Wierman, 2007). Consensus is used to determine how much the members of each demographic group agree with their % importance rating. Consensus (*Cns(X)*) is a measure of agreement within Likert data and ranges from 0 (complete lack of consensus) to 1 (complete consensus) (Tastle & Wierman, 2007).

$$Cns(X) = 1 + \sum_{i=1}^{n} p_i \log_2\left(1 - \frac{|X_i - \mu_i|}{d_X}\right) \tag{3.1}$$

Equation (3.1) calculates consensus by assigning an ordinal number (X) to each Likert category with "Very Important" = 5, "Important" = 4, …, "Not Important" =1. "I'm Not Sure" responses were excluded from the analysis. In equation (1) μ_X is the mean of X, d_X is $X_{max} - X_{min}$ ($d_X = 4$ for this study) (Tastle & Wierman, 2007).

3.4 Results

3.4.1 Demographics of the Survey Respondents

Demographics of the collected responses and their match to the 2017 ACS data for gender, race, and age in each of the three cities is presented in Table 3.1. A percent deficit was calculated by subtracting the 2017 ACS data from the collected responses; a positive deficit indicates an over-representation in that demographic and a negative deficit indicates an under-representation. Most of the deficits are between -5% to 5% and anything equal to or outside of that range is highlighted using bold italic text (Table 3.1). The largest negative deficit, or most underrepresented group in the survey data, is comprised of respondents identifying as Hispanic or Latino in Denver. Each city has some over-representation in the under 55 age groups, likely due to the online nature of the survey (Couper, Kapteyn, Schonlau, & Winter, 2007). Overall most demographics are matched and the established ± 10% threshold for evaluation is deemed to be appropriate (Krejcie & Morgan, 1970).

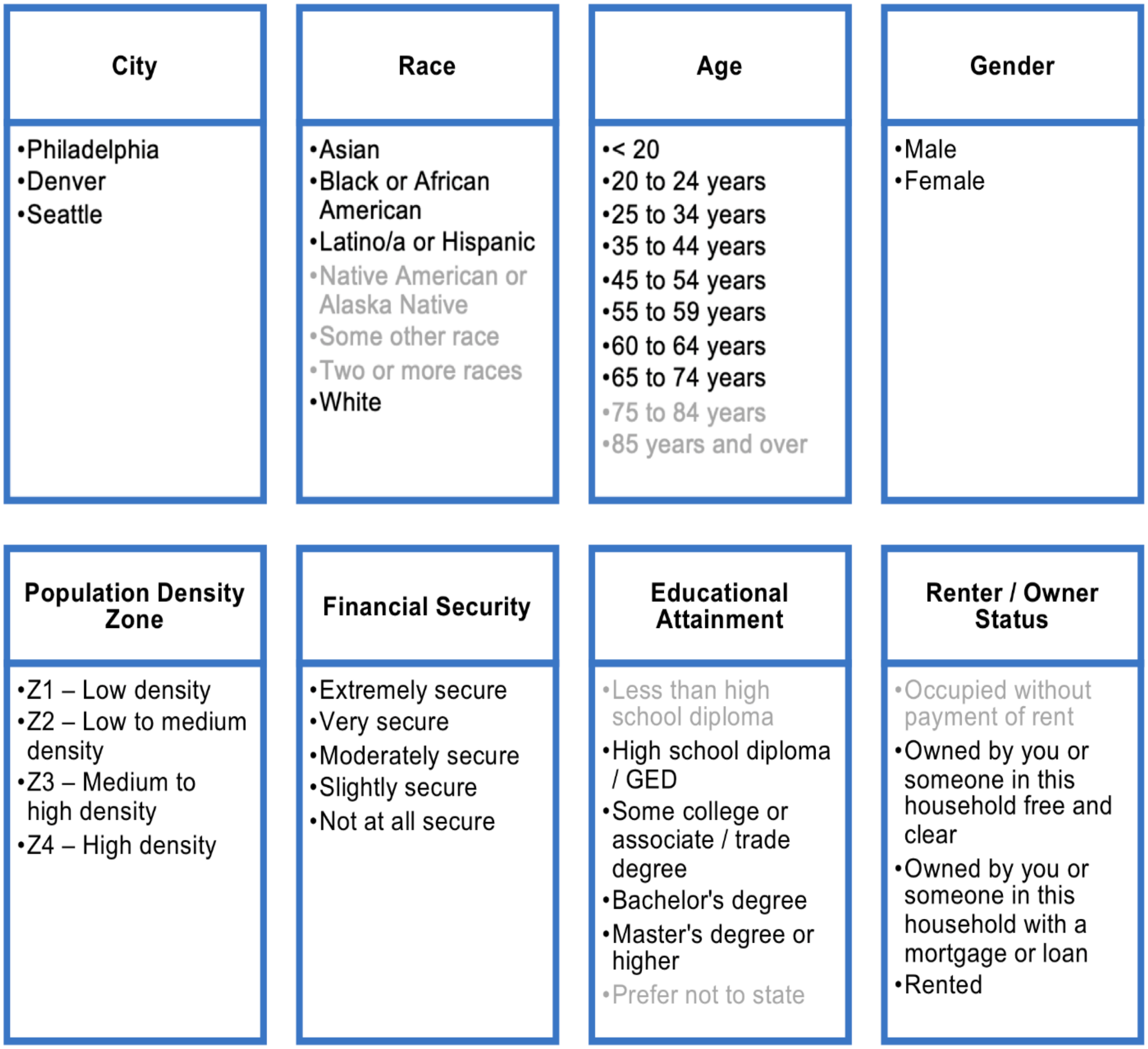
Details for the demographic fields that are used for analysis in the following sections are detailed in Figure 3.2. Of the 41 separate demographic groups identified, eight fields have less than 5% of the total survey sample size (less than 20 responses) and were not included in the analyses in this chapter. These eight fields are written in grey text (Figure 3.2). Except for the city-specific comparisons, the 30 remaining demographics groups (under the categories of race, age, gender, population density, economic security, educational attainment, and renter/owner status) are aggregated by field across each of the three cities.

3.4.2 Public Perception of Stormwater Management

To gauge the impact of the education component of the survey, respondents were asked about their general interest in stormwater management before and after the infographics and GSI/co-benefit preference questions. The spread of before and after responses for all survey respondents in shown in Figure 3.3A; respondents reported a 15% increase in interest ("I am extremely" and "I am very interested"). Most respondents are interested in stormwater when there is a storm or visible flooding (81%, Figure 3.3B) and are confident in their neighborhood's stormwater infrastructure to handle most storms (68%, Figure 3.3C). When both questions are analyzed by city no notable trends emerge.

Table 3.1: Gender, race, and age characteristics of survey respondents as matched to 2017 ACS data for each study city. The largest underrepresentation is Latinos/as or Hispanics in Denver.

	Denver, CO			Philadelphia, PA			Seattle, WA		
Key: ≤-5% or ≥5% deficit	2017 ACS	% Responses	Deficit	2017 ACS	% Responses	Deficit	2017 ACS	% Responses	Deficit
% Male	50.0%	46.7%	-3.3%	47.3%	43.6%	-3.7%	50.1%	50.4%	0.4%
% Female	50.0%	52.5%	2.5%	52.7%	55.7%	3.0%	49.9%	48.7%	-1.2%
% White	76.9%	73.0%	-3.9%	41.6%	40.9%	-0.6%	66.9%	70.9%	4.0%
% Black or African American	9.5%	10.7%	1.2%	42.6%	39.6%	-3.0%	7.6%	8.5%	1.0%
% American Indian and Alaska Native	1.0%	3.3%	2.3%	0.4%	0.0%	-0.4%	0.6%	0.9%	0.2%
% Asian	3.6%	2.5%	-1.1%	7.1%	4.7%	-2.4%	15.0%	14.5%	-0.5%
% Native Hawaiian and Other Pacific Islander	0.1%	0.0%	-0.1%	0.1%	0.0%	-0.1%	0.5%	0.0%	-0.5%
% Some other race	5.5%	0.8%	-4.7%	5.6%	3.4%	-2.2%	2.6%	1.7%	-0.9%
% Two or more races	3.4%	1.6%	-1.8%	2.8%	2.0%	-0.8%	6.7%	4.3%	-2.4%
% Latino/a or Hispanic (of any race)	30.5%	15.6%	***15.0%***	14.1%	13.4%	-0.7%	7.2%	6.0%	-1.3%
% < 20	4.8%	4.9%	0.2%	6.4%	7.4%	1.0%	4.8%	3.4%	-1.3%
% 20 to 24 years	6.3%	7.4%	1.0%	8.0%	12.8%	4.7%	7.9%	7.7%	-0.2%
% 25 to 34 years	22.4%	28.7%	***6.3%***	18.3%	22.8%	4.5%	21.7%	22.2%	0.5%
% 35 to 44 years	15.7%	20.5%	4.8%	12.2%	20.1%	***7.9%***	15.5%	23.9%	***8.4%***
% 45 to 54 years	11.6%	14.8%	3.1%	12.0%	16.1%	4.1%	12.6%	18.8%	***6.2%***
% 55 to 59 years	5.4%	6.6%	1.2%	6.1%	8.7%	2.6%	5.8%	6.0%	0.2%
% 60 to 64 years	4.9%	6.6%	1.6%	5.4%	4.7%	-0.7%	5.6%	6.0%	0.4%
% 65 to 74 years	6.6%	8.2%	1.6%	7.2%	7.4%	0.2%	7.2%	11.1%	3.9%
% 75 to 84 years	3.1%	1.6%	-1.4%	3.9%	0.0%	-3.9%	3.2%	0.9%	-2.3%
% ≤ 85 years	1.6%	0.8%	-0.7%	1.8%	0.0%	-1.8%	2.0%	0.0%	-2.0%



City
- Philadelphia
- Denver
- Seattle

Race
- Asian
- Black or African American
- Latino/a or Hispanic
- Native American or Alaska Native
- Some other race
- Two or more races
- White

Age
- < 20
- 20 to 24 years
- 25 to 34 years
- 35 to 44 years
- 45 to 54 years
- 55 to 59 years
- 60 to 64 years
- 65 to 74 years
- 75 to 84 years
- 85 years and over

Gender
- Male
- Female

Population Density Zone
- Z1 – Low density
- Z2 – Low to medium density
- Z3 – Medium to high density
- Z4 – High density

Financial Security
- Extremely secure
- Very secure
- Moderately secure
- Slightly secure
- Not at all secure

Educational Attainment
- Less than high school diploma
- High school diploma / GED
- Some college or associate / trade degree
- Bachelor's degree
- Master's degree or higher
- Prefer not to state

Renter / Owner Status
- Occupied without payment of rent
- Owned by you or someone in this household free and clear
- Owned by you or someone in this household with a mortgage or loan
- Rented

Grey fields = < 5% of Sample Size (< 20 respondents)

Figure 3.2: Respondents were asked to identify themselves using the demographics categories and corresponding fields listed above. Fields in grey text were excluded from the demographic analysis due to small sample sizes.

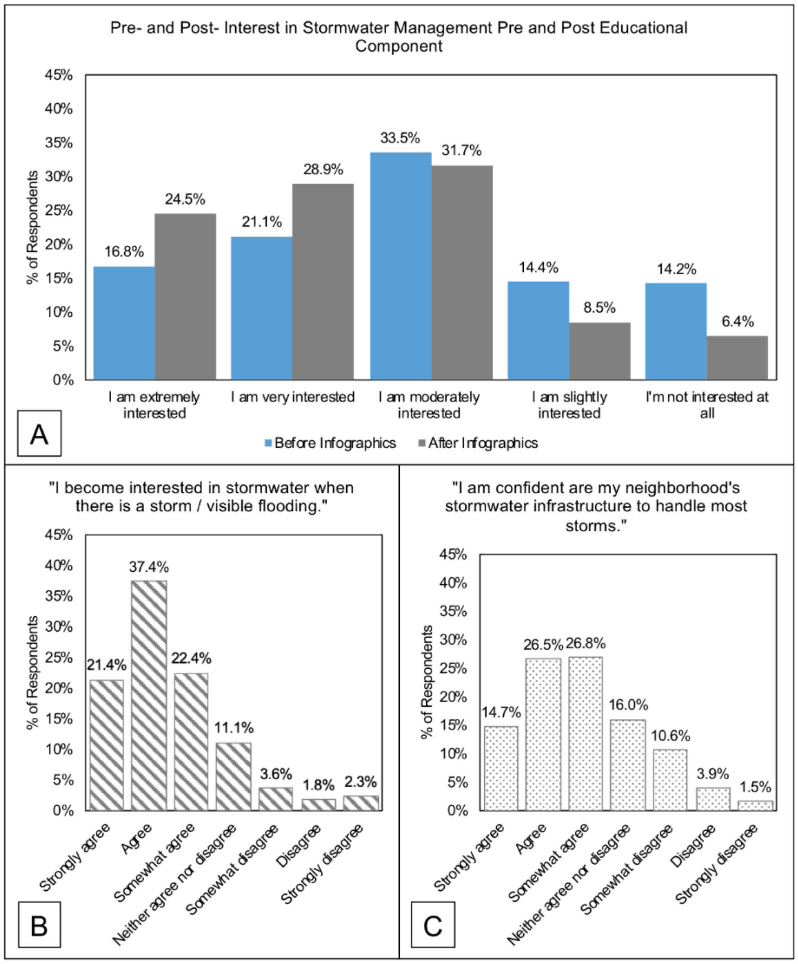


Figure 3.3: Respondents were queried for their interest and confidence in stormwater infrastructure. (A) Details changes in interest pre and post survey, (B) reports interested in stormwater when flooding is visible and (C) shows respondent's confidence in their neighborhood's existing infrastructure.

3.4.3 Preference for Green versus Grey Infrastructure

3.4.3.1 Preference for Green versus Grey Infrastructure by City

Results for stormwater infrastructure preference by city are found in Figure 3.4. The grey bars in each graph correspond with city residents' preference for the different types of infrastructure to handle stormwater in their neighborhood. The blue bars correspond with the respondents' preference for new infrastructure installations in their neighborhoods. A "no preference" option was excluded from the possible responses in the question relating to handling stormwater.

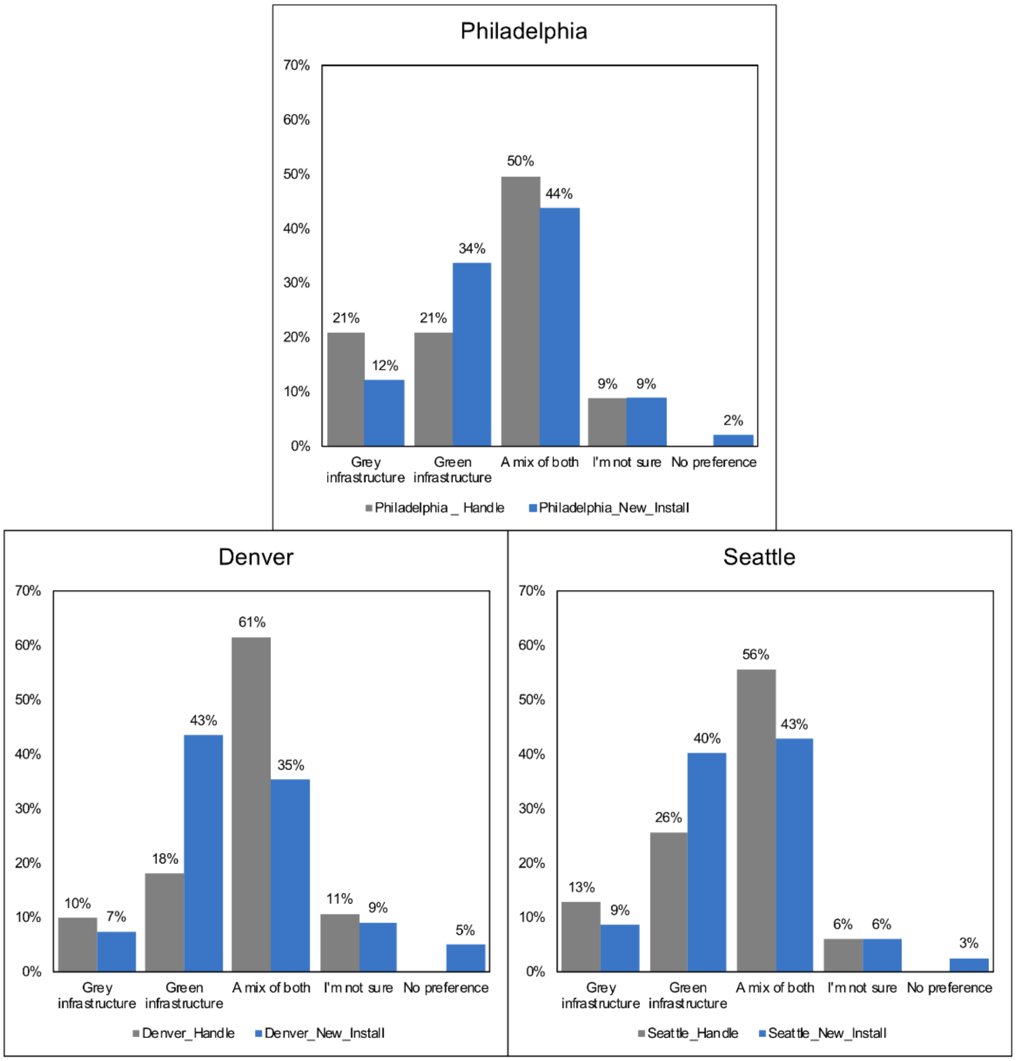


Figure 3.4: GSI preference is gauged using two question constructs: respondents were asked which type of infrastructure they felt could best handle storms (grey bars) and which type of infrastructure they would prefer to be installed (blue bars) in their neighborhood. Results of the responses are presented by study city.

For all cities, there is a general pattern of "A mix of both" as the most popular option for handling stormwater. Some of this preference shifts to GSI when respondents are asked in the context of new installations. Respondents in Denver have the biggest response to this trend; preference for GSI jumps from 18% to 43%. In addition to this pattern, residents in Philadelphia show a higher preference for grey infrastructure to handle stormwater in their neighborhood (21% vs. 10% and 13%).

3.4.3.2 Preference for Green versus Grey Infrastructure by Demographics

The demographic groups showing stronger or weaker preference for different infrastructure to handle stormwater is detailed in Table 3.2 (based on the ±10% threshold). Respondents identifying as Black or African American show higher preference for grey infrastructure in the context of handling stormwater. Respondents identifying as Asian or that have completed a Master's degree or higher show higher preferences for GSI to handle stormwater in their neighborhood. Latino/a-identifying respondents show a higher preference for "A mix of both" types of infrastructure.

Table 3.2: Preference for infrastructure types to handle neighborhood storms by selected demographics.

	Grey infrastructure	Green infrastructure	A mix of both	I'm not sure
All Respondents	**14.9%**	**21.4%**	**55.2%**	**8.5%**
Overall -10%	*4.9%*	*11.4%*	*45.2%*	*0.0%*
Overall +10%	***24.9%***	***31.4%***	***65.2%***	***18.5%***
Race: Asian	*3.7%*	***44.4%***	*44.4%*	7.4%
Race: Black or African American	***26.8%***	19.5%	*40.2%*	13.4%
Race: Latino/a or Hispanic	11.4%	18.2%	***65.9%***	4.5%
Age: < 20 years	*4.8%*	19.0%	47.6%	***28.6%***
Age: 65 to 74 years	20.6%	*8.8%*	61.8%	8.8%
Financial Security: Extremely secure	20.4%	28.6%	*42.9%*	8.2%
Education: Master's degree or higher	11.4%	***32.9%***	51.4%	4.3%

Demographic preference for installing new green infrastructure is similar to preference for ability of current systems to handle stormwater. Asian-identifying respondents and those with a Master's degree or higher continue to show higher preferences for new GSI (Table 3.3). Younger respondents, under the age of 20, and respondents identifying as Black or African American exhibit a lower preference for new GSI. For both questions, respondents under the age of 20 have a higher preference for the "I'm not sure" and "No preference" categories, when available.

Table 3.3: Preference for new infrastructure installations by selected demographics.

	Grey infrastructure	Green infrastructure	A mix of both	I'm not sure	No preference
All Respondents	9.5%	38.7%	40.7%	8.0%	3.1%
Overall -10%	*0.0%*	*28.7%*	*30.7%*	*0.0%*	*0.0%*
Overall +10%	***19.5%***	***48.7%***	***50.7%***	***18.0%***	***13.1%***
Race: Asian	7.4%	***55.6%***	*25.9%*	7.4%	3.7%
Race: Black or African American	15.9%	*25.6%*	40.2%	15.9%	2.4%
Age: < 20	9.5%	*23.8%*	33.3%	***19.0%***	***14.3%***
Education: Master's degree or higher	10.0%	***54.3%***	34.3%	0.0%	1.4%

3.4.4 Preference for Co-benefits

The majority of respondents in the survey rated co-benefits highly (either “Very Important” or “Important”) (Figure 3.5). Co-benefits are shown in the same order as they were asked on the survey to assess for changes in rating as the exercise progressed. The final seven co-benefits have similar trends over the Likert categories, which may be a result of decision fatigue. “Neighborhood cooling” and “Increased property values”, highlighted in red and orange respectively, diverge from the overall rating pattern with respondents selecting more “Moderately Important” for these co-benefits in relation to the other co-benefits (Figure 3.5).

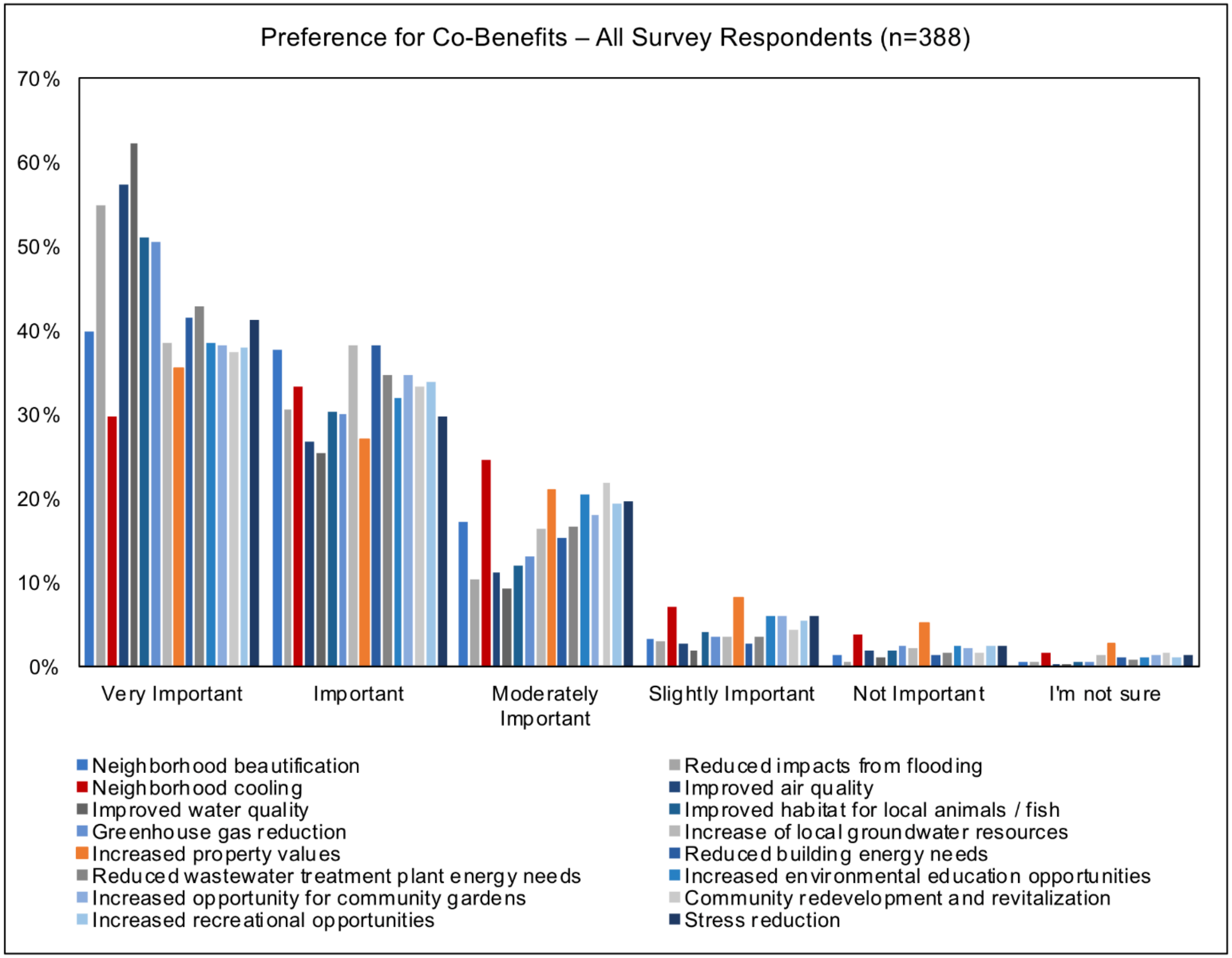


Figure 3.5: All respondent's preferences for co-benefits. The red and orange bars indicate two co-benefits ("Neighborhood cooling" and "Increased property values") that exhibit a lower preference trend as compared to the other co-benefits. Co-benefits are displayed in the same order as they were asked on the survey.

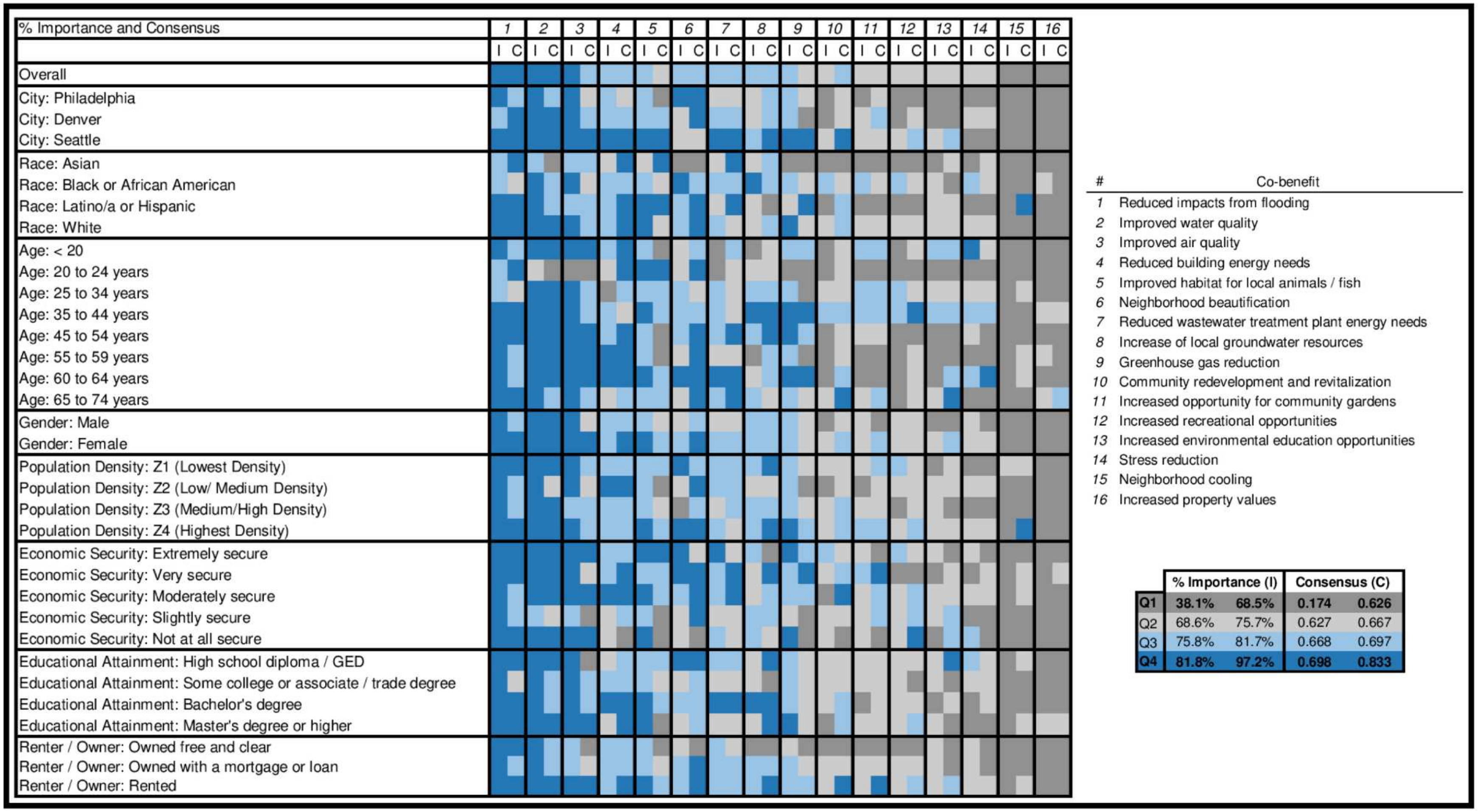
Using the ±10% threshold used in the GSI analysis, fewer trends are identified. To better understand the relationships between demographics and co-benefit preference, we created a heat map using quartile breaks of percent importance and consensus (Figure 3.6; ranges of quartile breaks shown in key). The order of co-benefits is rearranged using high/low quantile values to show a gradient of higher preference/consensus to lower preference/consensus from left to right (Figure 3.6). Higher preference/consensus pairs are interpreted to mean that respondents in this group rate the co-benefit higher and most members of the group agree with this higher rating. For lower preference/consensus pairs, groups tend to rate the co-benefit lower and have less agreement on this rating.

A clear trend of agreement between demographic groups, is observed for the first and last three co-benefits (Figure 3.6). "Reduced impacts from flooding", "Improved water quality" and "Improved air quality" have high preference/consensus for most demographic groups (with the notable exception of lower preference/consensus for "Improved air quality" in the 20 to 24 age group). "Stress reduction", "Neighborhood cooling" and "Increased property values" have low preference/consensus for most demographic groups (with the notable exception of high preference/lower consensus for "Stress reduction" in the under 20 age group). These low preference/consensus co-benefits provide data to confirm the observations of the spread in the bar graph in Figure 3.5.

3.5 Discussion

3.5.1 Stormwater Infrastructure Perception and Preference

Results of this survey show that the public's interest in stormwater management increases via two avenues: when infrastructure is not performing as expected (i.e., visible flooding) and after an educational intervention. High confidence in stormwater infrastructure combined with increased interest due to system failure builds on the interview findings of Keeley et al. (2013), wherein practitioners opined that the public viewed stormwater as "clean" and expected local government to handle stormwater problems. Capitalizing on increased interest after flooding through community-centric plans can be difficult (Godschalk, Brody, & Burby, 2003), suggesting that educational interventions may provide a more straightforward route to increase interest and help garner support for future stormwater efforts.



#	Co-benefit
1	Reduced impacts from flooding
2	Improved water quality
3	Improved air quality
4	Reduced building energy needs
5	Improved habitat for local animals / fish
6	Neighborhood beautification
7	Reduced wastewater treatment plant energy needs
8	Increase of local groundwater resources
9	Greenhouse gas reduction
10	Community redevelopment and revitalization
11	Increased opportunity for community gardens
12	Increased recreational opportunities
13	Increased environmental education opportunities
14	Stress reduction
15	Neighborhood cooling
16	Increased property values

	% Importance (I)		Consensus (C)	
Q1	38.1%	68.5%	0.174	0.626
Q2	68.6%	75.7%	0.627	0.667
Q3	75.8%	81.7%	0.668	0.697
Q4	81.8%	97.2%	0.698	0.833

Figure 3.6: Co-benefits grouped by importance and consensus. Across most demographics, top three ("Reduced impacts from flooding", "Improved water quality" and "Improved air quality") and bottom three ("Stress reduction", "Neighborhood cooling" and "Increased property values") trends emerge.

For this survey, the respondents' previous knowledge of stormwater infrastructure was unknown, but the increase in stormwater management interest results align with the myriad of literature that links education and outreach programs as components of GSI acceptance (H. L. Brown, Bos, Walsh, Fletcher, & Ross Rakesh, 2016; Dhakal & Chevalier, 2017; Giacalone, Mobley, Sawyer, Witte, & Eidson, 2010; Green, Shuster, Rhea, Garmestani, & Thurston, 2012; Thurston et al., 2010).

Looking at the preference results for types of stormwater infrastructure, there is a high preference in all cities for "A mix of both" green and grey infrastructure systems. When communities shift to GSI approaches, they maintain existing grey assets, creating mixed or "hybrid" systems. In this case, public perception is aligned with reality; optimal systems designed to address water quality and quantity issues will likely be hybrid in nature. Modeling and optimizing of these types of systems will require new tools that are currently being developed (Bell et al., 2019).

At the city-scale, Denver residents' higher preference for new GSI installations may be related to their location in the arid west and the lower amounts of green vegetation they experience (Spahr, Bell, McCray, & Hogue, 2020). The lower confidence exhibited by Denver residents for GSI to handle storms in comparison to their preference for new GSI installations suggests that Denver residents want more GSI despite their lower confidence in its ability to manage stormwater; this dichotomy should be investigated further using social science methods. Philadelphia's higher preference for grey infrastructure to handle storms may be linked to the lower preference Black or African American respondents in general expressed for GSI, given that 40.9% of the Philadelphia respondents identify as Black or African American. Additional research should be conducted to better understand these trends and their relationship to distribution of GSI across cities.

3.5.2 Co-benefit Preference

In general, the majority of demographic groups rated all co-benefits either "Very important" or "Important". These high ratings confirm the practitioner assumption that community members are generally favorable to co-benefits related to GSI (H. L. Brown et al., 2016). Some notable exceptions to this trend can be identified through the inclusion of the consensus metric and the quartile break analysis (Figure 3.6); not all co-benefits are important to all groups.

The general agreement on the importance of the top three co-benefits (“Reduced impacts from flooding”, “Improved water quality”, “Improved air quality”) aligns with the findings of Keeley et al. (2013), who found that practitioners in Cleveland, OH, and Milwaukee, WI, were only interested in two benefits (stormwater management and community amenity) in their communities. Mapping these two benefits to the 16 co-benefits included in this study, the stakeholders in Keeley et al (2013) seem to be prioritizing “Reduced impacts from flooding”, “Improved water quality”, and “Community redevelopment and revitalization”. Two of these co-benefits are found in the top three co-benefits of this study and “Community redevelopment and revitalization” falls in the middle for respondents in this study. The disparity of preference for “Community redevelopment and revitalization” is likely linked to the difference between population trends (negative to zero growth in Cleveland and Milwaukee vs. positive growth in Philadelphia, Denver, and Seattle) and study populations (stormwater management stakeholders in Cleveland and Milwaukee vs. general public in Philadelphia, Denver, and Seattle) in the Keeley et al. (2013) study and this study. Essentially, the stormwater management stakeholders in Cleveland and Milwaukee want to use GSI to help revitalize their cities with declining populations while the members of the public who responded to this survey are less concerned with revitalization, possibly because their cities are already experience growth and investment.

The split between the top three (“Reduced impacts from flooding”, “Improved water quality”, “Improved air quality”) and bottom three (“Stress reduction”, “Neighborhood cooling” and “Increased property values”) co-benefits (Figure 3.6), shows a split between environmental and social/ecological co-benefits. The respondents taking this survey have a higher preference for co-benefits related to water quality and quantity control and improved air quality. These results mirror findings in other studies, both in the US and internationally, that find that stakeholders consistently rank air and water quality improvements highly when given varying lists of co-benefits (Alves et al., 2018; McGarity et al., 2015). While water quality improvements from GSI are well documented, linking air quality improvements to GSI installations is often done through tree canopy research (Keeler et al., 2019). Not all GSI installations include trees, and some trees can actually contribute to air pollution through the release of volatile organic compounds (Keeler et al., 2019). Further research is required to assess the strength of the link between air quality improvements with the types of vegetation typically found in GSI.

Most of the co-benefit literature presents “Increased property value” as a positive outcome of GSI installation, but this may not always be the case, especially in high-rent urban areas. As seen in Figure 3.6, most demographic groups had the lowest measures of importance and consensus for “Increased property value” except for respondents between the ages of 35 to 44, 64 to 75 and those with Master’s degrees or higher. Many stormwater practitioners or developers have membership in one or two of these more favorable groups, which may explain their approach to higher property values as a positive result of stormwater infrastructure installation.

Lower rankings from most demographic groups (both renters and owners) of “Increased property value” may be linked to fears of displacement that may accompany community improvement and can result in neighborhood gentrification (Wolch, Byrne, & Newell, 2014). In addition to increased outreach to financially vulnerable groups by the stormwater utility, practitioners need to consider “just green enough” interventions that incrementally improve working-class neighborhoods while working with other government institutions to protect and maintain affordable housing (Curran & Hamilton, 2012; Wolch et al., 2014).

McGarity et al. (2015) hypothesized “some communities may value social benefits more than environmental benefits” after synthesizing the results of a co-benefit ranking exercise with stakeholders in Philadelphia. Based on the results of this survey, we did not see any evidence of this trend, as social benefits received lower importance and lower consensus scores for all groups, including Philadelphia residents. Of the three cities studied, Seattle residents showed a higher preference for additional environmental co-benefits (“Reduced building energy needs”, “Improved habitat for local animals” and “Greenhouse gas reduction”), which may be linked to the city and its inhabitants’ self-identification as progressive and environmentally friendly (Sanders, 2010).

Regardless of the label of co-benefit category, the three lowest rated co-benefits (“Stress reduction”, “Neighborhood cooling” and “Increased property values”) have direct public health and financial impacts on community members who live near the infrastructure being installed.

While we use “social”, “environmental” and “ecological” categories for co-benefits, this categorization is not consistent throughout the literature and often an additional category of “economic” co-benefits is included (Alves et al., 2018; McGarity et al., 2015; Raymond et al., 2017). Practitioners using the economic category of co-benefits often push the overall co-benefit analysis towards monetization, but the value of the environment or society and their individuals cannot be expressed in monetary terms (Bartelmus, 2000; Lozano, 2008). Often what is grouped into the economic category does not have direct financial impact on the agency making the decision and can be more appropriately represented in another category of benefits. We consider co-benefits to exist on an environmental/ecological/social spectrum with ecological co-benefits defined as benefits related to how species interact with the environment (i.e. “Improved habitat for local animals/fish and “Neighborhood cooling”).

“Reduced impacts from flooding” and “Improved water quality” are some of the most-cited co-benefits in the literature, but they are also the primary functions of stormwater infrastructure (Bell et al., 2019; Keeler et al., 2019). The prominence of these two co-benefits in the literature is likely due to the diversity of co-benefit and ecosystem service literature, which spans beyond stormwater management and includes different types of urban green infrastructure like tree canopies, parks, and open spaces. To simplify the nomenclature used and acknowledge the inclusion of multiple criteria in a typical planning process, we suggest that if stormwater infrastructure is specifically designed to meet flood reduction, water quality, and other benefits, practitioners should shift the language from “accruing co-benefits” to “designing for multiple benefits” as the nature of the benefits are no longer ancillary.

Some of the low co-benefit ratings may be related to the difficulty of attribution of the co-benefit to the infrastructure installation. “Stress reduction” and other health outcomes are often attributed to GSI in the literature but a 2019 meta review found that “[no] studies connected green infrastructure for stormwater and flood management to mental or physical health outcomes” (Venkataramanan et al., 2019). More interdisciplinary work needs to be done in this area to concretely link health benefits to GSI (Venkataramanan et al., 2019), which may provide an evidence-based approach to inform community outreach efforts.

Looking beyond the generalized trends for all demographics, some anomalies are found when exploring % importance or consensus numbers in the first or fourth quartiles (Figure 3.6).

For example, respondents that own their house free and clear find some of the community revitalization benefits (“Community redevelopment and revitalization”, “Opportunity for community gardens”, and “Increased recreational activities”) less favorable than the overall survey population. Additionally, respondents with a Bachelor’s degree have a higher preference for “Reduced wastewater treatment energy needs” and “Increase of local groundwater resources”. To fully explore why these trends exists, further engagement with these populations via social science methods is required.

3.5.3 Limitations and Future Applications

Using online surveys as a research tool automatically excludes some vulnerable subsets of the population. As administered, this survey likely excluded people that are unsheltered and experiencing homelessness, illiterate, visually impaired, without internet access or non-English/non-Spanish speakers. It is critical for agencies who are designing interventions to consider these and other underrepresented groups when taking stock of and creating policies based on public opinion.

Respondents’ knowledge of and experience with GSI were not queried as part of this work. Moving forward, semi-structured interviews with cross-sections of the population surveyed could help provide more information on how people’s preference for GSI is shaped. These interviews could help clarify or confirm some of the postulates made in this discussion section.

The intent of this work was to establish baseline data on GSI acceptability and co-benefits, which is useful in its own right, but also serves as basis for designing additional studies for a more detailed understanding of specific GSI planning needs. Agencies looking to meaningfully incorporate the public in their design process could adopt a similar approach to better understand residents where GSI interventions are needed. Stakeholder and public perception can often change the course of a GSI program; when (Alves et al., 2018) incorporated stakeholder preference into their decision framework, different infrastructure options became viable.

3.6 Conclusions

As stormwater agencies embrace greener infrastructure, stakeholder engagement becomes an integral part of a successful program. Practitioners need to engage and inform members of the public to help encourage future private property interventions and/or promote rate increases. By establishing baseline conditions for GSI acceptance, this study demonstrates that public preference may differ between large cities and may be contrary to commonly held perceptions, provides guidance for how to begin public engagement efforts, and identify gaps in understanding of citizen preferences in GSI planning.

Results from this survey found respondents have positive attitudes towards stormwater management in their neighborhood. While respondents' interest in stormwater increased during storm events or visible flooding, their interest was also peaked due to participation in and education received from the survey tool. Respondents in all cities preferred a mix of both types of infrastructure (green and grey) to handle storms in their neighborhoods. Of the three cities surveyed, Philadelphia residents showed a higher preference for grey infrastructure to handle storms while Denver residents showed a higher preference for new GSI installations. Demographically, Black or African American respondents had a higher preference for grey infrastructure to handle storms while Asian respondents and respondents with a Master's degree or higher had higher preferences for GSI to both handle stormwater and for new installations.

Respondents found most of the 16 co-benefits to be favorable, but when analyzed for group agreement a set of top three and bottom three co-benefits were identified. The top three co-benefits include "Reduced impacts from flooding" and "Improved water quality" which are often design parameters for stormwater infrastructure interventions. The third top co-benefit, "Improved air quality", is commonly cited in urban tree canopy research but may not be as strongly linked to most GSI installations which lack trees. Further research should be undertaken to improve understanding of GSI's impact on air quality, especially since the public shows an affinity for this benefit.

The bottom three co-benefits ("Stress reduction", "Neighborhood cooling" and "Increased property values") may have been harder for respondents to attribute to stormwater infrastructure and present an area for educational intervention. Notably, most demographic groups rated "Increased property value" the lowest of the suite of co-benefits, which identifies a spilt in perception from the literature that emphasizes this co-benefit and is often informed by groups who stand to benefit from property value increases (e.g., developers).

Building on the climate established with this research, additional social science methods should be employed to help inform neighborhood specific preferences. By characterizing and incorporating the public's preference into a larger stakeholder engagement model, agencies can shift from the current paradigm of designing GSI interventions and hoping to accrue co-benefits, to designing for multiple benefits informed equally by policy and stakeholders.

CHAPTER 4

INCORPORATING A MULTIPLE BENEFIT ANALYSIS INTO A STORMWATER HYDROLOGIC DECISION SUPPORT TOOL AT PLANNING LEVEL

A paper to be submitted to *Journal of Sustainable Water in the Built Environment*

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4.1 Abstract

As we move into an era of increased urbanization, stormwater practitioners are charged with creating multi-functional solutions through the installation of stormwater control measures (SCMs). Existing on a green (vegetated) to grey (concrete) continuum, SCMs can provide a range of benefits beyond the primary design objectives of stormwater management. Two drivers dictate the accrual of benefits in SCMs: decentralized hydrologic processes and vegetation. This study investigates the feasibility of incorporating hydrologic- and vegetation-based benefits into the SCM planning process. After a critical review of the literature, we use form and feasibility to allocate benefits to SCMs via an attribution matrix. The benefit allocation framework is then applied to a case study in the Berkeley neighborhood of Denver, CO to assess the scale of benefit accrual. Hydrologic benefits are assessed using hydrologic modeling results, and vegetated benefits are assessed using an urban green infrastructure (UGI) inventory. Results for hydrologic benefits find that vegetated swales provide the most attractive solution for the Berkeley neighborhood. From the vegetated benefit perspective, the UGI inventory finds that the proposed vegetated area associated with the vegetated swale solution would only add 1% more urban greenness to the Berkeley neighborhood. To maximize the vegetated benefit potential of the swales and consider existing socio-demographic and vegetation trends, we find the 4 C's (community, context, connectivity and canopy) should be used to leverage existing UGI. Finally, we identify areas of research that can fill knowledge gaps and provide for scientifically sound decisions when considering vegetation and SCMs. We advocate that municipalities adopt

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integrated multi-department vegetation goals to optimize the benefits of all types of urban green infrastructure.

4.2 Introduction

As urbanization drives changes in urban water quality and quantity, stormwater managers optimize their systems through the maintenance of existing infrastructure and implementation of new infrastructure. Individual units of stormwater infrastructure, or stormwater control measures (SCMs), exist on a green to grey continuum (Bell et al., 2019). Greener SCMs are typically vegetated and promote water management through natural hydrologic or water quality processes, while greyer SCMs are typically made of concrete and convey flows through a sewershed. When evaluating the cost/benefits of greener/greyer solutions, an increasing number of stormwater managers want to look beyond capital costs to consider life-cycle costs and co-benefits. Co-benefits are the “ancillary positive ecological, environmental, and social outcomes that coincide with the installation of SCMs” (Bell et al., 2019).

Co-benefits related to stormwater infrastructure are accrued due to the decentralized management of urban water and the addition of vegetation. Commonly cited co-benefits range from primary design components of SCMs (such as improved water quality and reduced impacts from flooding) to positive health outcomes related to increased exposure to green spaces (Bell et al., 2019). An SCM does not need to be on the greener end of the continuum to accrue co-benefits as long as it promotes decentralized hydrologic processes that result in the diversion of flow from the conventional piped system. Table 4.1 highlights an aggregated list of co-benefits from Bell et al. (2019) and identifies the primary benefit driver (i.e. hydrologic processes or vegetation). The selected citations are commonly used in the literature and span multiple disciplines. Hydrologic process benefits are considered to be physically based processes and are inclusive of water quality processes like settling or filtration.

Table 4.1: Commonly cited benefits and their functional definitions within the scope of stormwater management.

Benefit	**Benefit Driver**	**Functional Definition for Stormwater Management**	**Selected Citations**
Improved water quality	Hydrologic Processes	Contaminants can be removed in SCMs through settling, filtration, adsorption/adsorption, uptake, and denitrification.	(Eckart, McPhee, & Bolisetti, 2017)
Reduced impacts from flooding	Hydrologic Processes	SCMs can handle a range of storm intensities and frequencies.	(Sohn, Kim, Li, & Brown, 2019)
Reduced burden on existing infrastructure	Hydrologic Processes	Flows can be intercepted by SCMs during storm events. Stormwater in SCMs can be re-released to existing infrastructure later or is diverted to local natural hydrologic processes.	(Wang, Eckelman, & Zimmerman, 2013)
Increase of local groundwater resources	Hydrologic Processes	SCMs can divert water from storm sewer and infiltrate the diverted flows locally.	(Zhang & Chui, 2018)
Cistern-specific benefits	Hydrologic Processes	Collected rainwater can be used to irrigate landscape at a later point in time and can offset irrigation demand.	(Brown, Bos, Walsh, Fletcher, & Ross Rakesh, 2016)
Increased aquatic biodiversity	Hydrologic Processes	A standing pool in an SCM can provide habitat for aquatic life.	(Zhang & Chui, 2018)
Increased recreational opportunities	Vegetation	SCMs of a certain size and design can provide recreational opportunities.	(Rupprecht & Byrne, 2014)
Increased terrestrial biodiversity	Vegetation	Adding more vegetated areas can provide better urban habitats.	(Angold et al., 2006)
Increased property values	Vegetation	Addition of vegetation can increase property values of neighboring lots.	(Mazzotta, Besedin, & Speers, 2014)
Neighborhood beautification	Vegetation	Adding vegetation via grass, perennials, small trees and woody shrubs can improve the appearance of neighborhoods.	(Wolch, Byrne, & Newell, 2014)

Table 4.1 Continued

Human health and social well being	Vegetation	Managing stormwater quality and quantity along with adding vegetation can result in human health and social wellbeing benefits	(Venkataramanan et al., 2019)
Improved air quality	Vegetation	Vegetation can remove some air pollutants through gaseous uptake via leaf stoma and interception of airborne particles.	(Nowak, Crane, & Stevens, 2006)
Neighborhood cooling	Vegetation	Vegetation and standing pools in SCMs can provide cooling benefits through shade and evapotranspiration.	(Bowler, Buyung-Ali, Knight, & Pullin, 2010)

The addition of SCMs into a stormwater network can bolster the system's sustainability and resilience (Ahern, Cilliers, & Niemelä, 2014). Additionally, the incorporation of multiple co-benefits into the SCM planning process (i.e. multi-functional design) can maximize the environmental, economic, and social welfare of a community. Traditionally, greener stormwater infrastructure (GSI) interventions have been solely installed for water quality and quantity mitigation, which incorporates only two of the hydrologic-based co-benefits and none of the vegetated-based potential co-benefits related to urban greening (Newell et al., 2013). As cities shift their sights towards multi-functional interventions that optimize more co-benefits, the ancillary nature of the co-benefits drop away and they become design parameters. Moving forward, we identify the positive outcomes of SCMs as only "benefits" to streamline the discussion and acknowledge their role in the planning process.

The hydrologic-based benefits of SCMs are typically quantified using stormwater modeling, however, vegetated-based benefits of SCMs are more difficult to measure (Spahr et al., 2020). The literature on vegetated benefits can conflate GSI with larger, urban green infrastructure (UGI) benefits. For the scope of this paper, public UGI includes GSI, open space, bike paths, tree canopy, informal greenspace (e.g. vacant lots and medians), and parks (Figure 4.1). Other types of UGI provide some stormwater management functions, such as increasing potential for infiltration, but they are not explicitly designed to manage stormwater. Consequently, GSI can be added to other UGI to enhance the area's ability to address stormwater quality and quantity issues. For example, the primary design objective of a neighborhood park is to provide a “multi-functional public space” and when enhanced with GSI outcomes can include “multiple environmental and social benefits and [potential for cities to] grow or revitalize more equitably” (National Recreation and Park Association, 2017).

Figure 4.1: Greener stormwater control measures (SCMs) are a piece of urban green infrastructure (UGI). The types of urban green infrastructure identified are not part of an exhaustive list but represent common contributions to urban vegetation.

Due to the two different benefit drivers (i.e. decentralized management of water and vegetation), two different methodologies are required for the evaluation and measurement of these benefits. For this paper, hydrologic benefits will be assessed using modeling approaches while vegetation benefits will be assessed through the evaluation of UGI systems.

4.3 Background and Objectives

To better understand the potential benefits associated with SCMs, a critical review of the literature from the perspective of stormwater management is presented below. This review informed the functional definitions in Table 4.1.

4.3.1 Hydrologic Process-Based Benefits

Two of the most commonly cited benefits, improved water quality and reduced impacts from flooding, are design objectives in most SCM installations (Gallo, Bell, Mika, Gold, & Hogue, 2020; Panos, Hogue, Gilliom, & McCray, 2018; Wolfand, Bell, Boehm, Hogue, & Luthy, 2018). At a sewershed scale, model simulations use water quality and quantity goals (i.e. an average annual load of a contaminant or a flow exceedance frequency) to select appropriate SCM solutions (J. G. Lee et al., 2012). Two recent literature reviews find that while SCMs are effective at treating water quality and mitigating stormwater flows, the implementation of GSI alone cannot return sewersheds to pre-development conditions (Eckart et al., 2017; Jefferson et al., 2017). From the water quality perspective, Jefferson et al. (2017) hypothesize that "pollutant load decreases largely result from run-off reductions rather than lowered solute or particulate concentrations". On the water quantity side, Eckart et al. (2017) postulate that smaller, decentralized SCMs are better equipped to handle smaller storm events while larger events are best managed with larger SCMs like detention ponds. Continued monitoring of the performance of SCMs under different environmental conditions will provide more consensus on the appropriateness of different SCMs for different applications and will improve modeling inputs and outputs (Eckart et al., 2017).

The decentralized nature of SCMs results in the incorporation of flows into local urban water cycles. Decentralized management of stormwater can result in a reduced burden on infrastructure, increased local groundwater resources, and cistern-specific benefits. From the infrastructure perspective, diverted flows can result in fewer combined sewer overflows and reduced wastewater treatment costs in combined sewer systems where stormwater and wastewater comingle (Wang, Eckelman, & Zimmerman, 2013). When planning new infrastructure, the incorporation of SCMs can result in smaller pipes for stormwater conveyance or the overall elimination of conventional piped systems from a neighborhood's stormwater management approach. In areas looking to increase their groundwater resources, infiltration from

SCMs can increase available groundwater but care must be taken to mitigate contamination potential in commercial and industrial areas (Pitt, Clark, & Field, 1999). Cisterns and rain barrels can capture storm flows and save water for later uses (i.e. outdoor irrigation), potentially leading to reduced water bills and increased water independence (H. L. Brown et al., 2016).

Improved water quality and mitigated flows can have many positive impacts downstream of a sewershed, including reduced erosion and increased biodiversity of aquatic life (McGarity et al., 2015). SCMs that incorporate standing pools in their designs, like wet ponds and constructed wetlands, also have the potential to host and diversify local urban aquatic life (Kopperoinen, Itkonen, & Niemelä, 2014).

4.3.2 Vegetation based benefits

The accrual of vegetated benefits from GSI is dependent on what we summarize as the 4 C's: community, context, connectivity and canopy. Community refers to both the systems-level of analysis and the incorporation of demographic data, context refers to the vegetated trends in surrounding land use where a SCM is being installed, connectivity refers to the proximity of GSI to other UGI and canopy refers to the influence of trees, including the types of trees installed. For decision-makers to best incorporate vegetation-based benefits into their planning process, an easy to understand and scientifically sound approach that addresses the 4 C's is needed to tie vegetated benefits to modeled hydrologic outputs. The review below illuminates how the vegetated benefits listed in Table 4.1 interact with the four C's.

Connectivity of vegetated SCMs can result in increased recreational opportunities and increased terrestrial biodiversity. When evaluated at a single installation level, smaller vegetated SCMs, like bioretention cells, are more likely to mirror the vegetated benefits of informal green spaces, like vacant lots, than larger UGI like parks. At this smaller scale, vegetated SCMs "can offer residents an alternative experience to formal greenspace" (Rupprecht & Byrne, 2014). To optimize potential recreational opportunities, the American Planning Association suggests that "benefits are maximized when green infrastructure is planned as a physically connected network" (American Planning Association, 2017). Depending on the species of interest, connectivity and optimization of informal green spaces can result in increased terrestrial biodiversity (Angold et al., 2006; J. P. Evans, 2007; Soulé, 1991). Larger SCMs with standing pools, like detention ponds, can provide aquatic recreational activities and may have positive impacts on human health and well-being (Völker & Kistemann, 2011). Dry ponds and other large SCMs can also double as parks (City of Denver, 2017).

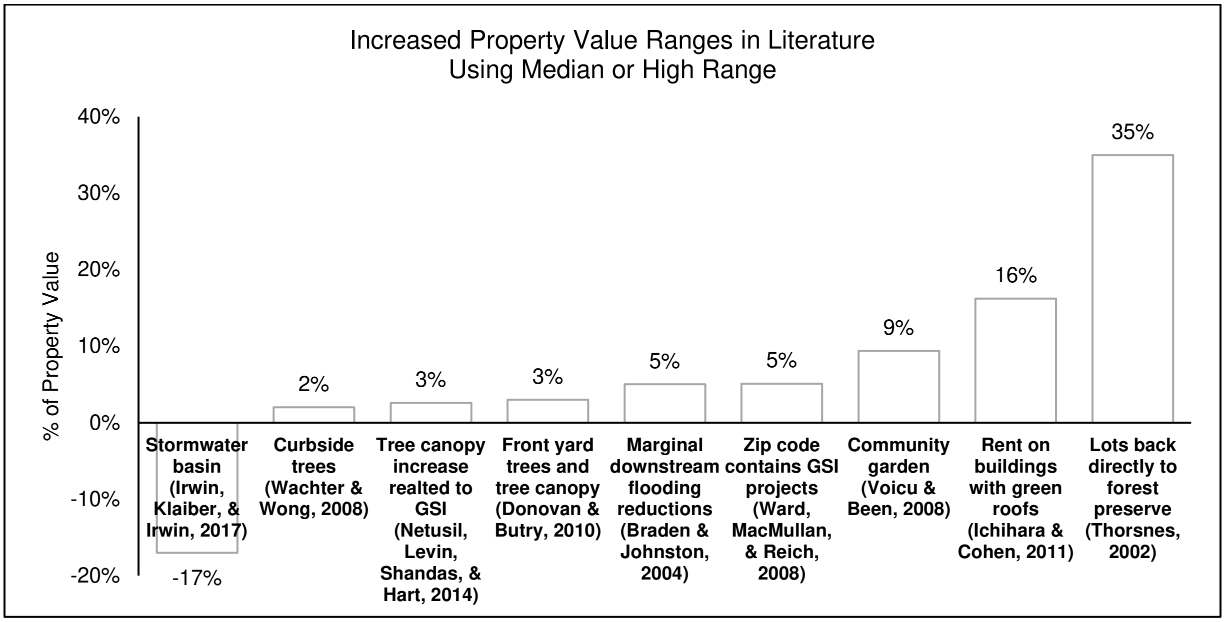


Figure 4.2: The impacts of different types of UGI on property values.

Increased property values can be attractive selling points for UGI programs. Planners are often over-optimistic when attributing the property value benefits of urban green infrastructure to GSI programs. Upon closer inspection of the literature, expected property value increases are variable and dependent on the size, quantity, and location of UGI. Figure 4.2 shows some of the spread in results of hedonic pricing models with type of UGI noted. The largest increase in property values is found in studies where houses directly back to a forest preserve (35%) or are close to a community garden (9%) (Thorsnes, 2002; Voicu & Been, 2008). Ichihara and Cohen found that apartments with green roofs in an upscale neighborhood of New York City were able to charge 16% higher rents (Ichihara & Cohen, 2011). Existing studies that look at the impacts of SCMs on property values have found that values may even decrease due to proximity to stormwater management structures (Irwin, Klaiber, & Irwin, 2017; J. S. Lee & Li, 2009). In a case study in College Station, TX, the authors found that a multi-use detention basin that was coupled with a park had a positive impact on adjacent property values, while property values for the homes that overlooked the paired detention basin that did not back to a park were significantly lower (J. S. Lee & Li, 2009). Additional hedonic pricing studies need to be performed using different sizes and scales of both UGI and GSI to better understand its impact on property values.

Improved community aesthetics via the installation of vegetated features is another selling point for GSI programs, especially in areas where practitioners are looking to revitalize neighborhoods (Keeley et al., 2013). Increased vegetation, especially from the installation of trees, can result in increased property values that can price vulnerable populations out of neighborhoods and lead to gentrification (Donovan & Butry, 2010; Netusil, Levin, Shandas, & Hart, 2014; Thorsnes, 2002; Wachter & Wong, 2008; Wolch et al., 2014). From an environmental justice perspective, not all residents may want the increased property values associated with GSI (Spahr, Smith, McCray, & Hogue, In prep) such that practitioners should aim for a “just green enough” approach that increases neighborhood vegetation and helps residents stay in their neighborhoods (Wolch et al., 2014).

GSI can potentially improve community public health through increased interactions with vegetation (Demuzere et al., 2014; Wolf, 2014). In a comprehensive review of the literature for links between human health and social well-being outcomes (i.e. physical health, mental health, economic well-being and flood residence and social acceptance of GSI), the authors found that “no studies connected [GSI] to mental health or physical health outcomes” (Venkataramanan et al., 2019). The authors go on to encourage “experts in social science, public health, and program evaluation to be integrated into interdisciplinary green infrastructure research” (Venkataramanan et al., 2019).

In addition to managing altered water quality and quantity associated with development, GSI is also linked to improved air quality and can contribute to neighborhood cooling. Air quality mitigation is primarily performed by urban trees which uptake gaseous pollutants via leaf stoma and intercept airborne particle on the plant surface (D. J. Nowak et al., 2006). Since particulate matter is intercepted, it can be re-introduced into the atmosphere and environment (D. J. Nowak et al., 2006). Tree canopies can also trap pollutants at ground level and emit volatile organic compounds (VOCs) depending on the tree species (Berland et al., 2017; D. J. Nowak et al., 2006). If practitioners are aiming to optimize their air pollution removal rate from trees, they may want to plant more conifers to make up for the leaf-off season of deciduous trees (Berland et al., 2017)

The context in which a vegetated SCM is installed impacts its ability to cool (Makido, Hellman, & Shandas, 2019). Adding more vegetation will result in some cooling impacts, but the impact varies based on the pre-intervention conditions (e.g. highly impervious areas get more cooling from green roofs) (Makido et al., 2019). Trees contribute to urban cooling due to shading from tree canopy and transpiration; the magnitude of impact from either of these processes is climate and location dependent (e.g. shading is more impactful in lower latitude cities whereas transpiration is more impactful in higher latitude cities) (Rahman et al., 2020). Trees and larger green spaces, like parks, likely provide more cooling than smaller, ground-level installations like bioretention cells (Bowler, Buyung-Ali, Knight, & Pullin, 2010). In arid environments, vegetative cooling can become an environmental justice issue as most vegetation, and especially trees, require irrigation (Schwarz et al., 2015). The cooling from blue infrastructure such as ponds is modeled to be similar to vegetative cooling (Cheung & Jim, 2019; Taleghani, Tenpierik, van den Dobbelsteen, & Sailor, 2014) but additional work needs to be performed to understand cooling contributions of green vs. blue infrastructure in at larger scales and different climates and land uses.

4.3.3 Incorporating benefits into stormwater planning

Decision makers are interested in incorporating a benefit analysis into their stormwater planning process as a way to embrace and plan for the multi-functionality of GSI (Hansen & Pauleit, 2014). Expanding a stormwater design analysis beyond water quality and quantity modeling requires decision makers to create boundary conditions for appropriate scope and level of complexity (Hansen & Pauleit, 2014). For a multi-functional GSI program to be successful and influence benefits beyond water quality and quantity, additional goals that incorporate environmental protection, economic development, and social equity need to be created (Newell et al., 2013). These goals would likely be implemented on a city-wide and multi-department level scale, so it is critical to track goals with universal metrics that can cross disciplines. Stormwater managers looking for multi-functional projects would benefit from understanding how GSI interacts with the other types of UGI in their city.

Hydrologic models, like the EPA’s System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN), can take in modeled or observed water quality and quantity data and create aggregate SCM solutions to meet design objectives (J. G. Lee et al., 2012). The summarized outputs of SUSTAIN, called evaluation factors, give decision makers water quality and quantity metrics (i.e. average annual flow volume, seasonal average groundwater recharge, and average annual concentration), which can be optimized in addition to capital costs (J. G. Lee et al., 2012). Vegetation plays a limited role in SUSTAIN; turf grass, perennials, small trees, woody shrubs, soil and planting material are included in the materials inventory used to calculate capital costs but do not influence any of the hydrology/water quality calculations (Shoemaker et al., 2009). In its current state, SUSTAIN outputs quantify only traditional, hydrologic-based, stormwater management benefits. The solutions output in SUSTAIN are presented as aggregate SCMs, so the majority of the information about vegetation quantity associated with modeled solutions is limited to potential vegetated surface area of selected solutions, which is not a current output/decision factor. To create a more robust tool that could be used to reach multi-functional goals, an additional vegetation-based benefit assessment needs to be included.

At present, integrating both vegetated and hydrologic benefits into hydrologic models like SUSTAIN at a planning level has four main avenues: theoretical frameworks, spatial analysis tools, monetization workbooks, and multi-criteria assessment approaches. Frameworks for incorporating stakeholder preference for benefits into the decision making process have been proposed as an avenue for community engagement and more holistic planning (Alves et al., 2018; McGarity et al., 2015). Spatial analysis tools, like the one outlined in Meerow and Newell (2017) and refined in Meerow (2019), use temporally limited data snapshots from interdisciplinary sources to identify areas where GSI interventions would have the most impact (Meerow, 2019; Meerow & Newell, 2017). While theoretical frameworks and spatial planning tools draw in more groups and perspectives to the decision-making process, data richness and stormwater management modeling complexity are often sacrificed for ease of use. Monetization workbooks have an additional level of complexity by including a larger breadth of metrics, but links to benefit outcomes in the literature is often weak and the uncertainty introduced in the monetization process is not clearly communicated (GIVaN, 2010; Guo & Correa, 2013). Monetization also reduces analysis to one metric which does not acknowledge the “multiple and often conflicting valuation languages” associated with social, ecological, and environmental outcomes (Gómez-Baggethun & Barton, 2013). Multi-criteria assessment has the potential to provide a methodology for post-processing of modeled solutions (Jia et al., 2013) but the metrics of associated benefits included need to be refined to an equivalent level of scientific support as the modeling results (Zhang & Chui, 2018).

4.4 Objectives

The goal of this study is to determine (based on physical form and feasibility) which SCMs have the potential to accrue hydrologic process and vegetation-based benefits at a stormwater planning level. First, a subset of benefits is given functional definitions based on design characteristics of SCMs. These definitions are used to create an attribution matrix that identifies which SCMs can achieve which benefits. Next, the attribution matrix is applied to a case study in the Berkeley neighborhood of Denver, CO to see how the hydrologic process and vegetation-based benefits compare when evaluating the continuum of greener vs. greyer solutions. Results from a previous stormwater modeling study in the neighborhood are used to evaluate select hydrologic process benefits and potential vegetated area. To assess the feasibility of vegetated benefits from SCMs, a spatial UGI inventory of SCMs, tree canopy, and parks is performed in the Berkeley neighborhood and city-wide to create vegetated benchmarks. Due to the dominance of tree-based vegetation benefits, the relationship between tree canopy, different types of UGI, and land use is explored. Finally, we discuss how the 4 C's (community, context, connectivity and canopy) can be used to leverage existing UGI to expand the impact of SMCs on vegetation-based benefits.

4.5 Methods

4.5.1 Benefit assessment

Benefits were screened for their inclusion in a planning level stormwater decision support tool using findings from the literature discussed in previous sections. Increased property value and human health and social well-being were not included because the literature suggests their benefits are weak or not clear; elucidating this issue requires additional academic study. The remaining benefits were attributed to a suite of green and grey SCMs found in a modified version of SUSTAIN using the attribution justification found in Table 4.2 which uses water quality and hydrology characteristic and design components from literature (Bell et al., 2019; Shoemaker et al., 2009; UDFCD, 2015). The attribution justifications were developed to provide a transparent means for attributing benefits to SCMs using their physical design forms.

Table 4.2: Benefit attribution justification using physical characteristics of SCMs as described in in Bell et al., (2019); Shoemaker et al., (2009); and UDFCD, (2015).

Benefit	Attribution Justification	Verification Source
Improved water quality	SCM is characterized by one or more water quality processes (i.e. settling, filtration).	(Bell et al., 2019)
Reduced impacts from flooding	SCM is characterized by hydrologic processes that include retention and/or detention.	(Bell et al., 2019)
Reduced burden on existing infrastructure	SCM is characterized by hydrologic processes that includes retention, detention, infiltration, evaporation or transpiration.	(Bell et al., 2019)
Increase of local groundwater resources	SCM is characterized by hydrologic processes that includes infiltration and does not have a liner in its design.	(Bell et al., 2019; UDFCD, 2015)
Cistern-specific benefits	SCM is a rain barrel or a cistern.	(Shoemaker et al., 2009)
Increased aquatic biodiversity	SCM is operated with standing pool.	(UDFCD, 2015)
Increased recreational opportunities	SUSTAIN SCM design has turf grass or SCM is operated with standing pool.	(Shoemaker et al., 2009; UDFCD, 2015)
Increased terrestrial biodiversity	SUSTAIN SCM design has turf grass, perennials, small tress, woody shrubs or soil and planting material.	(Shoemaker et al., 2009)
Neighborhood beautification	SUSTAIN SCM design has turf grass, perennials, small tress, woody shrubs or soil and planting material.	(Shoemaker et al., 2009)
Improved air quality	SUSTAIN SCM design has turf grass, perennials, small tress, woody shrubs or soil and planting material.	(Shoemaker et al., 2009)
Neighborhood cooling	SCM is characterized by hydrologic processes that includes evaporation and/or transpiration.	(Bell et al., 2019)

4.5.2 Case study application: Berkeley neighborhood

4.5.2.1 Hydrologic modeling

To better understand the relationships between SCMs and benefits at a planning scale, a case study was employed in the Berkeley neighborhood of Denver, CO. The Berkeley neighborhood is located in the northwest corner of Denver. Due to the aging housing stock and population boom in Denver, the Berkeley neighborhood is experiencing rapid infill development in which low density residential areas and vacant lots are being redeveloped into high density residential areas (Panos et al., 2018). Previous stormwater modeling in the area has focused on the hydrologic impacts of densification (Panos et al., 2018). For this study, we used outputs from modeling scenarios preformed in Gallo et al. (in prep) which assessed the relative hydrologic performance of greener/greyer SCMs across a range of hydrologic model outputs. Gallo et al. (in prep) used a modified version of SUSTAIN, called integrated decision support tool SUSTAIN (i-DST SUSTAIN), which includes a larger suite of SCMs and has an expanded suite of hydrologic evaluation factors. Because of these modifications, i-DST SUSTAIN provides insights into a broader range of hydrologic benefits allowing for green/grey solution comparison. Gallo et al. (in prep) used an existing model of flows in the Berkeley sewershed, modified the model for water quality and optimized for aggregate SCMs on the green to grey spectrum including bioretention (BR), infiltration trench (IT), porous pavement (PP), underground detention structure (UDS), underground infiltration structure (UIS), and vegetated swales (VS) (Gallo et al. in prep). This study used results from the modeled simulations and output metrics were assigned to selected benefits.

To help decision-makers better compare the final aggregate SCMs, each field was normalized by metric and color-coded based on a low/high number preference (i.e. low effluent water quality parameters are preferred). The source table for this data can be found in Appendix E. Five benefits were selected for this analysis: vegetated benefits, reduced impacts from flooding, increased groundwater resources, neighborhood cooling, and improved water quality. These benefits were selected to showcase some of the added functionality of i-DST SUSTAIN. Because i-DST SUSTAIN (like SUSTAIN) does not model the physical impacts of vegetation, vegetation-related benefits were aggregated into one benefit for this case study, as measured by total potential vegetated area. The four remaining hydrologic benefits were measured using model outputs.

4.5.2.2 Berkeley neighborhood and Denver UGI inventory

A spatial UGI inventory was performed for the Berkeley neighborhood and the City of Denver to evaluate how SCMs interact with the larger UGI system and assess the feasibility of including vegetation-related benefits in a stormwater planning tool. We assessed UGI at the neighborhood and city-wide scale to facilitate comparisons and benchmarking at both scales. UGI spatial data (i.e. tree canopy, SCMs, and parks) were acquired from the City of Denver's GIS repository (City of Denver, 2014, 2019b, 2019a). Each UGI dataset was evaluated for percent contributing area for the Berkeley neighborhood and Denver city boundaries. Tree canopy was also spatially evaluated by tree type (i.e. coniferous, deciduous, and unclassified). The Denver boundaries used in this study exclude the Census Tract in the northeast corner that contains the Denver International Airport; this area had inconsistencies in the tree canopy data was not seen as representative of typical Denver land uses.

The "storm detention and water quality areas" are considered to be the GSI layer as identified by the City of Denver and the attributes that comprise the layer were considered SCMs for this analysis. Because the tree canopy layer was created from 2014 imagery, SCMs were screened by installation date and all entries with a date before and including 2014 or a "null" date entry were included in the analysis. The "null" date field represents the majority (58.1%) of the SCM entries and was assumed to be a blank field due to legacy management of the layer making it likely that the SCMs were installed by the time of the 2014 tree canopy assessment. The park data were not adjusted for the 2014 tree canopy assessment as only 4% of the park acquisition dates were after 2014.

4.5.2.3 Denver SCM and land use tree canopy analyses

The types of vegetation that make up UGI exhibit vertical heterogeneity; trees can cover turf grass, which can alter the magnitude of vegetated benefits accrued (Pincetl, Gillespie, Pataki, Saatchi, & Saphores, 2013). The layers analyzed in this study do not have a vertical component so vertical interactions were investigated using tree canopy overlap on different types of UGI and land uses. For the purposes of this study, tree canopy was assumed to occupy a higher vertical sphere than SCMs and parks whose spatial extents are assumed to have ground-level vegetation cover. Tree canopy over parks and SCMs was calculated for the Berkeley neighborhood and the constrained Denver boundaries. Total effective UGI contribution was calculated at both scales by adding up area contributions from tree canopy, parks and SCMs and subtracting the tree canopy areas over parks and SCMs and the area of SCMs in parks.

Tree canopy coverage was also calculated by SCM type and land use within the constrained Denver boundaries. The scale of analysis for this work was expanded beyond the Berkeley neighborhood to the city boundaries of Denver (excluding the airport) to allow for a richer dataset. A 5-m buffer was applied to all SCMs in the truncated "storm detention and water quality areas" layer to be inclusive of perimeter vegetation. Land use data from 2013 from the City of Denver's GIS repository were used (City of Denver, 2013). Land use classes included in the analysis were agricultural, commercial industrial, mixed, multi-family, open space, public/quasi-public, and single family. Tree canopies over SCMs and land use types were evaluated for their ability to meet the City of Denver 20% canopy cover goal (Denver Parks and Recreation, 2019).

4.6 Results

4.6.1 Benefit assessment

Potential benefits are assigned to SCMs (Figure 4.3). Binary nomenclature is used to acknowledge the potential for the SCM to accrue the corresponding benefits based off the attribute justifications in Table 4.2. Note that even if an SCM is noted to have the potential to accrue a benefit, benefit accrual does not necessarily occur at a noticeable or meaningful level.

Based on the relationships presented in Table 4.3, vegetated SCMs have the potential to accrue more benefits than non-vegetated benefits. All SCMs can achieve "reduced burden on existing infrastructure" as its attribution justification (Table 4.2) requires the SCM to have any type of hydrologic process (i.e. retention, detention, infiltration, evaporation or transpiration) attributed to its form. Both "improved water quality" and "reduced impacts from flooding" can be achieved by all SCMs but one each (above ground storage and vegetated filter strip, respectively).

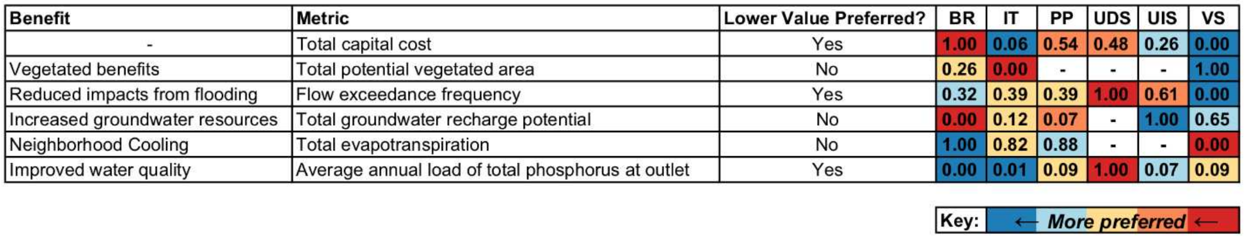
	Characteristics						Benefits										
SCM Name	Vegetated	Detention	Retention	Infiltration	Evaporation	Transpiration	Improved water quality	Reduced impacts from flooding	Neighborhood beautification	Reduced burden on existing infrastructure	Neighborhood cooling	Increase of local groundwater resources	Cistern-specific benefits	Increased recreational opportunities	Improved air quality	Increased aquatic biodiversity	Increased terrestrial biodiversity
Above ground storage structure	-	-	X	-	-	-	0	1	0	1	0	0	0	0	0	0	0
Underground detention structure	-	X	-	-	-	-	1	1	0	1	0	0	0	0	0	0	0
Underground infiltration structure	-	-	X	X	-	-	1	1	0	1	0	1	0	0	0	0	0
Underground gravel beds	-	-	X	X	-	-	1	1	0	1	0	1	0	0	0	0	0
Cistern	-	-	X		-	-	1	1	0	1	0	0	1	0	0	0	0
Rain barrel	-	-	X		-	-	1	1	0	1	0	0	1	0	0	0	0
Porous pavement	-	X	-	X	-	-	1	1	0	1	1	1	0	1	0	0	0
Sand filter	-	X	-	X	-	-	1	1	0	1	1	1	0	0	0	0	0
Sand filter (subsurface)	-	X	-	X	-	-	1	1	0	1	1	1	0	0	0	0	0
Wet pond	X	X	X	-	-	-	1	1	1	1	1	0	0	1	1	1	1
Dry pond	X	X	X	-	-	-	1	1	1	1	1	1	0	1	1	0	1
Constructed wetland	X	X	X	-	X	X	1	1	1	1	1	1	0	1	1	1	1
Infiltration basin	X	-	-	X	-	-	1	1	1	1	1	1	0	1	1	0	1
Infiltration trench	X	-	-	X	-	-	1	1	1	1	1	1	0	1	1	0	1
Green roof	X	X	-	-	X	X	1	1	1	1	1	0	0	0	1	0	1
Vegetated filter strip (buffer strip)	X	-	-	-	-	-	1	0	1	1	1	1	0	1	1	0	1
Grassed swale (vegetated swale)	X	-	-	-	-	-	1	1	1	1	1	1	0	1	1	0	1
Bioretention	X	X	X	-	X	X	1	1	1	1	1	1	0	1	1	0	1

Figure 4.3: Benefit attribution matrix with selected characteristics for each SCM incorporated into the i-DST SUSTAIN. An “X” is used to identify characteristics of a SCM and a “1” to attribute benefits to a SCM.

4.6.2 Case study application: Berkeley neighborhood

4.6.2.1 Stormwater modeling results

Normalized results from the i-DST SUSTAIN simulations are shown in Figure 4.4. Each SCM solution has a gradient of colors; no one solution has the highest preference in all benefit categories. The no-value fields align with the attribution matrix (Figure 4.3) and illustrate, among other gaps, the lack of vegetation in three SCMs (porous pavement (PP), underground detention structure (UDS), and underground infiltration structure (UIS)). UDS is the worst option from a benefit-driven perspective – while it does provide water quality and flood mitigation it rated lowest in both benefits. Vegetated swales (VS) are most preferred in three out the six metrics used, including capital cost, which is not an ancillary benefit but helps drive most stormwater management decisions (Bell et al., 2019). Surprisingly, VS rates lowest in neighborhood cooling/total evapotranspiration. This is due to the method that i-DST SUSTAIN uses to calculate evapotranspiration, which is based off SCM surface area and storage and not vegetation.



Benefit	Metric	Lower Value Preferred?	BR	IT	PP	UDS	UIS	VS
-	Total capital cost	Yes	1.00	0.06	0.54	0.48	0.26	0.00
Vegetated benefits	Total potential vegetated area	No	0.26	0.00	-	-	-	1.00
Reduced impacts from flooding	Flow exceedance frequency	Yes	0.32	0.39	0.39	1.00	0.61	0.00
Increased groundwater resources	Total groundwater recharge potential	No	0.00	0.12	0.07	-	1.00	0.65
Neighborhood Cooling	Total evapotranspiration	No	1.00	0.82	0.88	-	-	0.00
Improved water quality	Average annual load of total phosphorus at outlet	Yes	0.00	0.01	0.09	1.00	0.07	0.09

Key: ← More preferred ←

Figure 4.4: Results from the normalized i-DST SUSTAIN output that highlights how each SCM suite relatively compares over five benefits. The color-coding is based on high/low value preference and where blue/red represent best/worst in each category.

4.6.2.2 Berkeley neighborhood and Denver UGI inventory

Five of the benefits identified in Figure 4.3 (neighborhood beautification, neighborhood cooling, increased recreational opportunities, improved air quality and improved terrestrial biodiversity) cannot be linked directly to i-DST SUSTAIN output and were measured using the proxy of total potential vegetated area. An inventory of existing UGI was performed to understand how the modeled solutions would contribute to the Berkeley neighborhood vegetated area and gauge the feasibility of receiving vegetated benefits from the total potential vegetated area modeled.

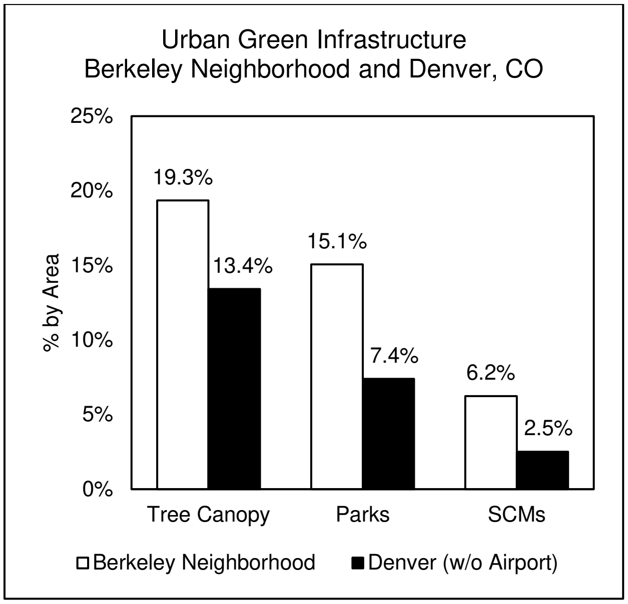


Figure 4.5: The spatial spread of different types of UGI in the Berkeley neighborhood as compared to Denver as described in terms of percent area.

By area, the Berkeley neighborhood has higher amounts of tree canopy, parks, and SCMs compared to Denver as a whole (Figure 4.5). Deciduous trees dominate the tree canopy by area in both Berkley (63.1%) and Denver at large (82.2%). By inventory the number of coniferous trees exceeds the number of deciduous trees (42.1% vs. 39.8% in Berkeley and 45.5% vs. 29.3% in Denver). Tree canopy coverage calculated in this study is less than the 19.7% city-wide coverage calculated in the report that corresponds with the data layer used (McPherson, Xiao, Wu, & Bartens, 2013); this is likely due to variable geometries used to define city boundaries. Potential vegetated area from the i-DST SUSTAIN modeled solutions range from approximately 9,000 m^2 (IT) to 13,600 m^2 (VS). If the modeled SCMs were installed at a scale that optimized all of their potential vegetated area, they would add an additional 4% to 6% to existing SCM area in the Berkeley neighborhood.

4.6.2.3 Denver SCM and land use tree canopy analyses

Across Denver, tree canopy is variable over SCM area and park area, resulting in a total effective UGI contribution (i.e. total UGI minus any overlaps between UGI types) of 32.3% in Berkeley and 21.1% in Denver (Table 4.3). The ponds in the Berkeley neighborhood, which account for 41.2% of park area in the neighborhood, influence the lower neighborhood canopy values over parks and SCMs. City-wide, SCMs and parks have higher tree canopies than in the Berkeley neighborhood and SCMs account for 11.2% of park area. Tree canopy over parks and SCMs at both scales is short of the 20% city-wide canopy goal.

Table 4.3: Tree canopy over SCM and park areas in the Berkeley neighborhood and Denver are used to calculate total effective UGI contribution.

	Berkeley Neighborhood		Denver (w/o Airport)	
	% Area	% Tree Canopy Coverage	% Area	% Tree Canopy Coverage
Tree Canopy	19.3%	-	13.4%	-
SCMs (no buffer)	6.2%	1.2%	2.5%	6.6%
Parks	15.1%	13.8%	7.4%	17.2%
Total Effective UGI Contribution	***32.3%***	**-**	***21.1%***	**-**

From a land use perspective, single family use has the highest contributing area (48.3%) and tree canopy (21.4%) and accounts for the majority of tree canopy across Denver (72.7%) (Table 4.4). Tree canopy over single family land uses is the only land use type that meets and/or exceeds the 20% city-wide canopy goal. The next highest tree canopy (13.0%) is over multifamily uses, which account for 11.7% of all land uses in 2013.

Table 4.4: Land use data from 2013 broken down by contributing area in Denver, tree canopy over land use type and contribution to the total tree canopy.

	% Area in Denver	% Tree Canopy Coverage	% of Total Tree Canopy
Agriculture	0.3%	3.6%	0.1%
Commercial	5.9%	8.8%	3.6%
Industrial	12.6%	3.0%	2.7%
Mixed	11.8%	5.5%	4.5%
Multi Family	11.7%	13.0%	10.7%
Open Space	0.0%	2.6%	0.0%
Public/Quasi-Public	9.3%	8.6%	5.6%
Single Family	***48.3%***	***21.4%***	***72.7%***

The 5-m buffer applied to SCMs marginally increased the tree canopy to 7.1% across Denver. Disaggregated by type, the larger, pond-like SCMs that dominate the stormwater system in Denver have less tree cover than smaller SCMs (Figure 4.6). As average SCM size gets smaller, tree canopy appears to trend higher. Three of the 16 SCMs analyzed exceed the 20% city-wide tree canopy goal (Denver Parks and Recreation, 2019). Six of the 16 SCMs analyzed exceed the city-wide tree canopy calculated in this study (13.4%).

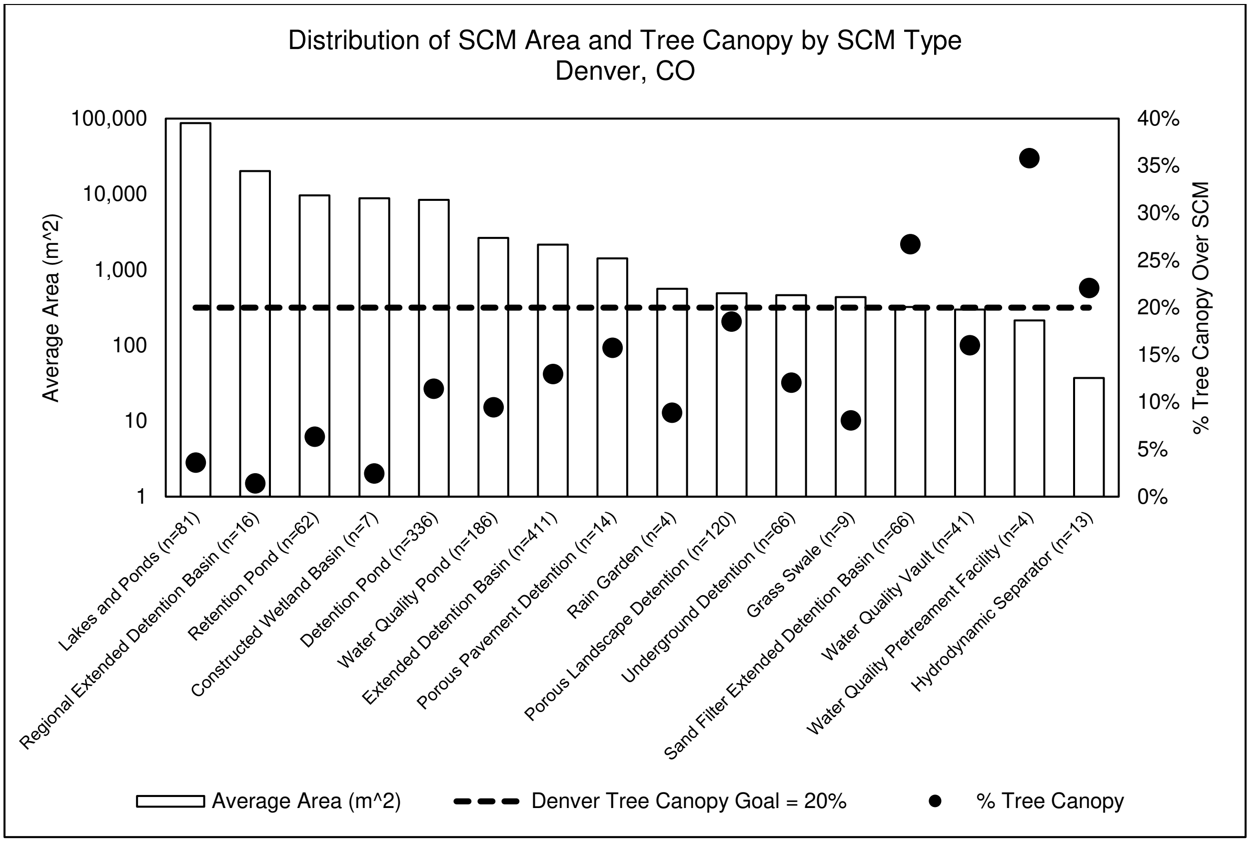


Figure 4.6: The relative size of SCMs (without buffer) and their corresponding tree canopy (with buffer) as compared to the City’s 20% tree canopy goal.

4.7 Discussion

4.7.1 Benefits analysis using stormwater modeling outputs

Results show no clear green/grey division in the benefit analysis; while the greener SCMs generally rate highly for the selected benefits, greyer SCMs are the highest rated for some categories (Figure 4.4). For example, porous pavement, typically considered a green SCM, rates in the middle for most of the categories while underground infiltration structures, a grey technology, rates highly for groundwater recharge. To help select optimal solutions, the data in Figure 4.4 could be converted into a multiple-criteria assessment matrix with the addition of weights for each benefit to refine planning priorities.

Without ratings, vegetated swales appear to be the most attractive option in the benefit analysis. Conveniently, vegetated swales also fit with the need to install smaller, vegetated SCMs to mitigate the increases in impervious surfaces resulting from infill development in the Berkeley neighborhood. In the next iteration of the stormwater planning, the modeler could optimize only smaller, vegetated suites of SCMs to refine and target the output solutions.

4.7.2 Maximizing vegetated benefits

Adding the modeled vegetated swales to the Berkeley neighborhood would only result in the increase of approximately 1% of the total effective UGI in the neighborhood. Since the UGI system is dominated by existing tree canopy and parks, new SCM installations should work to leverage existing UGI to ensure vegetated benefit maximization. The spatial spread of SCMs and the infill development trends identified in the Berkeley neighborhood are mirrored in the urban core of many US cities; the results from this study are likely transferable (Spahr et al., In prep). During the planning process for all vegetated SCMs, the following considerations of the four C’s should be evaluated to enhance vegetated benefit accrual.

4.7.2.1 Community

When evaluated as a systems level, Denver, and the Berkeley neighborhood in particular, have large, pond-like SCM dominated systems that are shifting to smaller, more vegetated SCMs due to population growth and infill development. The Berkeley neighborhood is wealthier and greener than Denver city-wide averages, as measured by median household income and UGI, respectively (US. Census Bureau, 2017). The Berkeley area is also experiencing late-state gentrification, thus property values have likely already priced out many lower income/vulnerable groups (City of Denver Office of Economic Development, 2016). Adding vegetation through implementation of SCMs could continue to improve community aesthetics and accelerate the displacement of vulnerable groups. Because the Berkeley neighborhood already has more UGI than the city-wide average, a “just green enough” approach may no longer be appropriate, suggesting focus should be placed on affordable housing, housing trust funds, and rent stabilization programs (Wolch et al., 2014).

From an equity perspective, the Berkeley neighborhood is not the best candidate for GSI intervention; Berkeley effective UGI already covers more than the Denver average (32.2% vs. 21.1% by area). The neighborhood was selected as a case study for this work as it builds on previous work and utilizes an existing observational network and stormwater model (Panos et al., 2018). Moving forward, demographic assessment should be integrated into study site selection to ensure that a broader range of economic, housing tenure and baseline vegetation perspectives are represented. Incorporating these demographic trends and outcomes from gentrification studies could insure that GSI interventions are timely and appropriate for the socio-demographic characteristics of the community.

4.7.2.2 Context

Benefit planning can be optimized by considering the context of and tradeoffs related to existing blue/green infrastructure where a SCM will be installed. For example, cooling from the addition of vegetated swales in the Berkeley neighborhood (which are expected to be surrounded by impervious surfaces) is likely to be less impactful than the cooling the neighborhood already experiences from the tree canopy and the two large detention ponds at the north end of the neighborhood. As the Berkeley neighborhood transitions from single family homes to multi-family homes, the tree canopy will likely decrease. If this decrease tracks with the land use canopy trends calculated in this study, more than 8% of tree canopy could be lost during this transition. Preserving trees and adding vegetated SCMs to redeveloped parcels, like vegetated swales, may be critical interventions required to maintain effective UGI benchmarks in the Berkeley neighborhood.

4.7.2.3 Continuity

After assessing the blue/green context in the Berkeley neighborhood, practitioners should use that information to leverage existing UGI through continuity. This study found that parks in the Berkeley neighborhood contain 41.2% of the SCM footprint. This relationship is much higher than the Denver average (11.2%) and exhibits how multi-functional interventions are manifesting at a neighborhood scale. Due to the likely decreases in vegetation from infill development, future SCM interventions in the Berkeley neighborhood should work on expanding the boundaries of existing UGI. Vegetated swales could be installed in a corridor between the two ponds on the north side of the neighborhood to expand the reach of existing benefits. Where park access is more limited, vegetated swales could also be installed around a block in the middle of the neighborhood to improve the green amenities in that area.

4.7.2.4 Canopy

Because of the dominance of tree-related outcomes in the vegetation-based literature, the tree canopy over SCMs provides some insights into the scale at which trees are included in SCM installations. The vegetated swales analyzed in this study have a tree canopy of 8%, which tracks with the low canopy cover over SCMs of only 6.6% in Denver (and 1.2% in the Berkeley neighborhood). The GSI evaluated in this study does not appear to incorporate many trees. The existing tree canopy over SCMs is likely low due to the dominance of pond-like systems where trees are only planted around the perimeter. The City has recently focused on smaller, more distributed GSI like rain gardens where young trees are likely installed after the tree canopy assessment in 2014. As these trees continue to grow, tree canopy over SCMs in Denver is likely to increase. The 20% city-wide tree canopy goal may not be the optimal goal for SCM tree canopy, even when focusing on smaller SCMs. This goal could result in increased irrigation demands for SCMs, especially during the establishment period of the trees, which counteracts other City goals related to water supply (Denver Parks and Recreation, 2019).

Looking at the tree canopy as a whole, deciduous trees dominate the canopy in Berkeley (and Denver), but by number there are more conifers. During in-leaf season, deciduous trees are likely removing more air pollutants and providing more shade and transpiration than conifers. The literature has not reached a consensus on the annual pollutant removal rates and cooling contributions of urban trees based on type in different climates. Additional studies need to be performed to disaggregate the cooling and air quality contributions of both types of trees in relation to their surrounding land use types. Stormwater practitioners can leverage the better understanding of the impacts of trees and can incorporate these findings into their designs.

4.7.3 Case study limitations

We selected the spatial datasets used in this study to simulate the use of publicly available data that practitioners likely have access to in larger cities with GIS capabilities. Smaller municipalities may not have access to as rich of datasets. Visual inspection of the layers over historical imagery identified some gaps in accuracy. The results presented in this paper should be evaluated from the lens of identifying general trends in the Berkeley neighborhood and Denver. Moving forward, accuracy and access can be improved through the use of remote sensing products over free platforms like Google Earth Engine (Gorelick et al., 2017). Additionally, future studies may benefit from separating the blue vs. green infrastructure, which is coupled under UGI in this study.

4.7.4 Challenges of analyzing benefits at a planning level

While tied to the built environment through land use and hydrologic data, i-DST SUSTAIN does not provide support for SCM siting, rather it outputs aggregate SCM solutions to meet design objectives. Without information on the 4 C's, a benefit assessment incorporated as a post-processing module to i-DST SUSTAIN would not be scientifically sound. Purposefully, none of the vegetation-based benefits are quantified in this study; we choose to only highlight the potential addition of vegetated area. We advocate that providing an estimate of potential vegetated area in combination with guidance for how to optimize installation for desired benefits provides decision makers with a realistic approximation of anticipated vegetated benefits and can help lead future modeling iterations and installation efforts.

The benefit analysis shown in this study could be modified to evaluate different hydrologic and water quality metrics, depending on the goals for the community or sewershed. To incorporate stakeholders, practitioners and community members can be engaged in a rating activity, much like Alves et al., (2018) performed, to use different groups' preferences for benefits to select final infrastructure solutions. The outputs from this analysis could be incorporated into a spatial planning tool, like the ones used by Meerow & Newell, (2017) that incorporate demographic data, to help site individual SCMs. The spatial tool could be made more robust by expanding its temporal scale and including known site constraints and/or any greenness goals a city may have developed to mitigate land use changes (Spahr et al., 2020). Presenting a benefit-led assessment of potential stormwater infrastructure installations may help encourage more private property interventions.

During the initial screening process, double counting of benefits was considered. For example, improved aquatic habitat was not analyzed in the case study because it was considered to have significant overlap with improved water quality and reduced impacts from flooding. In the future, a matrix like that developed in the Green Infrastructure Valuation Toolkit should be incorporated to show the inter-relationships between benefits (GIVaN, 2010). Ecosystem disservices were not included in the benefit analysis and their magnitude, while assumed small, warrants future academic study.

For GSI programs to shift to multi-functional approaches, like the inclusion of benefits into the planning process, more holistic vegetation goals need to be set by cities and municipalities. While the City of Denver's 20% tree canopy goal provides a starting point for GSI programmers to incorporate in their SCM designs, a larger framework should be set in place to create multi-department goals. Concepts like integrated urban water management (Mitchell, 2006) and integrated vegetation management (C. A. Nowak & Ballard, 2005) can be combined to create system-level urban vegetation goals that help promote and optimize vegetation-related benefits.

4.7.5 Future research

The following future interdisciplinary work is suggested based on the findings of this study with an emphasis on stormwater planning: (1) Developing a remote-sensing-based analysis that distinguishes the different components of UGI and tracks how they change over time, (2) Expanding hedonic pricing studies that investigate the relationship between large/small SCMs, urban/suburban stormwater management, and different climate regions, (3) Investigating what a "just green enough" intervention looks in multiple cities at a neighborhood scale, (4) Inventorying SCM plant species, including trees, in multiple cities with variable climates, (5) Expanding the work of Makido et al., (2019) to look at cooling of urban vegetation in arid environments, and (6) Investigating the neighborhood and city-wide impacts of blue vs. green infrastructure on cooling in different climates.

4.8 Conclusions

This study critically analyzes the hydrologic and vegetation-based UGI benefit literature from the lens of stormwater management. At a planning level, hydrologic benefits are easier to simulate than vegetated benefits using existing tools, because the technical knowledge on this topic is much more mature. Vegetated benefits often leverage the surrounding urban green infrastructure, so they should be evaluated using our framework of the 4 C's: community, context, connectivity, and canopy.

Using a case study in the Berkeley neighborhood, we find that when stormwater modeling outputs are evaluated for benefits, both green and grey SCMs accrue benefits. Without the incorporation of weightings, vegetated swales provided the most attractive option based on our benefit assessment. The modeled solutions would add approximately 1% to existing UGI in the Berkeley neighborhood, so it is critical that existing UGI is inventoried and leveraged to accrue the vegetated benefits that cannot be measured through stormwater modeling. Using the 4C's we outline how practitioners could inform their planning process by using existing socio-demographic and vegetation trends.

As vegetated benefit literature is heavily based on trees, a canopy assessment was performed to evaluate the interactions between trees, SCMs, and land uses. Using a tree canopy assessment across the city of Denver, we find that most SCMs do not have robust tree cover and do not meet the City's 20% tree canopy goal. Tree canopy analysis over land use finds that single-family uses have the highest canopy (21.4%). Through infill development, this tree canopy could be reduced to 13% if the redeveloped multi-family use matches the conditions in this study. Moving forward, we advocate for an integrated urban vegetation approach that manages vegetation at a systems level and provides a mechanism to optimize multi-functional UGI interventions.

CHAPTER 5

CONCLUSIONS AND BROADER IMPACTS

5.1 Conclusions

This research fills three areas of knowledge gaps associated with incorporating benefits of SCMs into the stormwater planning process. The three objectives of this work query the spatial influence of GSI, public acceptance of GSI and its ancillary benefits and the capacity of SCMs to accrue benefits. Insights into these three areas are discussed by science question and hypothesis below.

5.1.1 Objective 1: National Study of Urban Greenness

Q 1.1 How is greenness trending in cities that continue to develop and have signature greening programs?

Hypothesis 1.1 Greenness (as measured by the normalized difference vegetation index (NDVI) and corrected for climate signals) will be decreasing over city boundaries because cities do not implement signature greening programs at scales that offset development-related increases in impervious surfaces.

> *Findings 1.1* In the analysis of ten cities in the U.S., and after correcting for climate, we found that greenness trends in cities with signature greening programs varied. The majority of the cities exhibited no trend over the 1990 to 2016 study period. It is likely that different parts of each city with no trend is losing or gaining greenness but not at a scale that results in a city-wide trend. Seattle and Milwaukee, which had increasing greenness during the study period, are likely getting greener due to maturing vegetation of larger green spaces and not the installation of GSI.
>
> Three of the ten cities (Chicago, Philadelphia, and Washington DC) behaved as hypothesized; they lost greenness and are likely not installing GSI at a rate that offsets development. Population trends in these three cities were variable during the study period, which shows that growing populations are not the only drivers for development and loss of greenness.

Q 1.2 How do vegetated or non-vegetated stormwater control measures (SCMs) contribute to greenness trends?

Hypothesis 1.2 The installation of non-vegetated SCMs in Philadelphia has contributed to decreased city-wide greenness.

> *Findings 1.2* As hypothesized, by area the majority (62% by area) of SCMs installed in Philadelphia during the study period were non-vegetated and contributed to the loss of greenness during the study period. Volumetric goals as set by the Philadelphia Water Department and institutional comfort with non-vegetated SCMs seem to be driving these preferences.

Q 1.3 How does surrounding urban green infrastructure (UGI) impact zip-code level greenness trends?

Hypothesis 1.3 If the SCMs installed are smaller than the 30 by 30 meter Landsat pixel size, then the surrounding UGI exerts as much or more influence on a zip-code level greenness trends in Philadelphia.

> *Findings 1.3* In Philadelphia, much of the GSI was installed in conjunction with redevelopment of lower density lots to higher density uses. If the SCM installed was non-vegetated, overall greenness loss was compounded. The impact of the larger UGI system can be seen in the only Philadelphia zip code showing increased trends during the study period. In that zip code, a row of stormwater tree trenches contributed to as much increased greenness as a vacant lot in its vicinity. As hypothesized, the size of the SCMs compared to the Landsat pixel size influences how greenness is trending. Smaller SCMs require multiple installations and surrounding UGI to influence the pixel trend.

5.1.2 Objective 2: Public Perception of Stormwater Infrastructure and Public Preference for Co-Benefits

Q 2.1 What impacts do demographics (i.e. race, age, gender, population density, financial security, educational attainment and housing tenue) and city of residence (Philadelphia, PA; Denver, CO; Seattle, WA) have on a resident's preference for grey/green infrastructure?

Hypothesis 2.1 Preference for green/grey infrastructure will be consistent across all demographic characteristics and cities.

> *Findings 2.1* As written, the survey questions and potential responses did not create the most direct results to answer this question. Added complexity came from (1) asking about grey/green preference from a handle/new installation question construct and (2) including the possible response option of "a mix of both" for both questions. To evaluate this question, a ±10% threshold was used to evaluate higher or lower than average preference for grey/green infrastructure.
>
> Hypothesis 2.1 was written to be rejected. We understand that the public is not monolithic in their opinions but research in this area is insufficient to make educated guesses for demographic- or city-specific preferences. This survey was administered to help fill these knowledge gaps and add nuance. While there was consensus across most groups (which partially supports Hypothesis 2.1), some groups were found to have higher or lower preferences. Using the +10% threshold, respondents who identified as Asians and those with a Master's degree or higher had a higher preference for green infrastructure to handle storms and for new installations. Respondents who identified as Black or African American had higher preference (i.e. +10% over the overall results) for grey infrastructure to handle storms. From a lower preference perspective, respondents who identified as Black or African American and people under the age of 20 had a lower preference (i.e. -10% over the overall results) for new green infrastructure installations. Using these results, we can better inform hypothesis generation and social science methods (i.e. survey or interview development) for future iterations of this work.

Q 2.2 How does preference for grey/green infrastructure change when asked about ability of existing infrastructure to handle storms vs. the type of new installations preferred?

Hypothesis 2.2 Respondents will have a higher preference for grey infrastructure to handle storms and a higher preference for new installations of green infrastructure.

> *Findings 2.2* Given that the possible responses for both of these questions included "a mix of both" option, the combined option was the most popular for both question constructs. While not illuminating from a green vs. grey framing, most stormwater

systems considering adding green infrastructure already have piped grey networks, so the "a mix of both" option matches existing and likely future conditions. Looking beyond the "mix of both" preference, all respondents had a higher preference (i.e. +10% over the overall results) for new green installations than for green infrastructure to handle storms. We interpret this to mean that respondents like new green infrastructure installed in their neighborhoods but like their stormwater management systems to utilize grey infrastructure to manage flows.

When evaluated for city of residence, none of the three cities had preferences that supported both conditions of Hypothesis 2.2.; Denver residents supported the first condition of the hypothesis by having a higher preference for new green infrastructure installations. Philadelphia residents supported the second condition of the hypothesis by having a higher preference for grey infrastructure to handle storms. In the next iteration of this work, the handle vs. new install constructs should be separated.

Q 2.3 How are preferences for benefits influenced by demographic characteristics and city of residence?

Hypothesis 2.3 Preference for all benefits will be consistent across all demographic characteristics and cities.

Findings 2.3 Like Hypothesis 2.1, due to lack of data Hypothesis 2.3 was written to be rejected. Analysis of the survey responses show that most respondents rated all benefits either very important or important, which helps validate the assumption that the general public likes benefits. When evaluated at a finer resolution across demographics and city of residence, three benefits were found to be important across most groups: "reduced impacts flooding", "improved water quality", and "improved air quality". Conversely, three benefits were found to be less important across most groups: "stress reduction", "neighborhood cooling", and "increased property value". For the three top/bottom benefits, Hypothesis 2.3 is mostly correct.

For all benefits, especially those outside the top/bottom three, nuance is added when the results are evaluated by demographic group and city of residence. A heat map (Figure 3.6) was created to display variable preferences for benefits across demographic group by category (i.e. city, race, age, gender, population density, economic security, educational attainment, and renter/owner). Trends in Figure 3.6 can be identified visually when a demographic group's % importance and consensus score is a different shade or color than the color/shade given to overall field at the top. For example, respondents with a Bachelor's degree have a higher preference for "reduced wastewater treatment energy needs" and "greenhouse gas reduction". From a city perspective, residents' preferences for benefits tracked with overall trends but Seattle and Philadelphia residents showed higher preferences for "reduced building energy" and "improved habitat for local animals/fish", and "neighborhood beautification", respectively. Overall, the results find agreement among groups for some benefits (top/bottom three), which supports Hypothesis 2.3, but not across all 16 benefits included in the survey. Again, future work can use these results to inform hypothesis generation.

5.1.3 Objective 3: Incorporating Benefits in a Stormwater Planning Tool

Q 3.1 Based on physical form and feasibility, which stormwater control measures (SCMs) included in i-DST SUSTAIN have the potential to accrue hydrologic process and vegetation-based benefits?

Hypothesis 3.1 SCMs on the greyer end of the continuum will accrue hydrologic-based benefits but not vegetation-based benefits. SCMs on the greener end of the continuum will accrue both hydrologic and vegetation-based benefits.

Findings 3.1 As hypothesized, greyer SCMs accrue only hydrologic-based benefits and greener SCMs accrue both hydrologic- and vegetation-based benefits. All SCMs incorporated in i-DST SUSTAIN can reduce flows into existing systems and reduce the burden on infrastructure. Based on form and feasibility, most SCMs can improve water quality and reduce flooding impacts. Just because an SCM can achieve a benefit does not mean it will do so at a meaningful and actionable level. For example, according to the attribution matrix, a single bioretention cell (i.e. rain garden) has the potential to create increased recreational opportunities but if the cell is too small and/or installed in an inaccessible location, the recreation value will be limited or nonexistent.

Q 3.2 Spatially, what is the contribution of SCMs to urban green infrastructure (UGI) in the Berkeley neighborhood and across all of Denver, CO?

Hypothesis 3.2 If the spatial extent of SCMs is less than other types of UGI then a benefit analysis cannot be decoupled from UGI.

> *Findings 3.2* SCMs contribute to 6.2% and 2.5% of the Berkeley neighborhood and Denver, respectively. As hypothesized, the spatial extent of SCMs is less than other types of UGI (i.e. parks account for 15.1% (Berkeley) and 7.4% (Denver) of area and tree canopy accounts for 19.3% (Berkeley) and 13.4% (Denver) of area) so a benefit analysis should not be decoupled from UGI. To optimize vegetated benefits in future GSI interventions, planners should leverage and optimize existing UGI benefits.

Q 3.3 Given that vegetation-based benefits are dependent on trees, how does tree canopy vary with SCM type in Denver?

Hypothesis 3.3 If SCMs are larger and more pond-like then they will have trees around their perimeter and their tree canopy will be low. If SCMs are smaller then they will have more trees planted directly into their spatial extent so they will have a higher tree canopy.

> *Findings 3.3* Most tree canopy over the SCMs evaluated is less than the City's 20% goal. As hypothesized, larger SCMs have less tree canopy due to their pond-like characteristics that result in perimeter-only trees. Because Denver is dominated by these larger (regional) SCMs, city-wide average tree canopy over SCMs is low (6.6%). Also, as hypothesized, smaller SCMs included in this analysis were found to have higher tree canopy values, but quality control of the data found buffer overlap in smaller installations resulting in the double counting of trees. When evaluated by land use, single-family land uses had higher tree canopy than multi-family land uses (21.4% vs. 13.0%). As cities like Denver continue to densify using infill development, preserving trees and adding vegetated SCMs to redeveloped parcels may be critical interventions required to maintain effective UGI benchmarks. To get tree-based benefits, like improved air quality, which is important to all respondents in the survey from Objective 2, practitioners should consider adding more trees to new SCMs.

5.2 Broader Impacts

Stormwater management, especially when driven by compliance, uses a top down approach. Water quality and quantity goals are set and infrastructure systems are designed to meet these goals. When shifting to a multiple benefit approach, the "range of outcomes has broaden, so has the scale to which urban water managers much expand the boundaries of their systems" (Gabe, Trowsdale, & Vale, 2009). This can be difficult as, in most institutional structures, water management is siloed from vegetation management. Urban vegetation managers engage in a more bottom-up approach favored by urban planners that emphasizes consensus building between residents and institutions. The approach proposed in this dissertation is a hybrid of top-down and bottom-up management. By querying residents of three US cities, we found public consensus around the environmental benefits attributed to GSI (Chapter 3). This tracks with literature that finds that environmental objectives and indicators are often similar when comparing top down and bottom up approaches for sustainable urban water management (Gabe et al., 2009). We advocate that environmental benefits from GSI installations can be managed at a top-down approach while socio-economic benefits require a bottom-up approach. Managers of GSI programs should feel comfortable shifting between the two approaches to accommodate environmental justice concerns.

When considering the potential impact of GSI on socio-economic conditions, the "…sole provision of water infrastructure may not have as much influence on the wider social context" (Gabe et al., 2009) in which GSI is being installed. Similarly, when evaluating the impact of vegetation from GSI on broader environmental trends like air quality mitigation, GSI programs are "not likely to be an effective means for reaching" air quality mitigation goals (Pataki et al., 2011). From the literature review performed in Chapter 4, we can reasonably replace "air quality mitigation" in the previous sentence with most vegetated benefits. We advocate that GSI is one tool in urban planners' toolboxes that should be employed in a manner that is complementary and adds value towards more impactful programs. For example, the US Department of Housing and Urban Development (HUD) from 2011 to 2015 used Sustainable Community Initiative grants to support "regional and local planning efforts that helped communities integrate housing, transportation, infrastructure and environmental goals" (HUD, 2020). Grant programs like this should be continued and funded at a state and municipal level.

The effectiveness of stormwater management programs is typically measured through water quality and quantity goals. Metrics for water quality and quantity are standardized and widely understood across disciplines. Currently, the effectiveness of GSI is measured through the same water quality and quantity metrics. Hydrologic benefits can easily be identified using traditional stormwater management metrics and the hydrologic impact of GSI can be quantified. Vegetated benefits cannot be measured using traditional stormwater management metrics; the closest complementary metrics that could be borrowed from urban vegetation managers is tree canopy coverage. As shown in Chapter 4 of this dissertation, individual GSI installations have low tree canopy cover and thus another metric is needed to quantity the effect of installing vegetated SCMs. Chapter 2 of this dissertation explored the use of remote sensing metrics, like NDVI, to track changes in city-wide development. As GSI contributes only a small amount to overall land cover (2.5% in Denver), the methods presented in Chapter 2 would need to be refined to disaggregate and compare the greenness impacts of GSI and other types of urban green infrastructure, including landscaping on private property (i.e. lawns).

The installation of GSI can also result in less favorable outcomes, often called ecosystem disservices. These outcomes can include increased pollen from new vegetation, breaking of concrete by tree roots, and increased pests. In the arid west, GSI often comes with an irrigation demand that can stress already limited water resources. Frequency of maintenance of GSI can determine how much benefit or disservice installations can provide to a community. Most of the benefit analysis in this dissertation assumes that the GSI is well-maintained. Poorly managed GSI could re-release captured water quality pollutants into the environment and create cover for nefarious activities. Optimization of benefits in one neighborhood through the use of GSI may negatively impact surrounding neighborhoods. For example, if an upstream community optimizes their GSI to recharge groundwater levels, these diversions could reduce surface water flows to downstream users. In water-stressed states like Colorado that function under the doctrine of prior appropriation, this injury to the downstream user likely has legal implications. Moving forward, cities that implement wide-spread GSI should track the impacts of their programs beyond design parameters and benefit accrual to ensure disservice minimization and regional equity.

Challenges in multi-benefit stormwater management planning can be assessed through the lens of implantation science. The over-allocation of benefits to GSI is a result of one way, supply driven knowledge production (Hering, 2018) in which academic institutions identified relationships between urban green infrastructure and then pushed these results to the practitioner community without careful communication of study limitations. Practitioners then took these results and passed them on to the public to soften the impacts of rate increases or other inconveniences related to GSI programs. Demand-driven research, in which practice and management of GSI is used to inform new knowledge production (Hering, 2018), is a limited but growing field. Researchers in this area have typically focused on water quality and quantity outcomes, governance structures and financing schemes. Measurement and confirmation of benefit accrual has yet to be implemented at a meaningful level. A communication gap is likely between practitioners and the public in which feedback that organizations receive is limited to the subset of the public that has time to and understands how to engage with practitioners. To move towards a more integrated system, the communication and feedback loops between academics, practitioners, and the public need to be strengthen such that the research performed can have actionable results when implemented at a large scale that positively impacts communities in ways that align with consensus values and priories.

5.3 Recommendations for Future Work

The work performed in this dissertation could be expanded and improved on via the following efforts:

5.3.1 Spatial Analysis and Remote Sensing

- Stormwater managers could improve their asset management of SCMs to minimally include spatial extent, vegetation type installed, and installation date. This information would improve benefit allocation and tracking at the utility.
- A remote-sensing-based analysis that uses classification schemes on Quickbird imagery to distinguish the different components of UGI, including SCMs, should be performed to identify boundaries and track how they change over time.

- Remote sensing and demographic data could be combined to define what a "just green enough" intervention looks in multiple cities with different climates at a neighborhood/Census Tract scale.

5.3.2 Social Science

- Additional research should be conducted to better understand how demographic preference for different types of infrastructure match with current and planned GSI across cities.
- Stormwater managers could incorporate surveys and other social science techniques into their community outreach to bolster stakeholder engagement and public participation.
- Multi-disciplinary practitioners that design, implement, and maintain all types of UGI should be interviewed to identify areas of consensus and synergy for multi-functional planning approaches.

5.3.3 Benefit Attribution for Stormwater Management

- Hedonic pricing studies could be expanded to investigate the relationship between large/small SCMs, urban/suburban stormwater management, and different climate regions.
- Urban cooling studies could be expanded to quantify the neighborhood and city-wide impacts of blue and green infrastructure urban vegetation in different climates.
- In the arid West, the interaction between vegetation, irrigation, and cooling potential should be studied at neighborhood and city-wide levels.

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APPENDIX A

CO-BENEFITS OF GREEN INFRASTRUCTURE

A.1 Introduction

To control the precipitation that falls on impervious areas in urban settings, municipalities employ stormwater control measures (SCMs). These SCMs can range from pipes installed to collect flows within a neighbor and route them to natural water bodies to vegetated installations that infiltrate the locally-generated stormwater. SCM technologies exist on a continuum from grey to green, with the greyer technologies characterized by centralized management using pipes and greener technologies characterized by decentralized management using natural hydrologic processes.

Historically, large urban areas have installed centralized greyer technologies to manage stormwater. The oldest cities in the United States use combined sewer systems in which stormwater and sewer flows are collected from residences and neighborhoods using the same piping infrastructure. During dry times, the mixed nature of these systems introduce minimal risk to public and environmental health as wastewater treatment plants can treat full system flows before discharging into receiving waters. During storm events, flows in the systems increase and can exceed treatment capacities of wastewater plants. When the capacity is exceeded, untreated flows are often discharged directly into receiving waters which has an adverse effect on water quality and increases public and environmental health risks.

Green infrastructure for stormwater management (GI) has become one tool for municipalities with combined sewer systems to use to reduce storm event flows and reduce (or eliminate) the volume of untreated wastewater discharged. As part of legal agreements between municipalities and regulatory agencies, cities with combined systems have been installing GI SCMs to capture and infiltrate stormwater flows in a decentralized manner. For cities with separate stormwater sewers, GI SCMs provide an attractive option as the natural hydrologic processes employed have some water quality and flow attenuation benefits that are harder to achieve with greyer systems.

Introducing GI to practitioners and decision makers can be a difficult sell, especially if the municipality is not required to install GI as part of a compliance program. Challenges related to GI adoption are related to the perceived novelty of the technology and can include a lack of institutional knowledge (technical and bureaucratic), unknown municipality-specific costs (capital and operation and maintenance), and unknown performance (water quality and quantity). When discussing the merits of GI, co-benefits are often cited as additional elements to consider in the infrastructure selection process. For the purposes of this paper, co-benefits are defined as ancillary positive ecological and social outcomes that coincide with the installation of SCMs (McGarity et al. 2015). In practice, identifying and enumerating the co-benefits associated with SCMs can tip the scales in favor greener technologies. Greyer SCMs also have co-benefits associated with their installations, but a co-benefit analysis has not historically been part of the greyer decision-making process.

A.2 Literature Review

After a review of 13 relevant articles, Table A.1 below was created to show a list of 52 commonly identified co-benefits. The co-benefits are categorized as social or ecologic, based off of the author's understanding of the co-benefit's impact.

Table A.1: Co-benefits cited in the literature.

Co-Benefit	Articles Cited	Type of Co-benefit
Aesthetic value	c, d, f, i, k	Social
Flood control and mitigation	a, d, f, i, l	Ecological
Urban heat island mitigation	b, d, i, k, l	Ecological
Improved air quality	a, d, e, i	Ecological
Improved water quality	a, d, h, i	Ecological
Habitat enhancement (aquatic and terrestrial)	d, h, i, k	Ecological
Greenhouse gas reduction	a, b, d, k	Ecological
Aquifer and sub-surface flow enhancement	b, d, k, l	Ecological
Increased property values	d, f, i	Social
Reduced building energy needs	a, b, d	Ecological
Reduced wastewater treatment plant energy needs	b, d, k	Ecological
Enhanced environmental education	a, d, e	Social
Increased food access	d, e, l	Social
Community redevelopment and revitalization	c, g, h	Social
Increased recreational opportunities	d, e, i	Social
Water flow regulation and runoff mitigation	d, e, f	Ecological

Table A.1 Continued

Climate change adaptation	j, l	Ecological
Health and restorative benefits	a, l	Social
Mental health and functioning benefits	a, m	Social
Healing and therapy benefits	a, m	Social
Increased walkability and access to active living	i, m	Social
Increased biodiversity (aquatic and terrestrial)	d, l	Ecological
Enhanced streetscape with access to parks and transit stations	i, m	Social
Interacting with flora and fauna benefits	e, f	Social
Reduced heat stress	d, i	Social
Erosion control	d, i	Ecological
Waste treatment	e, h	Ecological
Stream bank and creek restoration	f, i	Ecological
Reduced household utility bill through water savings	d, f	Social
Noise reduction	e	Ecological
Pollination and seed dispersal	e	Ecological
Reduced burden on WWTP	b	Ecological
Increased opportunity for people to enjoy nature	m	Social
Stress reduction	m	Social
Social capital	m	Social
Increased tax revenue	i	Social
CSO detention and retention benefits	b	Ecological
Increased system resilience	c	Ecological
Climate regulation	e	Ecological
Improved community economics	m	Social
Contributions to healthy lawns	f	Ecological
Green job creation	d	Social
Enhanced equality	d	Social
Increased green space	c	Ecological
Increased neighborhood cohesion	i	Social
Increased household self-reliance	f	Social
Increased community amenities	d	Social
Moderation of environmental extremes	e	Ecological
Independence from water restrictions	f	Social
Water storage for periods of fire risk	f	Ecological
Restored endangered ecosystems on rooftops	b	Ecological
Traffic easing	i	Social

The literature related to co-benefits is discussed on two scales: ecosystem services and green infrastructure for stormwater management. Ecosystem services, in the context of an urban study area can also be referred to as green urban infrastructure. Falling under the umbrella of ecosystem services is green infrastructure for stormwater management (GI). It is important to distinguish the two as GI tends to be evaluated on a smaller, more decentralized scale than ecosystem services. Table A.2 identifies which articles in Table A.1 are categorized as ecosystem services or GI (Stormwater).

Table A.2: Citations for Table A.1.

Cross Reference	Citation	Type of Article
a	(Demuzere et al. 2014)	Ecosystem Services
b	(Gaffin et al. 2012)	Stormwater
c	(Odom Green et al. 2012)	Stormwater
d	(McGarity et al. 2015)	Stormwater
e	(Gómez-Baggethun and Barton 2013)	Ecosystem Services
f	(Brown et al. 2016)	Stormwater
g	(Desimini 2013)	Stormwater
h	(Odom Green et al. 2013)	Stormwater
i	(Pandit et al. 2017)	Ecosystem Services
j	(Pyke et al. 2011)	Stormwater
k	(Spatari et al. 2011)	Ecosystem Services
l	(Walsh et al. 2016)	Stormwater
m	(Wolf 2014)	Stormwater

A.3 Co-Benefit Discussion

Of the 52 co-benefits identified in this literature review, 26 are categorized as ecological and 26 are categorized as social. When focusing in on the co-benefits most commonly cited (appearing in 3 or more articles) over 62% of them are ecological. These data could suggest that while social co-benefits are equally counted, practitioners in the field are more comfortable identifying and discussing ecological co-benefits.

Some co-benefits are easily identified and measured using standard metrics, like cost, that can be easily incorporated in to the decision-making process. Other co-benefits are more nebulous to quantify into measured outcomes (Demuzere et al. 2014) and establishing a direct causal link can be difficult (i.e. relating green infrastructure installation to health outcomes) (Gómez-Baggethun and Barton 2013). In addition, co-benefits can be region- and scale-specific; a rain garden installed in a parking lot in Seattle will have different co-benefits when compared to a bioswale installed in front of a home in Los Angeles (Gómez-Baggethun and Barton 2013).

Table A.3 on the following page, adapted from the Center for Neighborhood Technology's 2010 Value of Green Infrastructure Report, shows potential co-benefits associated with each SCM on the green to grey continuum (Center for Neighborhood Technology 2010). In assigning co-benefits, the author assumes relatively large installations; co-benefits might not be realized at smaller scales. Certain SCMs may realize more of a co-benefit at a smaller scale (i.e. enhanced environmental education from a green roof) while other SCMs need a larger scale to have a significant impact on the co-benefit category (i.e. the flood control and mitigation capacity of porous pavement). This divide may occur between ecological and social categories of co-benefits, with social co-benefits typically starting to incur impacts at smaller scales while ecological co-benefits requiring larger scales for significant impact. The co-benefit relationship in Table A.3 is identified as potential because of the subjective nature of measurement of many co-benefits (i.e. aesthetics).

Co-benefits are often linked to green infrastructure but they are not exclusive to green SCMs, as shown in Table A.3. Well-planned grey infrastructure could improve community aesthetics and provide flood control, two of the most cited co-benefits in our review of the literature. As projects approach the greener end of the spectrum, more co-benefits are realized as pre-development hydrologic conditions are mimicked. Larger-scale green SCMs that increase contiguous vegetated area, like constructed wetlands, will have larger impact on co-benefits like habitat enhancement and increased recreational opportunities than a single smaller stormwater control measure like a vegetated filter strip. When employed in a community-scale distributed manner, the net impact of vegetated filter strips on co-benefits like aquifer and sub-surface flow enhancement can match or exceed those incurred by a constructed wetland.

Table A.3: Potential for each SCM classification to provide the co-benefits (adapted from (Center for Neighborhood Technology 2010) and expanded to include greyer infrastructure techniques)

Co-Benefit	Aesthetic value	Flood control and	Urban heat island	Improved air quality	Improved water	Habitat enhancement (aquatic and	Greenhouse gas	Aquifer and sub-surface flow	Increased property	Reduced building energy needs	Reduced wastewater treatment plant energy needs (for	Enhanced environmental education	Increased food access	Community redevelopment and	Increased recreational opportunities	Water flow regulation and runoff mitigation
WWTP	ø	●	○	ø	●	ø	○	○	○	○	○	ø	○	●	○	●
Storage Tunnel	○	●	○	○	ø	○	○	○	○	○	●	○	○	○	○	●
Underground Detention	○	●	○	○	ø	○	○	○	○	○	●	○	○	○	○	●
Underground Retention	○	●	○	○	ø	○	○	○	○	○	●	○	○	○	○	●
Perforated Pipes	○	●	○	○	ø	○	○	●	○	○	●	○	○	○	○	●
Underground Gravel Beds	○	●	○	○	ø	○	○	●	○	○	●	○	○	○	○	●
Above Ground Storage	●	●	○	○	○	○	○	○	○	○	●	○	○	○	○	●
Underground cisterns	○	●	○	○	○	○	○	○	○	○	●	○	○	○	○	●
Above ground cisterns	○	●	○	○	○	○	○	○	○	○	●	○	○	○	○	●
Porous pavement	○	●	○	○	ø	○	○	●	○	○	●	●	○	○	○	●
Sand filter	ø	●	ø	○	●	ø	○	●	○	○	●	ø	○	●	ø	●
Sand filter (subsurface)	ø	●	ø	○	●	ø	○	●	○	○	●	ø	○	○	○	●
Wet pond	●	●	ø	○	ø	●	○	●	ø	○	●	ø	○	●	●	●
Dry pond	ø	●	ø	○	ø	ø	○	●	ø	○	●	ø	○	●	●	●
Constructed wetland	●	●	●	○	●	●	ø	●	●	○	●	●	○	●	●	●
Infiltration basin	●	●	●	●	●	●	●	●	●	ø	●	●	●	●	●	●
Infiltration trench	●	●	●	●	●	●	●	●	●	ø	●	●	●	●	●	●
Green roof	●	●	●	●	●	●	●	●	●	●	●	●	●	●	ø	●
Vegetated filter strip	●	●	●	●	●	●	●	●	●	ø	●	●	●	●	●	●
Grassed swale	●	●	●	●	●	●	●	●	●	ø	●	●	●	●	●	●
Bioretention	●	●	●	●	●	●	●	●	●	ø	●	●	●	●	●	●

● Yes ○ No ø Maybe

A.4 Incorporating Co-Benefits into the Decision-Making Process

Moving forward, many municipal organizations may want to incorporate a co-benefit analysis into their decision-making process, but a national framework to do so does not exist. To create this framework, the author suggests adopting the service and benefit framework similar to that established in (Demuzere et al. 2014). In this framework, ecosystem services like regulation of water flows can be tied to benefits like reduced problems with flooding (ecological outcome) and social and individual coping capabilities (social outcome). This framework allows for a measurable component (water flows) to be associated with co-benefits that can be difficult to quantify (problems with flooding and/or coping capabilities). By creating a flexible and comprehensive framework that associates measurable outcomes with co-benefits, decision makers will gain a more holistic understanding of all the ancillary impacts of infrastructure on the green-grey continuum. This framework could also account for co-benefits that are associated with more than one ecosystem service, and conversely, for ecosystems services that are associated with more than one co-benefit. For example, the services of adding green space and peak flow attenuation can be related to the co-benefit of improved property values due to the decreased incidents of flooding. Adding green space can also be related to the co-benefits of improved aesthetics and improved air quality.

Presenting a co-benefit analysis to decision makers as part of the infrastructure selection process could lead to a more holistic decision-making process. One challenge to this approach is establishing the scale of impact for co-benefits. Stormwater management does not exist in a vacuum, so the installation of one greener SCM into an already redeveloping area may have minimal impact on neighborhood aesthetics. The scale of incremental impact for additional ecological co-benefits will be directly tied to existing hydrologic conditions and thus a more detailed model input will be required to more realistically characterize ecological co-benefit gains related to SCM installation. Establishing a baseline to measure improvements from for social co-benefits is likely more challenging and not a component of existing decision-making processes at most stormwater management agencies. Before a co-benefit analysis framework can be implemented at one of these agencies, a baseline assessment should be performed to identify which social metrics will be used to track social co-benefits related to SCM installation. Part of this assessment should include identifying agencies that are already tracking metrics of interest and forming collaborative partnerships to share data and planning efforts.

By incorporating a co-benefit analysis into an agency's stormwater decision-making process, practitioners can move beyond compliance-based decision making. While compliance is still a top priority, decision makers can leverage additional co-benefits related to SCMs to holistically improve the ecological and social impacts on neighborhoods. Stormwater practitioners are likely more familiar with the ecological co-benefits related to SCMs and may lack capacity to evaluate social co-benefits. This gap in knowledge should be seen as an opportunity to create collaborations with local agencies who track social outcomes. These collaborations could result in a more streamlined operation and could open up additional funding sources to all agencies involved.

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APPENDIX B

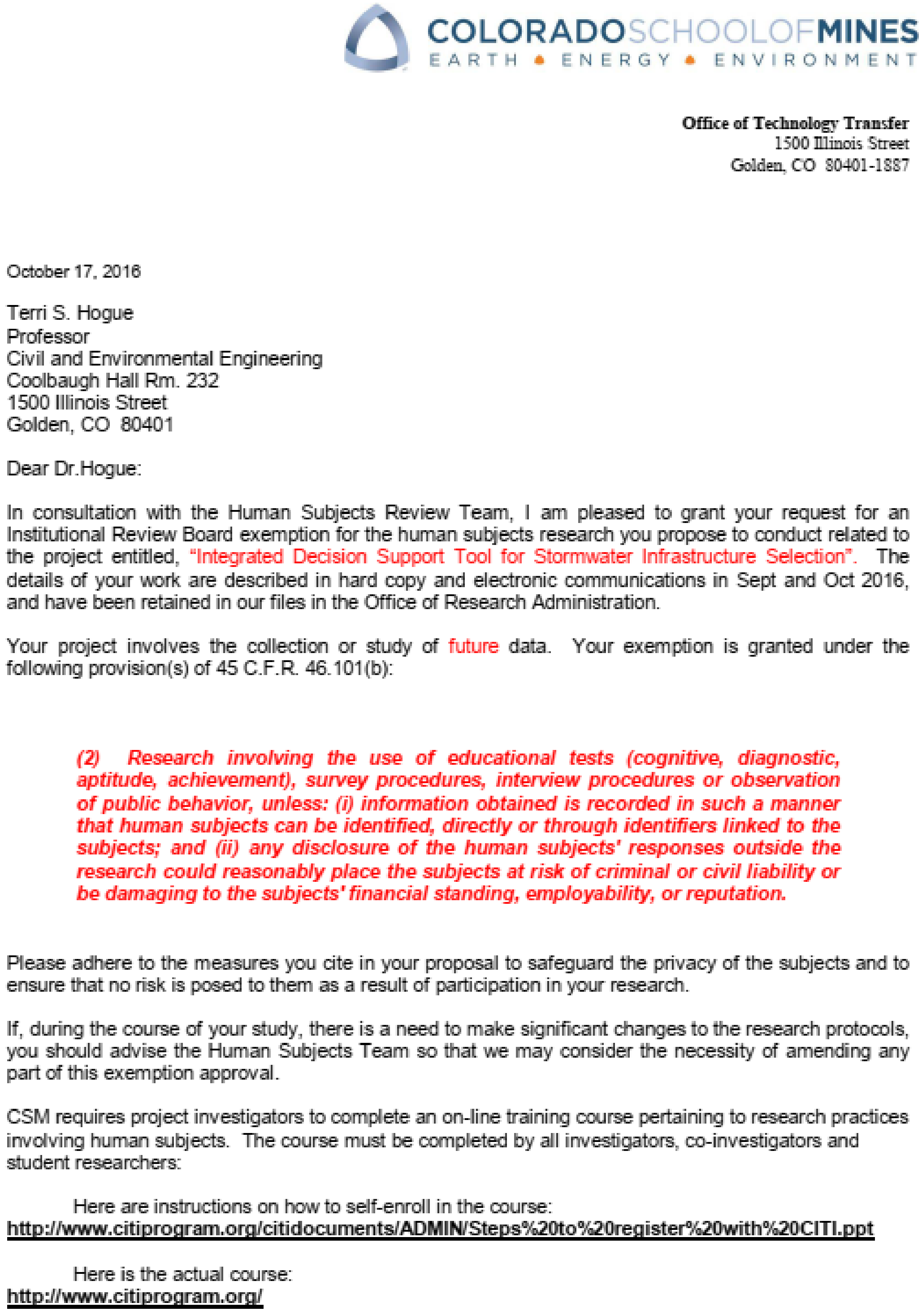
TEN CITIES GREENNESS TRENDS 2010 TO 2016

Table B.1: Results of the 2010 to 2016 linear regressions between year and $NDVI_{aamc}$ to test for changes in greenness due to GSI program implementation. The only significant trend found was for Philadelphia (decreasing by 0.5%).

City	**Slope**	**R^2**	**P**
Austin	0.009	0.23	0.28
Charlotte	-0.002	0.23	0.28
Chicago	0.009	0.36	0.16
Denver	0.003	0.22	0.18
Denver- Residuals	0.001	0.01	0.80
Los Angeles	-0.006	0.25	0.26
Los Angeles - Residuals	-0.002	0.06	0.59
Mesa	-0.005	0.22	0.29
Mesa - Residuals	-0.005	0.29	0.21
Milwaukee	0.003	0.03	0.69
Philadelphia	***-0.005***	***0.68***	***0.02***
Seattle	0.005	0.43	0.11
Washington DC	-0.003	0.10	0.49

APPENDIX C

INSTITUTIONAL REVIEW BOARD EXEMPTION APPROVAL LETTER



COLORADO SCHOOL OF MINES
EARTH • ENERGY • ENVIRONMENT

Office of Technology Transfer
1500 Illinois Street
Golden, CO 80401-1887

October 17, 2016

Terri S. Hogue
Professor
Civil and Environmental Engineering
Coolbaugh Hall Rm. 232
1500 Illinois Street
Golden, CO 80401

Dear Dr.Hogue:

In consultation with the Human Subjects Review Team, I am pleased to grant your request for an Institutional Review Board exemption for the human subjects research you propose to conduct related to the project entitled, "Integrated Decision Support Tool for Stormwater Infrastructure Selection". The details of your work are described in hard copy and electronic communications in Sept and Oct 2016, and have been retained in our files in the Office of Research Administration.

Your project involves the collection or study of future data. Your exemption is granted under the following provision(s) of 45 C.F.R. 46.101(b):

> ***(2) Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behavior, unless: (i) information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and (ii) any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.***

Please adhere to the measures you cite in your proposal to safeguard the privacy of the subjects and to ensure that no risk is posed to them as a result of participation in your research.

If, during the course of your study, there is a need to make significant changes to the research protocols, you should advise the Human Subjects Team so that we may consider the necessity of amending any part of this exemption approval.

CSM requires project investigators to complete an on-line training course pertaining to research practices involving human subjects. The course must be completed by all investigators, co-investigators and student researchers:

Here are instructions on how to self-enroll in the course:
http://www.citiprogram.org/citidocuments/ADMIN/Steps%20to%20register%20with%20CITI.ppt

Here is the actual course:
http://www.citiprogram.org/

You should select the module "Social & Behavioral Research - Basic/Refresher, Basic Course". The course takes about 8 hours to complete and it is designed to allow you to access, save, and continue on multiple occasions so that you do not need to take the whole course in one unit. Please print the certification of completion page and provide a copy humansubjects@mines.edu for our files. If you have questions about the website contact the Human Subjects Team for assistance.

Sincerely,

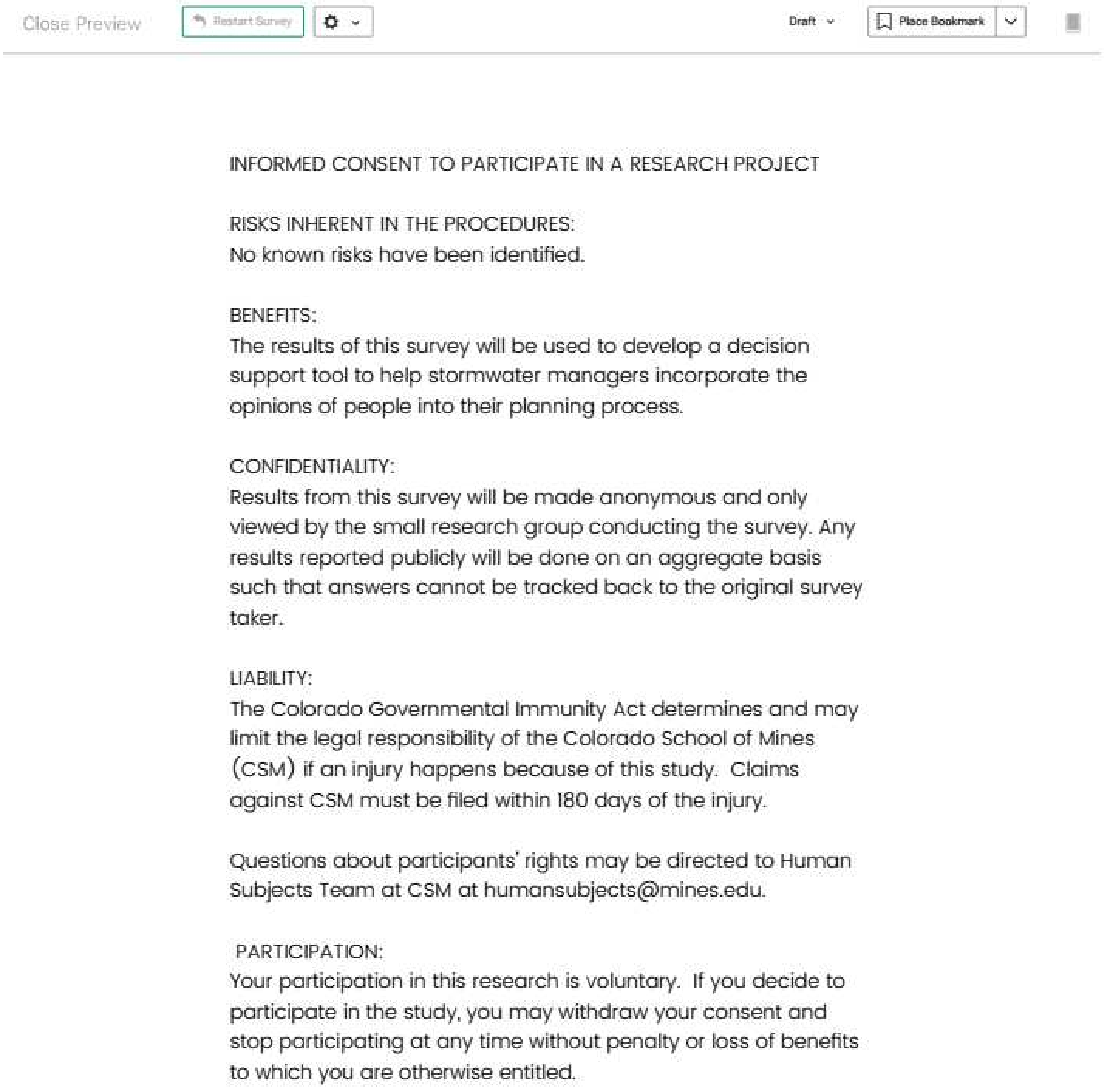
Will Vaughan

Will Vaughan
Director of the Office of Technology Transfer

cc: File
Tony Dean, Vice President for Research and Technology Transfer
Michelle Merz-Hutchinson, Associate Counsel
Johanna Eagan, Office of Research Administration
Jane Rosenthal, Policy and Compliance
Department Head
All co-investigators

APPENDIX D

FULL SURVEY AS ADMINISTERED BY QUALTRICS



INFORMED CONSENT TO PARTICIPATE IN A RESEARCH PROJECT

RISKS INHERENT IN THE PROCEDURES:
No known risks have been identified.

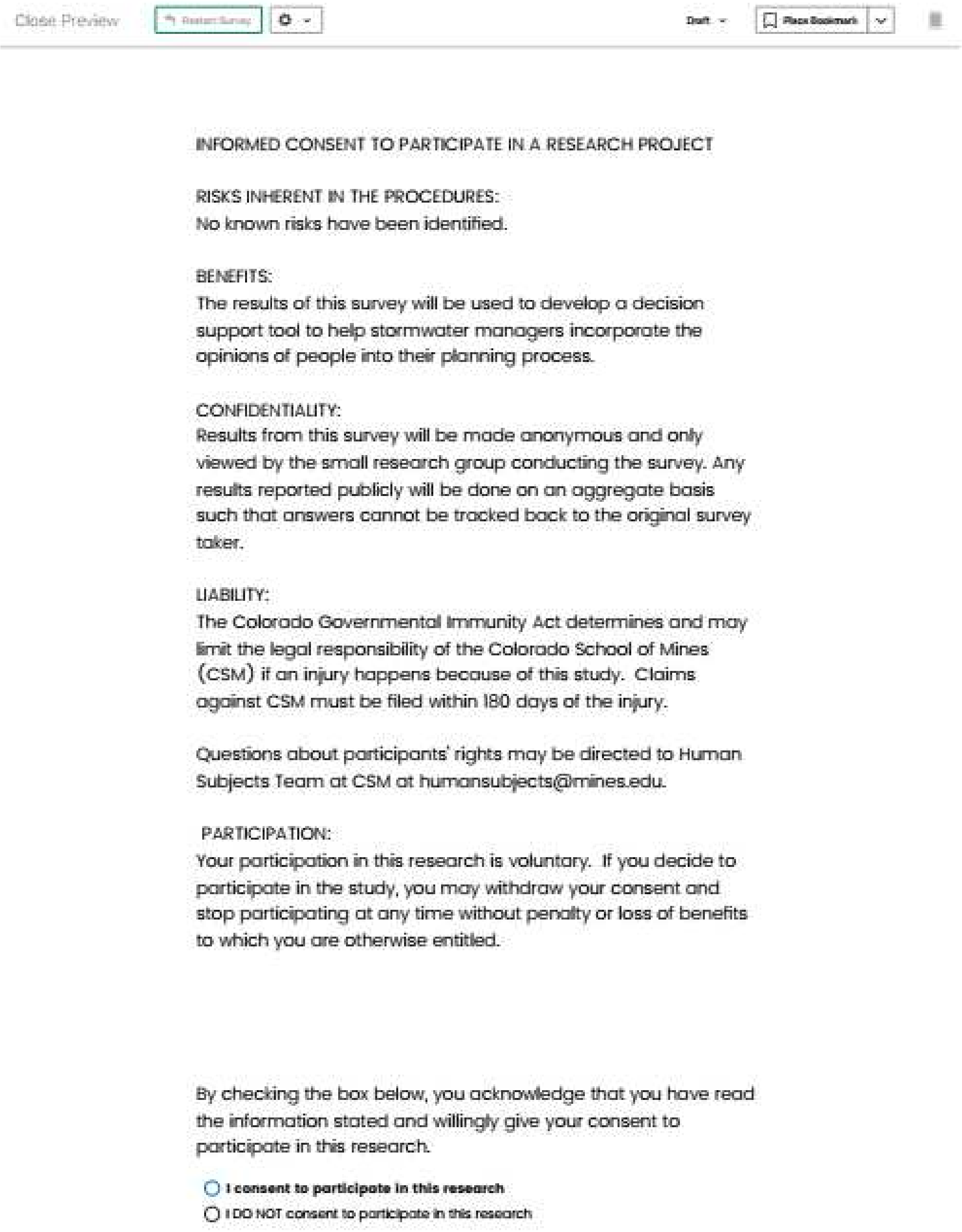
BENEFITS:
The results of this survey will be used to develop a decision support tool to help stormwater managers incorporate the opinions of people into their planning process.

CONFIDENTIALITY:
Results from this survey will be made anonymous and only viewed by the small research group conducting the survey. Any results reported publicly will be done on an aggregate basis such that answers cannot be tracked back to the original survey taker.

LIABILITY:
The Colorado Governmental Immunity Act determines and may limit the legal responsibility of the Colorado School of Mines (CSM) if an injury happens because of this study. Claims against CSM must be filed within 180 days of the injury.

Questions about participants' rights may be directed to Human Subjects Team at CSM at humansubjects@mines.edu.

PARTICIPATION:
Your participation in this research is voluntary. If you decide to participate in the study, you may withdraw your consent and stop participating at any time without penalty or loss of benefits to which you are otherwise entitled.



INFORMED CONSENT TO PARTICIPATE IN A RESEARCH PROJECT

RISKS INHERENT IN THE PROCEDURES:
No known risks have been identified.

BENEFITS:
The results of this survey will be used to develop a decision support tool to help stormwater managers incorporate the opinions of people into their planning process.

CONFIDENTIALITY:
Results from this survey will be made anonymous and only viewed by the small research group conducting the survey. Any results reported publicly will be done on an aggregate basis such that answers cannot be tracked back to the original survey taker.

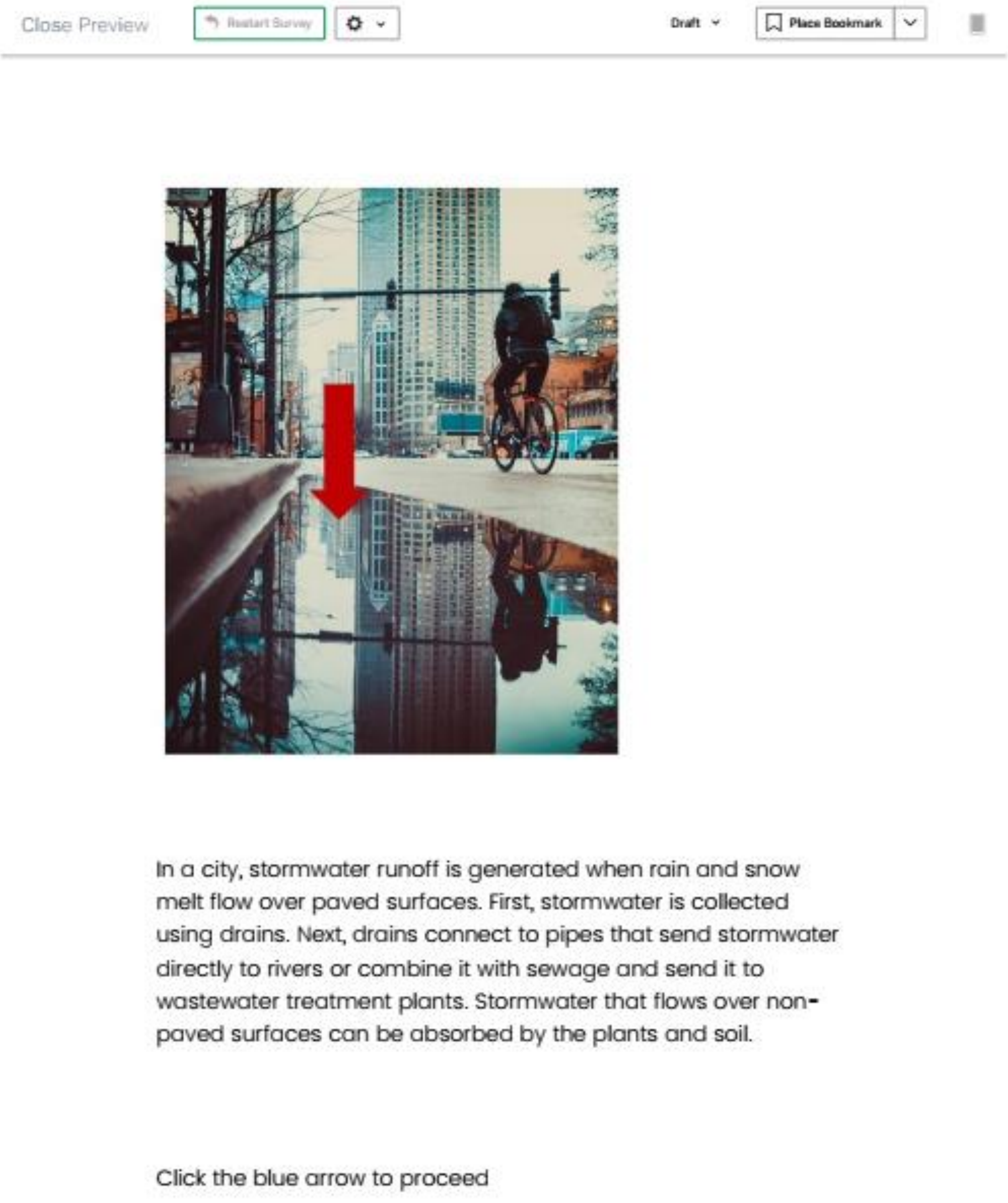
LIABILITY:
The Colorado Governmental Immunity Act determines and may limit the legal responsibility of the Colorado School of Mines (CSM) if an injury happens because of this study. Claims against CSM must be filed within 180 days of the injury.

Questions about participants' rights may be directed to Human Subjects Team at CSM at humansubjects@mines.edu.

PARTICIPATION:
Your participation in this research is voluntary. If you decide to participate in the study, you may withdraw your consent and stop participating at any time without penalty or loss of benefits to which you are otherwise entitled.

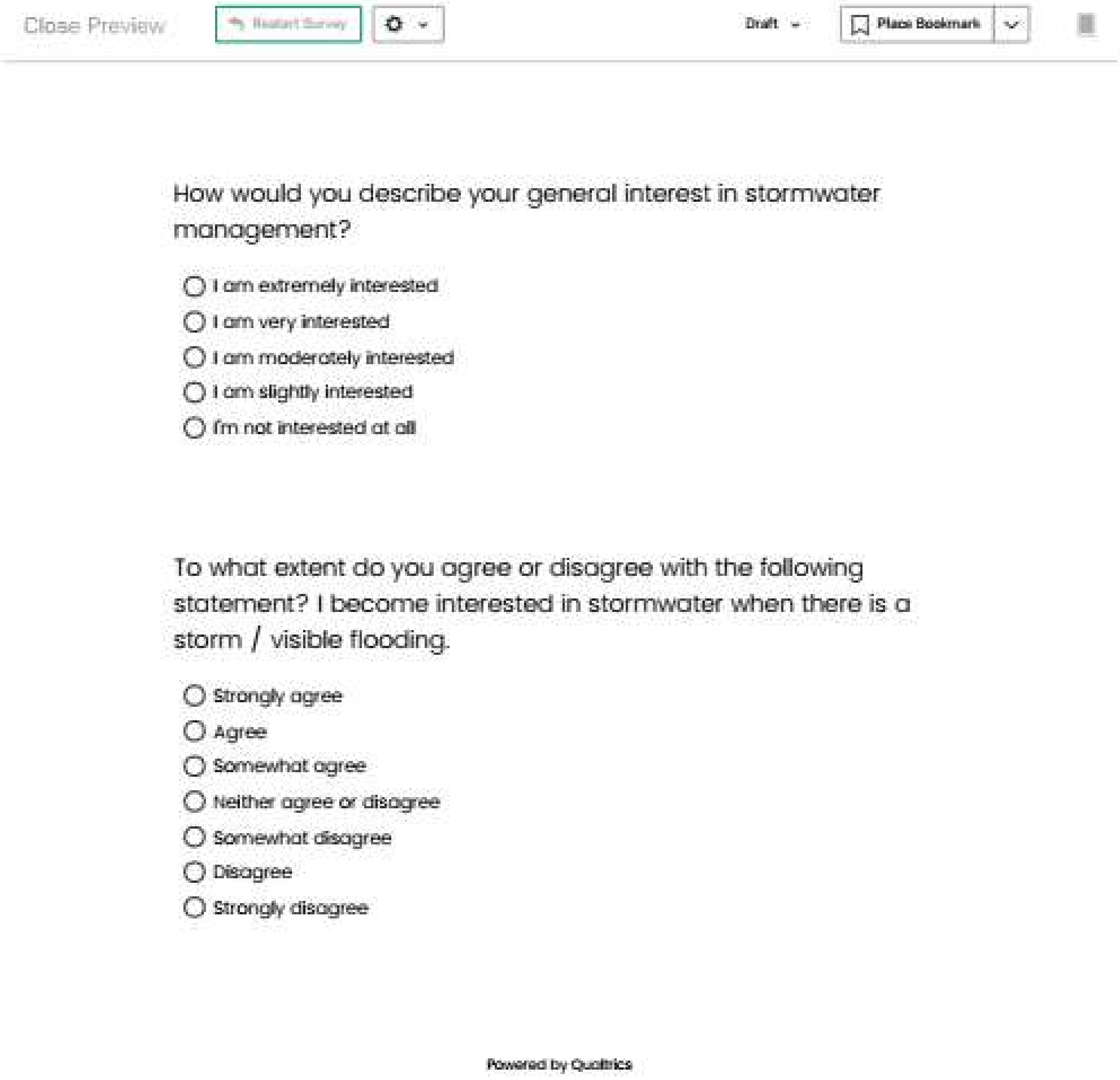
By checking the box below, you acknowledge that you have read the information stated and willingly give your consent to participate in this research.

○ **I consent to participate in this research**
○ I DO NOT consent to participate in this research



In a city, stormwater runoff is generated when rain and snow melt flow over paved surfaces. First, stormwater is collected using drains. Next, drains connect to pipes that send stormwater directly to rivers or combine it with sewage and send it to wastewater treatment plants. Stormwater that flows over non-paved surfaces can be absorbed by the plants and soil.

Click the blue arrow to proceed

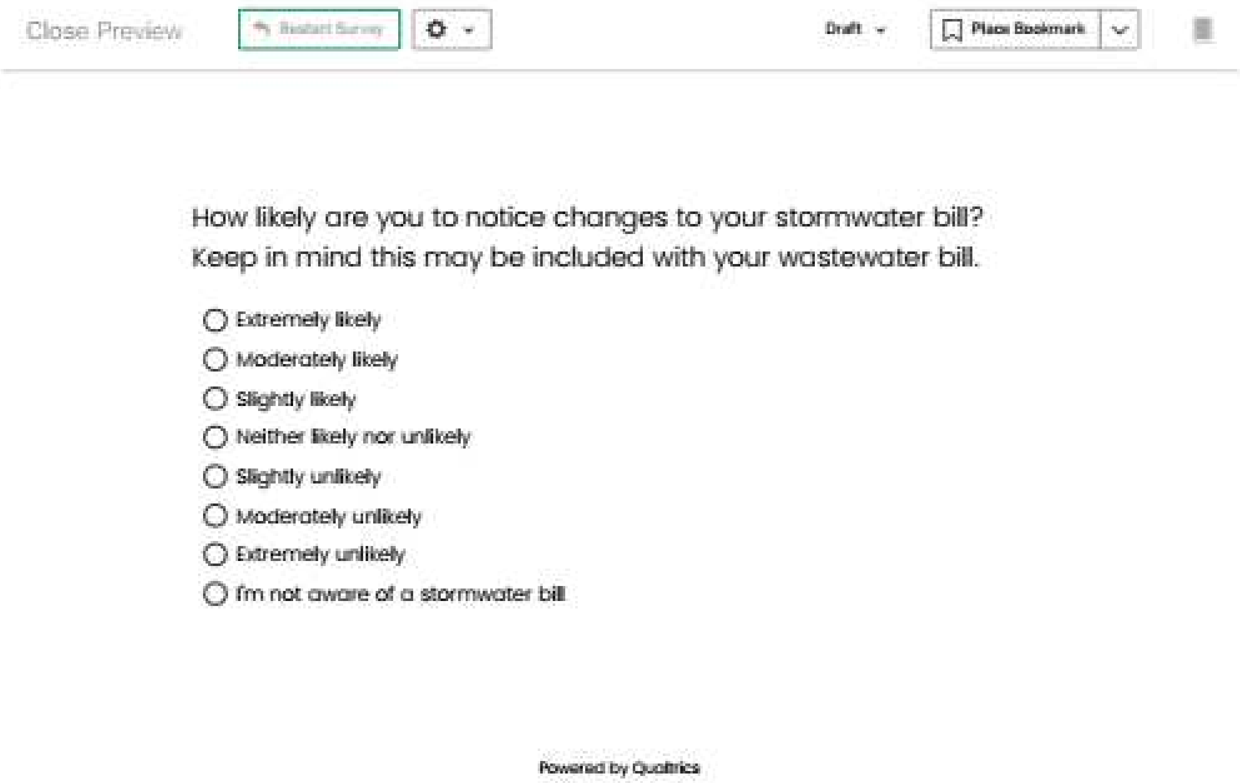


How would you describe your general interest in stormwater management?

○ I am extremely interested
○ I am very interested
○ I am moderately interested
○ I am slightly interested
○ I'm not interested at all

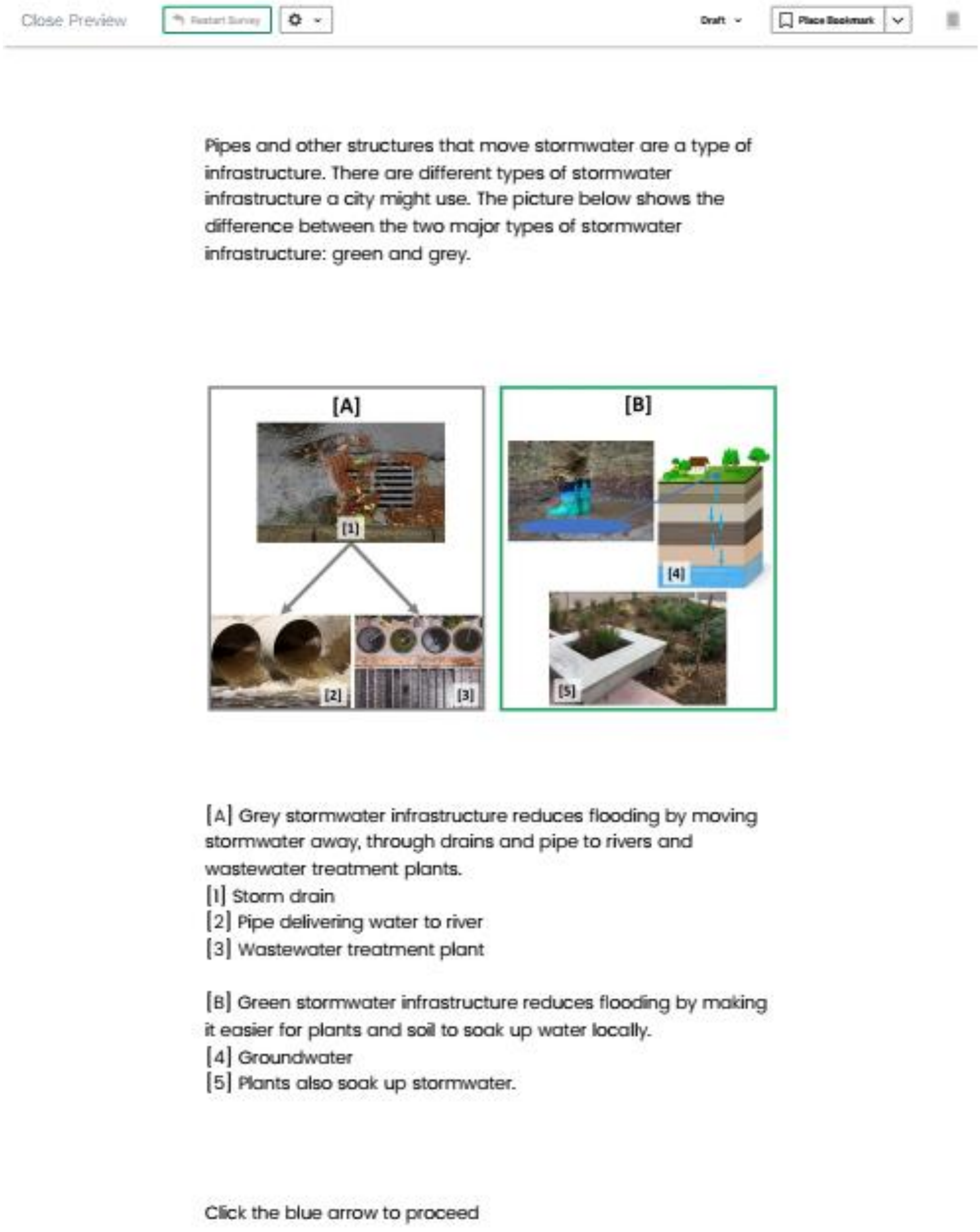
To what extent do you agree or disagree with the following statement? I become interested in stormwater when there is a storm / visible flooding.

○ Strongly agree
○ Agree
○ Somewhat agree
○ Neither agree or disagree
○ Somewhat disagree
○ Disagree
○ Strongly disagree



How likely are you to notice changes to your stormwater bill? Keep in mind this may be included with your wastewater bill.

- ○ Extremely likely
- ○ Moderately likely
- ○ Slightly likely
- ○ Neither likely nor unlikely
- ○ Slightly unlikely
- ○ Moderately unlikely
- ○ Extremely unlikely
- ○ I'm not aware of a stormwater bill



Pipes and other structures that move stormwater are a type of infrastructure. There are different types of stormwater infrastructure a city might use. The picture below shows the difference between the two major types of stormwater infrastructure: green and grey.

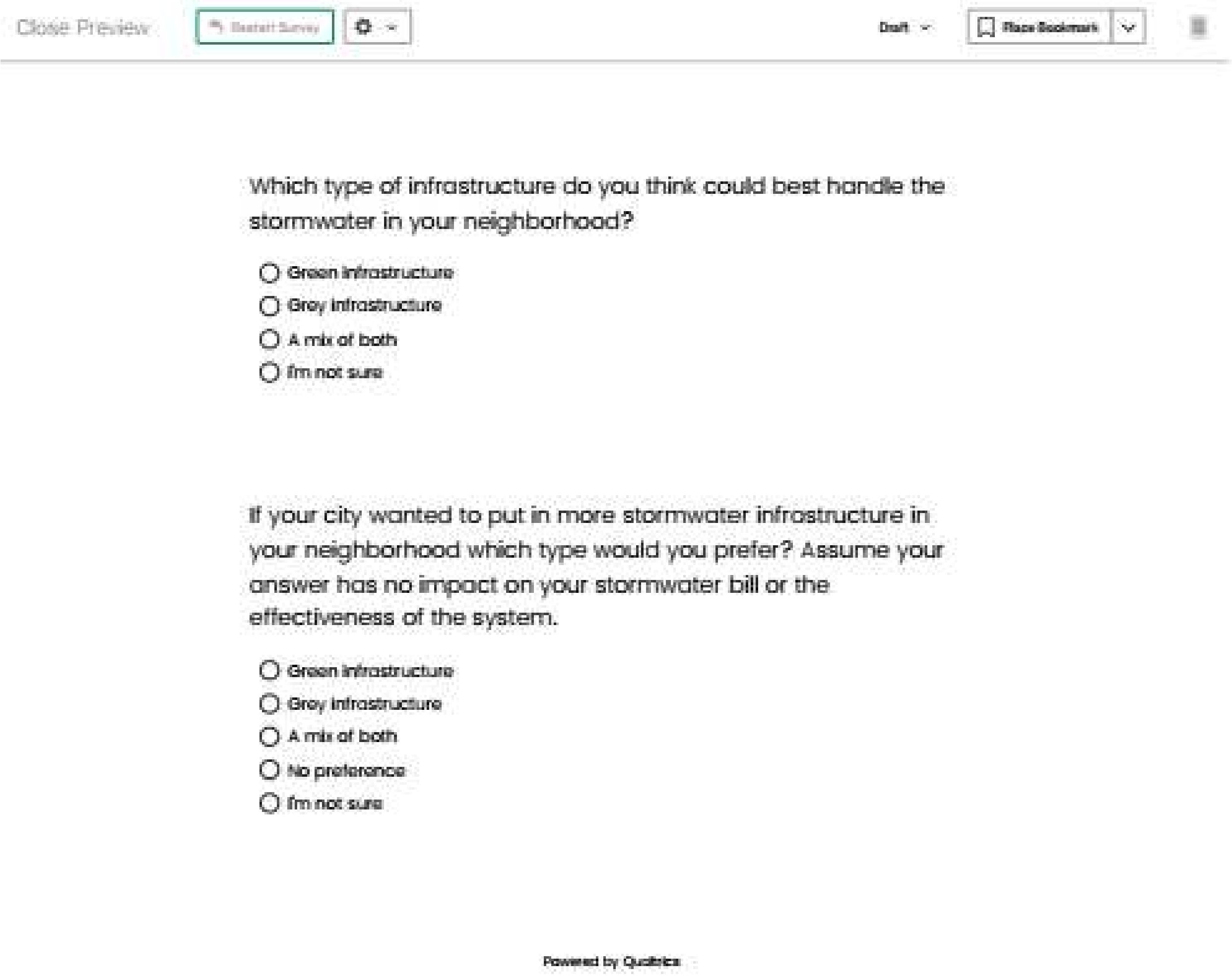
[A] Grey stormwater infrastructure reduces flooding by moving stormwater away, through drains and pipe to rivers and wastewater treatment plants.
[1] Storm drain
[2] Pipe delivering water to river
[3] Wastewater treatment plant

[B] Green stormwater infrastructure reduces flooding by making it easier for plants and soil to soak up water locally.
[4] Groundwater
[5] Plants also soak up stormwater.

Click the blue arrow to proceed

To what extent do you agree or disagree with the following statement? "I am confident in my neighborhood's stormwater infrastructure to handle most storms."

○ Strongly agree
○ Agree
○ Somewhat agree
○ Neither agree nor disagree
○ Somewhat disagree
○ Disagree
○ Strongly disagree

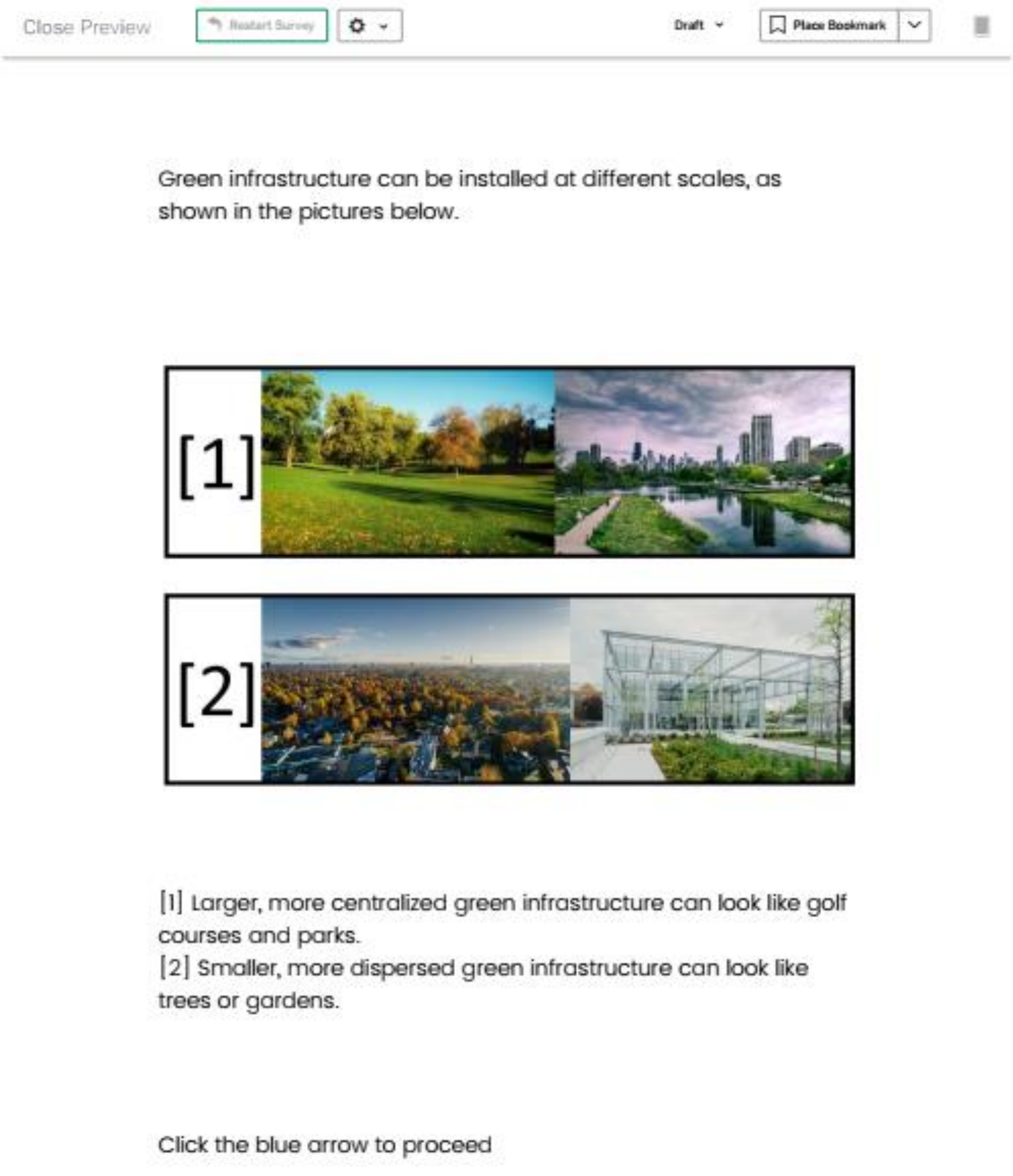


Which type of infrastructure do you think could best handle the stormwater in your neighborhood?

○ Green infrastructure
○ Grey infrastructure
○ A mix of both
○ I'm not sure

If your city wanted to put in more stormwater infrastructure in your neighborhood which type would you prefer? Assume your answer has no impact on your stormwater bill or the effectiveness of the system.

○ Green infrastructure
○ Grey infrastructure
○ A mix of both
○ No preference
○ I'm not sure



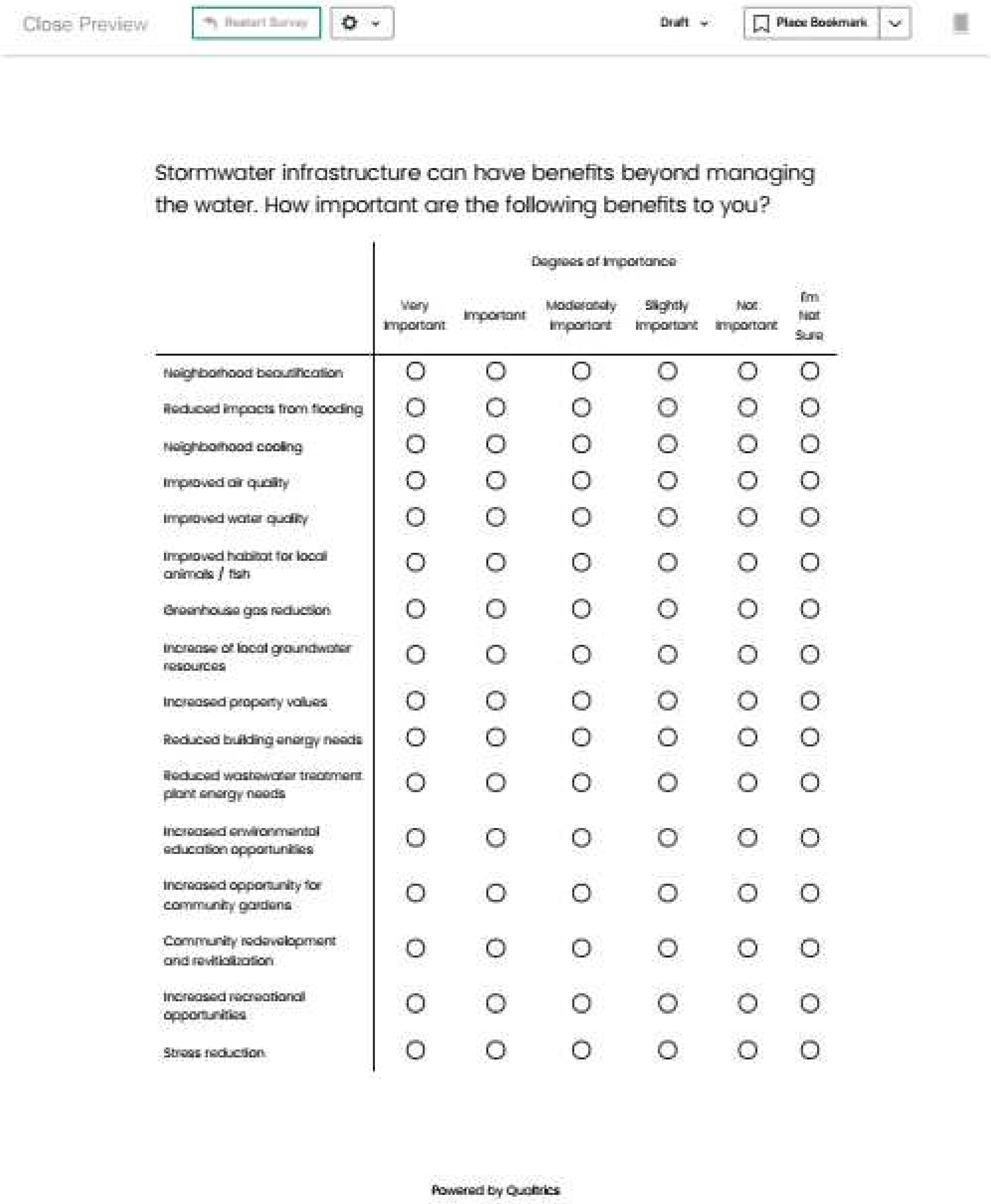
Green infrastructure can be installed at different scales, as shown in the pictures below.

[1] Larger, more centralized green infrastructure can look like golf courses and parks.
[2] Smaller, more dispersed green infrastructure can look like trees or gardens.

Click the blue arrow to proceed

If your city wanted to put in more green infrastructure in your neighborhood, which scale would you prefer? Assume your answer has no impact on your stormwater bill or the effectiveness of the system.

- ○ Larger, park-sized systems in one neighborhood location
- ○ Smaller, planter box-sized systems distributed througout the neighborhood
- ○ A mix of both
- ○ No preference
- ○ I'm not sure



Stormwater infrastructure can have benefits beyond managing the water. How important are the following benefits to you?

	Degrees of Importance					
	Very Important	Important	Moderately Important	Slightly Important	Not Important	I'm Not Sure
Neighborhood beautification	○	○	○	○	○	○
Reduced impacts from flooding	○	○	○	○	○	○
Neighborhood cooling	○	○	○	○	○	○
Improved air quality	○	○	○	○	○	○
Improved water quality	○	○	○	○	○	○
Improved habitat for local animals / fish	○	○	○	○	○	○
Greenhouse gas reduction	○	○	○	○	○	○
Increase of local groundwater resources	○	○	○	○	○	○
Increased property values	○	○	○	○	○	○
Reduced building energy needs	○	○	○	○	○	○
Reduced wastewater treatment plant energy needs	○	○	○	○	○	○
Increased environmental education opportunities	○	○	○	○	○	○
Increased opportunity for community gardens	○	○	○	○	○	○
Community redevelopment and revitalization	○	○	○	○	○	○
Increased recreational opportunities	○	○	○	○	○	○
Stress reduction	○	○	○	○	○	○

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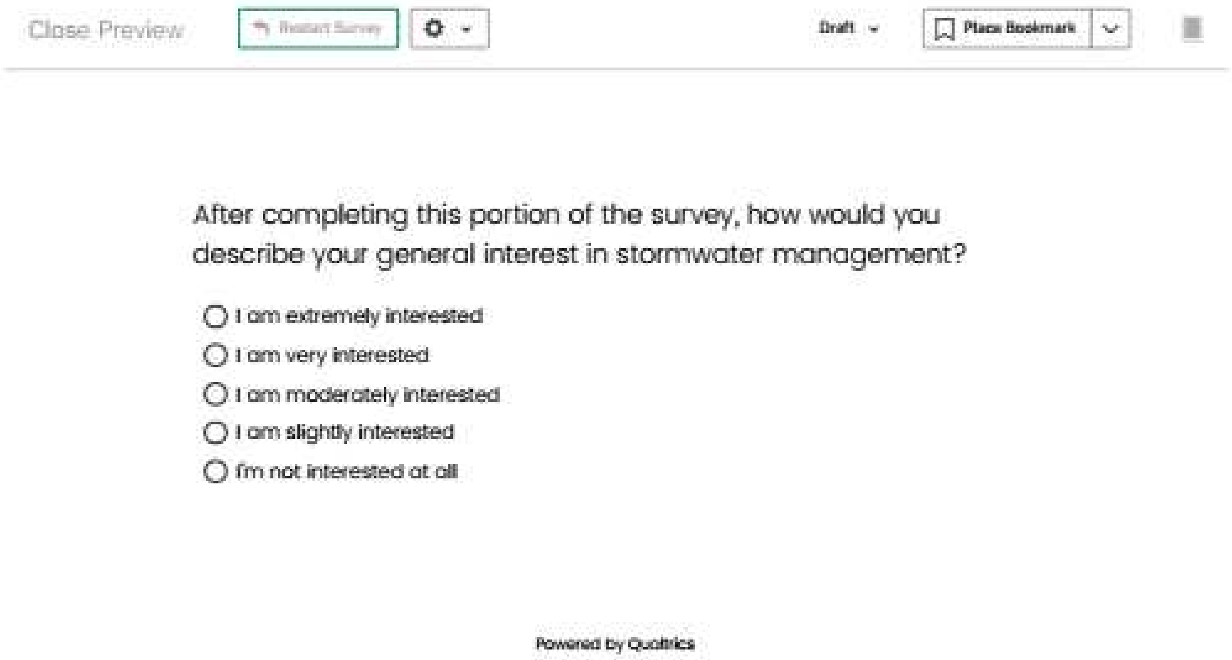
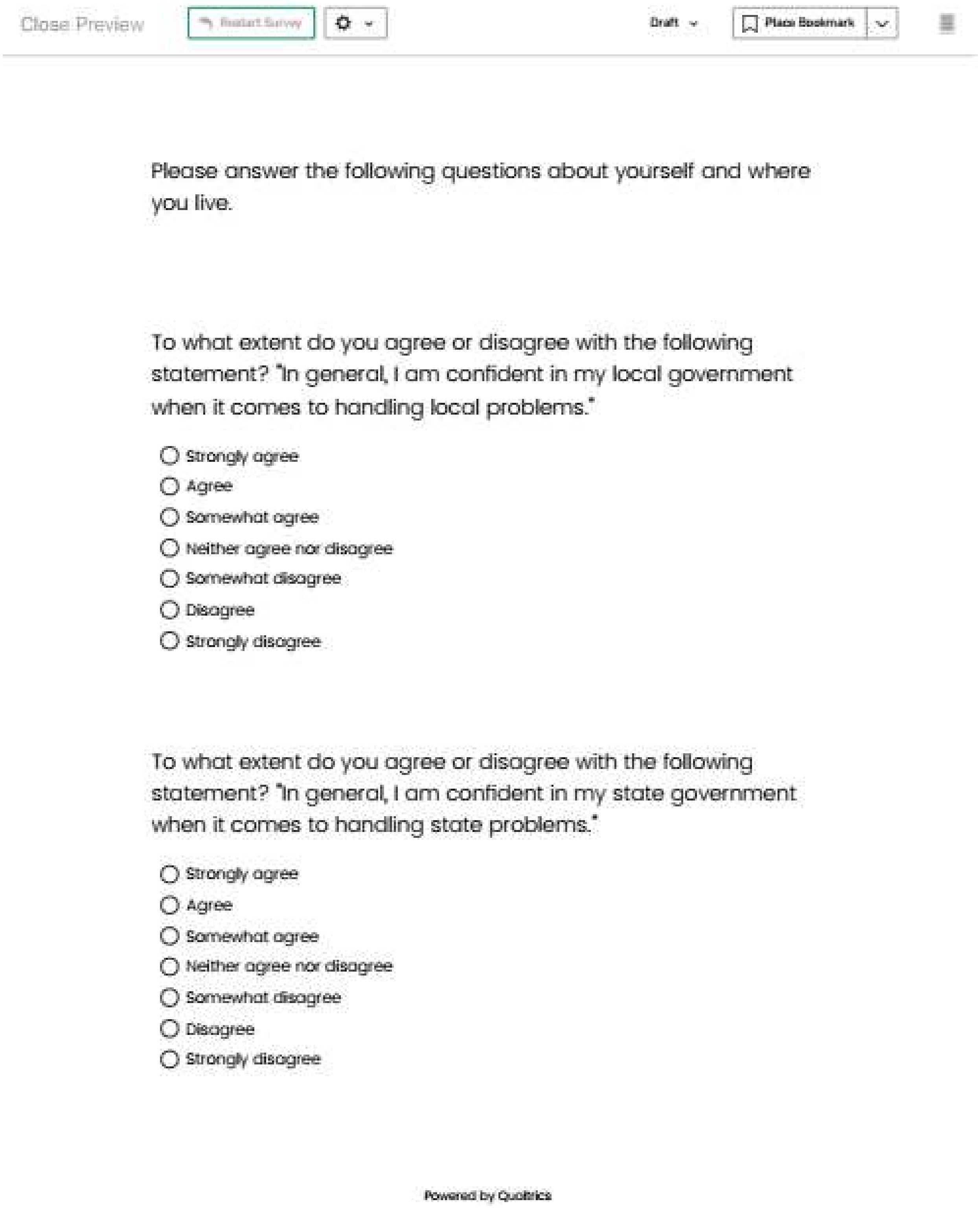


After completing this portion of the survey, how would you describe your general interest in stormwater management?

○ I am extremely interested
○ I am very interested
○ I am moderately interested
○ I am slightly interested
○ I'm not interested at all



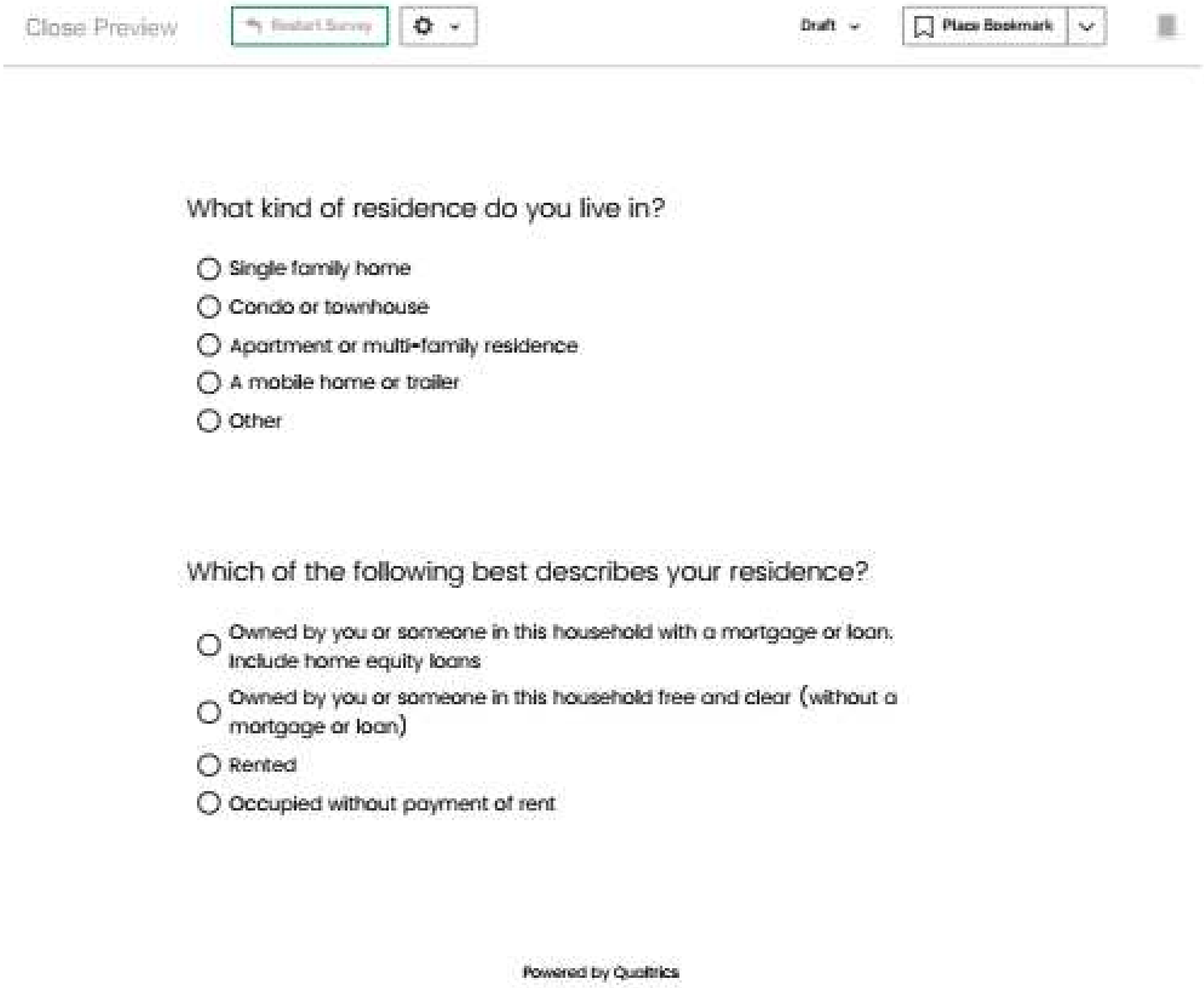
Please answer the following questions about yourself and where you live.

To what extent do you agree or disagree with the following statement? "In general, I am confident in my local government when it comes to handling local problems."

○ Strongly agree
○ Agree
○ Somewhat agree
○ Neither agree nor disagree
○ Somewhat disagree
○ Disagree
○ Strongly disagree

To what extent do you agree or disagree with the following statement? "In general, I am confident in my state government when it comes to handling state problems."

○ Strongly agree
○ Agree
○ Somewhat agree
○ Neither agree nor disagree
○ Somewhat disagree
○ Disagree
○ Strongly disagree



What kind of residence do you live in?

○ Single family home
○ Condo or townhouse
○ Apartment or multi-family residence
○ A mobile home or trailer
○ Other

Which of the following best describes your residence?

○ Owned by you or someone in this household with a mortgage or loan. Include home equity loans
○ Owned by you or someone in this household free and clear (without a mortgage or loan)
○ Rented
○ Occupied without payment of rent

How many **years** have you lived at this residence? (Use whole number and round if necessary)

How many people live or stay at your residence?

Is English the primary spoken language in your household?

- ○ Yes
- ○ No
- ○ Prefer not to state

How secure do you feel with the financial situation of your household?

- ○ Not at all secure
- ○ Slightly secure
- ○ Moderately secure
- ○ Very secure
- ○ Extremely secure

Are you the head of the household?

- ○ Yes
- ○ No
- ○ Not applicable
- ○ Prefer not to state

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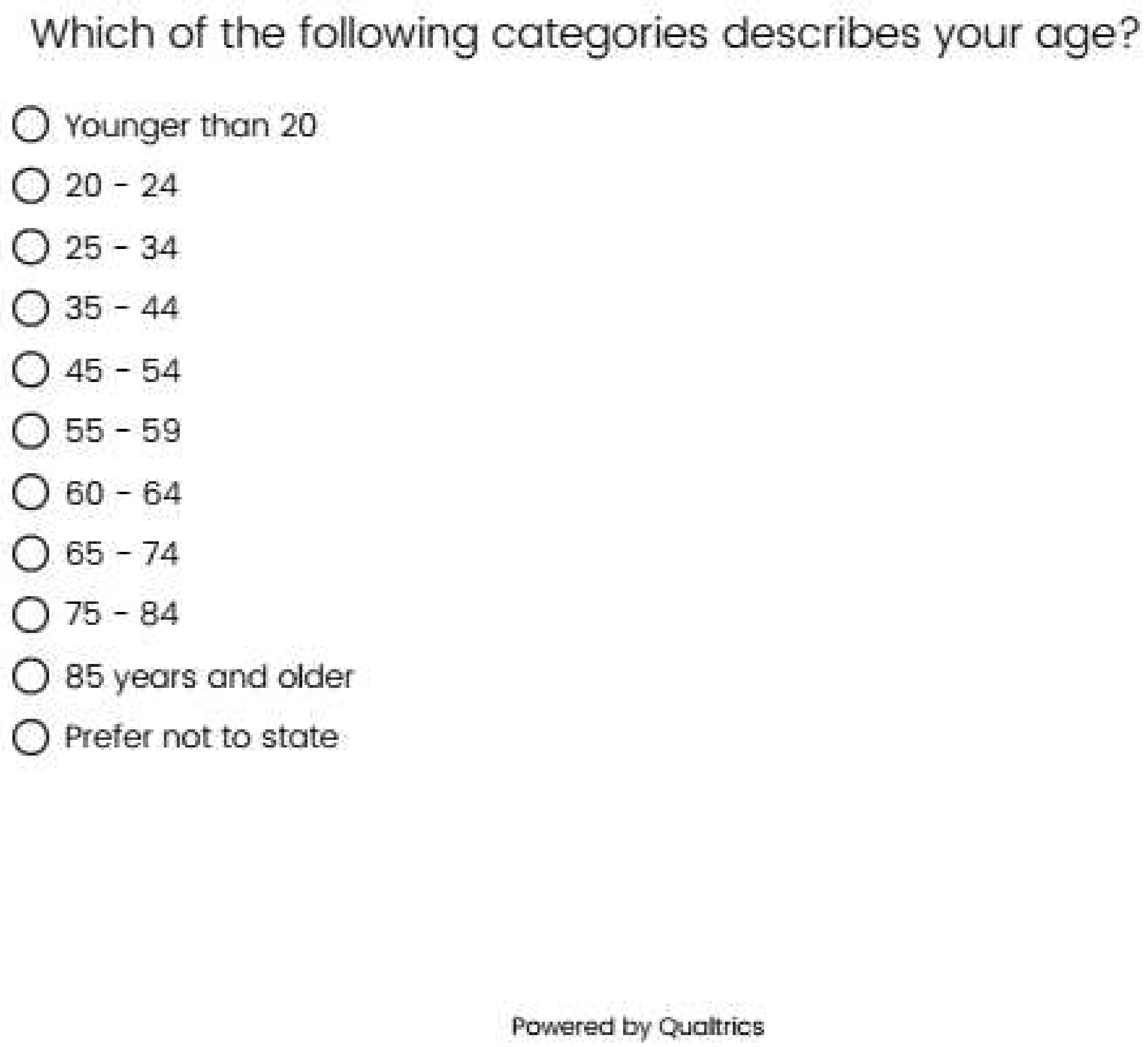

Which of the following categories describes your age?

○ Younger than 20
○ 20 - 24
○ 25 - 34
○ 35 - 44
○ 45 - 54
○ 55 - 59
○ 60 - 64
○ 65 - 74
○ 75 - 84
○ 85 years and older
○ Prefer not to state

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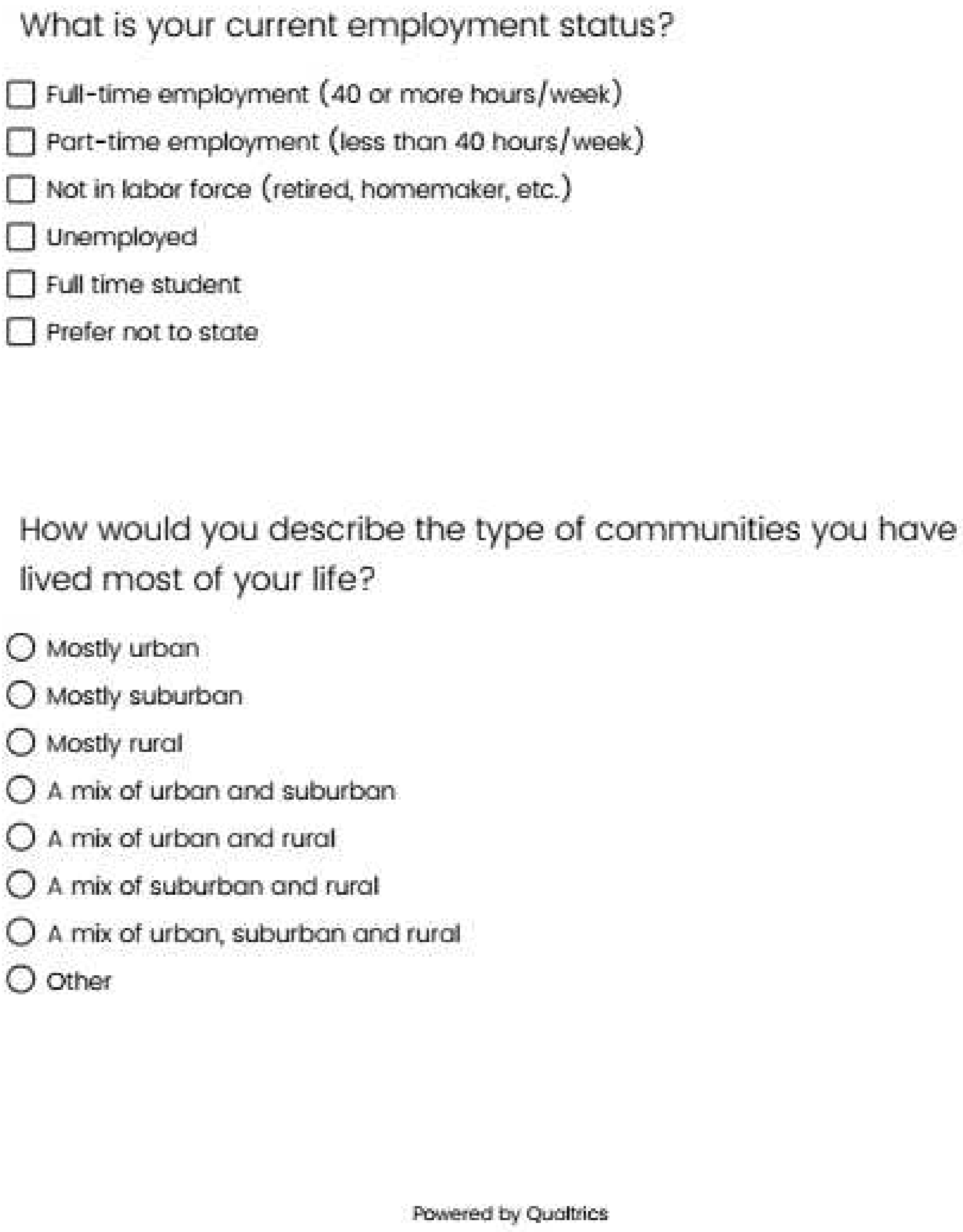


What is your current employment status?

☐ Full-time employment (40 or more hours/week)
☐ Part-time employment (less than 40 hours/week)
☐ Not in labor force (retired, homemaker, etc.)
☐ Unemployed
☐ Full time student
☐ Prefer not to state

How would you describe the type of communities you have lived most of your life?

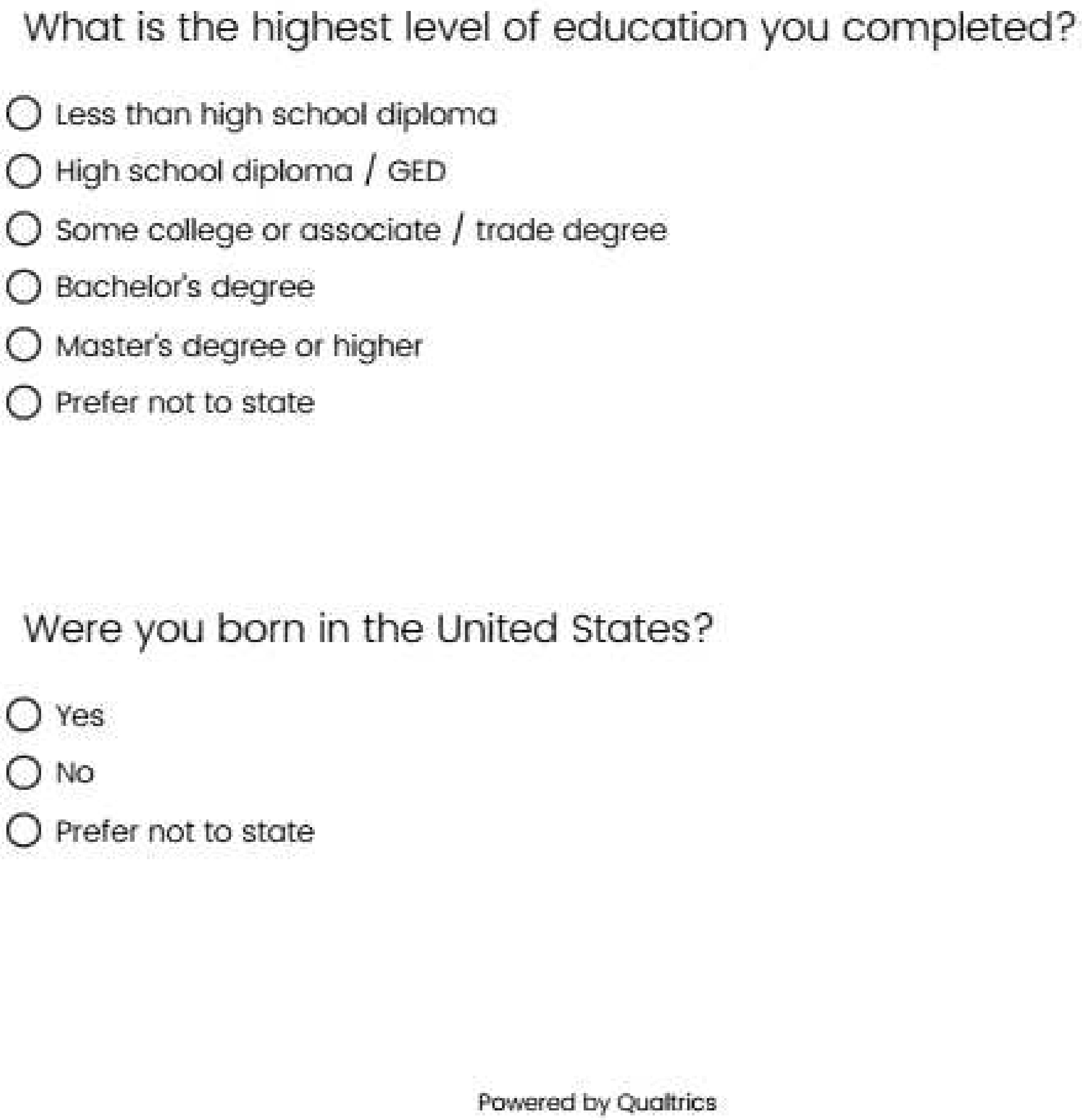
○ Mostly urban
○ Mostly suburban
○ Mostly rural
○ A mix of urban and suburban
○ A mix of urban and rural
○ A mix of suburban and rural
○ A mix of urban, suburban and rural
○ Other

With which racial and ethnic group(s) do you identify? (Mark all that apply)

☐ Asian
☐ Black or African American
☐ Latino/a or Hispanic
☐ Middle Eastern or North African
☐ Native Hawaiian or Other Pacific Islander
☐ Native American or Alaska Native
☐ White
☐ Some other race
☐ Two or more races
☐ Prefer not to state

How do you describe your gender identity?

☐ Male
☐ Female
☐ -
☐ Prefer not to state



What is the highest level of education you completed?

○ Less than high school diploma
○ High school diploma / GED
○ Some college or associate / trade degree
○ Bachelor's degree
○ Master's degree or higher
○ Prefer not to state

Were you born in the United States?

○ Yes
○ No
○ Prefer not to state

We thank you for your time spent taking this survey.
Your response has been recorded.

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APPENDIX E

I-DST SUSTAIN MODEL RESULTS SOURCE TABLE

Table E.1: Full results from i-DST SUSTAIN model runs and the corresponding normalized data.

Evaluation Factors		i-DST SUSTAIN Modeled Output							Normalized Data					
	Units	No BMP	BR	IT	PP	UDS	UIS	VS	BR	IT	PP	UDS	UIS	VS
Vegetated?	-	-	1	1	0	0	0	1	-	-	-	-	-	-
Units of BMPs	#	0	548	485	507	545	379	806	0.4	0.25	0.3	0.39	0	1
Acres treated	acres	0	71.8	63.5	66.4	71.4	49.6	105.6	0.4	0.25	0.3	0.39	0	1
Cost per cubic foot	$/ft^3	0	11.6	4.8	12	14	12.4	8	0.74	0	0.79	1	0.83	0.35
Total capital Cost	$	0	3.92E+06	1.34E+06	2.66E+06	2.48E+06	1.87E+06	1.17E+06	1	0.06	0.54	0.48	0.26	0
Surface area	acres	0	2.5	2.2	2.3	0	0	3.4	0.26	0	0.09	-	-	1
Total Potential Vegetated Area	m^2	0	1.02E+04	8.98E+03	0	0	0	1.36E+04	0.26	0	-	-	-	1
Surface Storage Volume	acre-ft	0	1.3	1.7	0.1	4.1	2.4	1.7	0.29	0.39	0	1	0.58	0.4
Soil Storage Volume	acre-ft	0	2.8	2	2.2	0	0.4	0.7	1	0.63	0.72	-	0	0.11
Surface and soil volume (ac-ft)	acre-ft	0	4.1	3.6	2.2	4.1	2.8	2.4	1	0.75	0	0.98	0.34	0.1
PDF	ft^3/sec	195.2	186.6	180.8	190.7	189	184.9	194.5	0.42	0	0.72	0.6	0.3	1
Average Peak Flow Reduction	%	-	8.3	7.1	7.7	0.2	6.2	9.8	0.84	0.72	0.78	0	0.63	1
BMP PDF	ft^3/sec	49.3	44.7	34.9	45	45.9	38	48.6	0.72	0	0.73	0.81	0.23	1

Table E.1 Continued

Average BMP Peak Flow Reduction	%	-	29.8	26	27.9	0.8	22.8	36.2	0.82	0.71	0.77	0	0.62	1
BMP FEF 15 cfs	ft^3/sec	-	44.7	45.7	45.7	53.7	48.5	40.5	0.32	0.39	0.39	1	0.61	0
Total ET	ft^3	-	1.33E+06	1.17E+06	1.23E+06	0	0	4.61E+05	1	0.82	0.88			0
Average annual ET	ft^3	-	2.66E+05	2.35E+05	2.45E+05	0	0	92281	1	0.82	0.88	-	-	0
Total GWRP	ft^3	-	2.64E+06	2.80E+06	2.74E+06	0	3.95E+06	3.50E+06	0	0.12	0.07	-	1	0.65
Average annual GWRP	ft^3	-	5.28E+05	5.60E+05	5.47E+05	0	7.91E+05	6.99E+05	0	0.12	0.07	-	1	0.65
AAL TSS at outlet	lb	128126.9	1.21E+05	1.21E+05	1.23E+05	124476.2	1.23E+05	1.23E+05	0	0.15	0.52	1	0.5	0.49
AAC TSS at outlet	mg/L	151.4	151.4	152.2	154	147.1	153.8	153.8	0.63	0.74	1	0	0.98	0.97
AAL TP at outlet	lb	334.1	310.3	310.5	312.4	334	312	312.3	0	0.01	0.09	1	0.07	0.09
AAC TP at outlet	mg/L	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0	0.07	0.5	1	0.39	0.49
AAL Zn at outlet	lb	127.6	119.6	119.7	121.3	125.7	121.1	118.6	0.13	0.15	0.38	1	0.36	0
AAC Zn at outlet	mg/L	0.2	0.2	0.2	0.2	0.1	0.2	0.1	0.42	0.46	1	0	0.95	0.11
AAC TSS at SCM	mg/L	112.5	101.2	104.6	113.2	95.7	112.5	112.3	0.31	0.51	1	0	0.96	0.95