EVALUATING THE EFFECTIVENESS OF GREEN STORMWATER INFRASTRUCTURE IN DALLAS, TEXAS: A MODELING AND PUBLIC PERCEPTION STUDY

A Thesis

by

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ABSTRACT

Impervious surfaces such as paved roads, buildings, and parking lots, are a staple feature of urban development, but they prevent infiltration, leading to increased runoff volumes and pollutant loads. Green stormwater infrastructure (GSI) takes a more centralized and connected approach to stormwater management, using engineered soil and vegetation to capture pollutants and decrease runoff velocities. The increased popularity of GSI calls for the need for more research on public perception and watershed-scale impacts of GSI. This study focuses on the City of Dallas, modeling the Five-Mile Creek Watershed surrounding South Oak Cliff High School (SOC) and surveying Oak Cliff residents for perceptions of GSI. A SWMM model was developed to test the effects of rain gardens, bioretention, and rainwater harvesting at the SOC campus on a 291-acre portion of Five Mile Creek on peak runoff, total runoff, and runoff delay for an optimized scenario for runoff reduction. Both single practice and combined practice scenarios were developed for varying rates of adoption. Bioretention was the single most effective GSI practice at the site, considering the suitability criteria. The addition of rainwater harvesting did not greatly aid in runoff volume reduction. The recommended GSI system, based on the success of the scenarios, is a combination of bioretention and rain gardens, with bioretention covering 50% of suitable space and rain gardens covering 20% of suitable space. Furthermore, the results of the online public perception study revealed that respondents care more about water quality and rainwater retention benefits of GSI more than visual attractiveness and recreation. GSI is highly valued among respondents, rainwater harvesting and bioretention cells more so than others. There were positive relationships between flood experience, frequent park usage, and the belief that climate change is problematic for flooding with GSI valuation.

DEDICATION

This thesis is dedicated to my loving family who has been my support system through this entire process, lifting me up, encouraging me to be all that I can be.

To the community of Oak Cliff, the focus of this study, who has allowed me into their home. My hope is that I can continue to serve this community through my work.

And lastly, I dedicate this thesis to the Almighty God, thank you for the guidance, strength, power of mind, protection, and skills to finish this work. All of these, I offer to you.

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1. INTRODUCTION

Urban areas are expected to experience an increased population in the coming decades, which will likely result in increased development and impermeable surfaces (Hoover & Hopton, 2019). While impermeable surfaces make services such as transportation possible, they prevent infiltration, leading to increased runoff volumes and pollutant loads (Douglas, 2018; Liu et al., 2003). Traditional stormwater measures convey and collect runoff waters in a centralized approach, leading waters away from urban areas and rapidly into basins and streams (Ando & Freidas, 2011). This method at conveyance occurs at the expense of disrupting natural hydrologic connectivity (Dhakal & Chevalier, 2017), preventing groundwater recharge (Aad et al., 2010), and increasing peak flows into streams (Ercolani et al., 2018). This approach also concentrates urban pollutants such as nutrients and heavy metals and introduces them, untreated, into the hydrologic cycle (Jaber, 2015).

Green stormwater infrastructure (GSI) takes a decentralized approach to stormwater management, treating runoff near its source (Ando & Freidas, 2011; Lim & Welty, 2017). The U.S. Environmental Protection Agency defines green infrastructure as "the range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspirate stormwater and reduce flows to sewer systems or to surface waters" (U.S. Environmental Protection Agency, n.d.). These stormwater control measures include but are not limited to rain gardens, bioretention areas, green roofs, green walls, bioswales, and rainwater harvesting. These systems capture pollutants and decrease runoff velocities primarily due to their infiltration capacities (de Graaf-van Dinther et al., 2021) and can be placed outside of, or within, existing green spaces, such as parks.

Many cities have developed climate change and stormwater management plans that include GSI because of the proposed benefits and its cost-effective nature (Dhakal & Chevalier, 2017), but research shows that public awareness of GSI and its benefits are low (Venkataramanan et al., 2020). This limited awareness of GSI and its benefits by the public shows the need for increased stakeholder engagement (Montalto et al., 2013). Additionally, this lack of public awareness of GSI and its benefits among the public contributes to poor implementation. Public support and involvement have been shown to be advantageous to the success of public projects, demonstrating more trust in local governance and aiding in collaborative communication and partnerships between stakeholders (Barclay & Klotz, 2019).

Resistance to GSI implementation also persists because of lack of awareness of the disservices of traditional gray infrastructure (Chaffin et al., 2016) and the benefits of ecosystem services GSI provides (Barnhill & Smardon, 2012). Additionally, many GSI public perception studies focus on socio-demographics and environmental knowledge as factors of GSI valuation, but research is lacking exploring the relationship between flood experiences, park usage, and GSI valuation of the public. This calls for the need for more research on public perception of GSI including how the public values GSI, for what reasons, and what affects these perceptions.

Hydrologic modeling with GSI considerations has increased in the past two decades due to software advancements (Elliot & Trowsdale, 2007). Initially many models focused on site-scale impacts, but GSI impacts at the watershed scale have garnered increased interest. Modeling the watershed hydrologic processes to reveal the impact of GSI at the watershed scale is a growing research area (Ahiablame et al., 2013) and could benefit from more modeling studies, given that GSI performance depends on input properties and can vary by location. Significant watershed-scale runoff and peak flow reduction can better help justify GSI implementation. Also combined GSI measures in series rather than single GSI measures have shown significant runoff reduction rates, calling for more research in how to optimize their layouts and areas for effectiveness. Accurate GSI modeling for site-optimization can help address many flood management concerns such as the persistent flooding problems in Dallas, Texas, the focus of this study.

The Five-Mile Creek Watershed in the Oak Cliff neighborhood of Dallas, Texas is 70-square miles with a 49% African American population (U.S. Census Bureau, 2012). According to hydrologic models, Dallas neighborhoods south of the Trinity River experience frequent flooding. The Five Mile Creek Greenbelt Master Plan outlines plans to build 22 miles of trail along Five Mile Creek in southwest Dallas. The Five Mile Creek watershed spreads 70-square miles, part of which is the Alice Branch. Furthermore, South Oak Cliff High School sits adjacent to Alice Branch Creek. South Oak Cliff High School has also been subjected to several environmental health issues including flooding, roof issues, water damage, pest control, HVAC problems, gas leak

(Gibson, 2021), mold, drinking water contamination, sewage leak, (Plasencia & Fernandez, 2021), trash, litter, and overgrowth on the creek (For Oak Cliff, n.d.), hazardous asbestos, and lead pipes (FOX4 News Dallas-Fort Worth, 2016). The school was renovated in January 2020, but many of the same problems persist such as leaking pipes and water damage. These considerations make both Five Mile Creek and South Oak Cliff High School high priority areas for increased green space and flood protection.

The goal of this thesis is to evaluate GSI through both an environmental and social lens, determining its impact on runoff reduction and its perceived value from the public. This thesis will also serve an educational role in informing the public about GSI. The research objectives are to (1) conduct a public perception study of community members of Oak Cliff and (2) model the effects of an optimized comprehensive GSI system of bioretention, rain gardens, and rainwater harvesting on peak flow, total runoff, and time delay of peak runoff of a subwatershed in Five Mile Creek. To accomplish these objectives, the study will consist of two procedures: a survey of community members including a testing survey of a selected community group followed by a Qualtrics questionnaire of available community members and modeling of the subcatchment of the Five-Mile Creek watershed in which South Oak Cliff High School resides.

1.1. Organization of the Thesis

Four chapters comprise this thesis document. Chapter One introduces the subject of the thesis with the broader impacts of the research, knowledge gaps, and the overall problems that will be addressed. Chapters Two and Three each comprise a stand-alone manuscript for the modeling study and the public perception study. Chapter Four is a summary of the objectives, methods to address each objective, results, and conclusions from the results, as well as future work.

2. MODELING OF GSI

2.1. Introduction

According to observed values and global circulation models, heavy precipitation events are expected to become more frequent and more intense (O'Gorman, 2015; Trenberth, 2011), leading to larger flood events globally. Flooding occurs most frequently of all natural disasters and has the highest number of people impacted across the world (Mignot et al., 2019; Hirabayashi et al., 2013), as well as the highest death toll in the last 30 years (Schumacher, 2017). Cities are particularly vulnerable to floods and have a high risk due to high population values, high population density, density of infrastructure, high property values, and variety of economic activities (Kubal, 2009). Approximately 41 million Americans live within a 100-year floodplain, which is 2.6-3.1 times higher than FEMA flood map calculations (Wing et al., 2018). Across the United States the average 100-year floodplain is projected to increase by 45% in riverine environments, affecting many U.S. cities located near those areas (AECOM, 2013). By the year 2100, damages from flooding could cost up to $1.5 billion annually, with an average increase of 31% (Wobus et al., 2014).

Urban flooding can present as localized flooding due to heavy rainfall, insufficient drainage, flooding from small streams in the urban area, flooding from large rivers in the urban area, and coastal flooding (Ahmad & Simonovic, 2013; Douglas et al. 2008). Even relatively small rainfall events can result in urban flooding due to poor drainage. The severity of urban flooding can vary based on the source of the flooding waters. Localized flooding can receive less attention than other floods due to the smaller scale of individual events as well as the number of impacted people (Dawson et al., 2008; Moftakhari et al., 2018). Localized urban flooding can receive even less attention, as it can result from even minor storms, which do not typically receive local, state, or federal funding for relief (FEMA, 2005).

Traditional stormwater measures collect runoff in a centralized approach, leading waters away from urban areas, and into basins and streams (Andos & Freidas, 2011). This system focuses on the rapid transfer of rainwater and its pollutants away from urban areas at the expense of disrupting natural hydrologic connectivity. Additionally, many municipalities are struggling with aging and degraded stormwater and wastewater conveyance infrastructure (Chaffin et al., 2016). A lack of infiltration collects pollutants while decreasing groundwater recharge and increasing peak flows. Green stormwater infrastructure (GSI) takes a more decentralized and connected approach to stormwater management (Andos & Freidas 2011), and instead of curbs, gutters, inlets, manholes, and pipes, engineered soil and vegetation is used (Dhakal & Chevalier, 2017).

Green stormwater infrastructure as a stormwater mitigation measure has gained popularity in recent decades (Morash et al., 2019). Cities and municipalities are beginning to implement this form of infrastructure in local stormwater plans, even implementing them in climate change mitigation efforts because of their numerous ecosystem services. The U.S. Environmental Protection Agency (EPA) defines green infrastructure or GSI as "the range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspirate stormwater and reduce flows to sewer systems or to surface waters" (U.S. Environmental Protection Agency, n.d.). GSI can delay the timing of peak runoff as well as reduce the runoff volumes that traditional gray infrastructure receives (Chaffin et al. 2016). These systems capture pollutants and decrease runoff velocities primarily due to their elevated infiltration capacities (de Graaf-van Dinther et al., 2021). Apart from hydrologic improvements, the services GSI provides include urban heat mitigation (Block et al., 2012), habitat for wildlife (Prudencio & Null, 2018), air quality improvement (Shaneyfelt et al., 2017), among others. These stormwater control measures include but are not limited to rain gardens, bioretention areas, green roofs, permeable, bioswales, and rainwater harvesting.

Bioretention, developed in the 1990s, is one of the most widely used nature-based rainwater management methods worldwide (Li et al., 2021), with potential to improve runoff quality and manage runoff volume. Bioretention systems are depressions consisting of a top vegetated layer, followed by a growth media, drainage material, and underdrain (Vijayaraghavan et al., 2021). Runoff directed to the bioretention area is allowed to pool at a certain depth and slowly infiltrate through the soil. Pollutant removal takes place through filtration, sorption, ion exchange, and biological uptake (Hsieh et al., 2007). The goal of bioretention, and most other GSI practices, is to mimic pre-development hydrologic state through enhanced permeation and evaporation (Li et al., 2021). Studies show a wide range of success rates for water quantity reduction, reporting 40-97% of volume and peak flow rate reductions (Jaber, 2015).

Rain gardens, very similarly to bioretention, are depressed areas with a soil layer and suitable vegetation for stormwater mitigation. Unlike bioretention cells, rain gardens have no gravel drainage or underdrains. Additionally, bioretention cells are generally larger and handle large drainage areas while rain gardens are smaller and are more popular in residential areas (ECI, 2015; Mason et al., 2019). Although the two practices have been labeled interchangeably, for the purposes of this study, the two will be classified differently, as the EPA Stormwater Management Model (SWMM) defines rain gardens as having no gravel bed and drain, whereas bioretention cells do (Rossman, 2015). Rain gardens use similar biological and hydrological processes as bioretention to improve water quality (Sharma & Malaviya, 2021). Rain gardens have similar runoff reduction rates to bioretention, reductions ranging from 51.5-99.8% (Jennings, 2016). Rain gardens may also accompany rainwater harvesting systems, acting as catchment basins for the rain barrel outlet (Jaber et al., 2012).

Historically, rainwater harvesting (RWH) has been used to address water supply issues, but more recently, have been used as a low-impact development (LID) control to manage stormwater (Campisano et al., 2017). These systems use rain barrels or cisterns to collect roof runoff and allow it to release slowly from the system. The rooftop catches the water, then a conveyance apparatus diverts the water through gutters and downspouts to the rain barrel (Jaber, 2015). When the water level reaches the outlet, it will overflow and exit the system. When combined with infiltration based GSI practices, such as bioretention cells and rain gardens, excess overflow from the rainwater harvesting system can aid in aquifer recharge (Campisano et al., 2017).

Although flow reduction is influenced by tank size, number of tanks, and drainage network location, rainwater harvesting has been known to reduce local flooding from 3-44% (Deitch & Feirer, 2019; Litofsky & Jennings, 2014).

Most GSI impact studies conducted at the watershed scale are model based (Pennino et al., 2016). L-THIA-LID (Long-term Hydrology Impact Assessment-Low Impact Development) (Liu et al., 2015), EPA SWMM (Storm Water Management Model) (Rossman, 2015), and SUSTAIN (System for Urban Stormwater Treatment and Analysis Integration) (Shamsi et al., 2014) are some of the more widely used models for determining watershed scale and combined practice impacts of LID for water quality and quantity. SWMM is more widely used for surface runoff simulations and was one of the earliest adopters of LID options in simulations (Luan et al., 2017). SWMM has been widely used to model urban flooding and mitigation efforts through GSI (Bai et al., 2019; Jack et al., 2021; Luan et al., 2019; Xu et al., 2017; Xu et al., 2019) for both single and combined GSI strategies using both hydrologic and hydraulic models (Rai et al., 2017), thus it is the model used in this study. Modeling the watershed hydrologic processes to reveal the impact of GSI at the watershed scale using combined GSI practices and various levels of adoption is also not widely studied (Ahiablame et al., 2013; Liu et al., 2015). Additionally, GSI retrofits create more challenges when they are not site specific for optimization (Pour et al., 2020; Shamsi et al., 2014). To fill this gap, this study seeks to add to this growing body of GSI modeling research and find comprehensive measures that optimize runoff reduction in the study area. Significant watershed-scale runoff and peak flow reduction can better help justify GSI implementation.

According to hydrologic models, Dallas neighborhoods south of the Trinity River experience frequent flooding. In 2017, The City of Dallas identified 84 flood-prone sites for funding to address flood protection, storm drainage and erosion control. The plan highlighted 14 critical areas where flooding issues are of greater concern than others, 7 of which were in Oak Cliff (Jimenez, 2019). Additionally, three creeks in the city have been identified as flood-prone, among them are Five-Mile Creek, Joes' Creek, and Dixon Creek (Jack et al., 2021). According to American Community Survey data, 28% of the watershed residents are living in poverty, 4% are unemployed, and 95% are racial minorities (Centers for Disease Control and Prevention, 2018). Since the national poverty rate is 11.8%, pre-COVID-19, (US Census Bureau, 2019d), the national unemployment rate is 3.5, pre-COVID-19, (U.S. Bureau of Labor Statistics, 2020), and the minority percentage is 42.1% (U.S. Census Bureau, 2019d), the watershed of Five Mile Creek is socially vulnerable to poverty, unemployment, and minority population. Based on this data, it is urgent to better manage flood risk in this sector of the city. GSI can help address many of the concerns of flood management. Modeling these systems can aid in these efforts.

Modeling the sub-watershed of the study area will be conducted in EPA SWMM 5.1. The following procedure will be followed: (1) Use spatial and monitoring data to create the input files and define network parameters in SWMM, (2) define object and simulation properties, (3) define green infrastructure parameters and determine suitable space, (4) run simulations of single GSI practices and combined GSI practices, and (5) analyze and discuss the results. Achieving hydrologic mitigation heavily relies on reducing the volume of runoff entering the stormwater system, reducing peak flow rate of runoff entering the system, and staggering the arrival of peak flows into the system (Fassman-Beck & Saleh, 2021); therefore, total runoff, peak runoff, and time delay of peak of the watershed will be the primary results analyzed as a metric to determine an optimized GSI solution. The goal of this study is to demonstrate the proposed methodology so that these methods can be applied to other sites.

2.2. Literature Review

2.2.1. Stormwater Modeling

Hydrologic simulation began in the 1950s and 60s. Stanford University researchers Crawford and Linsley introduced the Stanford Watershed Model in 1966, the first of its kind to model the hydrologic cycle in its entirety (Donigian & Imhoff, 2006). Soon hydrologic models, helped by the advancement of the computer, began to replace manual computation. Through the expansion of hydrologic and watershed models, engineers and scientists were no longer confined to modeling individual hydrologic components (Singh & Frevert, 2003). The US government began developing stormwater models in the early 1970s (Zoppou, 2001) and were primarily used for drainage design and management (Stephenson, 1989). The US Environmental Protection Agency, the US Geological Survey, the US Army Corp of Engineers, and most other scientific federal agencies all began developing hydrologic modeling systems, as reviewed by Donigian and Imhoff (2006) and evolved into current models such as EPA Storm Water

Management Model (SWMM), MODFLOW, and the Hydrologic Engineering Center's River Analysis System (HEC-RAS).

The introduction of GIS in hydrologic modeling greatly expanded the capabilities of watershed analysis. GIS for hydrologic analysis in urban areas was scarce until the late 1980s and early 1990s (Donigian & Imhoff, 2006). It was and is still primarily used for determining input parameters, such as soils, imperviousness, and land use, and representing watershed surfaces (Bahaya et al., 2019; Greene & Cruise, 1995). Digital Elevation Models (DEM), often used in GIS, are frequently employed in hydrologic modeling to identify stream networks and land slope to determine contributing flow to watersheds (Daniel et al., 2011). Many hydrologic models now have GIS components, making them easier to use and visualize (Elliot and Trowsdale, 2007).

Stormwater modeling consists of both rainfall-runoff processes and routing, which incorporates hydrology and hydraulics (Zoppou, 2001; Haris et al., 2016). Stormwater modeling considers the concepts and components of areal precipitation, watershed representation, surface runoff, infiltration, subsurface flow, interflow, groundwater flow, baseflow, evaporation, evapotranspiration, abstraction, rainfall excess, soil moisture, snowmelt runoff, stream-aquifer interaction, reservoir flow routing, and channel flow routing (Singh & Frevert, 2003). Surface runoff modeling has been used for both water quantity and quality estimates, as runoff is a main transport for contaminants. Runoff modeling is used to quantify catchment yields, water availability and forecasting. It answers questions about the hydrologic processes of stormwater modeling (Sitterson et al., 2018). Rainfall- runoff modeling considers soil, vegetation, and topography of a watershed (Jain et al., 2004), among other factors, to determine the effect precipitation has on runoff processes. Rainfall-runoff models are usually distributed, able to simulate the spatial distribution of precipitation and catchment characteristics (Yu et al., 2001).

Flow routing requires simulating flow through a stream network (Sitterson et al., 2018), which involves the determination of fluctuations in magnitude, velocity, and shape of a flood wave (Farzin et al., 2018). Flood and flow routing in hydrologic models are essential to producing hydrographs (Borah et al., 2009), which helps in understanding how discharge varies with time at a particular point in a watershed (Sulistyono & Wiryanto, 2017). Routing uses both hydraulic and hydrologic approaches, considering both the principles of conservation of mass and the dynamic effects of flow through the momentum equation (Barati et al., 2012). Inertial and pressure influences are typically neglected, focusing on gravity as the primary driver of flow (Shelef & Hilley, 2013).

2.2.2. GSI Modeling

Modeling of GSI practices began in the 1990s and 2000s, according to a review of GSI models by Elliot and Trowsdale (2007). Most models allowed for the implicit representation of a GSI practices, mostly focusing on on-site infiltration practices such as trenches, swales, and detention ponds (Kronaveter et al., 2001). Hydrologic models also began adding imperviousness as an input for runoff. Modeling of GSI systems has increased in popularity and grown to include many more complex practices, but combining natural features and anthropogenic features has proven to be a complex challenge (Shamsi et al., 2014). Models with GSI capabilities typically must account for flow routing, infiltration, evapotranspiration, underdrain, deep percolation, groundwater recharge, pollutant routing, pollutant removal, and sediment trapping (Lee et al., 2012).

Elliot and Trowsdale (2007) reviewed various models with GSI integration capabilities, revealing there is a wide range of existing models capable of modeling the water quality and flow effects of GSI. Since then, even more models have added GSI capabilities and new models have been developed. Many have developed their own models (Dell et al., 2021; Massoudieh et al., 2017). The models greatly vary in their considerations of catchment representation, groundwater components, flow-routing capabilities, types of GSI included, and graphic user interface features. Below, the most widely used models with recently published results are summarized.

The Cooperative Research Center for Catchment Hydrology in Australia developed the Model for Urban Stormwater Improvement Conceptualisation (MUSIC) in 2000 (Elliot & Trowsdale, 2007). MUSIC, rather than being a design tool, serves primarily as a decision support tool for stormwater management systems. Users can determine if a particular conceptual stormwater management system is appropriate for a subcatchment (Imteaz et al., 2013). It is a stochastic model that uses continuous simulation and the rainfall-runoff model SIMHYD (Schubert et al., 2017) to simulate runoff processes. The model can simulate catchment (agricultural, forest, or urban) hydrology and generate urban runoff through definition of impervious area and soil moisture storage, model water quality generation and treatment, and determine the hydraulic efficiency of stormwater systems (Wong et al., 2002). Much like EPA

SWMM, MUSIC can model bioretention systems, infiltration systems, media filtration systems, gross pollutant traps, buffer strips, vegetated swales, ponds, sediment basins, rainwater tanks, wetlands, detention basins, and generic treatment nodes (eWater, n.d.). These systems can be used in series or in parallel (Imteaz et al., 2013).

In addition to SWMM, the U.S. EPA began developing the System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) in 2003 to model and evaluate stormwater best management practices (BMP) (Lee et al., 2012). While it is no longer being updated, it has proved to be a useful tool for practitioners. Similar to MUSIC, SUSTAIN can serve as a decision support tool for stormwater management. SUSTAIN is a mapping-modeling package that uses ArcGIS and links to SWMM to determine the best placement for GSI and their performance in reducing and treating runoff. The model is also capable of determining the cost-effectiveness of various BMPs (Shamsi et al., 2014). Using algorithms adapted from SWMM, SUSTAIN simulates the flow and pollutant routing in a subcatchment. The BMP siting tool in SUSTAIN helps users create a suitability criterion based on elevation, slope, soil type, urban land use, roads, water table depth, stream location, and drainage area using a DEM. SUSTAIN simulates the flow through various BMPs such as bioretention cells, rain barrels, green roofs, vegetated swales, infiltration chambers, wetlands, retention ponds, and detention ponds (Lee et al., 2012).

Researchers at Purdue University adapted the Long-Term Hydrologic Impact Assessment Low-Impact Development L-THIA-LID model from the L-THIA model to evaluate the hydrologic and cost effectiveness of LID controls at the watershed scale. L-

THIA-LID is a lumped parameter model without routing capabilities (Wright et al., 2016). Watersheds are represented through a combination of hydrologic response units (HRU). The model requires daily rainfall data, hydrologic soil group data, and land use data using the NRCS Curve Number Method to determine runoff and pollutant loads. The model uses data from the International Stormwater Best Management Practices Database to determine the impacts of LID on runoff loads. It supports bioretention, rain gardens, grass swales, open wooded space, porous pavement, permeable patio, rain barrel/cistern, and green roofs. Each LID is paired with a drainage area based on the characteristics of the LID. LIDs can be placed individually or in series (Liu et al., 2016).

The U.S. Environmental Protection Agency's Storm Water Management Model (SWMM) is a rainfall-runoff model typically used for simulating runoff quantity and quality in urban catchments for continuous and single-events. The model operates through subcatchment areas that receive precipitation and generate runoff and pollutant loads. Runoff generation is also produced through the routing of pipes, channels, storage/treatment devices, pumps, and regulators. The model allows for the measurement of the results through flow rate, flow depth, and quality of water in each pipe and channel (Rossman, 2015). At its basics, it is a rainfall-runoff model that can simulate stormwater runoff, combined sewers, sanitary sewers, open channels, irregular natural channels, other drainage systems, and, more recently, LID controls. SMMM began offering explicit LID control options in 2009 (McCutcheon et al., 2012). SWMM 5.1, the latest iteration of SWMM, incorporates LID control options and has been popular for modeling green stormwater infrastructure (Rossman, 2015). The LID controls available in the model include bioretention cells, rain gardens, green roofs, infiltration trenches, permeable pavement, rain barrels, and vegetative swales. With the option to add LID controls, streamflow, base flow, and runoff of watersheds are better able to be modeled accurately with GSI options (Ahiablame et al., 2013). EPA SWMM was ultimately chosen for this study, as it has a large body of published performance results, is actively updated, open-source, and free.

2.2.3. GSI Modeling Performance and Limitations

Different GSI practices have shown varying performance effectiveness results among modeling studies. Thorsby et al. (2020) found that when comparing rainwater harvesting, rain garden, bioretention cell, and green roof runoff reduction performance, bioretention cells and rain gardens were the most effective practices, reducing runoff by 65% and 67%, respectively. The authors concluded that single large-scale GSI, such as bioretention cells, may reduce runoff more effectively than small-scale practices such as rain gardens and rain barrels, which may be more effective at higher quantities and small volumes in small areas. Similarly, Bai et al. (2019) found that GSI practices based on infiltration (green roofs, concave green belts, bioretention cells, permeable pavement, infiltration trenches, and vegetative swales) performed more efficiently at peak flow and volume reduction than storage based GSI practices (rain barrels). Consistently, James and Dymond (2012) concluded that infiltration-based practices were more effective at runoff reduction than non-infiltration-based practices. Shannak et al. (2014) observed that rain barrels overflowed frequently during storms, more so when water was not released. Ahiablame et al. (2012) observed that green roofs and rain barrels were limited in runoff reduction due to detention capacity, while practices such as permeable pavement resulting in higher runoff reduction primarily due to a reduction in impervious surfaces. They also found bioretention's runoff reduction to be relatively low (2%), which is not consistent with other modeling and field studies but can be attributed to its low percentage of total area (7%) compared to all other practices in the study. Luan et al. (2019) observed that permeable pavement, bioretention, and detention basins were most successful in runoff volume reduction and concluded it might have been related to the size of each practice.

Many modeling studies find that GSI performance is greater for smaller rainfall events (Bai et al., 2019; Guo et al., 2019; Liao et al., 2018; Palla & Gnecco, 2015), most likely due to the total precipitation. Bai et al. (2019) found that for all the LIDs tested, runoff reduction increased as rainfall amount increased until rainfall reached 81.8 mm, after which peak runoff reduction plateaued. Guo et al. cited total precipitation is the main determinant of runoff reduction ratio, coupled with influences from duration and peak rainfall. James and Dymond (2012) observed that bioretention under conditions of 10-year or more frequent recurrence intervals would achieve acceptable runoff reduction results. Therefore, GSI alone cannot effectively treat runoff for large, infrequent storm events, but can be retrofitted with conventional drainage techniques (Qin et al., 2013).

GSI has been proven effective at the site scale (Lim & Welty, 2017). Many GSI modeling studies focus on site-scale impacts on runoff and water quality, but few focus on watershed and city scale efforts to mitigate runoff (Dell et al., 2021; Pennino et al., 2016). GSI performance at the watershed scale depends on the GSI properties and climate and will vary by location. At this scale, peak flow reduction, volume reduction, and hydrograph delay are typically used as success metrics (Hu et al., 2017). Types and percentages at which to apply both single and aggregated GSI are also complex because of the numerous possibilities at the watershed scale (Liu et al., 2016) due to placement and percentage of area of implementation. For example, Wright et al. (2018) determined that a limit to streamflow reduction was reached as bioretention cell size grew, suggesting that GSI can have threshold limits for effectiveness. Ahiablame and Shakya (2016) concluded that the GSI effectiveness increases with increasing implementation levels. Also, many models with GSI capabilities are lumped or semi-lumped and lack the ability to account for spatial variability of location of GSI practices in a watershed and its effects on the hydrologic process (Lim & Welty, 2017).

Additionally, combined and aggregated GSI measures in series are not widely studied (Dell et al., 2021; Lee et al., 2012). The few studies that compared aggregated GSI measures and single GSI measures found that the aggregated significantly reduced runoff compared to the limitations of the single measures. The modeling study conducted by Liu et al (2014) resulted in runoff reduction ranging from 85-100% for aggregated GSI depending on the storm recurrence interval. Thorsby et al. (2020) also found that combining two GSI practices resulted in higher flood prevention during small storms. Ahiablame and Shakya (2016) reported that combining two practices appeared to be as effective as combining three practices. Not only do aggregated and single GSI systems need to be compared, but aggregated systems need to be compared to find an optimal layout scenario. Liao et al. (2018) determined that optimal area of each GSI determines effectiveness of each practice. When they compared various scenarios of green roofs, permeable pavement, and green spaces, they found that the 35% permeable pavement conversion and 50% green space conversion scenario was approximately 8% more effective at reducing runoff than the 35% green roof conversion, 35% permeable pavement conversion, and 50% green space conversion scenario, although their construction areas were approximately the same. This indicates that area is not the only factor in the effectiveness of aggregated GSI measures.

As shown previously, different GSI practices have resulted in varying modeled performance levels for runoff reduction. This may be attributable to a wide variety of parameters, such as model used, suitability criteria for each practice, imperviousness of treatment area, size of treatment area, placement, design parameters and standards, and storm recurrence intervals, among others. This has resulted in inconsistencies in GSI representation and performance among different hydrologic models (Ahiablame et al., 2012). This modeling study seeks to address the issues of the lack of studies about watershed-scale, comprehensive GSI measures, and adoption rate by percentage of area of implementation.

2.3. Methods

The methods used to accomplish the objectives are listed below.

- Develop SWMM model of subcatchment in Five Mile Creek around South Oak Cliff High School using proper inputs
- Determine inputs for each practice: imperviousness/perviousness treated, suitable area, and design parameters

- Test single and comprehensive scenarios and compare
- Identify optimized scenario for peak runoff and total runoff reduction and runoff delay

2.3.1. Study Area

The Dallas-Fort Worth Metroplex has a humid subtropical climate and experiences mild winters and hot summers. The average annual temperature is 66.6 degrees Fahrenheit with an average high of 76.8 and an average low of 56.5. The metroplex receives an average of 37 inches of rain per year (Data retrieved from https://www.weather.gov/fwd/dfw_normals). The neighborhood of Oak Cliff lies in the southwest area of Dallas, Texas, and is one of the oldest neighborhoods in the city (Oakcliff.org, n.d.), lying in the upper Trinity River Basin. Five Mile Creek, which lies in Oak Cliff, is an intermittent tributary in the Trinity River watershed and typically runs dry during the summer season (Bryan, 1953). Its watershed covers 70 square-miles.

The campus of South Oak Cliff High School (SOC) lies east of the one-mile-long Alice Branch of Five-Mile Creek. Stakeholders of the campus have reported historical flooding of the creek. In addition to flooding, the campus has experienced numerous issues such as roof issues, water damage, pest control, HVAC problems, gas leak (Gibson, 2021), mold, drinking water contamination, sewage leak, (Plascencia and Fernandez, 2021), trash, litter, and overgrowth on the creek (For Oak Cliff, n.d.), hazardous asbestos, and lead pipes (FOX 4 News Dallas-Fort Worth, 2016). The school was renovated, which saw completion in January of 2020, but three months later, many of the same problems persisted. Repairs have been difficult to commence due to spring rains. Evidently, this area is of high priority for flood protection and beautification, therefore, is the focus of this study. For the purposes of this study, the South Oak Cliff High School campus is the study area with the following boundaries: Alice Branch creek on the east, Overton Road to the north, S. Marsalis Avenue to the west, and Garza Avenue to the south. The campus can be viewed in Figure 2.1.

Figure 2.1 South Oak Cliff High School Campus. Source: Google Earth

2.3.2. Modeling Development

A SWMM model was developed for a 291-acre portion of Five-Mile Creek surrounding the SOC campus. The catchment representation can be seen in Figure 2.2. The results of the study will examine the impacts of retrofitting GSI at the SOC campus on the watershed. The following data were collected and fit to the watershed areas in Dallas to create the input files and determine parameters for the model.

- Spatial Data
    - Topography: A digital elevation model (DEM) with a 10-m resolution was obtained from the U.S. Geological Survey (USGS) (USGS, 2021). The DEM was used to delineate the subcatchments and map the inlets and channels with their surface elevations.
    - Land use/cover: A land use/cover (LULC) map was downloaded from the USGS (USGS, 2016) and used to calculate the impervious area of the subcatchments. This data was supplemented by aerial imagery to determine the localized impervious and pervious features on the SOC campus.
    - Storm drainage design, built: A stormwater network file was created from the City of Dallas stormwater engineering plats and pre-constructed ArcGIS layers of stormwater systems. This file includes locations of inlet catch basins and sewer pipe characteristics. The data from the plats were digitized into ArcGIS format, and the City’s ArcGIS files were utilized to update the digitized plat files.
    - Storm drainage design, natural: Channel and river flow lines were obtained from USGS NHD dataset (USGS, 2018).
- Monitoring Data

- Precipitation data: A 2-year (50%), 24-hour storm event was used for simulations. This data uses Atlas 14 precipitation data from NOAA (Perica et al. 2018), transformed to hourly storm data using the NRCS Type III Distribution (USDA-NRCS, 2015) to create the hyetographs. Figure 2.3 shows the hyetograph of the storm event.
- Flow data: There is no stream gauge located near the site. This made direct model calibration unfeasible, however, the model is part of a larger model of the city of Dallas that was calibrated for maximized watershed area. The subwatershed delineations for this model are calibrated.

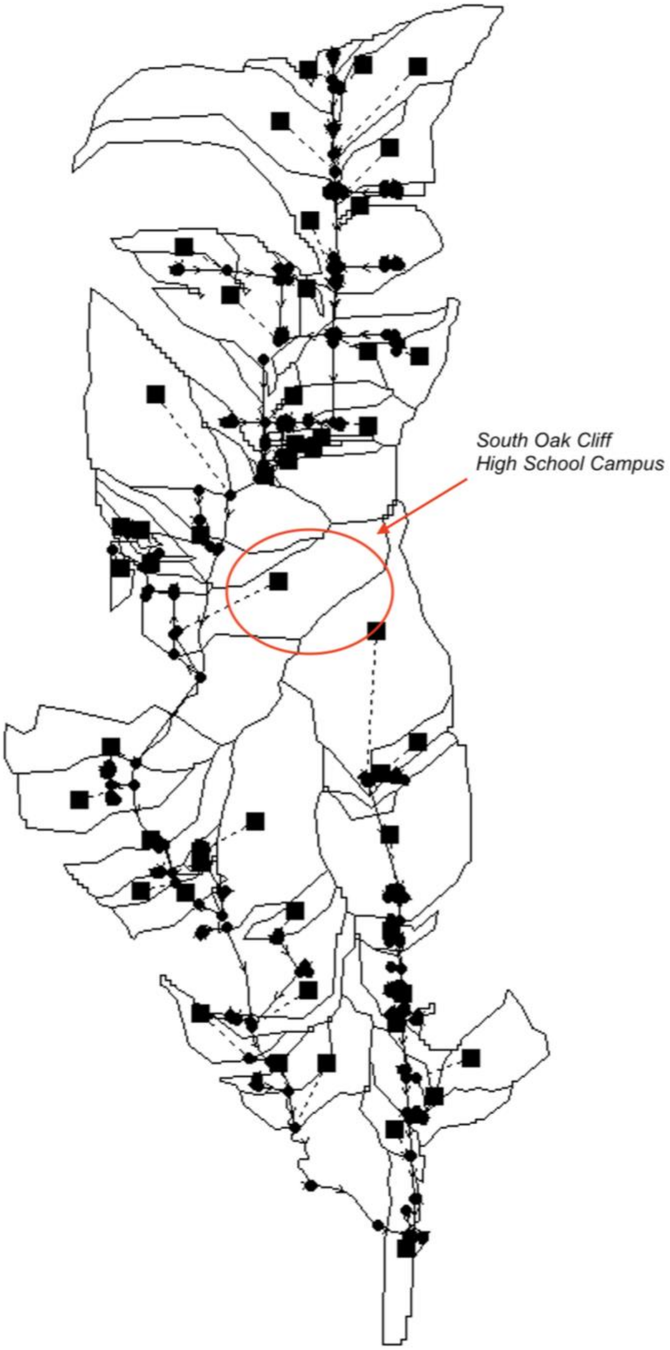

Figure 2.2 The 291-acre catchment representation of the SWMM model. The red circle indicates where the South Oak Cliff High School campus resides in the catchment. Squares represent subcatchments, circles represent nodes in the stormwater network, lines represent pipes, and dashed lines connect the subcatchment to its respective outlet node.

2.3.3. SWMM Model

2.3.3.1. Object Properties

Subcatchments: Outlet, area, width, % slope, % impervious, N-impervious, and N-pervious (manning's n) are specific to each subcatchment. The remainder of the properties are the same throughout each subcatchment. The initial values of sensitivity parameters are based on general recommended values from the SWMM manual.

Nodes: The invert elevation and max depth are specific to each node. Initial depth, surcharge depth, and ponded area were zero for each node.

Conduits: Shape, max depth, length, inlet offset, and outlet offset are specific to each conduit. The roughness coefficient for each conduit was 0.013.

2.3.3.2. Simulations

Process Models: Given that we were not measuring rainfall dependent inflow/infiltration, snowmelt, water quality, or groundwater impacts of GSI, our process models were only Rainfall/Runoff and Flow Routing.

Routing Model: Dynamic Wave was used as the routing model, which determines which model is used to route flows through the conveyance system.

Infiltration Model: Green- Ampt was used as the infiltration model, which determines how rainfall will infiltrate in the upper soil zone.

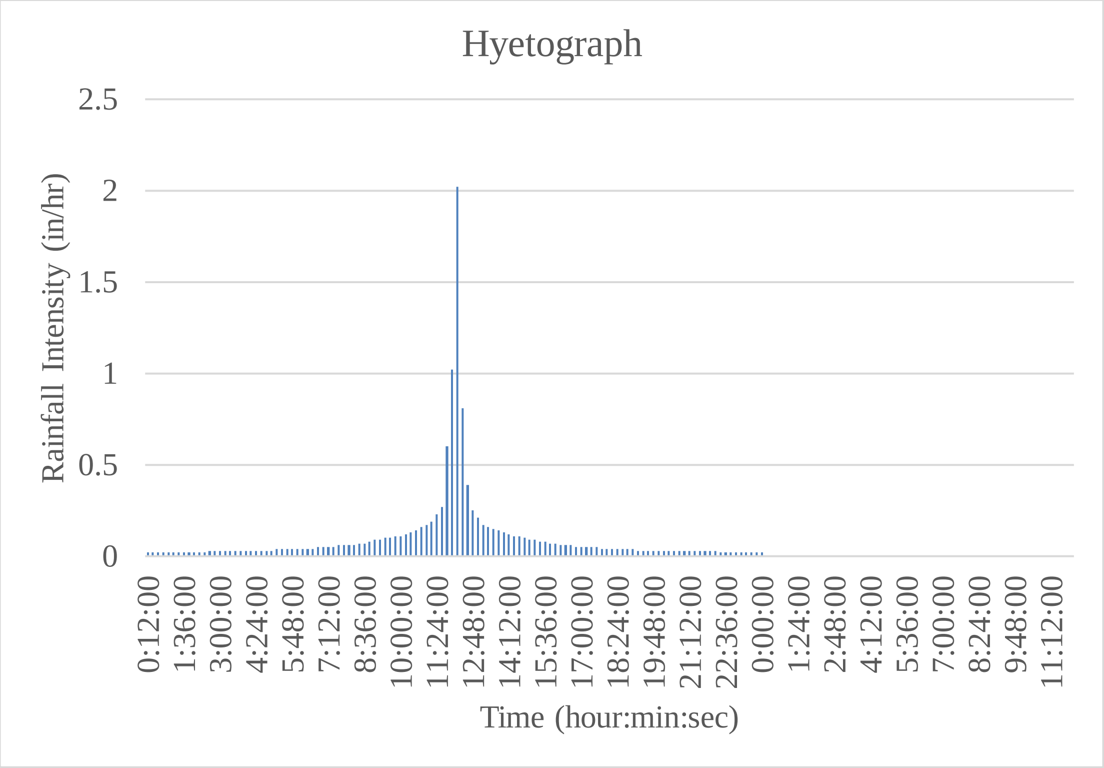

Figure 2.3 Hyetograph of 2-year, 36-hour storm event

2.3.4. Network Adjustment

Three components of the model required adjustments from the city data to properly run the simulations without error: (1) The invert elevations in the watershed required high invert elevations to low invert elevations as the watershed flows downstream. (2) Nodes without conduits connecting them to the full network or smaller networks without a connection to the full network both required conduits. (3) The max depths for all conduits required adjusting so that the max depths increase as the watershed flows downstream.

2.3.5. LID Input Parameters and Spatial Suitability

The SOC campus has widespread parking lots, athletic fields, grassed medians, and vegetated courtyards, with both permeable and impermeable spaces. The campus lies in a residential area. The total subcatchment area is 31 acres. For this study, we used three types of GSI: bioretention cells, rain gardens, and rainwater harvesting. These are suitable, considering the characteristics of the site, as they are more cost effective than green roofs and permeable pavement. Table 2.1 shows the parameters for each GSI practice.

Table 2.1 The parameters for each GSI practice by surface, soil, storage, and drain. Bioretention cells, rain gardens, and rainwater harvesting are listed as BRC, RG, and RWH, respectively.

Layer	Parameter	Unit	BRC	RG	RWH
Surface	Berm Height	in	3	8	--
	Vegetation Volume Fraction	volume fraction	0.3	0.3	--
	Surface Roughness	--	0.1	0.1	--
	Surface Slope	percent	1	1	--

Table 2.1 Continued

Layer	Parameter	Unit	BRC	RG	RWH
Soil	Thickness	in	18	6	--
	Porosity	volume fraction	0.4	0.4	--
	Field Capacity	volume fraction	0.2	0.2	--
	Wilting Point	volume fraction	0.05	0.05	--
	Conductivity	in/hr	50	0.43	--
	Conductivity Slope		48	40	--
	Suction Head	in	1.93	2.4	--
Storage	Thickness	in	18	--	--
	Void Ratio	voids/solids	0.4	--	--
	Seepage Rate	in/hr	0.01	0.5	--
	Clogging Factor		0	--	--
	Barrel Height	in	--	--	120

Table 2.1 Continued

Layer	Parameter	Unit	BRC	RG	RWH
Drain	Flow Coefficient		1.3	--	0
	Flow Exponent		0.5	--	0.5
	Offset	in	18	--	120
	Drain Delay		--	--	0
	Open Level		0	--	0
	Closed Level		0	--	0
	Control Curve		--	--	--

The spatial criteria of each of the practices was adapted from Jack et al. (2021) which follows the City of Dallas' Code of Ordinances. Bioretention cells were deemed suitable in spaces with over 20% parking lots, 35% vegetated road medians, 35% nonresidential sidewalks that are greater than 8 ft wide, 35% planting strips in residential neighborhoods, and 10% parks. 400 sq-ft rain gardens were applied for 1400 sq-ft structures, which was based on the average house size in the immediate area. The high school building and additional structures on the campus were divided into 1400 sq-ft areas to represent houses. Rain barrels were applied using a method explained in the Threshold Analysis section.

The suitable drainage area of each practice was based on features of the practice: (1) Rain barrels only treated runoff from the roof tops. (2) Rain gardens, which are more suitable for smaller drainage areas, treated the overflow from the rain barrels and direct runoff from permeable and impermeable areas around the school building. (3) Bioretention, more suitable for larger drainage areas, was designed to treat runoff from the athletic fields. ESRI ArcMap's measure tool was used to measure the pervious and impervious spaces which resulted in 10.3 and 20.7 acres, respectively. Table 2.2 shows the imperviousness and perviousness treated by each GSI practice.

Table 2.2 The imperviousness and perviousness areas treated by each GSI practice and their respective percentages. Bioretention cells, rain gardens, and rainwater harvesting are listed as BRC, RG, and RWH, respectively.

	Acres			Percent		
	BRC	RG	RWH	BRC	RG	RWH
Perviousness Treated	7.90	2.41	N/A	76.65	23.35	0
Imperviousness Treated	15.01	2.84	2.84	72.52	13.74	13.74

2.3.6. Threshold Analysis and Comprehensive Measures Scenarios

Bioretention and rain garden simulations were run based on percent of total suitable area. The total suitable area adoption ranged from 0 to 100% in 10% increments. Each run assumed only one unit was used in the simulation. Based on peak runoff, a threshold was found by determining after which adoption rate a plateau began to occur. The point at which the plateau begins was determined as the threshold, as the adoption rates thereafter would yield negligible reductions in peak runoff. Only bioretention and rain garden thresholds were determined using this method, because efficiency of these practices are based on area, whereas rainwater harvesting success is based on volume.

Thirteen rainwater harvesting simulations were run based on varying barrel sizes from 1000 to 60000 gallons. Storage for 75% capacity was used for each simulation. Both the barrel height and offset (height of the drain line above the bottom of the barrel) were assumed at 10 feet for consistency. The offset was set the same as the barrel height so the tank would fill to capacity before overflow occurred, maximizing storage. One unit per simulation was also assumed. A plateau in peak runoff determined at which storage size would yield a threshold. The thresholds for each practice were considered optimized adoption rates. Table 2.3 shows the scenarios used for each practice to determine the thresholds.

Table 2.3 Scenarios in SWMM by GSI practices used, percent of suitable area of each practice used and/or volume capacity of each practice used

Scenario Name	**GIS/LID Used**	**% Of Suitable Area**	**Volume Capacity (gallons)**
Without LID	N/A	0	0

Table 2.3 Continued

Scenario Name	GIS/LID Used	% Of Suitable Area	Volume Capacity (gallons)
BRC	Bioretention	100%	N/A
		90%	N/A
		80%	N/A
		70%	N/A
		60%	N/A
		50%	N/A
		40%	N/A
		30%	N/A
		20%	N/A
		10%	N/A

Table 2.3 Continued

Scenario Name	**GIS/LID Used**	**% Of Suitable Area**	**Volume Capacity (gallons)**
RG	Rain Garden	100%	N/A
		90%	N/A
		80%	N/A
		70%	N/A
		60%	N/A
		50%	N/A
		40%	N/A
		30%	N/A
		20%	N/A
		10%	N/A

Table 2.3 Continued

Scenario Name	GIS/LID Used	% Of Suitable Area	Volume Capacity (gallons)
RWH	Rainwater Harvesting	N/A	1000
		N/A	5000
		N/A	10000
		N/A	15000
		N/A	20,000
		N/A	25000
		N/A	30,000
		N/A	35000
		N/A	40000
		N/A	45000
		N/A	50000
		N/A	55000
		N/A	60000

Once optimized adoption rates for each of the three practices were determined, four comprehensive measure scenarios that included multiple practices were ran: BRC/RG, BRC/RWH, RG/RWH, and BRC/RG/RWH. Three scenarios combined two of the practices, and the final scenario combined all three. All four of the scenarios were compared to determine which yielded the optimized runoff reduction.

2.3.7. Analysis

A threshold analysis was performed to determine the point at which each GSI practice would have negligible performance improvement thereafter. To determine thresholds for peak runoff, trend lines were fit to the graphs of adoption rate vs. peak runoff and the change in slopes at each point (peak runoff) on the graph were calculated. A plateau is assumed to follow the largest change in slope. Total runoff and delay of peak were also used as a performance metric for each practice scenario. Percent change was analyzed for each scenario to document effectiveness of each. The hydrographs of each comprehensive measures' scenario were also analyzed for shape and start time for runoff. The correlation coefficient was calculated in Excel to determine the relationship between percent of area covered for each scenario and total volume of runoff.

2.4. Results and Discussion

2.4.1. Threshold Analysis

Figure 2.4 shows the peak runoff for bioretention and rain gardens. Based on the criteria and 100% adoption of each GSI practice, bioretention would result in the highest peak runoff reduction at 69%. Rain gardens followed at 21%. Refer to Table 2.4 for runoff reductions for bioretention cells and rain gardens. Rainwater harvesting resulted in 9%. Refer to Table 2.5 for runoff reductions for rainwater harvesting. Peak runoff for both bioretention and rain gardens generally decreased as the adoption rate increased from 0 to 100%, as shown in Figure 2.4. Bioretention saw a slight increase from 0% to

20% adoptions by 3% but continuously decreased from that point. Rain gardens increased up to 10% adoption rate by 1% and continuously decreased from that point. Figure 2.5 shows the peak runoff for rainwater harvesting. For rainwater harvesting, an increase in peak runoff was observed, but until rain barrel size reached 45000 gallons, the range of peak runoff change was 0.015 cfs. At 100% adoption, rainwater harvesting reduced peak runoff by 9%. The poor performance of rainwater harvesting may be due to it reaching capacity, indicated by the second plateau. Once the rain barrel reaches 75% capacity during a storm event, the rain barrel is designed to overflow into the rain garden.

Total runoff followed a similar pattern of reduction as peak runoff for each of the practices. At 100% adoption, bioretention, rain gardens, and rainwater harvesting reduced total runoff by 41%, 25%, and 3%, respectively. Figures 2.5 and 2.6 show the total runoff progression for bioretention, rain gardens, and rainwater harvesting.

On a 12-min time step, peak runoff, as well as the peak rainfall of 2.02 inches, occur 12 hours and 12 minutes into the rainfall event. A delay in peak runoff was only observed for bioretention, with an 84-min delay at 100% adoption. A delay was not observed until adoption reached 30%, at which a 12-min delay occurred. Thereafter, peak runoff continued to be delayed gradually up to 84 minutes. Although peak rainfall occurred at 12:12, the bioretention was able to withstand the rainfall intensity.

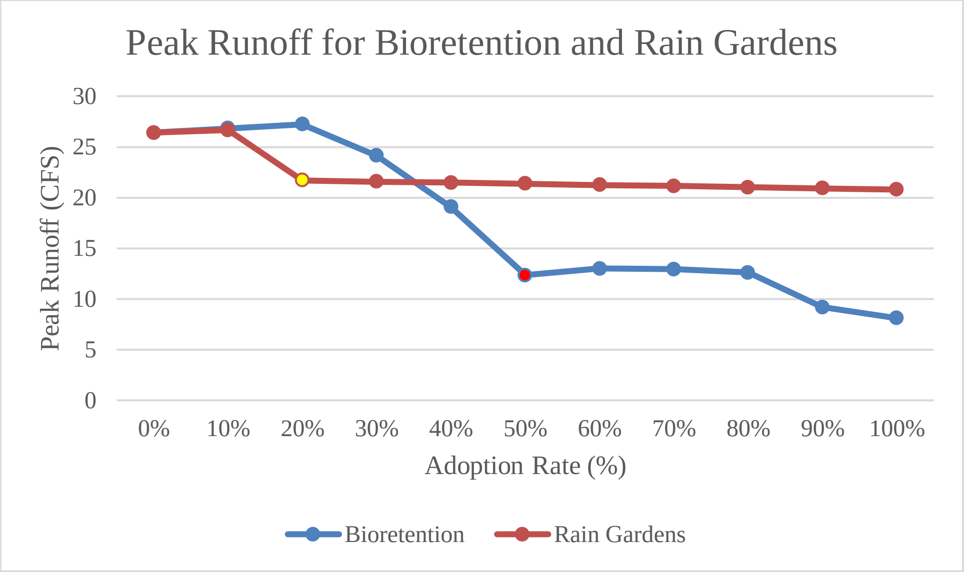

Figure 2.4 Peak runoff changes by adoption rate for both bioretention and rain gardens

Table 2.4 Percent reductions for bioretention cells and rain gardens

	% of Total Suitable Area	**Peak Runoff (CFS)**	**% Reduction for Peak Runoff**	**% Reduction for Total Runoff**
Bioretention Cells	0%	26.41	0%	0%
	10%	26.81	-2%	4%
	20%	27.22	-3%	8%
	30%	24.12	9%	13%
	40%	19.07	28%	17%
	50%	12.34	53%	22%
	60%	12.98	51%	24%
	70%	12.94	51%	28%
	80%	12.6	52%	32%
	90%	9.18	65%	38%
	100%	8.11	69%	41%

Table 2.4 Continued

Rain Garden	0%	26.41	0%	0%
	10%	26.66	-1%	6%
	20%	21.69	18%	11%
	30%	21.58	18%	15%
	40%	21.47	19%	19%
	50%	21.36	19%	22%
	60%	21.24	20%	23%
	70%	21.13	20%	24%
	80%	21.01	20%	24%
	90%	20.9	21%	25%
	100%	20.79	21%	25%

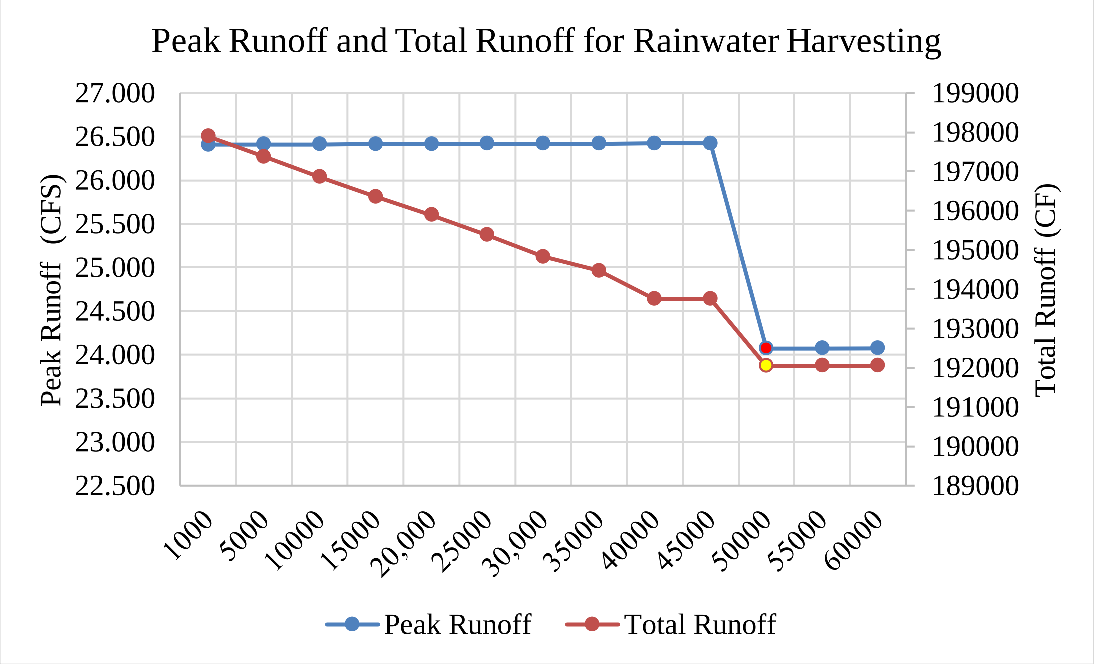

Figure 2.5 Peak runoff and total runoff changes for rainwater harvesting

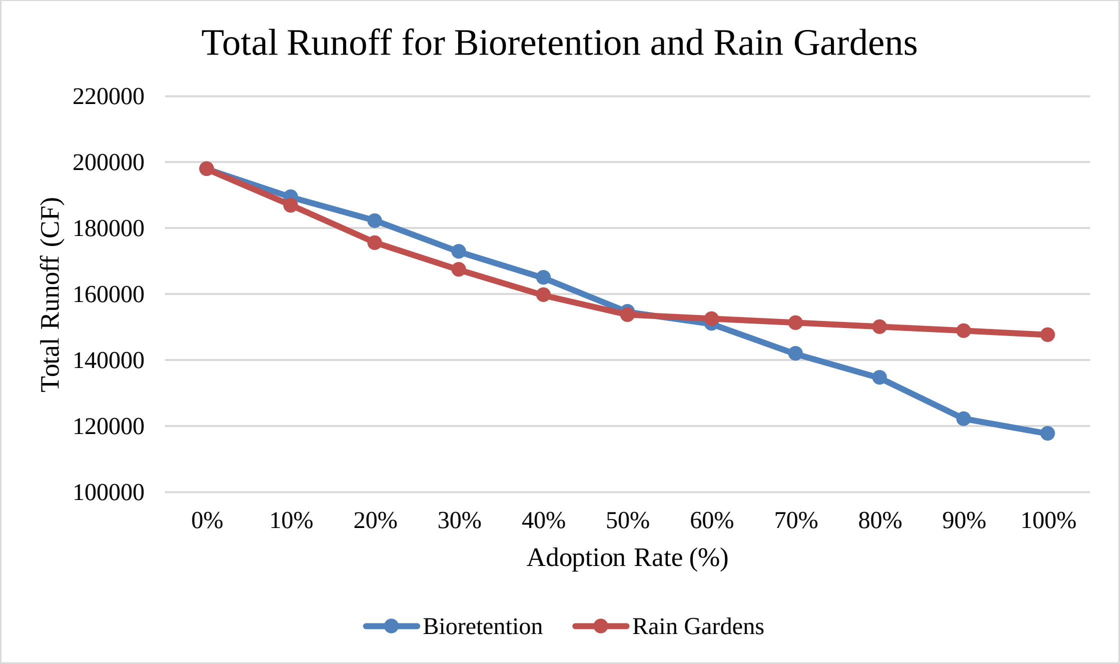

Figure 2.6 Total runoff changes by adoption rate for bioretention and rain gardens

Table 2.5 Percent runoff reduction for rainwater harvesting

Storage (gal)	Peak Runoff (CFS)	% Reduction of Peak Runoff	% Reduction of Total Runoff
1000	26.409	0.00%	0.0%
5000	26.410	0.00%	0.3%
10000	26.412	-0.01%	0.5%
15000	26.413	-0.02%	0.8%
20,000	26.415	-0.02%	1.0%
25000	26.417	-0.03%	1.3%
30,000	26.419	-0.04%	1.5%
35000	26.420	-0.04%	1.7%
40000	26.422	-0.05%	2.1%
45000	26.424	-0.06%	2.1%
50000	24.074	8.84%	2.9%
55000	24.074	8.84%	3.0%
60000	24.073	8.85%	3.0%

Table 2.6 shows the results of the slope analysis. The slope analysis of peak runoff revealed that after 50% and 20% for bioretention and rain gardens, respectively, the performance improvement was negligible, as demonstrated by the red and yellow dots on the graph. The largest change in slope occurred from 40% to 50% adoption rate for bioretention, decreasing by 6.73 cfs/%. For rain gardens, the largest change in slope occurred from 10% to 20% adoption, decreasing by 4.97 cfs/%. For rainwater harvesting, the slopes were very similar, alternating between 0.001 and 0.002 cfs/% until the rain barrel size reached 50000 gallons. There was no very little change in slope after that point. The slope analysis revealed that 50000 gallons was the threshold for rain gardens.

Table 2.6 Slope Analysis results for each GSI practice, showing the slope of the trendline by point range. Point range refers to the range between each consecutive adoption rate (bioretention and rain garden) or barrel size (rainwater harvesting)

Rain Garden		**Bioretention**		**Rainwater Harvesting**	
Point Range	Slope of Trendline	Point Range	Slope of Trendline	Point Range	Slope of Trendline
0 to 1	0.25	0 to 1	0.4	1 to 2	0.001
1 to 2	***-4.97***	1 to 2	0.41	2 to 3	0.002
2 to 3	-0.11	2 to 3	-3.1	3 to 4	0.001
3 to 4	-0.11	3 to 4	-5.05	4 to 5	0.002
4 to 5	-0.11	***4 to 5***	***-6.73***	5 to 6	0.002
5 to 6	-0.12	5 to 6	0.64	6 to 7	0.002

Table 2.6 Continued

Rain Garden		**Bioretention**		**Rainwater Harvesting**	
Point Range	Slope of Trendline	Point Range	Slope of Trendline	Point Range	Slope of Trendline
6 to 7	-0.11	6 to 7	-0.04	7 to 8	0.001
7 to 8	-0.12	7 to 8	-0.34	8 to 9	0.002
8 to 9	-0.11	8 to 9	-3.42	9 to 10	0.002
9 to 10	-0.11	9 to 10	-1.07	***10 to 11***	**-2.35**
				11 to 12	0
				12 to 13	-0.001

2.4.2. Comprehensive Measures Scenarios

Based on the threshold analysis of the single-event scenarios, the comprehensive measures scenarios were developed. The 50%-adoption, 20%-adoption, and 50000-gallon thresholds for bioretention, rain gardens, and rainwater harvesting were used in each of the four comprehensive measures scenarios.

Table 2.7 shows the results of each scenario, and the hydrographs can be seen in Figure 2.7. The outlet where runoff was measured was at the SOC campus. The W/O_GSI scenario, with no GSI present, began generating runoff shortly after rainfall beings, at approximately 24 minutes into the event. The RG_RWH scenario follows shortly after, at 36 minutes, indicating it has poor performance in delaying runoff generation. The BRC_RG and BRC_RWH are similar in performance at approximately 3 hours and 12 minutes, indicating that the addition of bioretention aided in delaying runoff generation. The BRC_RG_RWH scenario delayed runoff generation the most, by 12 hours and 12 minutes.

Table 2.7 Peak runoff, total runoff, and runoff start time results of each scenario

Scenario Name	GIS Used	% of Suitable Area	Volume Capacity (gallons)	Peak Runoff (CFS)	Peak Runoff Reduction (%)	Total Runoff (CF)	Total Runoff Reduction (%)	Runoff Start Time (hour: min)
W/O_GSI	N/A	0	0	26.41	N/A	197894	N/A	0:24
BRC_RG	BRC	50%	N/A	12.24	53.6	132793	32.9	3:12
	RG	20%	N/A					
BRC_RWH	BRC	50%	N/A	12.34	53.2	148827	24.8	3:00
	RWH	N/A	50000					
RG_RWH	RG	20%	N/A	19.39	26.6	169804	14.2	0:36
	RWH	N/A	50000					
BRC_RG_RWH	BRC	50%	50000	12.24	53.6	127484	35.6	12:24
	RG	20%						
	RWH	N/A						

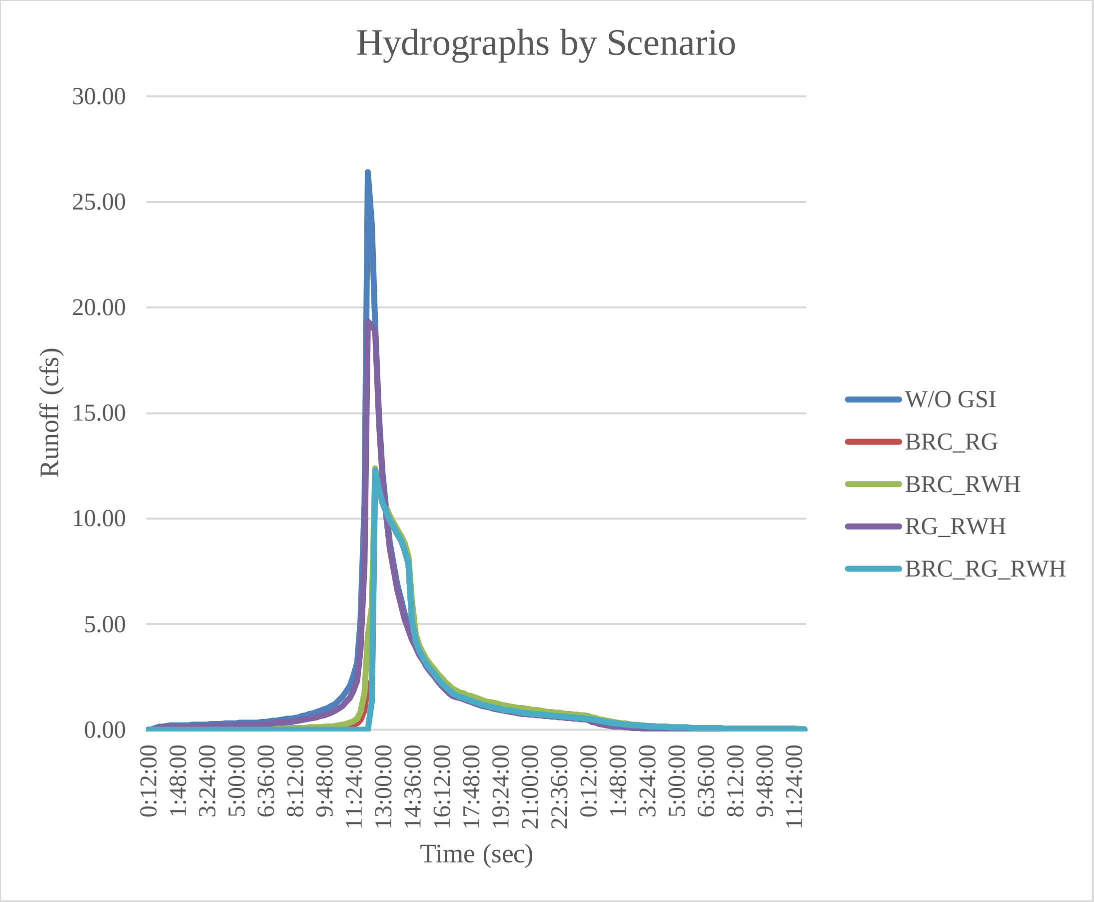

Figure 2.7 Hydrographs for each scenario

When comparing both the single-event scenarios and the comprehensive scenarios, the rainwater harvesting was the least effective. The BRC_RG_RWH and BRC_RG scenarios were very similar with 36% and 33% runoff volume reduction, respectively. The BRC_RWH and BRC scenarios were also very similar with 25% and 22% respectively. The RG_RWH and the RG results were similar at 14% and 11%, respectively. It is worth noting that the addition of rainwater harvesting to bioretention cells and rain gardens did delay the start of runoff by an additional 9 hours and 12 minutes. This information indicates that rainwater harvesting, based to the criteria used in the scenarios, does not greatly increase the effectiveness of GSI systems at reducing runoff when combined with other practices, although it can aid in delaying runoff. The addition of rain gardens aided in runoff reduction, given that BRC alone resulted in 22% reduction, but when combined with rain gardens, increased to 33%. Rainwater harvesting and rain gardens paired together resulted in 14% reduction, compared to the 3% reduction of rainwater harvesting alone. The addition of rain gardens to both bioretention cells and rainwater harvesting increased the system effectiveness by 11%. Because rain gardens were designed to capture rainwater harvesting overflow, the rain barrels likely collected a limited depth, and the rain gardens handled the rest of the rainfall. Similar results were found in a case study performed by Jennings et al., which indicated that when rain barrels and rain gardens were used in tandem, a 16-28% reduction in runoff was observed, but 90% of the decrease was due to the rain gardens (2013).

The results also indicate that as the area encompassed by GSI increases, so does the runoff reduction, which is consistent with other modeling studies (Ahiablame et al., 2012; Luan et al., 2019). The r-squared value as a percentage was 96.8%, indicating a high correlation between area percentage and runoff volume reduction. Figure 2.8 shows the comparison of each scenario according to area percentage and runoff volume reduction. Rainwater harvesting effectiveness may be limited because it lies in a significantly smaller area than the other practice scenarios. As the area for bioretention and rain gardens increase, so does their water-holding capacity. Runoff will only occur once the rainfall intensity is higher than the infiltration rate or the soil is completely saturated. Since all scenarios assumed no antecedent moisture conditions, the bioretention and rain gardens were allowed to fill completely with larger areas before runoff began.

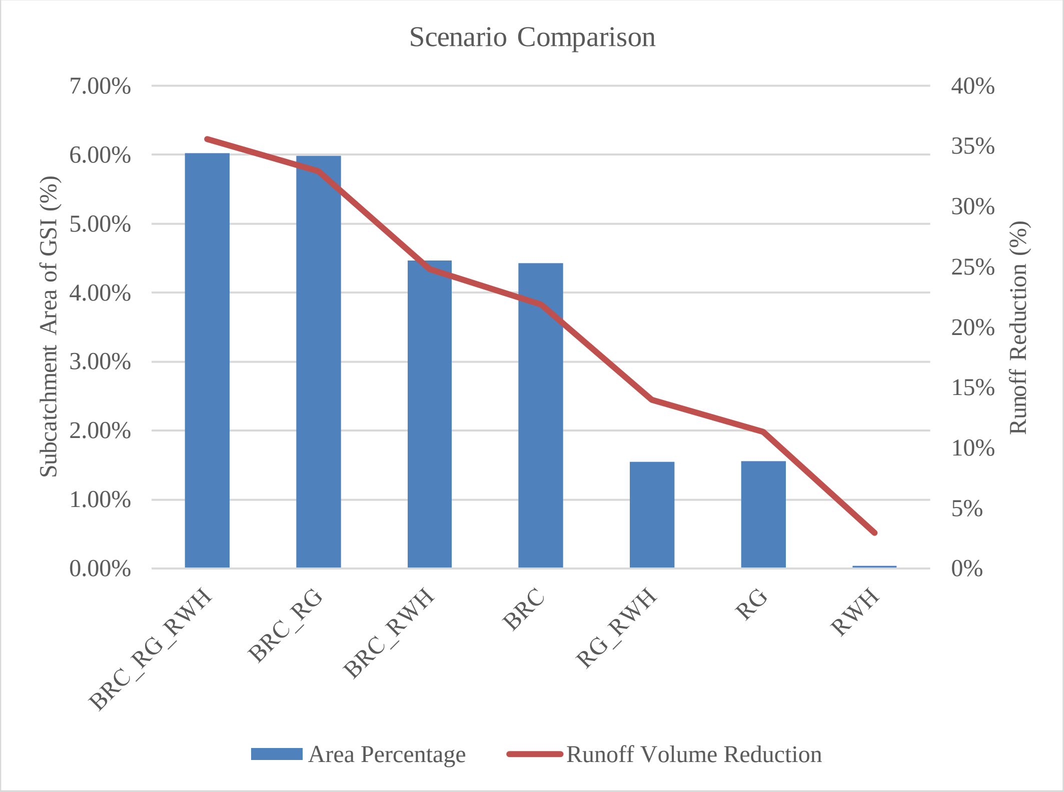

Figure 2.8 Percent of subcatchment area and runoff reduction for each scenario

2.5. Summary and Conclusions

Focusing on the South Oak Cliff High School campus, this study examined the watershed impacts of three GSI practices on the campus, measuring peak runoff, total runoff volume, and time delay of peak runoff. SWMM was used to model these impacts and evaluate the performance of each individual GSI and four scenarios of comprehensive measures. This study contributes to the understanding of performance of site-specific GSI retrofits and their impacts at the watershed scale. Based on the data, bioretention, rain gardens, and rainwater harvesting can have varying levels of runoff retention success depending on the site characteristics, as well as the treatment area of each practice. It can be concluded that for the South Oak Cliff High School campus, bioretention is the single most effective GSI practice, considering the suitability criteria gives bioretention the most area. Each single practice and comprehensive measures scenario were effective at reducing peak runoff and total runoff volumes to some degree. The addition of rainwater harvesting does not greatly aid in runoff volume reduction. The recommended GSI system, based on the success of the scenarios, is a combination of bioretention and rain gardens, with bioretention covering 50% of suitable space and rain gardens covering 20% of suitable space. The second and third alternatives are bioretention alone followed by rain gardens alone.

Future research at both this site and others should attempt to change the selection criteria and the treatment area to determine how each practice performance may be affected. In addition, it is worth it to further investigate placement opportunities in each site using other models, as SWMM only allows for unit number and area amount. Finally, the effect of less frequent storm recurrence intervals may be helpful in determining the GSI effects on the watershed as well. The results of this study are specific for the study area and following the same methodology may result in different combinations in different areas.

3. PUBLIC PERCEPTION

3.1. Introduction

The U.S Environmental Protection Agency (EPA) defines green infrastructure, also referred to as green stormwater infrastructure, from Section 502 of the Clean Water Act as "...the range of measures that use plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspirate stormwater and reduce flows to sewer systems or to surface waters." (U.S. Environmental Protection Agency, n.d.). The more popular forms of GSI are bioretention, rain gardens, green roofs, rainwater harvesting, bioswales and permeable pavement (U.S. Environmental Protection Agency, 2010). While the term “green infrastructure” has been used to define green spaces that do not have engineered components as a stormwater solution, for the purposes of this study, green infrastructure with the aforementioned criteria will be referred to as “green stormwater infrastructure” or GSI. The primary method of GSI is to allow water to infiltrate and permeate the soil layer, which allows water to recharge aquifers and prevents the overloading of streams during heavy storm events (de Graaf-van Dinther et al., 2021).

GSI has been known to provide several services that contribute to public health and increase the quality of life of citizens, benefits known as ecosystem services (Bolund & Hunhammar, 1999). Although GSI’s primary benefits are increased hydrologic performance and water quality improvement (Dagenais et al., 2017), its secondary environmental benefits include mitigation of urban heat islands (Block et al., 2012), promotion of wildlife habitat and biodiversity (Prudencio & Null, 2018), air quality improvement (Shaneyfelt et al., 2017), and aquifer recharge (Dibaba et al., 2020), among others. More recently, the cultural, social, and economic benefits of GSI have been explored, findings concluding that GSI raises property values, reduces gray infrastructure construction costs, reduces energy consumption and costs, creates visually attractive streets and rooftops, and increases quality of life (Qi & Barclay, 2021; U.S. Environmental Protection Agency, 2010.). GSI allows for more exposure to green space and helps prevent stress associated with flooding damage among flooding victims (Mason et al., 2019). Dunn (2010) goes further to argue that installing GSI creates jobs during installation, and maintenance and provides space for growing produce. Although the benefits of GSI are well studied, awareness of the vast array of benefits as well as how the public feels about them are still lacking (Ando & Freitas, 2011; Baptiste, 2014; Baptiste et al., 2015).

In a socio-hydrology context, public participation has been widely studied for water resources management (Barclay & Klotz, 2019), but research on public perception of GSI benefits are scarce (Duan et al., 2018; Qi & Barclay, 2021; Suppakittpaisarn et al., 2019). While implementation has increased, GSI use has not become widespread (Venkataramanan et al., 2020), and large barriers to implementation remain, including the need for increased stakeholder engagement (Montalto et al., 2013). One of the largest barriers to urban green space planning is spatially based, social valuation methods, such as individual perceptions, preferences, and non-monetary values of environmental features (Rall et al., 2019; Dhakal & Chevalier, 2017). A lack of awareness of GSI and its benefits among the public also contributes to poor implementation. It also runs the risk creating GSI that the public finds unappealing (Suppakittpaisarn et al., 2019). Many studies on public perception only focus on green space rather than GSI. The studies that do focus on GSI report high willingness to implement regardless of socio-demographics and environmental knowledge, with environmental knowledge being gained from lived experiences (Baptiste, 2014; Baptiste et al., 2015; Duan et al., 2018). Many of the concerns were based on cost and maintenance of GSI (Ando & Freitas, 2011: Barnhill & Smardon, 2013; Carriquiry et al., 2020). Resistance also persists because of lack of awareness of the disservices of traditional gray infrastructure and the common belief that stormwater runoff is not an immediate environmental and public health issue (Chaffin et al., 2016; Keeley et al., 2013). Barriers to GSI implementation, both technical and non-technical, are not largely understood, but public support and involvement have been shown to be advantageous to the success of public projects, demonstrating more trust in local governance and aiding in collaborative communication and partnerships between stakeholders (Barclay & Klotz, 2019; Faehnle, 2014) Shandas (2015) concluded that residents' perceptions about GSI benefits decreased when educational outreach decreased. This study seeks to better understand the context in which residents value GSI, as well as increasing outreach and education among the community so that they can be better involved with projects concerning their immediate environment.

Not only is GSI increasing in popularity, but interest in GSI in park spaces has also grown (U.S. Environmental Protection Agency, 2017). However, research on how GSI performs in parks and other green spaces as well as how they can improve the stormwater management in parks is limited. Current stormwater management practices in parks mirror traditional gray infrastructure in that it operates with a centralized approach to directing stormwater runoff. Implementation of GSI requires research on how park visitors use parks, adding a social criterion that can ensure that interaction between GSI and park visitors can be optimized. Additionally, more information is needed on the relationship with park usage and GSI perception of users. This study aims to determine how the public uses parks and if it affects how users value GSI.

The goal of this study is to conduct a public perception survey of nearby community members to measure their knowledge of GSI and valuation of different practices. Community members include local groups, organizations, and businesses, such as high school alumni associations, church groups, neighborhood associations, apartment complexes, recreation clubs and groups, city services, non-profit organizations, etc. The study was performed through an online survey of the community members. The survey includes questions on (1) valuation of bioretention, bioswales, green roofs, permeable pavement, rainwater harvesting, and rain gardens and how important the practices are for water quality, rainwater retention, visual attractiveness, and recreation, (2) personal experience with flooding and water quality issues in the neighborhood and Alice Branch Creek, (3) park usage, and (4) demographics.

3.2. Literature Review

3.2.1. Public Awareness of GSI

Most studies agree that increasing awareness of GSI is important when trying to implement more GSI (Carlet, 2015; Dhakal & Chevalier, 2017), given that public engagement increases likelihood of success of public projects (Barclay & Klotz, 2019). One study also concludes that a lack of knowledge about GSI has limited widespread implementation (Ureta et al., 2021). In a review study, Venkataramanan et al. (2020) discovered that public knowledge and awareness of GSI is low, based on their systematic literature review of 85 studies on the human dimensions of GSI. Williams et al. (2019) surveyed residents about their awareness of GSI in multiple community developments in England, in which GSI was made very visible. In only a few communities were residents aware of the presence of GSI before moving to these areas. This implies that unless residents have been visibly exposed to GSI, they lack awareness of it. GSI awareness amongst low to moderate-income residents may also be low (Mason et al., 2019), indicating that income, among other factors, may affect exposure and awareness of GSI.

3.2.2. Known Variables Affecting GSI Perception

Environmental knowledge and environmental attitude are highly regarded as a defining factor in perceptions of GSI and willingness to implement (Baptiste et al., 2015). Environmental attitude is about how people think about and relate to the environment and is known to influence people's behavior toward the environment (Dipeolu at el., 2021). Ramsey and Rickson (1976) report that increased environmental knowledge results in positive attitudes toward the environment, which may lead to promotion of better environmental quality. Personal experience also affects how environmental issues are understood, especially at the local level (Hopkins & Warburton, 2015). When surveying managers of steel company in Iran, Safari et al.

(2020) found that environmental knowledge and awareness directly affected managers' environmental behavior, and indirectly affected behavioral intentions, environmental attitude, and commitment to the environment. It can be concluded that environmental awareness, attitude, and knowledge has large effect on environmental behavior, including willingness to implement GSI.

In addition to environmental knowledge and attitude, sociodemographic variables, such as education level, race, ethnicity, and socioeconomic status have little influence on environmental knowledge. Lived experiences, not necessarily resulting from age, of flooding and it impacts, are more influential toward GSI perceptions (Baptiste et al., 2015). Meanwhile, age has been shown to influence environmental awareness (Sañudo-Fontaneda & Robina-Ramírez, 2019). Location of residence, gender, and education level have been found to influence efficacy, aesthetic preference, and cost consideration of residents, which do effect GSI perceptions and willingness to implement GSI practices (Baptiste et al., 2015).

3.2.3. Ecosystem Services and Perceptions

GSI provides a plethora of ecosystem services (Prudencio & Null, 2018), which can attract more potential users of GSI. Research on valuation of these ecosystem services through public perception is increasing (BenDor et al., 2018; Hagen et al., 2017; Rall et al., 2019). BenDor et al. (2018) developed a framework for valuation of GSI based on ecosystem services and used Portland, Orgegon, and Durham, North Carolina as case studies. Rall et al. introduced public participation GIS, a spatially based survey method, to evaluate how respondents in Berlin socially value GSI. Hagen et al. (2017)

found that single-family residents in the metropolitan Phoenix area reported improved green space, aesthetics, and sense of community after constructed wetlands were built for wastewater treatment, indicating GSI has cultural ecosystem services in addition to its environmental ecosystem services.

Research suggests that many people are not aware of what ecosystem services are and the necessity of their benefits. Barnhill and Smardon (2012) indicated that their focus group participants, stakeholders in Syracuse, New York, demonstrated a lack of understanding of ecosystem services, such as carbon sinks, mitigate air quality, modify microclimate, and reduce urban runoff, when asked if they were familiar. Although the public may not have much education on ecosystem services, once provided with information about their broader impacts to society, they may be better able to associate GSI with these benefits. Miller and Montalto (2019) found that New York City stakeholders have positive views of ecosystem services other than stormwater management. Williams et al. (2019) discovered that once they were aware of GSI presence, which were made very visible in their community, most survey respondents (80-97%) associated GSI with flood management, while less (7-33%) associated GSI with pollution control. Respondents mainly associated GSI with flooding, pollution control, and air quality. Alves et al. (2018) also found that the various stakeholders in Thailand rated rainwater harvesting, amenity/aesthetics, and biodiversity/ecology higher than other ecosystem services. This indicates that the environmental services of GSI are more well-known and highly ranked than the social and cultural benefits.

3.2.4. Stormwater Awareness and Concern

As previously mentioned, general environmental knowledge affects environmental perceptions and concern for the environment. This also extends to flood knowledge and perceptions. Hopkins and Warburton (2015) explored flood risk perceptions after the upper Ryedale flood of 2005 in northern England and found that local flood knowledge is an important factor when determining perception of flood risk and causes of flooding, while socio-demographic variables had little effect. McEwen et al. (2016) cites that sharing flood knowledge and experiences amongst residents can help increase awareness, creating ‘productive mutual learning’. Ureta et al. (2021) surveyed residents of coastal areas in South Carolina and found that GSI’s ability to mitigate flooding was highly valued and influenced whether they wanted to adopt rain gardens. It can be inferred that people who have personal experience with floods may be more likely to highly value GSI due to its ability to retain stormwater, as measured by Mason et al. (2019) in their study surveying low- and moderate-income residents in Knoxville, Tennessee.

Additionally, although Moser (1984) found that many people are tolerant of water pollution, public environmental awareness and concern has increased over time (Gao et al., 2018). Canter et al. (1993) concluded that perceptions of water quality depend on whether the pollution is visible, how people use the water source, sociodemographic variables, and engagement with government officials among others. Ureta et al. (2021) also concluded that people who value water quality improvements are more likely to desire rain garden implementation. Their results showed that many respondents (50%) perceived that flooding reduces the water quality of streams, rivers, and coastal waters, and many (66%) also believed that improvement of water quality is very important. Gao et al. (2018) found that awareness of local water quality issues influences attitudes toward GSI implementation. Further research on water pollution awareness and its influence on attitudes toward GSI would be helpful in increasing public implementation of GSI.

3.2.5. Park Usage and Environmental Concern

Not only is GSI increasing in popularity, but interest in GSI in park spaces has also grown. GSI can revitalize parks, maximize their functionality, and make use of their highly visible nature to existing park users (LID Center for NRPA, n.d.). However, research on how GSI performs in parks and other green spaces as well as how they can improve the stormwater management in parks is limited. Many current stormwater management practices in parks mirror traditional gray infrastructure in that it operates with a centralized approach to directing stormwater runoff (Shinde, 2002), so research is needed on GSI retrofits in parks.

Research also suggests that park users are more likely to have concern for the environment and enjoy being in nature (Kellison et al., 2017; Lin et al., 2014). Kellison et al. (2017) also found, according to survey results, 40% of respondents visit a park at least once a month, with the most popular activities being relaxation, picnicking, or fitness. Lin et al. (2014) reported 62% of their survey respondents, citizens of Brisbane, Australia, visiting parks in the past week. One can assume that park users may also be more likely to implement and advocate for more GSI. While this study does not measure GSI effects in park spaces, surveying residents of the neighborhood on how often they use parks and why can add a social component to placement of GSI in parks, providing information of how park users can interact with GSI.

3.3. Site Description

The neighborhood of Oak Cliff, approximately 87 square miles, is in the southwest area of the city of Dallas, with a population of approximately 387,000 (U.S. Census Bureau, 2019a). The study area is roughly surrounded by Loop-12 on the west, Interstate-30 on the north, the Trinity River on the northeast, Interstate-45 on the east, and Interstate-20 on the south. It is one of the oldest neighborhoods in Dallas (Oakcliff.org, n.d.). According to hydrologic models, Dallas neighborhoods south of the Trinity River have experienced frequent flooding. In 2017, The City of Dallas proposed 84 flood protection projects. The plan highlighted 14 critical areas where flooding issues are of greater concern than others, seven of which are in Oak Cliff (Jimenez, 2019).

According to American Community Survey data, 28% of Oak Cliff residents are living in poverty, 4% are unemployed, and 93% are racial minorities (Centers for Disease Control and Prevention, 2018). Since the national poverty rate is 11.8%, pre-COVID-19, (U.S. Census Bureau, 2019d), the national unemployment rate is 3.5, pre-COVID-19, (U.S. Bureau of Labor Statistics, 2020), and the minority percentage is 42.1% (U.S. Census Bureau, 2019d), the neighborhood of Oak Cliff is socially vulnerable to poverty and unemployment and is a historically underserved minority community. Determining the GSI perceptions in a historically underserved area could reap much needed benefits.

3.4. Methodology

The methods used to accomplish the objectives are as follows:

- Create a literature table and review existing body of public perception studies, identifying methods used, study regions, sample size, and stakeholders surveyed to guide question selection
- Survey testing sample to edit questions if needed
- Survey Oak Cliff community to gather information on GSI valuation and factors that influence it
- Compare park usage, flooding perception, climate change perception, and sociodemographic data to determine their influence on GSI valuation

3.4.1. Survey Development and Literature Review

A literature review was conducted on public perception of green stormwater infrastructure, which included studies on various GSI practices, such as bioretention cells, rain gardens, bioswales, green roofs, rainwater harvesting and permeable pavement. The purpose of the literature review was to gauge how the literature defines GSI and to guide the formulation of the survey questions, as well as the methodology. A literature review was conducted using TAMU Libraries and Google Scholar to find public perception studies on green stormwater infrastructure for stormwater mitigation that surveyed or interviewed participants. The following key words were used in the search: 1) green infrastructure 2) stormwater 3) perception 4) environmental quality. After initial review of the terms alternative terms used for GSI, 1) SUDS (Sustainable Urban Drainage System) and 2) LID (Low-Impact Development) were also added to the search terms. Snowball sampling, using a reference list of a paper to find more papers, was also used to find more studies from the studies in the initial search. A literature matrix was then developed from the review. Thirty-one studies were selected and reviewed in a literature matrix. The studies were characterized according to author, year of publication, keywords, data collection method, study region, sample size, and affiliation of sample groups. Definition of GSI was a factor due to many studies labeling green infrastructure as simply green space without stormwater mitigation function. Based on the results of the literature review and possible barriers to implementation mentioned in the literature, socio-demographics, prior environmental knowledge, and perceptions of existing environmental conditions were identified as factors that affect perception of GSI. This paper is not an exhaustive literature search. See Appendix A for the literature table.

From the results of the literature matrix, a set of variables that affect public perception of GSI, which was adapted from Baptiste et al. (2015), was developed to guide the formation of the survey questions. The variables are (1) socio-demographics, such as age, race, education level, profession, living situation, (2) prior environmental knowledge of GSI, benefits of GSI, and other ecosystem services, and (3) perceptions of existing environmental conditions such as aesthetics, flooding, water quality perception, and maintenance of surrounding environment. Basing the survey questions on a few of the surveys that were guided by similar research objectives, it was decided that valuation of different GSI practices would better measure environmental knowledge than simply asking the respondents what they know about GSI, because it accounts for the nuances of people’s opinions and their concerns on GSI benefits. Respondents are also asked if they perceive flooding and poor water quality in their neighborhood as well as if it is perceived as problematic.

The finalized survey was 31 questions. The survey can be seen in Appendix B. The respondents were asked if they have observed any flood prone areas in the neighborhood. They were then given information about rain gardens along with a picture and asked how important it is that rain gardens be present in their neighborhood based on rating water quality, rainwater retention, visual attractiveness, and recreation on a scale of 0 to 7. They were also asked if it is important that they see more rain gardens in their community. The same questions were asked about bioswales, rainwater harvesting, bioretention cells, green roofs, and permeable pavement. Participants were also asked a series of questions about personal experience with flooding and water quality issues. They were asked if they personally experience any problems with flooding and how. The same questions were asked about water quality but for Alice Branch Creek. Participants were then given information on the climate change implications on flooding and asked if they perceive it as problematic for the neighborhood. Questions about park usage followed, such as how often respondents visit small and large parks such as Deer Path Park (small) and Lake Cliff Park (large). A picture of each park was shown in the question. They were then asked why they visit both small and large parks with options of recreation, physical activity, visual attractiveness, rest/tranquility, socialization, events, and other. Demographic information was requested of them such as age, gender, ethnicity, and neighborhood affiliation. Lastly, respondents were asked if there was anything else they would like to add about stormwater control in their neighborhood. In closing, they were asked if they would like to be contacted for further questions and directed to respond with their email address if so.

The survey was administered online via Qualtrics. Once the survey questions were finalized, the survey was sent out to two groups for testing before being sent to community members: a peer group and a general population group. Because of the COVID-19 pandemic, which limited in-person contact, limited response rates and a less randomized subject pool were expected. Since the survey was to be administered online instead of in-person, internet access for respondents was a limiting factor. The survey was accessible via computer, tablet, or mobile device.

3.4.2. Recruitment

This research uses 1) convenience sampling and 2) snowballing for recruitment, meaning that 1) no criteria besides being affiliated with Oak Cliff and 2) participants were encouraged to assist in recruiting other participants. Recruiters include contacts from local groups, organizations, and businesses, such as high school alumni associations, church groups, neighborhood associations, apartment complexes, recreation clubs and groups, city services, and non-profit organizations. Recruiters were asked to recruit and distribute the survey to their members, constituents, and/or peers. On schedule, two emails were sent to recruiters, prompting them to take the survey. The two follow-up emails were reminders, including a way for recruiters to opt out if they choose, with a clear timeline. The emails to the recruiters and subsequent reminder emails included written text to send to the participants, reminding them not to coerce, force, or bribe participants. Recruiters were advised not to edit or adapt the text. In addition to emailing, social media was also used. The survey was allowed to be posted by responders and recruiters on social media such as Facebook, LinkedIn, and NextDoor.

Before recruitment and distribution of the survey began, the study was reviewed approved by the Texas A&M University's Institutional Review Board (IRB), titled "IRB2020-1462M- *Public Perception of Green Stormwater Infrastructure in Parks in South Oak Cliff"* with reference number 127366.

3.4.3. Analysis Methods

Responses were included in the sample if the participant finished the survey. According to Qualtrics, a survey is marked "Finished" if the respondent reached an end point in the survey by clicking the last Next/Submit button.

Descriptive statistics were conducted in the analysis of the responses such as mean, median, minimum, maximum, variance, and number of values. The relationships of personal flooding experience, water quality experience, climate change perception, and park usage to GSI and ecosystem service valuation were further analyzed using descriptive statistics. Text answers for flooding experience, water quality experience, park usage, and additional stormwater concerns were analyzed for sentiments.

3.5. Results

3.6. Literature Review Results

From the 31 studies, several themes were noted from the content of the articles. It is evident that the body of research on public perception of GSI is young, given that the articles in the literature review range from 2009-2021. Nine of the studies were conducted outside of the United States (frequently in Spain and Greece). The remainder of the 22 studies in the United States were conducted throughout the country, 9 of them in the northeast region, 3 in the west, 5 in the south, 3 in the Midwest, and 1 conducted nationally. The most common region was the northeast, with 4 of those studies in New York (3 in Syracuse and 1 in New York City), which consist of coastal areas that are vulnerable to tropical conditions such as hurricanes. The studies in the west took place in Portland, Oregon (Everett et al., 2018; Shandas, 2015) and Phoenix, Arizona (Hagen et al., 2017). The studies in the southern region took place in Knoxville, Tennessee, Houston, Texas, Atlanta, Georgia, Raleigh, North Carolina, and coastal counties in South Carolina, most of these states being coastal. The number of studies conducted in coastal states may indicate that GSI is popular in areas that experience frequent flooding. This study would add to the growing body of public perception studies in the southern region.

The studies also varied in terms of affiliation of sample groups and data collection methods. Twenty-two of the studies surveyed citizens and lay persons alone. Three of the studies only surveyed practitioners. Six of the studies surveyed a combination of laypersons, citizens, residents, practitioners, government representatives, and organization representatives.

Majority of the studies utilized questionnaires and surveys (23), with the second most popular method being interviews and focus groups. One study used regression analysis on existing census tract data (Ando & Freitas, 2011), which was the second oldest study in the literature review and may have been because of a lack of perception data at the time of the study. Another, the fourth oldest study, used agent-based modeling to predict decisions based on the emergence of GSI and census data (Montalto et al., 2013). Four of the studies used a mixed-methods approach which included a survey (Barclay & Klotz, 2019; Carriquiry et al., 2020; Hagen et al., 2017). The other methods included community meetings, historical documentation, policy documents, government reports, interviews, field notes, and trend analysis.

Many of the studies were conducted by first authors with social science as their primary affiliation. Six of the studies were conducted by first authors with an engineering background. This study also uses an engineering perspective to guide the research.

3.6.1. Sample Demographics

There were 29 respondents in the sample. The Friend of Oak Cliff Parks organization comprised the majority of the sample. Table 3.1 shows the demographics for the sample and for the neighborhood of Oak Cliff. There were more females (78.57%) present in the sample than males (21.43%). Most respondents were Caucasian (76.67%), followed by African American (13.33%), other (6.67%), and Hispanic (3.33%). Additionally, most respondents were over the age of 65 years old (58.62%), followed by 55-64 years old (24.14%), and 35-44 years old (10.34%). There was an equal number of respondents from the 25–34-year age bracket (3.45%) and the 45–54-year age bracket. Despite efforts to broaden recruitment through online outreach, the sample was not necessarily representative of Oak Cliff. Caucasians, females, and people over the age of 65 were overrepresented in the sample. Fifty percent of the sample have lived in the neighborhood, 19.05% have worked in the neighborhood, and 7.14% have attended school in the neighborhood. 23.81% of respondents chose "Other" for their neighborhood affiliation. Most respondents (65.38%) have been affiliated with the neighborhood for more than 5 years.

Table 3.1 Demographics of the sample compared to American Community Survey (ACS) results for Oak Cliff for gender (U.S. Census Bureau, 2019a), age (U.S. Census Bureau, 2019a), and ethnicity (U.S. Census Bureau, 2019b; U.S. Census Bureau, 2019c)

Demographics	**ACS 2015-2019 (%)**	**Sample (%)**
Gender		
Female	51%	78.57%
Male	49%	21.43%
Age		
18-24 years	11%	0%
25-34 years	14%	3.45%
35-44 years	12%	10.34%
45-54 years	12%	3.45%
55-64 years	10%	24.14%
65+ years	11%	58.62%

Table 3.1 Continued

Demographics	**ACS 2015-2019 (%)**	**Sample (%)**
Ethnicity		
Caucasian/	9%	76.67%
African American	31%	13.33%
American Indian or Alaska Native	0.4%	0.00%
Asian	1%	0.00%
Native Hawaiian or Pacific Islander	0.03%	0.00%
Hispanic	58%	3.33%
Other	6%	6.67%

3.6.2. Flooding, Water Quality, and Climate Change Perception

Most respondents (51.72%) have observed flood prone areas in the neighborhood, and 34.48% of respondents have personally experienced problems with flooding, as demonstrated in Table 3.2. 79% of respondents do not personally experience issues with stream water quality at Alice Branch Creek. There was no uncertainty regarding personal experience with flooding in general, indicated by the 0% response for “I do not know”. However, 17.24% of respondents answered “I do not know” regarding personal experience with water quality issues in Alice Branch Creek. Since the majority of respondents have not personally experienced water quality issues at Alice Branch, it was assumed that most respondents did not regularly interact with Alice Branch Creek or were not aware of any water quality issues. Only one respondent personally experienced water quality issues at Alice Branch Creek. Most (62%) of respondents perceive climate change impacts on flooding as problematic for the neighborhood. 14% of respondents were uncertain about problematic climate change impacts on flooding.

Table 3.2 Responses for flooding, water quality, and climate change perceptions and experiences

Answer	**Do you observe any flood prone areas in this neighborhood?**	**Do you personally experience any problems with flooding?**	**Do you personally experience any issues with stream water quality at Alice Branch Creek?**	**Do you perceive climate change impacts on flooding as problematic for this neighborhood?**
Yes	51.72%	34.48%	3.45%	62%
No	41.38%	65.52%	79%	24.14%

Table 3.2 Continued

Answer	Do you observe any flood prone areas in this neighborhood?	Do you personally experience any problems with flooding?	Do you personally experience any issues with stream water quality at Alice Branch Creek?	Do you perceive climate change impacts on flooding as problematic for this neighborhood?
I don't know	6.90%	0%	17.24%	14%

Ten survey respondents gave text answers for personal flooding experience, as shown in Figure 3.1. One respondent mentioned a public flooding experience. When asked how they personally experience flooding, many respondents mentioned street, yard, and creek flooding. Two respondents indicated their garage and driveway floods. According to their answers, flooding occurred due to heavy rain events or occurs as frequently as after all ordinary rain events. Many respondents claimed to live near creeks, which they named, and indicated that those creeks were overwhelmed during rain events. Flooding of local and neighborhood streets was the most common flooding occurrence in the responses. Pooling and standing water were also areas of concern. Negative concerns about increased urban development were mentioned twice. The relationship between soil absorption or lack thereof was mentioned twice as well. Two respondents mentioned GSI practices as solutions to flooding.

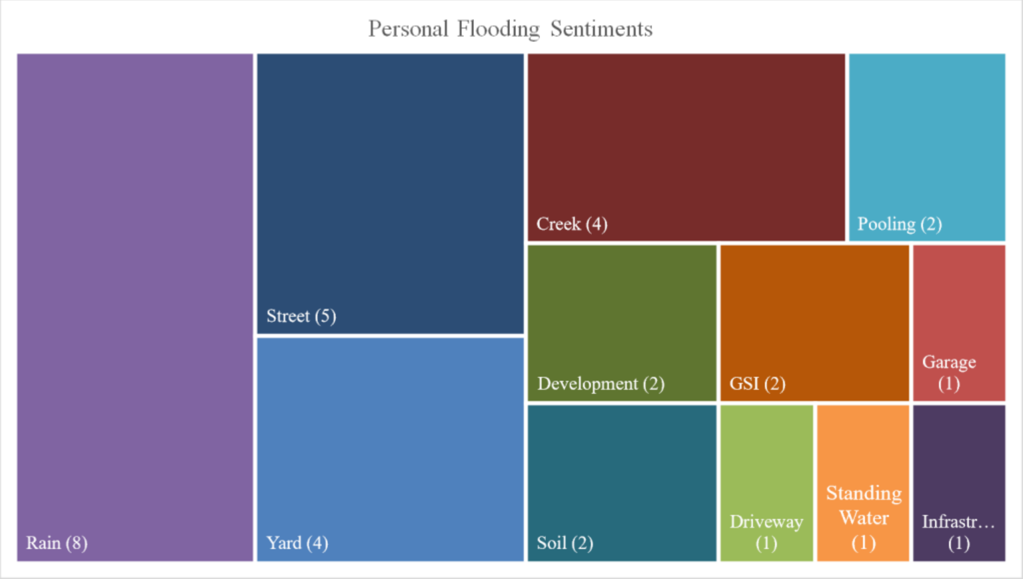

Figure 3.1 Personal flooding sentiments in a tree map, visualizing the frequency each term is mentioned by how large the rectangle is. The larger the rectangle, the more frequent a term was mentioned.

3.6.3. Valuation of GSI

Most respondents indicated that it was important to see more of all the GSI practices in their community. Rainwater harvesting garnered 100% “Yes” responses, indicating that rainwater harvesting may be more popular and well-known in the community. Green roofs had the least amount of positive support (82.1%) for importance and the most negative support (10.7%). Green roofs also had the most “I do not know” answers (7.1%). Bioretention cells were the second most popular practice, indicated by the 96.6% “Yes” response and 0% “No” response. Bioretention cells were followed by rain gardens (93.1%), bioswales (89.7%), and permeable pavement (89.7%) equally. Permeable pavement had the second most level of uncertainty with 6.9% of respondents answering, “I do not know”. Table 3.3 shows these results.

Table 3.3 Responses to "Is it important to you to see more [of this practice] in your community?

Practice	**Yes**	**No**	**I don’t know**
Rain Garden	93.10%	0%	6.90%
Bioswales	89.70%	3.40%	6.90%
Rainwater Harvesting	100%	0%	0%
Bioretention Cells	96.60%	0%	3.40%
Green Roofs	82.10%	10.70%	7.10%
Permeable Pavement	89.70%	3.40%	6.90%

100% of respondents who personally experience flooding perceive having more rain gardens, bioswales, rainwater harvesting, bioretention cells, and green roofs as important. 90% of those respondents see importance for more permeable pavement in their communities, with 10% responding “I don’t know”. 93% of respondents who observe flood prone areas in their community also see importance in having more rain gardens, bioswales, green roofs, and permeable pavement. 100% of respondents who observe flood prone areas in their community see importance in having more rainwater harvesting and bioretention cells.

Additionally, 100% of respondents who deem climate change impacts on flooding as problematic see importance in having more of all GSI practices, except for permeable pavement (94%). A majority of respondents who do not view climate change as problematic for flooding also see importance in having more of all GSI practices, but the results are more varied. Only rainwater harvesting and permeable pavement received 100% response from those who do not view climate change as problematic. Green roofs received the lowest amount of support of 57%.

As shown in the table in Appendix C, regarding environmentally, i.e., water quality and rainwater retention, rainwater harvesting received the highest average for water quality. Rain gardens received the highest average for rainwater retention. Regarding leisure, rain gardens also received the highest average for both visual attractiveness and recreation. Each practice, apart from green roofs, was rated higher for environmental ecosystem services than leisure ecosystem services. For each practice, leisure had the lowest average rating. While rainwater retention had the highest average rating for green roofs, the second highest rating was for visual attractiveness.

The range of ratings for each ecosystem service is indicated by the minimum and maximum ratings. In terms of water quality, rain gardens, green roofs, and permeable pavement had a full range of responses from 0 to 7. Bioswales had a slightly smaller range, from 2 to 7. Rainwater harvesting and bioretention cells had the smallest range, from 3 to 7. Regarding rainwater retention, green roofs had a full range of responses from 0 to 7. All other practices had a range of 2 to 7. For visual attractiveness, bioswales and green roofs had full range of responses, while rainwater harvesting, bioretention cells, and permeable pavement had a range of 1 to 7. Rain gardens had a range of 2 to 7. For recreation, all practices except rain gardens had a full range. Rain gardens had a range from 1 to 7.

It is also worth noting that response rates declined as respondents progressed through the valuation questions. Rating of rain gardens, the first question, had responses from all 29 participants. Permeable pavement, the last question, had 27 responses for the first three ecosystem services and 24 responses for the last ecosystem service.

As shown in Table 3.4, on average, whether a respondent personally experienced flooding slightly influenced how they ranked importance of ecosystem services for each GSI practice, although this was not statistically significant based on the chi-square test. For most of the practices (bioswale, rainwater harvesting, bioretention, and green roof), respondents who do not personally experience flooding ranked water quality and rainwater equally or higher than those who personally experience flooding.

Table 3.4 Comparing the average responses of how respondents ranked water quality and rainwater retention for each GSI practices based on whether they personally experience flooding. The values indicate mean response. Responses were on a scale of 0-7.

	Rain Garden		**Bioswale**		**Rainwater Harvesting**		**Bioretention**		**Green Roof**		**Permeable Pavement**	
Ecosystem Service	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*	*Yes*	*No*
Water Quality	6.1	5.6	5.6	5.7	5.7	6.2	5.4	5.8	4.7	4.7	5.7	5.2
Rainwater Retention	5.8	5.9	5.7	5.7	5.5	6.1	5.7	5.8	4.7	4.7	5.7	5.4

3.6.4. Park Usage

A similar number of respondents visit small (37%) and large parks (37.9%) a few times a year, which was the most common response for park usage frequency. Respondents answered “Not at all” more often for small parks than large parks, indicating large parks are visited more often among the sample. Respondents that visit parks at least once a month are more likely to visit large parks. Respondents that visit parks at least once a week are more likely to visit small parks. Respondents that visit parks daily are more likely to visit large parks. Results are shown in Table 3.5.

Table 3.5 Responses to park visitation frequency questions for small and large parks

Answer	How often do you visit small parks in your neighborhood?	How often do you visit large parks in your neighborhood?
Not at all	22.20%	13.80%
A few times a year	37.00%	37.90%
At least once a month	18.50%	20.70%
At least once a week	22.20%	20.70%
Daily	0%	6.90%

Respondents interact with small and large parks similarly. Most respondents visit both small and large parks for physical activity. Respondents visiting parks leaned toward visual attractiveness for large parks (17.48%) slightly more than small parks (12.5%). Respondents seeking rest and tranquility leaned toward small parks (17.5%) slightly more than large parks (16.5%). Socialization was more popular at small parks (13.75%) than large parks (11.65%), but events are more popular at large parks (13.59%) than small parks (12.5%). Respondents attend small parks for a larger variety of other reasons. Results are shown in Table 3.6.

Table 3.6 Responses to questions asking why respondents visit small and large parks

Answer	Why do you visit small parks in your neighborhood (check all that apply)?	Why do you visit large parks in your neighborhood (check all that apply)?
Recreation	11.25%	12.62%
Physical Activity	20%	21.36%
Visual Attractiveness	12.50%	17.48%
Rest/Tranquility	17.50%	16.50%
Socialization	13.75%	11.65%
Events	12.50%	13.59%
Other	12.50%	6.80%

Generally, park frequency had a positive effect on how respondents valued GSI. While 100% of those who do not attend parks at all wanted to see more GSI in their community, the more frequent a park user visits a park, the more likely they were to want to see more GSI. This was true for all GSI practices.

Respondents who visit both small and large parks typically do so to walk dogs, volunteer, and garden. Respondents who visit small parks also do so to entertain visitors, entertain children, and go birding. The most popular activities for small park users are dog walking, entertaining visitors, and entertaining children. The most popular activities for large park users are dog walking and volunteering. Figures 3.2 and 3.3 show the results for small and large parks, respectively.

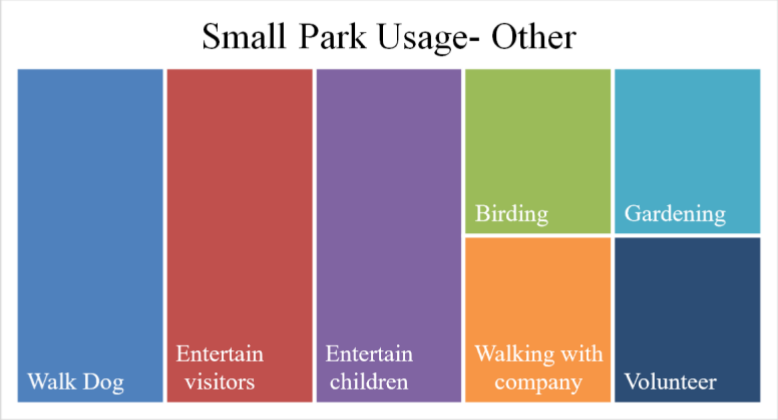

Figure 3.2 Small-park usage responses when respondents indicated "Other"

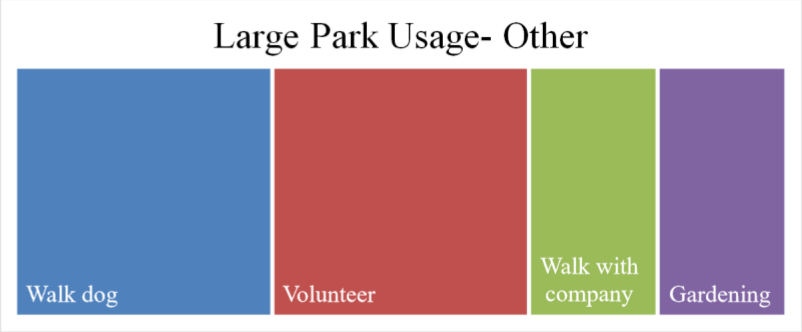

Figure 3.3 Large-park usage responses when respondents indicated "Other"

3.6.5. Additional Sentiments

When asked if they would like to give any more information about stormwater control in their neighborhood, respondents either offered information on their personal experiences or gave recommendations on how to better manage stormwater. Sentiments about personal experiences are summarized below and edited for clarity:

"This neighborhood is hilly which aids in speeding runoff."

"Water used to settle on the [South Oak Cliff High School] field. So far that has not happened since they reconstructed the field."

"The city ignores our attempts to get their attention to our concerns."

"Not enough people take the time to help prevent stormwater pollution."

"Stop paving the world!"

"Need more awareness events."

The sentiments expressed indicate that respondents who gave additional information about stormwater control have negative experiences with how stormwater is managed.

3.7. Study Limitations

Due to the COVID-19 pandemic, in-person recruitment and advertisement of the survey were prohibited, which created a challenge in recruiting survey respondents. Mail and door-to-door recruitment was the initially preferred method, but email recruitment was ultimately decided upon. The final sample was 29 respondents, limiting the scope of statistical analysis performed on the data as well. The final sample was skewed toward older adults, females, and Caucasians, so the results were not analyzed to determine any effects on age, gender, and ethnicity/race on GSI or ecosystem service valuation. In the future, mailing surveys and door-to-door recruitment efforts may be more successful in obtaining a more demographically representative sample.

3.8. Discussion and Impacts

A green stormwater infrastructure valuation survey based on flooding, park usage, and ecosystem services was performed. The relationship between flooding perception and GSI valuation was studied, as well as the relationship between park usage and GSI valuation.

It is worth noting that the survey received overrepresentation from Caucasians, females, and people over the age of 65. The demographics of the study are consistent with literature finding that young people and minority ethnic groups have low survey response rates (Sheldon et al., 2007). This may indicate that most respondents reside in the northern area of Oak Cliff, as this is where most of the non-Hispanic population of Oak Cliff resides. This study reveals that minority ethnic groups and young people in the study area need to be better engaged to counter low response rates, especially because minorities and people under 65 make up most of the neighborhood of Oak Cliff. Also, the study could benefit from more male perspectives, as there are documented gender differences in environmental perspectives (Wallhagen et al., 2018).

The results indicate that most respondents expressed they observe flood prone areas in their neighborhood. While most do not personally experience flooding, approximately one-third of respondents do experience flooding problems personally, which is a significant portion of the sample. Almost 80% of respondents do not personally experience issues with stream water quality at Alice Branch Creek, a high priority area for flood mitigation and water quality concerns in the Oak Cliff neighborhood. Approximately 17% are unaware of any water quality issues there. Based on the results, it can be concluded that most respondents do not regularly interact with Alice Branch Creek. Additionally, 14% of respondents were unsure of climate change impacts on flooding, and 24% did not perceive any problems associated with climate change. This may call for more education on climate change impacts on flooding.

Among respondents who personally experience flooding, there was large concern for street and yard flooding. Respondents experience both minimal flooding, shown by concern for yard flooding, pooling, and standing water, and sizeable flooding, indicated by flooding of their streets. The respondents who personally experience flooding have high environmental knowledge and accurate views of how floods happen, giving information on overwhelmed creeks during rain events, clogged soils, and impermeable surfaces. Two respondents mentioned the GSI practices of rainwater harvesting, which one respondent stated they already use, and bioswales, which they stated they hoped to see more of. This indicates that some respondents are aware of GSI as possible solutions to flooding, either because they took the survey, as this question was asked after given information on GSI, or they were previously aware. A few respondents were concerned about increased development, such as housing developments, parking lots, and shopping centers, having a negative effect on flooding, revealing that respondents who experience flooding are aware that increased development and impermeable surfaces influence flood risk, indicating high environmental knowledge.

While most respondents (82-100%) want more GSI practices in the community, each practice was supported at varying levels. Rainwater harvesting had the most support, and green roofs had the least support and the most uncertainty. This indicates that green roofs may not be very popular or well-known in the community, while rainwater harvesting, which one respondent stated that they use, may be the most popular or well-known in the community. Additionally, when surveying a community in Philadelphia, Kuper (2009) found that residents knew little about green roofs.

The relationship between flooding/water quality/climate change perception and valuation of GSI was explored. There revealed to be a positive relationship between them, which is not surprising and consistent with prior literature on the topic (Mason et al., 2019). Most respondents who observed flood prone areas in their community and personally experience flooding and water quality problems indicated it was important to see more GSI. This is also true for those who believe climate change impacts on flooding are problematic. Compared to those who believe climate change is problematic for flooding, those who do not believe this gave less support for GSI, although it was still generally positive, indicating opinions on climate change do affect GSI valuation. Rain gardens, bioswales, rainwater harvesting, bioretention cells, and green roofs were equally important to those who personally experience flooding. Rainwater harvesting and bioretention cells were the most popular among respondents who observe flood prone areas. Perhaps professionals and officials need more rainwater harvesting and bioretention cell education and implementation programs for residents in this area.

When ranked by ecosystem service, rainwater harvesting had the highest average for water quality, which was its highest average among all ecosystem services for any practice. The most popular uses for rainwater harvesting are for water storage for irrigation, not water quality improvement (Thomas et al., 2014). Generally, rainwater harvesting is more well known for rainwater retention. Many studies measuring the water quality of rooftop rainwater harvesting systems found that the water captured is highly contaminated (Meera & Ahammed, 2006). Although filtration and disinfection may be employed in rainwater harvesting systems, more public education on the water quality of harvested rainwater is necessary. Rainwater harvesting and rain gardens, had an equal average for rainwater retention, indicating their popularity for runoff volume mitigation. All the practices received average ratings over 5, so respondents are highly aware of the flood reduction impacts of GSI. All practices also received ratings over 5 for visual attractiveness as well, which may have been aided by the pictures of each practice in the survey. This is evidence citing that respondent find GSI to be aesthetically pleasing, and GSI should be included in efforts to beautify public areas. None of the practices rated over 5 for recreation, ranging from 3.5 to 4.4, just above the median, indicating that compared to water quality, rainwater retention, and visual attractiveness, respondents do not see great value in GSI for recreational purposes. Gao et al. (2018) believes that emphasizing the functionality of GSI was effective in persuading for adoption.

It appears that personal flooding experience negatively affects how respondents ranked GSI practices in terms of water quality and rainwater retention. Since most respondents who personally experience flooding indicated they would like to see more GSI in their community, it was expected that experiences with flooding would cause a respondent to rank GSI practices higher for water quality and rainwater retention, indicating a higher priority for those ecosystem services, that was not the case here. Respondents who experience flooding may be more critical of GSI for water quality and rainwater retention due to negative experiences associated with flooding. More research is needed on this relationship.

Green roofs received the lowest rating for water quality, rainwater retention, and visual attraction, which is contradictory to reported benefits of green roofs. Green roofs have been known to both enhance roof runoff quality and retain roof runoff quantity (Berardi et al., 2014), in addition to being rated as aesthetically pleasing (Köhler et al., 2002; Kuper, 2009). Kuper (2009) notes a green roof education program at Temple University following a public perception study that included constructing a ground-based replica of a green roof with educational signage. More education on the benefits of green roofs would be beneficial to this community, as also indicated by green roofs having the least amount of positive support when respondents were asked on GSI practice importance.

Park users in the sample primarily visit parks for physical activity, visual attractiveness, rest, and tranquility. Other reasons commonly given by park users were dog walking, entertaining visitors, and entertaining children. This aids in catering GSI in parks to how users interact with the parks. Also, the more frequently a respondent visited parks, the more likely they were to want to see more GSI in their community. Perhaps GSI in parks can be centered around trails, which aid in physical activity. GSI can also be placed around trees and park benches and tables where users can get rest and tranquility. Placing GSI near commonly used places in parks can better expose users to GSI and educate them on their benefits.

Sentiments given about stormwater control in respondents’ neighborhoods prompted two types of responses: personal experiences and recommendations. The recommendations indicate that respondents want more education events, more efforts to prevent stormwater pollution, and view increased pavement as negative. The personal experience anecdotes indicate that respondents personally experience flooding and feel their efforts to gain the City’s attention are ignored. More educational events around GSI, flooding, and stormwater pollution are needed in the community. The educational events may be more meaningful coming from the city government as well.

3.9. Conclusions

The goal of this study was to explore public perceptions about green stormwater infrastructure in the Oak Cliff community through an online survey. The survey asked respondents about flooding experiences, water quality observations, climate change perception, valuation of GSI, ecosystem services, and park usage. Based on their answers, respondents are knowledgeable about flooding and its impacts, indicating high environmental knowledge and lived experiences. Respondents are generally concerned about increased flood risk due to climate change and increased urban development. GSI is highly valued among respondents, rainwater harvesting and bioretention cells more so than others. Green roofs are not as highly valued, and respondents are less knowledgeable about them. Respondents care more about water quality and rainwater retention benefits of GSI more than visual attractiveness and recreation. Respondents who are park users primarily visit parks for physical activity. There were positive relationships between flood experience, frequent park usage, and the belief that climate change is problematic for flooding with GSI valuation. More information is needed on the relationship between ecosystem service valuation of GSI and flood experiences. Based on the data about park usage, placing GSI near trails may be beneficial for exposure to the public.

This information tells us that more education and outreach about GSI and its benefits, especially its social and cultural benefits, are needed in the Oak Cliff community. A closer study of residents near Alice Branch Creek is needed to better analyze water quality perceptions in the area. More education on the benefits on each practice may be needed to counter the levels of uncertainty of each practice's importance.

4. CONCLUSION

This thesis evaluated green stormwater infrastructure (GSI) from two perspectives: environmental and social, one of few studies to do so. This study brought awareness to GSI and its benefits to the environment and the public, particularly in a historically underserved community of racial minorities. The relationship between flood experiences, park usage, and GSI valuation of the public was investigated, an unrealized research area. This study also explored environmental impacts of GSI on the surrounding watershed of a community that has experienced persistent localized flooding. This is one of few studies that examines GSI impacts at the watershed level and uses comprehensive and combined GSI measures to do so, examining their runoff reductions for an optimized GSI system. To carry out this study, the following objectives were sought:

1) conduct a public perception study of community members of Oak Cliff through an online survey
2) model the effects of an optimized comprehensive GSI system of bioretention, rain gardens, and rainwater harvesting on peak flow, total runoff, and time delay of peak runoff of a subwatershed in Five Mile Creek

The first objective involved a survey of the Oak Cliff community in Dallas, Texas. A literature matrix was created, reviewing the existing body of public perception studies on GSI to identify methods used, study regions, sample size, and stakeholders surveyed. The literature review was also used to guide the formation and selection of questions used in the survey. A testing sample was recruited to take the survey to determine if the survey needed possible editing, then recruitment of the larger Oak Cliff community was done. The survey served to gather information on how the public values GSI, primarily based on sociodemographic data, park usage, experience with flooding and water quality problems, and climate change opinions. GSI valuation was determined by whether respondents wanted to see more GSI in their community and what ecosystem services they deemed as important from GSI.

The second objective was accomplished by modeling a subcatchment in Five Mile Creek in which South Oak Cliff High School resides. An existing model was adapted to fit the high school campus. Inputs for each GSI practice (bioretention cell, rain garden, rainwater harvesting) were determined using an adapted suitability criteria and design parameters. Impervious and pervious areas treated for each GSI were calculated using ArcGIS. Single practice simulations with increasing adoption rates by area were modeled to determine effectiveness of each practice alone, as well as to determine effectiveness thresholds based on area. Comprehensive practice scenarios were formed based on the effectiveness thresholds in which all practices were combined to work simultaneously. An optimized scenario was chosen according to peak runoff and total runoff reduction and runoff delay.

4.1. Summary of Findings

The survey respondents were predominantly Caucasian, females, and people over the age of 65, skewing the data. With that being said, the results indicate that most respondents are knowledgeable about flooding and its impacts, are generally concerned about increased flood risk due to climate change and urban development, and highly value GSI of all types, albeit some more than others. For example, green roofs and permeable pavement were not as supported as rainwater harvesting and bioretention cells. Generally, respondents are more concerned about the water quality and rainwater retention benefits of GSI than the visual attractiveness and recreation benefits. Park usage frequency varied among respondents, nevertheless a large percent of respondents visits both small and large parks a few times a year, primarily for physical activity, visual attractiveness, rest, and tranquility.

When examining the relationship between flood and water quality experiences and GSI valuation, the results were consistent with the literature, as most respondents who observed flood prone areas in their neighborhood or personally experienced flooding were more likely to want more GSI in their community. Similar results were observed when climate change opinions were tested. Those who did not believe climate change as problematic for flooding were less likely to support GSI. Interestingly, it was observed that respondents with personal flooding experience were slightly less likely to rank water quality and rainwater retention as important than those who do not personally experience flooding. Lastly, the more frequently a park user visited parks, the more likely they were to deem more GSI in their community as important.

In the modeling study, the results of the single practice simulations revealed that 100% adoption of each GSI practice would result in bioretention cells having the highest runoff reduction, followed by rain gardens and rainwater harvesting at 69%, 21%, and 9%, respectively. The threshold analysis revealed that 50% of bioretention's suitable area, 20% of rain gardens', and 50,000 gallons of rainwater harvesting would result in optimum effectiveness of each practice, and thus were chosen to represent each practice in the comprehensive measures scenarios. Compared to the scenario in which no GSI/LID was present, the bioretention/rain garden and bioretention/rain garden/rainwater harvesting scenarios produced the largest peak runoff reduction of approximately 54% for both scenarios. Although the addition of rainwater harvesting to bioretention and rain gardens did not greatly increase peak runoff reduction, it did delay the start of runoff drastically. On the other hand, rain gardens performed even better at aiding runoff reduction when combined with both bioretention and rainwater harvesting. Lastly, the addition of bioretention to any practice significantly aided in runoff reduction, and thus, was the most effective practice. This may be due, in part to the bioretention having the largest suitable area and drainage area.

Both studies contribute knowledge to watershed studies and public perception knowledge. The modeling study contributes to the body of watershed modeling studies that examine the effects of GSI practices, both single and combined. This study also adds to a small body of research on the GSI thresholds. Additionally, the public perception study adds variables such as flood experience, climate change perception, and park usage that may influence GSI perception.

Together, the two studies reveal that both social and technical criterion may be considered when determining effectiveness of GSI and possible implementation. For example, while the modeling study revealed rainwater harvesting is not the most effective at reducing runoff, it is very popular amongst respondents in the public perception study, showing two factors to be considered. Also, bioretention cells are very effective at runoff reduction and popular amongst respondents, so bioretention may be considered for implementation. Rain gardens are moderately popular and effective at runoff reduction.

4.2. Future Work and Recommendations

More public perception studies exploring feelings about GSI in communities of color and low-income communities would benefit this body of research. Further insight into the factors of flood experience, climate change perception, and park usage, as well as how and how often the public spends in nature, would also be helpful, as these are understudied areas. This may give city officials another perspective, besides an environmental one, on GSI placement and utilization. Additionally, more research on ecosystem service valuation of GSI would be valuable. More rigorous recruitment methods in underserved communities for surveys may help increase response rates in these communities, especially in Oak Cliff. More public engagement and education on GSI, especially green roofs and permeable pavement, may help increase public interest in GSI. Moreover, placement optimization of GSI may aid in developing more accurate watershed models, as well as varying the selection criteria and treatment area. Threshold effectiveness of GSI in watersheds is an under researched area, and more research into this topic could be beneficial for GSI design standard development.

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APPENDIX A

LITERATURE TABLE

Author	Year	Keywords	Data Collection	Study Region	Sample Size	Type of Sample
Ando and Freitas	2011	LID, consumer demand, stormwater management, transaction costs	Regression analysis	Chicago, Illinois	863	Census tracts
Baptiste	2014	behavioral intentions, environmental knowledge, green infrastructure, stormwater management, stated willingness to implement	Survey	Syracuse, New York	208	Residential households
Baptiste, Foley, and Smardon	2015	Environmental concerns, environmental knowledge, green infrastructure, Syracuse	Survey	Syracuse, New York	229	Residential Households
Barclay and Klotz	2019	Green stormwater infrastructure, community participation, urban planning, urban development,	Mixed methods	Atlanta, Georgia	14	City persons, federal government agencies, community residents, and community non-governmental
Barnhill and Smardon	2012	Health, well-being, healthy ecosystems, ecosystem services, green infrastructure	Focus groups	Syracuse, New York	16	Residential housholds
Carlet	2015	Attitudes toward green infrastructure, innovation diffusion, innovation adoption, technology acceptance, local government	Survey	United States	256	Municipal officials who work for engineering, environmental, planning or similar offices of incorporated places
Carlson et al.	2015	Storm water runoff, sustainable urban water management, low-impact development (LID), climate change, public good provision, somerville, survey results	Interviews	Somerville, Massachusetts	41	Representatives from local, state, and federal agencies, local nonprofits and nongovernmental organizations, and residents of the targeted neighborhood.
Carriquiry, Sauri, and March	2020	sustainable urban drainage system, urban stormwater management, community participation, stakeholders perception, Barcelona	Mixed methods	Barcelona, Spain	10	Government, technicians, social organizations, and local community citizens
Coleman et al.	2018	Residential stormwater management, environmental behavior adoption, norms, social-ecological system, infiltration trenches, rain gardens	Survey	Vermont	577	Residents
de Graaf-can Dinther et al.	2021	SUDS, sponge city, permeable pavement, tranformative infrastructure, stormwater infilitration resilience, urban water, market receptivity	Focus groups, survey	The Netherlands	34	Practitioners
Descher and Sinasac	2020	climate change, green infrastructure, stormwater, social-psychology, theory of planned behavior, urban	Survey	Hamilton, Ontario, Canada	88	Residents
Duan et al.	2018	Perception, UGI, environmental risks, human well-being, questionnaire survey	Survey	Guangzhou, China	396	Laypeople
Everett et al.	2018	flood mitigation, public engagement, sustainable drainage systems, water quality	Interviews	Portland, Oregon	45	Residents
Gao et al.	2018	urban runoff, water quality, rain barrel, rain garden, longitudinal environmental awareness	survey	Tippecanoe County, Indiana	850- 1000	Residents
Gavrilidis et al.	2020	green management, urban planning, urban actors	Survey	Romania	300	Citizens, public authorities, and economic agents
Hagen et al.	2017	ecosystem services, green infrastructure, socioeconomic impacts, alternative wastewater treatment, contingent valuation	Mixed methods	Phoenix, Arizona	331	Residential households
Hasala, Supak, and Rivers	2020	green infrastructure, participatory mapping, minority communities, urban planning, flooding, locally undesirable land uses (LULUs)	Survey, participatory mappin	Raleigh, North Carolina	95	Residents
Karanikola et al.	2016	Greece, well-being, green infrastructure, opinions and perceptions, urban park	Interviews	Kalamaria, Greece	385	Residents
Kim, Kim, and Demarie	2017	low impact development (LID), stormwater management, best management practices, survey, urban development	Survey	Houston, Texas	91	Practitioners
Kuper	2009	N/A	Survey	Amber, Pennsylvania	100	University Students
Larson, Caldwell, and Cloninger	2014	N/A	Survey	Howard County, Maryland	110	Residents
Mason, Ellis, and Hathaway	2019	Urban, climate change, flooding, green infrastructure, income	Survey	Knoxville, Tennessee	234	Residents
Miller and Monalto	2019	N/A	Survey	New York City, New York	105	Practitioners and residents
Montalto et al.	2013	Green infrastructure, urban sustainability, stormwater, participatory modeling, agent-based modeling	Agent-based modeling	Philadelphia, Pennsylvania	10363	Single family residential tax lots
Sañudo-Fontaneda and Robina-Ramírez	2019	Amenity, community resilience, food and water systems, green stormwater infrastructure, self- organisation, water sensitive urban design	Survey	Cáceres, Spain	276	Residential Households
Shandas	2015	CHANS, stewardship, stormwater management, urban	Survey	Portland, Oregon	650	Residents
Suppakittpaisarn, Larsen, and Sullivan	2019	bioretention, factor analysis, landscape preference, stormwater management	Survey, photo-questionnaire	US and International	614	Laypeople and design professionals
Tsantopoulos	2018	green roofs, public attitudes, urbanization, urban ecology, urban green	Survey	Athens, Greece	800	Apartment owners
Turner, Jarden, and Jefferson	2016	Stormwater Management, Residential Landscapes, Urban Ecology, Planning, Environmental Management	, interview, local government	Parma, Ohio	36	Residents
Ureta et al.	2021	Green infrastructure, stormwater management, adoption behavior, perception, generalized ordered logit model	Survey	South Carolina	1031	Residents
Williams et al.	2019	N/A	Survey	England	406	Residents

APPENDIX B

SURVEY

This questionnaire is performed by the Texas A&M AgriLife Dallas Center for a study about the role and importance of green stormwater infrastructure in urban environments, specifically in park spaces, in the Five Mile Creek community in South Oak Cliff. The questionnaire is about green space in your work, home, and/or school environments. The questions also inquire about your experience with flooding and water quality. Completing this survey serves in furthering our understanding of green stormwater infrastructure as well as this community's needs. Your responses will also be collected for the master's thesis research for Mikela Pryor, a graduate student in biological and agricultural engineering at Texas A&M University in College Station.

When it rains, a lot of water needs to be directed away from streets. This happens mostly via stormwater drains, and a small share soaks into the soil. Creeks and rivers also store water. Still, a heavy rain event may lead to local flooding: streets can become flooded and sometimes the water even enters people's homes. This happened recently occurred in July. Flooding causes financial damage and may lead to sewage overflow which poses a serious risk to public health. Green stormwater infrastructure serves as a solution to flooding and water quality. It can replace traditional stormwater infrastructure through vegetated depressions to store the water and hold it slowly, allowing the water to soak into the soil.

Do you observe any flood prone areas in this neighborhood?

○ Yes

○ No

○ I do not know

A rain garden is a depressed area that collects water. How important is it to you that environments such as this rain garden be used in your neighborhood?

	Not Important	Important	Very Important

	0	1	2	4	5	6	7
Water Quality:							
Rainwater retention:							
Visual attractiveness:							
Recreation							

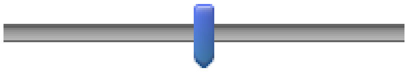
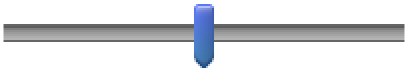
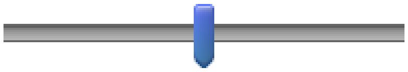
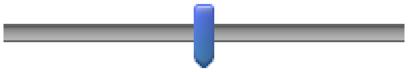
Is it important to you to see more rain gardens in your community?

○ Yes

○ No

○ I do not know

Bioswales are vegetated channels that direct stormwater. How important is it to you that environments such as this bioswale be present in your neighborhood?

	Not important Important Very important
	0 1 2 4 5 6 7
Water Quality:	
Rainwater retention:	
Visual attractiveness	
Recreation:	

Is it important to you to see more bioswales in your community?

○ Yes

○ No

○ I do not know

Rainwater harvesting collects and stores water from downspouts for later use. How important is it to you that technologies such as rainwater harvesting be used in your neighborhood?

Not important Important Very important

0 1 2 4 5 6 7

Water Quality	
Rainwater retention	
Visual attractiveness	
Recreation	

Is it important to you to see more rainwater harvesting in your community?

○ Yes

○ No

○ I do not know

Bioretention cells store and treat stormwater runoff. How important is it to you that environments such as bio-retention cells be used in your neighborhood?

	Not important Important Very important 0 1 2 4 5 6 7
Water Quality	
Rainwater retention	
Visual attractiveness	
Recreation	

Is it important to you to see more bio-retention cells in your community?

○ Yes

○ No

○ I do not know

Green roofs are covered in vegetation and prevent stormwater from entering gutters and streets. How important is it to you that environments such green roofs be used in your neighborhood?

Not important Important Very important

0 1 2 4 5 6 7

Water Quality	
Rainwater retention	
Visual attractiveness	
Recreation	

Is it important to you to see more green roofs in your community?

○ Yes

○ No

○ I do not know

Permeable pavement allows stormwater to pass through instead of remaining on the surface. How important is it to you that practices such as permeable pavement be used in your neighborhood?

Not important	Important	Very important

	0 1 2 4 5 6 7
Water Quality	
Rainwater retention	
Visual attractiveness	
Recreation	

Is it important to you to see more permeable pavement in your community?

○ Yes

○ No

○ I do not know

Do you personally experience any problems with flooding?

○ Yes

○ No

○ I do not know

If yes, how are you impacted by flooding?

____

Do you personally experience any issues with stream water quality at Alice Branch Creek?

○ Yes

○ No

○ I do not know

If yes, how are you impacted by water quality issues?

Climate change is expected to lead to more frequent and extreme rain events. There will be more flooding incidents that last longer, swamping basements and streets so that traffic is hindered and costs rise. Do you perceive this as problematic for this neighborhood?

○ Yes

○ No

○ I do not know

How often do you visit small parks in your neighborhood such as Deer Path Park?

○ Not at all

○ A few times a year

○ At least once a month

○ At least once a week

○ Daily

Why do you visit small parks in your neighborhood? Check all that apply.

☐ Recreation

☐ Physical Activity

☐ Visual Attractiveness

☐ Rest/Tranquility

☐ Socialization

☐ Events

☐ Other ____

How often do you visit large parks in your neighborhood (such as Lake Cliff Park)?

○ Not at all

○ A few times a year

○ At least once a month

○ At least once a week

○ Daily

Why do you visit large parks in your neighborhood? Check all that apply.

- ☐ Recreation
- ☐ Physical Activity
- ☐ Visual Attractiveness
- ☐ Rest/Tranquility
- ☐ Socialization
- ☐ Events
- ☐ Other ____

Please tell us about yourself.

Age

○ 18 -24 years old

○ 25 - 34 years old

○ 35 - 44 years old

○ 45- 54 years old

○ 55 - 64 years old

○ 65 + years old

Gender

○ Male

○ Female

○ Other

○ I prefer not to say

Ethnicity

- ☐ White
- ☐ Hispanic
- ☐ Black
- ☐ American Indian or Alaska Native
- ☐ Asian
- ☐ Native Hawaiian or Pacific Islander
- ☐ Other ____

How are you affiliated with the neighborhood? Check all that apply.

☐ I have lived in the neighborhood

☐ I have worked in the neighborhood

☐ I have attended school in the neighborhood

☐ Other ____

How many years have you been affiliated with the neighborhood?

○ Less than 3 years

○ 3 - 5 years

○ More than 5 years

Is there anything else you would like to tell us about stormwater control in your neighborhood?

____

Thank you for taking this survey with us. Would you like to be contacted for further questions?

○ Yes

○ No

If yes, please include your email below.

____

APPENDIX C

ECOSYSTEM SERVICE VALUATION TABLE

Responses to “How important is it to you that environments such as this [practice] be used in your neighborhood?”, showing minimum, maximum, and mean ranking, as well as variance and n values.

	Ecosystem Service																			
	Min	**Max**	**Mean**	**Variance**	**n**	**Min**	**Max**	**Mean**	**Variance**	**n**	**Min**	**Max**	**Mean**	**Variance**	**n**	**Min**	**Max**	**Mean**	**Variance**	**n**
Practice	Water Quality					Rainwater Retention					Visual Attractiveness					Recreation				
Rain Garden	0	7	5.76	2.8	29	2	7	5.9	1.9	29	2	7	5.7	1.9	29	1	7	4.4	3.2	29
Bioswales	2	7	5.66	2.02	29	2	7	5.7	2.1	29	0	7	5.3	3	29	0	7	3.5	4.5	28
Rainwater Harvesting	3	7	6	1.56	27	2	7	5.9	2.1	28	1	7	5.2	2.7	28	0	7	3.8	4.6	26
Bioretention Cells	3	7	5.69	2.08	29	2	7	5.8	2.3	29	1	7	5.5	3.2	29	0	7	3.6	4.8	27
Green Roofs	0	7	4.7	4.21	27	0	7	5.2	3.2	28	0	7	5	4	27	0	7	3.6	4.8	25
Permeable Pavement	0	7	5.41	3.72	27	2	7	5.5	3.1	27	1	7	5.2	3.5	27	0	7	3.5	5.8	24