ADVANCING GREEN STORMWATER INFRASTRUCTURE THROUGH UNDERSTANDING THE INFLUENCES OF SOCIAL FACTORS

by

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ABSTRACT

JINGYI QI. Advancing Green Stormwater Infrastructure Through Understanding the Influences of Social Factors.
(Under the direction of DR. NICOLE BARCLAY)

Green stormwater infrastructure (GSI) is a nature-inspired engineering solution to stormwater management that has gained increasing attention over the last two decades. While the technical evidence supporting the efficacy and efficiency of GSI is crucial, it alone does not necessarily translate to a significant increase in GSI adoption. Even with the recent research focus gradually turning toward the social benefits of GSI implementation, the social factors that influence its implementation remain underexplored. Furthermore, successful GSI adoption and implementation requires a collaborative effort in governance transitioning, public engagement, and adequate consideration of demographic constraints. Therefore, it is essential to understand the social barriers that hinder the adoption of GSI. This dissertation draws interdisciplinary linkages between social barriers and the cognitive biases that may affect rational decision-making for GSI adoption.

Mecklenburg County, the most population-dense county in North Carolina, is an ideal case study location to represent future scenarios for other urbanized areas across the United States. The case study, including an online survey and interviews with local officials, reveals patterns that resonate with the literature's findings that negative public opinions hinder long-term support for GSI. This study created a simulation model to streamline decision-making processes based on individual behaviors to explore long-term local GSI adoption patterns. The simulation model developed in this study shows that cognitive biases, such as loss aversion and status quo, could impede broader GSI adoption.

The contribution of this work is drawing attention from both academia and practitioners in terms of long-term planning for sustainable infrastructure development in residential areas where government incentives are limited. Furthermore, it facilitates improved data collection on residents' opinions of GSI over time, allowing the refinement and validation of the proposed simulation model to improve accuracy. Simultaneously, the survey can serve as a consistent means of public education and engagement, working

to bridge the knowledge gap. This dissertation lays the groundwork for identifying potential conflicting decision-making patterns related to eco-friendly behaviors, specifically focusing on small-scale GSI in residential properties. Such insights are crucial for securing resident financial support for stormwater management, thereby alleviating pressure on already stretched federal resources.

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DEDICATION

To my mom

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CHAPTER 1. INTRODUCTION

1.1 Background

As the world's population continues to grow, the progress of urbanization has been significantly accelerated. It results in land use changes, such as vegetation cover being replaced by impervious surfaces, and thus an increase in stormwater runoff volumes and peak flows (Barbosa, Fernandes, & David, 2012). With the aid of photogrammetric engineering, the trend of urban impervious coverage in the contiguous United States can be observed. Even though the increase rate has slowed down in the 2006-2011 period in contrast to the change in the previous five-year period, it is continuously climbing by approximately 0.1% per year. (Homer et al., 2015). This change could lead to more frequent street flooding events. Climate change-associated impacts can exacerbate the problem even further due to inefficient control of rainwater in urban areas. As supported by scientifically established data, the globally averaged combined land and ocean surface temperature, the globally averaged sea level change, and the globally averaged greenhouse gas concentrations have all drastically increased since the post-industrial era. The resulting impacts include ocean acidification, sea level rise, and increased frequency of extreme precipitation events (Allen et al., 2014). The data from Federal Emergency Management Agency (FEMA) reveals that there has been a noticeable increase in economic losses resulting from significant flooding events (FEMA, 2021). Their data shows that all states have been impacted by flooding between 1996 and 2016, where the southern and the eastern states were more vulnerable, as shown in **Figure 1.1** (FEMA, 2021).

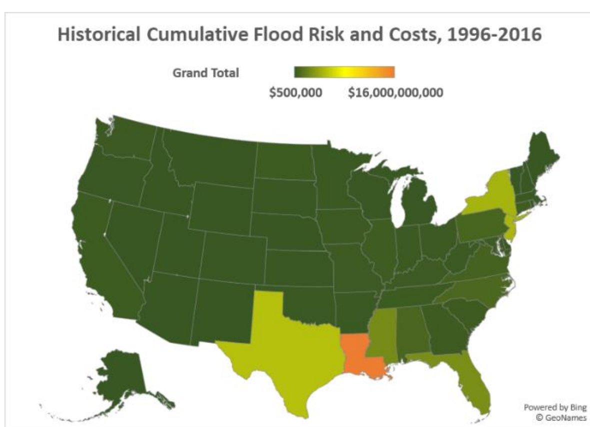

Figure 1.1 *Cumulative Flood Risk and Costs from 1996-2016: A State-by-State Analysis.*

Stormwater runoff discharges, which may include rainwater and snowmelt, usually flow into either separate stormwater drains or combined sewer pipes (Barbosa et al., 2012). When heavy precipitation occurs, the overflow that could not be captured by these pipelines disperses waste from its original sources, which can cause substantial environmental contaminations in the receiving waterbodies and the adjacent ecosystems (De Sousa, Montalto, & Spatari, 2012; Xu, Jia, Xu, Long, & Jia, 2019). Diminished natural infiltration of rainwater as the result of the wide use of impervious surfaces is the leading cause of excess stormwater runoff in urbanized areas, which in turn depletes groundwater storage. To mitigate the impacts induced by rapid urban expansion and climate change in the stormwater section, there is a need for improved urban stormwater infrastructure that can achieve triple-bottom-line goals simultaneously. Stormwater management is indispensable since excess runoff can negatively impact urbanized societies-environmentally, economically, and socially.

The National Pollutant Discharge Elimination System (NPDES) stormwater program was put into place for more than 30 years with the aim of monitoring and controlling pollutants in urban runoffs in addition to peak flow control. However, it failed to fulfill its expected goal because stormwater is neither a pollutant nor considered discharged from a point source. Furthermore, although private sources contribute significantly to the discharge, the NPDES does not have the authority to regulate the discharge of pollutants from these sources. (Dhakal & Chevalier, 2017; Malinowski, Wu, Pulugurtha, & Stillwell, 2018). On the other hand, traditional infrastructure such as combined sewerage systems, which collect both domestic sewage and wastewater, are facing increased challenges due to the elevated runoff flow rate caused by increased urban imperviousness. This can seriously harm the receiving water bodies downstream because the overflows of the combined sewer circumvent the treatment processes as they should be. Traditional urban stream management has an emphasis on water quantity management. But it often prioritizes less in-stream water quality and aquatic life quality in receiving streams. Retrofitting allows the restoration of water quality to also be the center of the management strategies, which therefore minimizes the damages to the environment due to extreme flooding events (Malinowski et al., 2018).

As a supplementary alternative, green stormwater infrastructure (GSI), has been proposed and applied in many urban areas in the form of decentralized natural processes that can mitigate stormwater runoff at its source in addition to providing socio-ecological benefits to the community and adaptable climate resilience (Benedict & McMahon, 2012). GSI manages stormwater runoff mainly through on-site infiltration and rainwater harvesting, which could be relatively more effective in water quantity reduction compared to the conventional approach, but the effects may vary noticeably depending on the types of GSI selected and the location it was at (**Figure 1.2**). According to the literature, GSI also requires less investment in capital and maintenance costs, in addition to reduced energy usage in wastewater treatment (Cherrier, Klein, Link, Pillich, & Yonzan, 2016).

A complete transformation of an urban region from being managed solely by traditional stormwater infrastructure to GSI demands a significant amount of effort, such as demolishing the outdated pipelines, meticulous urban planning for GSI to maximize GSI's performance, extensive labor on the construction of the GSI sites, etc., which could deter the willingness to switch.

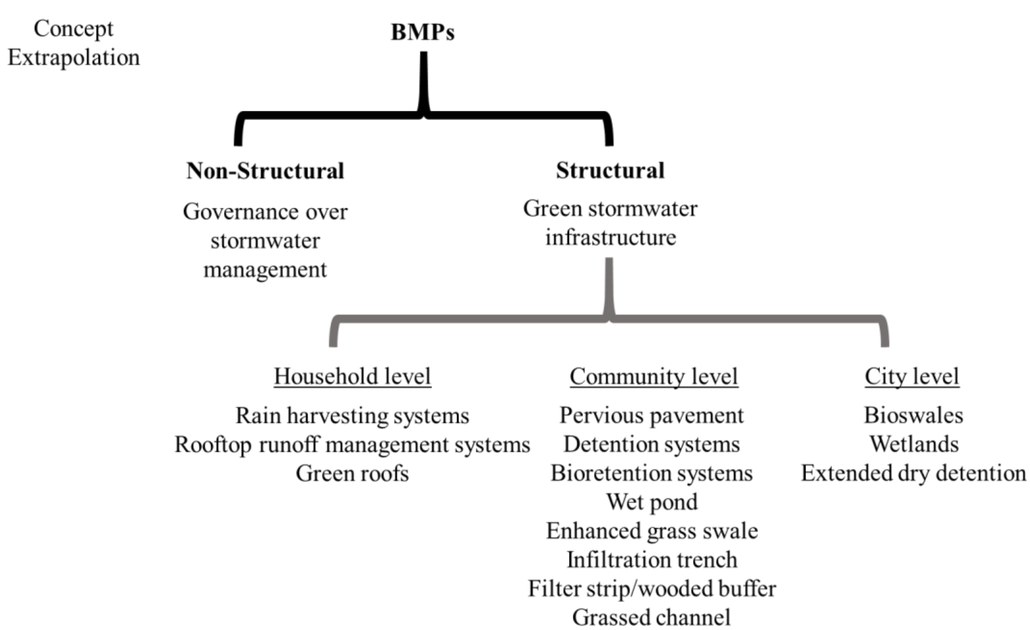

Figure 1.2 *Concept Extrapolation of the Definition of Green Infrastructure by EPA (USEPA, 2020, 2021).*

1.2 Challenges to Green Stormwater Infrastructure

Even though GSI has multi-sector benefits (such as an increase in city resilience to climate change, community life quality improvement, and improved stormwater management effectiveness), it is still facing various barriers to its implementation. One major barrier is difficulty in long-term funding sources (Gordon, Quesnel, Abs, & Ajami, 2018). Recently, great efforts have been made on infrastructure investment. For example, the State of North Carolina has approved more than $240 million in loans to improve water and wastewater infrastructure statewide as of 2018 (NCDEQ, 2018). However, GSI still needs to be proven as economically sustainable for long-term support on implementation practice and more funding to roll into this area. What primarily hinders the funding opportunities of GSI is the lack of sufficient historical performance data, the uncertainty in measuring the trade-off between the benefits and investment, and the scarcity in holistically evaluating GSI's multi-sector functionality (Dhakal & Chevalier, 2017). In addition, it is important to note that social performance is a critical factor in improving opportunities for multi-sector funding and encouraging the adoption of GSI (Carlet, 2015; Tayouga & Gagné, 2016). To secure additional financial support and expedite research on the collection of reliable data on GSI performance, it is necessary to address the problem of insufficient public awareness, particularly among key stakeholders, regarding the importance of GSI (Derkzen, van Teeffelen, & Verburg, 2017; Giacalone, Mobley, Sawyer, Witte, & Eidson, 2010).

Creating sustainable ecosystem services, such as those provided by GSI, will require a strong integration of the social-ecological systems through learning, participation, connectivity, system dynamics, system thinking, governance, and diversity and redundancy as suggested by Biggs et al. (2015). The adaptation of the principles shown in **Figure 1.3** is that any emerging focus, trend, or concept, such as resilience building, needs to begin with knowledge diffusion to facilitate learning and public engagement as a form of participation. This will lead to connections and collaborations among different sections, which will synergize systems thinking and accentuate the associated system dynamics. These changes could prompt governance guidelines and rules for participation to balance the need for diversity and redundancy.

The knowledge crystallized through this process will, in turn, reshape the approach to learning for populations which have not previously been involved in this entire cycle.

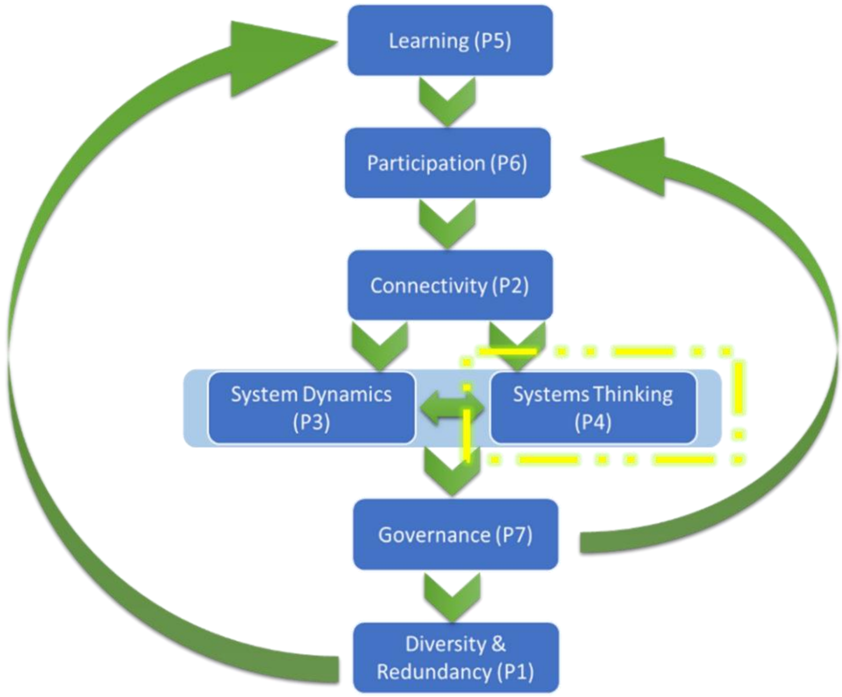

Figure 1.3 *Concept adaption for resilience building from Biggs et al., 2015.*

1.3 Multi-Sector Performance Assessment

Many modeling tools have been developed to simulate stormwater runoff quality and quantity since the 1970s, and recently the economic aspect has also been incorporated into the time simulation scope (Jayasooriya & Ng, 2014). On the contrary, some unquantifiable factors under the social performance sector of GSI are often not receiving due consideration. As one of the fundamental studies that address the involvement of social parameters in environmental development, Freeman's publication emphasized the importance of evaluating psychopathological effects that the environment can have on individuals. Thus, it is necessary to understand which parameters are valued by the communities and the major decision-makers. These parameters can be potentially used in assisting with the development of a universal standardized framework for an exhaustive GSI performance evaluation, applied to various GSI cases across various locations for different purposes in the U.S. Furthermore, even though residents' acceptance is necessary for increasing local implementation rates of GSI practice, principal decision-makers play a very key part in sustainable stormwater management as well (Carlson, Barreteau, Kirshen, & Foltz, 2014). Therefore, options from both parties need to be closely examined in order to build a comprehensive and adaptive GSI framework.

The performance in the environmental sector is to measure improvement in ecology and habitat, carbon reduction, air quality benefits, the importance of stormwater capture, etc. However, when predicting a model for a site with unavailable data, traffic flows, rainfall characteristics, antecedent dry periods, drainage area, and land use are the most significant variables to consider (Barbosa et al., 2012). This sector is often considered the key focus of the stormwater management side. SWMM has been widely used for stormwater runoff management (Wang et al., 2016).

The factors taken into account in the economic sector are cost reductions regarding changed stormwater management processes, boost in property values, reduction in energy consumption, reduction in operational costs, benefit-to-cost (B/C) ratio, and willingness to pay (Barbosa et al., 2012). The economic sector is usually a prior focus for investment parties.

The social impacts of GSI are yet well-understudied with most of the current evaluation methods. The attributes of interest are the urban heat island effect, increases in public engagement, increases in food production, improvement in the quality of life, access to better infrastructure, and increase in job opportunities, etc. They tend to fall short of a quantitative approach to the assessment of the increase in public participation in environmental issues (Gordon et al., 2018). In his paper, Freeman stated that there was a lack of clear evidence on the environmental influence on physical and emotional well-being. However, it could exert a detrimental influence on society if the psychological and physical health of its own citizens were not taken into consideration during city planning. (Freeman, 1978). Pickett et al. emphasized the involvement of spatial dimensions of social differentiation, and concepts and data on patch dynamics in ecology are necessary elements for a comprehensive understanding of urban ecosystems. This can be applied to GSI by the inclusion of social performance to have the capability to balance and/or maintain biological, social, and physical components of the urban systems (S. T. A. Pickett et al., 2001).

The publication by Brown (2015) was one of the early works that advocated the need for institutional urban stormwater management. They pointed out that it was the lack of structured governance that hindered the implementation of alternative sustainable stormwater management techniques and processes. Pearson et al. (2010) demonstrated that the incorporation of an effective social learning process in decisions would benefit practitioners in the sustainable decision-making process.

1.4 Research Objectives

GSI offers a unique set of benefits to urban ecosystems as a sustainable stormwater management strategy. Despite efforts to plan and evaluate GSI performance, social barriers may limit its widespread adoption. To address this issue, this dissertation examines some possible root causes of social barriers by focusing on the public perceptions of GSI in residential areas and how they may influence adoption behaviors. Specifically, the study aims to examine how cognitive biases could influence the residents' decision-making in stormwater infrastructure implementation, an area that has not been previously studied.

The literature suggests that increasing environmental knowledge and concern can promote environmentally friendly behaviors (Giacalone et al., 2010). Additionally, for effective adoption of sustainable stormwater management, it is vital to customize the message according to the specific needs of local communities. (Carlson et al., 2014; Derkzen et al., 2017). By exploring public perceptions and cognitive biases, this dissertation seeks to contribute to the knowledge base on GSI adoption and inform strategies for promoting its implementation.

1.5 Chapter Outlines

The first chapter serves as an introduction on the study subject and highlights the research gaps in the field. The dissertation is structured into three core chapters (Chapter 2-4), which are presented as individual papers. Every paper comprises a separate abstract, introduction, body, and conclusion. These chapters, as a whole, aim at exploring the social factors that are inhibiting GSI implementation in regions that are in elevated risk of flooding yet low in GSI usage. Chapter 2 (Article 1) focuses on the social hindrances to Green Stormwater Infrastructure (GSI) implementation in the US, including cognitive biases that impede rational decision-making. It underlines the importance of assessing the viewpoints of private landowners to develop successful intervention approaches that encourage GSI adoption. The article also reviews quantitative analysis for decision support in water management. Article 2 (Chapter 3) focuses on understanding public perceptions of GSI in residential areas and how they influence residents' adoption behaviors. It aims to bridge the gap between modeling and practical implementation and provide a better understanding of stakeholders' perspectives and concerns. Article 3 (Chapter 4) builds upon the previous work and develops a quantitative decision support tool that connects the social and technical aspects involved in GSI implementation in residential areas. The overall goal is to identify approaches to encourage long-term GSI adoption in highly urbanized areas. Chapter 5 synthesizes the findings from each article, discusses the overall applications and implications, and concludes with the recommendations for future works.

CHAPTER 2. SOCIAL BARRIERS AND THE HIATUS FROM SUCCESSFUL GREEN STORMWATER INFRASTRUCTURE IMPLEMENTATION ACROSS THE US[1]

2.1 Introduction

Urbanization can affect the hydrologic functions of urban watersheds and precipitation patterns (Blöschl et al., 2007; Brath, Montanari, & Moretti, 2006; Ntelekos, Oppenheimer, Smith, & Miller, 2010; Recanatesi & Petroselli, 2020; G. Wang, Liu, Kubota, & Chen, 2007). The consequential increased use of impervious surfaces results in substantial increments of stormwater runoff volume and peak flow (Barbosa, Fernandes, & David, 2012). Thus, the transition from the conventional approach into a more sustainable stormwater management paradigm which includes green stormwater infrastructure (GSI), is indispensable to reducing substantial environmental, economic, and social damage (Howard, Bowen, & Antoine, 2016; McIntyre et al., 2018; Tsihrintzis & Hamid, 1997). Hence, there is also a need to understand the hindrances and limitations of GSI implementation.

GSI offers a promising solution to stormwater management by mimicking natural hydrological processes to reduce localized flooding events and water quality improvement through decentralized natural or engineered processes to treat stormwater runoff at its source (Chini, Canning, Schreiber, Peschel, & Stillwell, 2017). In the US (United States), awareness of GSI has slowly increased over the past two decades. Its historical progress in stormwater management and background knowledge is documented in several in-depth publications (Chunhui Li et al., 2019; NRC, 2009; Roy et al., 2008; Walsh et al., 2016). Research teams across nations have developed various GSI practices and in addition, retrofits, and hybrid measures on different spatial scales (such as watershed scale and site scale, etc.) with diverse primary purposes have been developed (Cherrier, Klein, Link, Pillich, & Yonzan, 2016; Golden & Hoghooghi, 2018; Malinowski, Wu, Pulugurtha, & Stillwell, 2018; Erik Porse, 2013; Wise et al., 2010; Yang & Li,

[1] Reprinted from Journal of Hydrology, Vol 8(1), Jingyi Qi and Nicole Barclay, Social Barriers and the Hiatus from Successful Green Stormwater Infrastructure Implementation across the US, 10, Copyright (2021), with permission from the authors by the licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).

2013). The details of these practices are well documented in the literature (Berndtsson, 2010; Chui, Liu, & Zhan, 2016; Jennings, Adeel, Hopkins, Litofsky, & Wellstead, 2012; Keeley et al., 2013; Liu, Sample, Bell, & Guan, 2014a; Saraswat, Kumar, & Mishra, 2016; Tavakol-Davani et al., 2016; Vacek, Struhala, & Matějka, 2017).

Numerous studies have evaluated the performance of GSI, particularly in economic and technical aspects (Copeland, 2016; Eckart, McPhee, & Bolisetti, 2017; Congying Li, Fletcher, Duncan, & Burns, 2017; Chunhui Li et al., 2019; Zhang & Chui, 2018). GSI provides extra benefits to the community, such as raising property values, enriching life quality, and providing adaptable climate resilience (Gordon, Quesnel, Abs, & Ajami, 2018; Newell et al., 2013; Venkataramanan et al., 2019). Urban stormwater management has advanced gradually over the last two decades, thus various terminologies are used to define new principles and practices, where the concepts behind them often overlap (Fletcher et al., 2015; Chunhui Li et al., 2019). Using these different terms may reduce effective communication in certain circumstances, such as when documenting all the alternative stormwater practices used in the US to assess their performance in general (Fletcher et al., 2015). To avoid confusion, the term GSI was used throughout this work in referring to all types of multi-purpose structural stormwater management practices that involve natural processes for runoff volume and water quality control.

Despite the progress, there are limited study efforts on non-technical factors, such as public perceptions and knowledge, that could explain the slow advancement in the wide adaptation of GSI to the desired level for stormwater management and sustainability capacity building (Thornton & Laurin, 2005). The contradiction between the low implementation rate of GSI in major regions of the US and the actual demand to address climate change impacts suggests that certain factors are hindering the relevant decision-making processes (M. Hu & Shealy, 2020; Olorunkiya, Fassman, & Wilkinson, 2012). Furthermore, a study discovered a mismatch in the percentage of survey participants that expressed an intention to support GSI and the number of those who actually adopted GSI (Rasoulkhani, Logasa, Presa Reyes, & Mostafavi, 2018). This result agrees with the findings in an exhaustive review (Battaglio Jr, Belardinelli, Bellé, & Cantarelli, 2019). Irrational decision-making behaviors in energy-related decisions have been interpreted through the cognitive bias perspective (Klotz, 2011; Zhou, Chen, Xu, & Wu, 2018), where cognitive biases can be defined as a belief that hampers one's ability to make rational decisions given the facts and evidence (Acciarini, Brunetta, & Boccardelli, 2020). It has been supported by various studies that cognitive biases are influential in decision-making and planning (Acciarini et al., 2020). Yet, little attention has been given to the potential influence of cognitive biases in GSI implementation, despite numerous studies on the perceptions of various GSI stakeholder groups (Barnhill & Smardon, 2012; Miller & Montalto, 2019; O'Donnell, Maskrey, Everett, & Lamond, 2020). This study aims to bridge this knowledge gap.

Historically, quantitative decision support tools have been developed with the main aim to maximize GSI performance to control runoff and water pollution and to be cost-effective (Carrera, Standardi, Bosello, & Mysiak, 2015; Huizinga, De Moel, & Szewczyk, 2017; Pellicani, Parisi, Iemmolo, & Apollonio, 2018; Van Oijstaeijen, Van Passel, & Cools, 2020; Wu, Song, Wang, & Friedler, 2020). On the other hand, despite the extensive attempts made to expand the assessment work to include the social aspect of decision support (Barclay & Klotz, 2019; Brian C Chaffin et al., 2016; Feingold, Koop, & van Leeuwen, 2018; Flynn & Davidson, 2016; Hale et al., 2015; Hart et al., 2015; Heckert & Rosan, 2016; Lieberherr & Green, 2018; Erik Porse, 2013; Schirmer & Dyer, 2018; Shandas, 2015; William, Garg, & Stillwell, 2017; Wu et al., 2020; Young, Zanders, Lieberknecht, & Fassman-Beck, 2014), they lack a deeper understanding of the public perceptions and associated cognitive bias perspective to resolve the implementation dilemma from a bottom-up approach (Baptiste, Foley, & Smardon, 2015) as examined in other environmental issues (Acciarini et al., 2020; Zhou et al., 2018). This shortcoming can affect the expected outcomes envisioned by major decision-makers (Das & Teng, 1999; Klotz, 2011). This study focuses on the barriers that could be linked to biased perceptions due to social factors in GSI development and implementation.

This work was conducted to examine the relevant social factors through the lens of cognitive biases, which may lead to implementation barriers during GSI adoption processes. The scope of social factors can vary significantly as they are commonly assessed in combination with factors from other dimensions, such as socio-ecological, social-cultural, socio-economic, and socio-technical factors (Chini et al., 2017; Kati & Jari, 2016; Staddon et al., 2018; Tayouga & Gagné, 2016; Turner, Jarden, & Jefferson, 2016). We use a concept adapted from Gifford and Nilsson (2014) to define social factors as the internal differences among people and the contextual factors that define them in this study. This study aims to understand the potential connections of cognitive biases with these barriers, and to recommend an approach to analyze and address the associated problems. Studies have been conducted to analyze cognitive biases with agent-based modeling (ABM) in various contexts (Chen & Gostoli, 2014; Sobkowicz, 2018; Xu, Liu, & Liu, 2014). However, no study has done a similar analysis in the context of GSI implementation. ABM is a methodology that can incorporate the autonomy, heterogeneity, and adaptability of individuals in a social system to study the resulting global patterns through a bottom-up approach (Bruch & Atwell, 2015; J. Gray, Hilton, & Bijak, 2017). It is also an approach that can carry exploratory simulations for a deeper understanding of the underlying adaptive behaviors and interactions that could lead to the emergence of phenomena that were previously overlooked (Rasoulkhani et al., 2018). However, the models developed solely based on social and physical science are usually fragmented in their fields, rely on qualitative analysis, or are difficult to incorporate into quantitative models (Bharathy, 2006). This work was conducted to answer the following questions:

1. What social factors have been identified as barriers to GSI implementation?
2. How do these social factors connect to cognitive biases?
3. How can ABM accommodate these cognitive biases for better quantitative decision support?

To address these research questions, we reviewed the literature on GSI implementation barriers that arise from social aspects and on the connections between cognitive bias with these barriers. Subsequently, we reviewed the literature to show and assess the applicability of ABM in addressing the issue of social factors' hindrances to GSI adoption and implementation.

2.2 Materials and Methods

A literature review was conducted on two main topics in this study using a combination of platforms, including the literature search engine Web of Science (WoS) and relevant referenced articles in the papers collected through the means mentioned above. Firstly, studies that were conducted to understand the restraints to wider/efficient/effective GSI adoption were examined. Reported barriers to GSI implementation that may link to social factors in the literature were identified using the search terms: 'social', 'barrier* OR challenge* OR difficult*', 'stormwater OR storm water', and 'infrastructure' as the primary screening criteria. Only peer-reviewed papers written in English published between 1900 to 2020 were considered. Seven records were first excluded before the screening due to a lack of access to the full text. Four book chapters and 20 articles that were not directly relevant to the social barriers in GSI were eliminated. Finally, the social context that could contribute to barriers that are dependent on local government regulations and governance practices (Meerow, 2020; Wu, Song, Wang, & Friedler, 2020; Young, Zanders, Lieberknecht, & Fassman-Beck, 2014) and socio-ecological context (Coleman, Hurley, Rizzo, Koliba, & Zia, 2018; Young et al., 2014), the records that did not explicitly study the social barriers in the US were excluded from the final results. As a result, the search within the scope of this study yielded 34 papers in total (**Figure 2.1**). The final results are further divided into three groups, where one (20) is the collection of empirical-based studies that examined the barriers, and another (14) is the collection of studies that developed qualitative frameworks to incorporate social factors to reduce such barriers as decision support tools (the works focused solely on qualitative post-construction performance evaluations were excluded). Note that analytical simulation-based works found through this search were rearranged to the second part of the review. These barriers were reviewed through the concepts of cognitive biases proposed by Haselton, Nettle, and Murray (2015a): Biases resulted from heuristics, artifacts, and error management.

In their article, Bukszar Jr (1999) provided strong evidence that failing to address cognitive biases among decision-makers can cause strategic heuristics and biases, thus hampering the strategy's adaptability. They argued for the need for a higher capability to accommodate such cognitive biases for greater strategic success. Thus, the second part of this review was conducted using the same search platforms of records written in English and published between 1900 and 2020 to evaluate the potential applicability of ABM in addressing the issues studied in the first review topic. Due to the limited studies conducted within stormwater management, research that analyzed innovation diffusion in water infrastructure, in general, was also considered in this review. Thus, a total of 10 results were finalized (**Figure 2.2**). The key search terms used were 'agent based OR agent-based', 'infrastructure', 'perception* OR cogniti*', 'model*', and 'water'. This yielded 6 outcomes with 11 additional articles from external references. Additionally, the Institute of Electrical and Electronics Engineers (IEEE) was employed due to its particular research focus on computational simulations using a combination of key search terms of 'water', 'infrastructure', 'percept*', 'cogniti*', and 'agent-based'. It yielded 34 additional results. One record was eliminated from the WoS results because it was a conference proceeding. A total of 38 additional studies were excluded after abstract screening because they were not directly relevant to the interpretation of cognitive biases or perceptions of innovative water management strategies simulated through ABM. It was noted that all search outcomes from IEEE were not within the scope of the search objectives for this review.

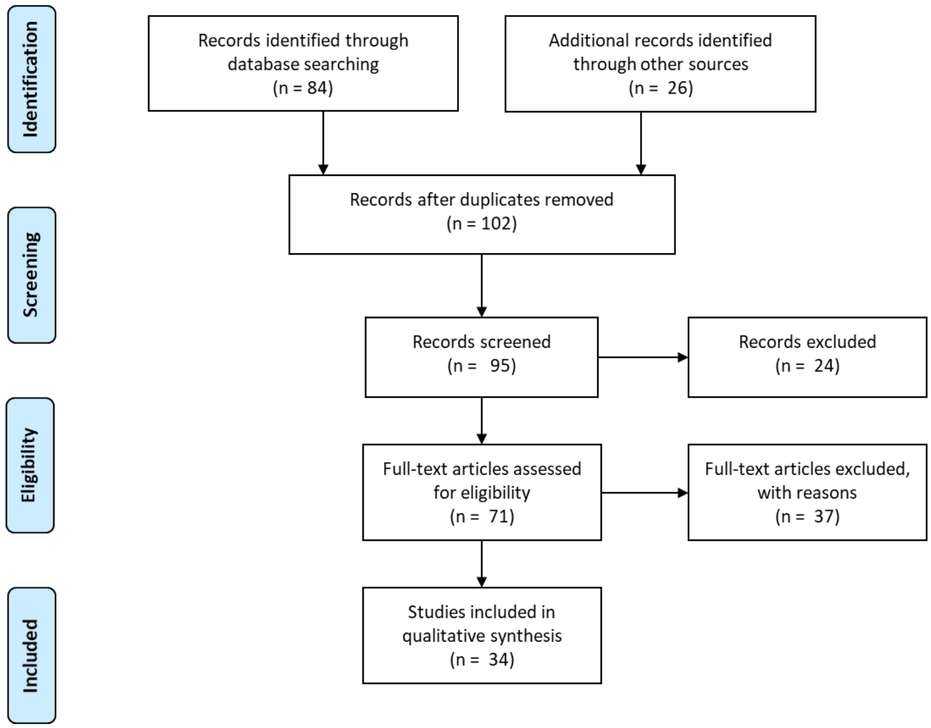

Figure 2.1 *Flow diagram of the search results of the first topic following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol (Moher, Liberati, Tetzlaff, Altman, & Group, 2009).*

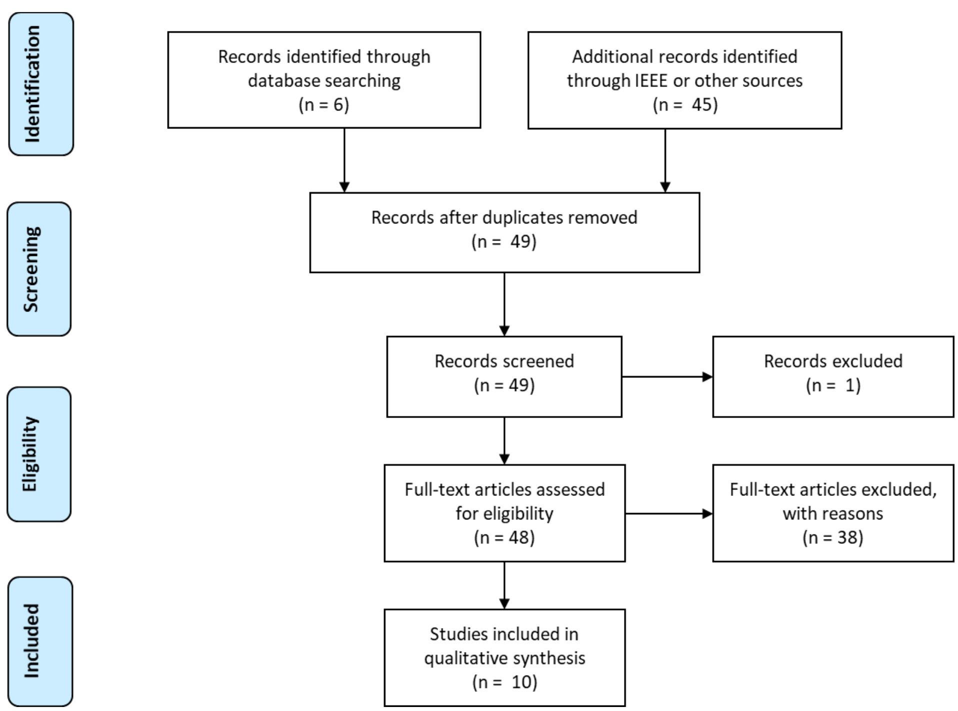

Figure 2.2 *Flow diagram of the search results of the second topic following the PRISMA protocol (Moher, Liberati, Tetzlaff, Altman, & Group, 2009).*

2.3 Results and Discussion

2.3.1 Identified Social Barriers to GSI Implementation

The barriers to GSI have been studied by numerous international research teams, ranging from individual perceptions and attitudes, financial burdens, resource allocations, and governance rigidity to conflicts across institutions (Bain, Elliott, Thomas, Shelef, & River, 2019; Barnhill & Smardon, 2012; Coleman et al., 2018; K. P. Dhakal & L. R. Chevalier, 2017; Qiao, Kristoffersson, & Randrup, 2018; Turner et al., 2016; Winz, Brierley, & Trowsdale, 2011). Barriers originating from social factors may be harder to address, as the values of which are usually difficult to quantify yet should not be overlooked (Baptiste, Foley, & Smardon, 2015; Hale et al., 2015; Shandas, 2015). Barriers primarily identified as associated with social factors, in terms of their potential influence on the implementation of GSI, are attributed to three main categories from the literature. They mostly cover governance discord, public participation, and demographic constraints (**Table 2.1**). Governance refers to the inconsistent strategies among or within governance entities; public participation refers to the involvement of the public in the decision-making of GSI regulations and collaborations; and demographic constraints refer to the general demographic factors, social norms, and perceived environmental concerns. However, there always is a possibility of unrecognized social factors in the published studies. For example, though not directly addressing the issues in stormwater management adaptation, a study brought forth the dilemma of regenerating historical cities of which preserving the historical cores was paramount (Chahardowli, Sajadzadeh, Aram, & Mosavi, 2020). It is thinkable that advancing GSI in such areas may encompass greater complexities than others. Additionally, the underlying interrelations across infrastructure sectors and even industries are also likely to influence sustainable decision-making in general (Laspidou, Mellios, Spyropoulou, Kofinas, & Papadopoulou, 2020; Nosratabadi et al., 2019).

Table 2.1 *Relevant social factors that could influence the implementation of GSI in the US.*

Social Barriers	Barrier Subcategories	GSI Types	Spatial Scales	Location	Stakeholder	Study Methods	Source
Demographic constraints & public engagement	Race, ownership status, relevant knowledge of GSI, knowledge dissemination platform	Rainwater harvesting, pervious paving, rain gardens, lawn depression	Sub-watershed	Two sub-watersheds in the Chesapeake Bay watershed	Private landowners	Knowledge, attitude, and practice questionnaire	(Maeda et al., 2018)
	Age, education, homeownership, prior experience of floods, lack of awareness, underuse of social capital	Rain barrels, rain gardens, and permeable pavement	Region	Knoxville, TN	Private landowners (households)	Survey	(Mason, Ellis, & Hathaway, 2019)
Governance	Limited focus on the multifactional of GSI to respond to local needs, lack of interdepartmental collaboration, and private-public partnership	Green alleys with various GSI features	Region	Various locations in the US	Government agencies, non-governmental organizations (NGOs), community groups	Narrative analysis	(Newell et al., 2013)

Social Barriers	Barrier Subcategories	GSI Types	Spatial Scales	Location	Stakeholder	Study Methods	Source
	Conflicting visions in hydro-social relations	GSI in general	Region	Chicago, IL, and Los Angeles, CA	Government entities, NGOs	Interviews, participant observation, literature review, survey	(Cousins, 2017a)
	Leadership in transitioning governance (informal, multiorganizational)	GSI in general	Region	Ohio	Community NGOs, environmental NGOs/land trust, the federal government, local government/regional authority, university /contractor	Social network analysis survey	(B. C. Chaffin, Floyd, & Albro, 2019)
	Departmental silos (stakeholders' multiple and competing social perspectives)	GSI in general	Region	Chicago, IL	NGOs, governmental entities	Q-methodology	(Cousins, 2017b)
	Tensions and convergences among different management strategies	GSI in general	Region	Pittsburgh, PA	Community organizations, municipalities, advocacy groups	Interviews, participant observation	(Finewood, 2016)

Social Barriers	Barrier Subcategories	GSI Types	Spatial Scales	Location	Stakeholder	Study Methods	Source
	Conflicting perceptions, implementation priority, and limited focus on multifunctionality during the planning	GSI in general	Region	New York, NY	Agencies, city departments, national and local nonprofits, research institutions	Spatial analyses, surveys, interviews, participant observation	(Meerow, 2020)
	Inequity for disadvantaged communities	GSI in general	Sub-watershed	Los Angeles, CA	Government agencies, non-profits, community organizations, and others	Statistical analyses	(E. Porse, 2018)
Public engagement	Failing to recognize the values of social capital for long-term productivity	Rain gardens, rain barrels	Household site	Cincinnati, OH	Landowners	Experimental reverse auction	(Green, Shuster, Rhea, Garmestani, & Thurston, 2012)
	Perception (status quo bias)	Rain gardens, bio-swales, green alleys with permeable pavement	Region	Cincinnati, OH, and Seattle, WA	Engineering graduate students	Functional near-infrared spectroscopy	(Green et al., 2012; M. Hu & Shealy, 2020)

Social Barriers	Barrier Subcategories	GSI Types	Spatial Scales	Location	Stakeholder	Study Methods	Source
	Ineffective information dissemination, underuse of social capital	Rain barrels, rain gardens, permeable pavement	Region	Washington DC	Homeowners	Voluntary stormwater retrofit program with statistical analyses	(Lim, 2018)
	Stormwater context (perception of neighborhood-level challenges, town-level stormwater regulation)	Rainwater harvesting, rain gardens, permeable pavers, infiltration trenches, and tree box filters	Cross-scale	Vermont	Residents	Statewide survey	(Coleman et al., 2018)
	Depreciation of community involvement (expertise, education)	GSI in general	Region	Houston, TX	Researchers, community	Participatory action research	(Meyer et al., 2018)
Governance & public engagement	Lack of awareness and responsibility for maintenance, education programs not aligned with local preferences	Stormwater ponds	Community	Southwest Florida	Homeowners, governmental entities	Survey, interviews	(Monaghan et al., 2016)

Social Barriers	Barrier Subcategories	GSI Types	Spatial Scales	Location	Stakeholder	Study Methods	Source
	Lack of awareness, ineffective regulation enforcement	Stormwater ponds	Region	Manatee County, FL	Landscape professionals, residents, government agents	Interviews, surveys, participant observation, and literature review	(Persaud et al., 2016)
	Lack of awareness, understanding, and sense of responsibility; geographic disconnection between watersheds and governing entities; fragmentation of responsibility among stakeholder groups	GSI in general	Region	Cleveland, OH, and Milwaukee, WI	Practitioners (regional sewer districts, local governments, community development organizations)	Interviews	(Keeley et al., 2013)
	Lack of awareness and adaptivity in policies to prioritize GSI measures to align with local values	Bioswales, green roofs, street trees, parks & natural areas, community gardens, and permeable playgrounds	Region	New York, NY	Residents and practitioners (individuals professionally engaged in the siting, design, maintenance, public engagement, and/or monitoring of GSI programs)	Preference assessment survey and semi-structured interviews	(Miller & Montalto, 2019)

Social Barriers	Barrier Subcategories	GSI Types	Spatial Scales	Location	Stakeholder	Study Methods	Source
	Outdated regulatory constructs, conflicted views among gray and green advocates, jurisdictional overlap, influences of social media coverage, leadership gaps, or influence of lobbying	GSI in general	\	USA	Residents, governmental entities, engineers	Narrative analysis	(W. D. Shuster & Garmestani, 2015)

The unclear distribution of responsibilities among stakeholders can impede the decision-making processes associated with GSI implementation. Particularly, the general public's involvement is the fundamental building block that could be influential in shaping the direction of GSI implementation (Keeley et al., 2013; O'Donnell, Maskrey, Everett, & Lamond, 2020; Porse, 2013). K. P. Dhakal and L. R. Chevalier (2017) stated in their study that, above all challenges, cognitive barriers and socio-institutional factors should be the primary issue to focus on. Furthermore, the multi-sector benefits will only be nuanced if the public is not willing to implement GSI (Baptiste, 2014). Similarly, one study stated that sustainable GSI implementation would necessitate the need for structured public participation and local partnerships. They emphasized that, in addition to putting more reach effort onto comprehensive cost-benefit evaluations on GSI, such needed engagement would foster the networks of non-governmental organizations, county and state agencies, municipal sewer districts, and federal research support, which could lead to a faster adaptation of GSI on larger scales (William D Shuster, Morrison, & Webb, 2008). Therefore, the barriers to the general public accepting GSI are crucial to dissect these aforementioned disconnections and providing practical yet effective decision support. To date, there are a limited number of conceptual frameworks that capture social factors in GSI implementation processes (**Table 2.2**). Yet there still is a need for quantitative analysis measures for better decision support for case based GSI adoption using standardized methods that could assist in horizontal comparison and further knowledge transfer. The frameworks listed in **Table 2.2** were categorized based on their main purpose: Classification scheme (proposed to enhance terminology clarity), planning strategy (suggesting new approaches to be adopted in current management regimes), process conceptualization (promoting a better understanding of complex socio-infrastructure systems), and framework efficacy assessment (evaluating the existing frameworks' usefulness in promoting GSI implementation).

Table 2.2 *Conceptual frameworks that consider social factors in GSI implementation processes.*

Framework Nature	Social Factors	Sub-Categories	Stakeholders	Method	Scale	Source
Classification Scheme	Governance, stakeholder engagement	Stakeholder interactions, governance, political contexts	Individuals and groups involved in rule-making processes, property owners	Social-ecological services framework	Cross-scale	(Flynn & Davidson, 2016)
	Public engagement, governance	Policy instrument assessment	Citizens	Policy instrumentations scheme	Region	(Lieberherr & Green, 2018)
	Public engagement, governance	Ownership status, political power	Governmental entities	Topology framework	Region	(Young, Zanders, Lieberknecht, & Fassman-Beck, 2014)
Planning Strategy	Governance, demographic constraints	Equitable GSI distribution, age, income, education, ownership status	Governmental entities, residents	Green infrastructure equity index	Region	(Heckert & Rosan, 2016)
	Public engagement, governance	Multifunctional strategy, multisectoral communication	All involved in decision-making processes	Millennium ecosystem assessment classification-based framework	Cross-scale	(Hoover & Hopton, 2019)

Framework Nature	Social Factors	Sub-Categories	Stakeholders	Method	Scale	Source
	Governance, public engagement, demographic restraints	Adaptive governance, stakeholder participation, inclusion	Governance, non-governmental organizations, communities, academia, industry	Adaptive socio-hydrology framework	Cross-scale	(Schifman et al., 2017)
	Public engagement	Interdisciplinary collaboration, university-stakeholder partnership, institutional capacity	Universities	An integrated framework combining social-ecological dynamics, knowledge-to-action processes, organizational innovation	Region	(Hart et al., 2015)
Process Conceptualization	Public engagement	Community participation in three themes (context, participation processes and outputs, and implementation results)	City, federal government agencies, community residents, and community NGOs	Public participation conceptual model	Watershed	(Barclay & Klotz, 2019)
	Public engagement, governance	Low stakeholder buy-in, discoordination in management objectives and goals among stakeholders, lack of awareness	Government researchers, stormwater managers, and community organizers	Adaptive management framework	Site	(Chaffin et al., 2016)
	Governance, public engagement, demographic restraints	Stakeholder interactions, governance, and political contexts	All that is involved in stormwater management	Integrated structure-actor-water framework	Cross-scale	(Hale et al., 2015)

Framework Nature	Social Factors	Sub-Categories	Stakeholders	Method	Scale	Source
	Public engagement, governance	Hybrid governance envisioning (management and monetary responsibilities)	Regulatory agencies, residents	Multi-criteria governance framework	Cross-scale	(Porse, 2013)
	Public engagement, governance	Perceptions, stewardship, human-environment interactions	Residents	Coupled human and natural systems framework	Region	(Shandas, 2015)
Existing Framework Efficacy Assessment	Governance	Governance, capacity, urbanization rate, the burden of disease, education rate, political instability	Government agencies, NGOs	City Blueprint® Approach	Region	(Feingold, Koop, & van Leeuwen, 2018)
	Public engagement, governance	Community education and awareness campaign, multifunctional strategy	Residents, governmental entities	Socio-ecological framework	Watershed	(Hager et al., 2013)

2.3.2 Interpretations through Cognitive Biases

Kahneman and Tversky (1996) pointed out that human decision-making can be subjected to cognitive biases (or cognitive illusions), especially when under uncertainty, which infers that an erroneous judgment may be formed subjectively (as judgmental heuristics). It is particularly profound when forming judgments based on certainty and probability under uncertainty (Tversky & Kahneman, 2015). Over the past several decades, research efforts have been made to study cognitive biases and how they can influence decision-making (Acciarini, Brunetta, & Boccardelli, 2021; Barnes Jr, 1984; Battaglio Jr, Belardinelli, Bellé, & Cantarelli, 2019; Das & Teng, 1999; Glynn, Voinov, Shapiro, & White, 2017). A deeper understanding of cognitive biases can assist in effective debiasing and re-biasing measures for better decision-making (Bhandari & Hassanein, 2012; Cantarelli, Bellé, & Belardinelli, 2020; Morewedge et al., 2015). Cognitive biases have been studied extensively in the sociological and psychological fields, yet these intellectual outputs have rarely been considered in other research domains (Cantarelli et al., 2020), such as in the stormwater management sector. In the context of governance strategy primarily for managing complex systems, such as natural resources, hazards, and the environment, one review study pointed out that there was a need to enhance participatory processes connecting scientists with stakeholders and policy-makers to propel successful governance and policy enforcement, in which biases, beliefs, heuristics, and values were the critical influencing factors (Glynn, Voinov, Shapiro, & White, 2017). The authors believe that despite being intrinsic to a certain extent (Barnes Jr, 1984), cognitive biases are shaped by surrounding contextual factors, such as social factors. Hence, this work is an early attempt to connect these two pieces in the context of GSI implementation with an envision of advancing quantitative insights on the slow progress in GSI adoption in the majority of the US territories. Only a limited number of studies have explored the social factors involved in the decision-making process of stakeholders at various levels in the context of stormwater management, and they tend to be based on simplified concepts to interpret the information transfer tarnished by cognitive biases (Kandiah, Berglund, & Binder, 2019; Rasoulkhani, Logasa, Presa Reyes, & Mostafavi, 2018).

Historically, there has been an ongoing debate on the definition and categorization of cognitive biases across different scientific domains. Furthermore, according to Caverni, Fabre, and Gonzalez (1990), *cognitive bias* is an evolving topic. Consequently, this review adopts the theory formulated by Haselton, et al. (2015b), given its widespread scholarly acceptance, its appropriateness for interpreting social factor-related barriers to GSI implementation, and its publication date. Through a literature search of the social barriers mentioned in the literature, three are salient in the context of stormwater management that may be associated with cognitive biases (**Table 2.1**). However, the authors acknowledge the limitation on the selection of the theory due to its novelty in the context of GSI adoption, particularly the three biases chosen in this review. Furthermore, interdisciplinary discussions are encouraged to strengthen research efforts on this topic for practical decision support.

2.3.2.1 Uncoordinated Regulations and Governance—Biases Resulted from Heuristics

People tend to rely on rules of thumb to simplify problems at hand that may deviate from the optimum range of decisions, which can be considered heuristics (Haselton et al., 2015b). The commonly studied bias based on heuristics is the status quo bias which can be seen in regulation adaptation progresses. The status quo bias first received a greater level of scientific attention through the work of Fernandez and Rodrik (1991), which can be used to explain the resistance to change within a group of people where the beneficiaries of the status quo have a stronger influence than the other group, which they referred to as the non-neutrality. This can be considered a bias due to human insensitivity to make predictions under the influence of representative heuristics where people predict future events based on intuition under uncertainty (Samuelson & Zeckhauser, 1988; Tversky & Kahneman, 1974). Hu and Shealy (2020) conducted a study to illustrate how setting up GSI resolutions can overcome the status quo bias which limits its adoption. They demonstrated that simple public engagement strategies using factual endorsement in a municipal resolution by regulatory organizations could favor GSI over conventional practices.

Status quo bias can also be observed among the key professionals whose preferences may largely set the direction of the reform. One study identified five typical types of decision-making patterns of students in civil engineering, which include risky, social, conflicted, purchasing, and influenced by built-environment decision-making (Hu & Shealy, 2019). By carefully examining these thinking patterns, it could contribute to overcoming potential cognitive biases among stormwater engineers. On the other hand, biases might be amplified if the role of the GSI-related implementation processes is heavily played by one stakeholder group, such as the contractor company, which takes the responsibility from the design to the construction phase. This might limit their scope, such as potential risks or alternatives. Rather, they could distribute the workload to a third-party design company, allowing further discussions on the optimal plan. A study found that professionals who had hands-on experience favored GSI (Olorunkiya, Fassman, & Wilkinson, 2012).

The general situation of stormwater management in the US has been depicted as lacking clear guidance and regulation (K. P. Dhakal & L. R. Chevalier, 2017; Roy et al., 2008). Stormwater management was not brought into the National Pollutant Discharge Elimination System (NPDES) program until 1987 (NRC, 2009). Further challenges lie in the adaptation of drainage system management when facing climate change and anthropogenic stressors, which has propelled the use of GSI (Babovic, Mijic, & Madani, 2018). Attempts made through the established federal regulations often conflict with the existing rules set on state and local levels, which have more discretions on primary goals and responsibility distributions. This has resulted in the current dilemma that, even though private sources count for a greater percentage of the flow generation or have a higher potential in fortifying stormwater storage capacity, NPDES and municipalities cannot enforce regulations in these areas (Malinowski, Wu, Pulugurtha, & Stillwell, 2018; NRC, 2009). In summary, the major weaknesses and gaps in these regulation-related issues are poor coordination across institutions due to land use as private properties and not prioritizing the control and storage capacity of the discharge volume (NRC, 2009). Several other studies listed in **Table 2.1** have also observed such barriers.

2.3.2.2 Low Public Engagement and Inefficient Knowledge Transferring—Biases Resulted from Artifacts

Artifact biases intentionally form unrealistic conditions on which people make decisions, for instance, framing and anchoring biases (Haselton et al., 2015b). It could suggest that if the information was not translated into a language that is appropriate to a specific audience, the efficiency in the transfer of such knowledge could be reduced, even causing the generation of erroneous interpretations. The framing effect occurs when a person changes their decision based on how the information is presented (Gonzalez, Dana, Koshino, & Just, 2005). A study has demonstrated that the biases can be prevented in the early stage of education by using the sustainability-conscious teaching approach to assist in decision-making for sustainable infrastructure like GSI, such as by using the Envision rating system (McWhirter & Shealy, 2017). On the other hand, it may lead to an anchoring effect if the parameters used in said rating systems are not properly determined (Klotz, 2011), where a biased estimate toward the set of arbitrary values will be formed even though they are far from rational estimations (Strack & Mussweiler, 1997).

Even though it can bring forth multi-sector benefits, GSI implementation still faces a range of practical barriers, including the poorly perceived necessity of effective stormwater management (Carlson, Barreteau, Kirshen, & Foltz, 2014). In addition, miscommunication due to terminology confusion or ineffective knowledge transfer can also hinder the progression of GSI development to the optimum level (Fletcher et al., 2015; Ugolini, Massetti, Sanesi, & Pearlmutter, 2015). These miscommunications might link to the conservative mindset about gray infrastructure, loss aversion attitude toward the related cost and performance of GSI, confusion between GSI and the gray option, and fear of taking maintenance responsibility as identified in the literature (Barnhill & Smardon, 2012; Coleman, Hurley, Rizzo, Koliba, & Zia, 2018; K. P. Dhakal & L. R. Chevalier, 2017; Qiao, Kristoffersson, & Randrup, 2018; Winz, Brierley, & Trowsdale, 2011). It was also pointed out by the U.S. Environmental Protection Agency (US EPA) that many of the barriers could be overcome if sufficient efforts were made as the policies and regulations evolved on a need basis. Given that, these aforementioned efforts need to be initiated first to achieve the expected outcome. The results from a study demonstrated that solely relying on GSI implementation was not adequate if public education and social learning were not enforced at the same time (Winz et al., 2011). The authors suggested the diversity of perspectives should not be omitted to encourage the successful transitioning of this stormwater management regime. To attract more financial support to advance and accelerate research on gathering reliable GSI performance data, inadequate public (especially the major stakeholders') awareness needs to be appropriately addressed (Derkzen, van Teeffelen, & Verburg, 2017; Giacalone, Mobley, Sawyer, Witte, & Eidson, 2010).

2.3.2.3 Perceived Demographic Constraints—Biases Resulted from Error Management

Error management bias occurs when people make decisions primarily to reduce consequential losses (Haselton et al., 2015b). The typical bias that falls into this category is risk (or loss) aversion. As pointed out by Tversky and Kahneman (1991), people tend to value any amount of loss greater than the same amount of gain, which infers that losses (or disadvantages) will be considered more than gains (or advantages). In the context of GSI implementation, one factor that hinders the decision-making process is the lack of convincing empirical data on multi-sector functionality in a life cycle (Demuzere et al., 2014; Gogate, Kalbar, & Raval, 2017; Wise et al., 2010). This bias might emerge due to unfamiliarity with long-term GSI performance and with the demand for capital cost and maintenance fees, of which the payback has not been clearly quantified. A study found that the most salient barrier to adopting innovations is the perception of risks (Olorunkiya et al., 2012). The authors suggested that extensive knowledge transfer in combination with equal sharing of contractual risk through team collaborations could contribute to easing such perceptual barriers. Great progress has been made to minimize these barriers. Without enough perceived incentives, it would be difficult for any major stakeholder to bring forth the input, whereas other studies have shown some positive influence of GSI in the triple bottom line (i.e., economic, social, and environmental) (Li et al., 2019; Raucher & Clements, 2010; Shaver, 2009; Suppakittpaisarn, Jiang, & Sullivan, 2017; Yang & Li, 2013).

In a study by Di Matteo, Maier, and Dandy (2019), their results suggested that being able to review trade-offs among solutions can minimize biases at the decision-making stage. According to Coleman's finding (2018), some private landowners favored small-scale GSI practices over community-wide alternatives, as they were more focused on addressing local issues rather than collective actions. On the other hand, some GSI practices are more likely to provide better performance if used in tandem (Bell, McMillan, Clinton, & Jefferson, 2016; Coleman et al., 2018), which could further complicate the multi-sector performance monitoring processes. Of particular note was that social performance was considered a critical factor for enhancing multi-sector funding opportunities and the adoption of GSI (Carlet, 2015; Tayouga & Gagné, 2016). Further studies are needed on the influential social features that affect the development of GSI to resolve the knowledge gaps among the public and to elucidate major social restraints (e.g., demographics and ruling regulations). Demographic factors were regarded as the contextual background. Policy enforcement and revision according to the current GSI implementation situation were mainly the responsibility of governmental entities at federal, state, and county levels. The field experts were considered the leading personnel responsible for designs based on the built environment within the region and the outreach for knowledge diffusion. Compared to the households that prioritize individual benefits, the local community tracks the interconnective components. Despite the efforts invested into understanding the influence of the social environment on GSI implementation, only limited research studied individual behaviors at the system level to identify the most potentially effective approach to increase social acceptance at a regional scale (Montalto et al., 2013).

2.3.3 Applied Agent-Based Modeling in Quantitative Decision Support

Tremendous research has addressed the hydraulic and hydrological and economic uncertainties of GSI, yet social contextual factors remain under-studied given its complexity and challenges in quantitative analysis. Our work reviews and analyzes the most identified social barriers including governance inconsistency, low public participation, and demographic constraints from the consequential behavior patterns by incorporating knowledge in cognitive biases. **Table 2.2** presents the most relevant frameworks that qualitatively assist in decision support for GSI implementation. They brought forth early attempts to solve the social dilemma identified in **Table 2.1** through various degrees of active public engagement, collaborative governance regimes, and strengthened knowledge transfer among stakeholders. A new conceptual framework (**Figure 2.3**) was proposed to take into consideration such barriers on their potential impacts on the adoption of GSI.

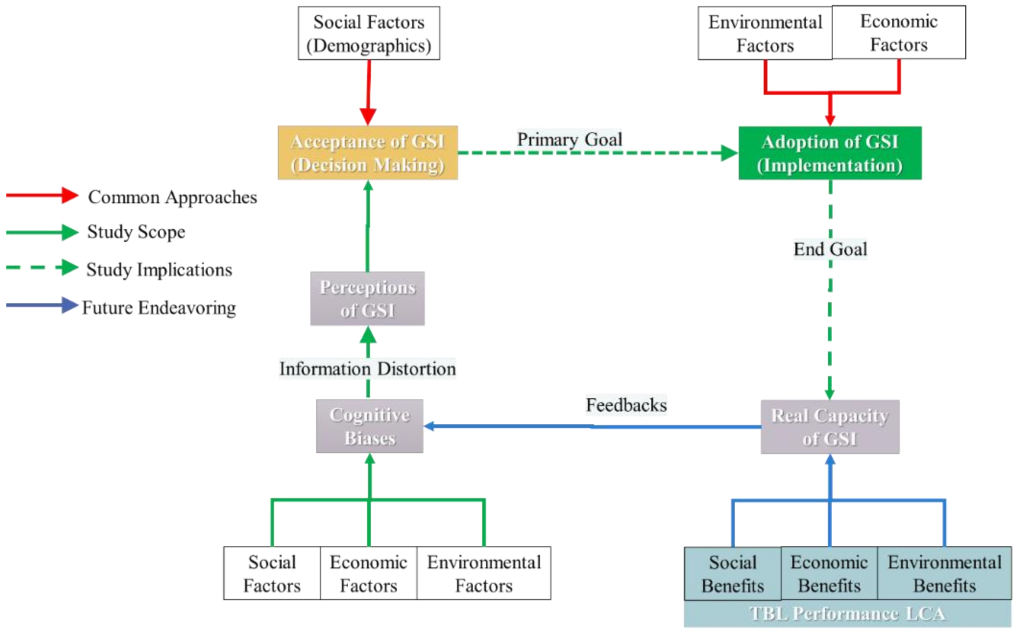

Figure 2.3 *The conceptual framework proposed in this study.*

Policymakers are usually required to make science-based decisions and actions by which they need to provide transparency in their prediction of the expected impacts of their decisions (Glynn et al., 2017). Hence, further efforts are needed to provide evidence-based quantitative analysis to gain advanced insights into practical decision support. Existing quantitative decision support tools used to simulate or evaluate GSI performance rely on the assumption of rationality, omitting the potential interference to the outcomes due to cognitive biases. For instance, several multi-criteria decision-making (MCDM) support systems made of decision support tools (DSTs or DSSs) have gradually incorporated as many relevant factors as possible (Gogate, Kalbar, & Raval, 2017). Despite their capacity in being able to address multiple criteria, these decision support tools for GSI implementations have limited considerations on the potential cognitive biases, which could result in less effective strategies implementation. For instance, a study indicated that individual bias has various effects on the organization's objectivity in both positive and negative directions and distorts individuals' process of creating, retaining, and transferring knowledge. Their study results suggested that for a system with high complexity, reducing individual bias may not necessarily enhance the objectivity of the organization. Thus, it is wise to examine specific social systems when developing cost-effective mediation strategies in case of simulating individual biases (Xu, Liu, & Liu, 2014).

Psychological- and sociological-based behavioral rules have been adopted in ABM by macroeconomics since the 1960s (Akerlof, 2002). As reviewed by Bharathy (2006), the combination of an understanding of human behaviors and systems thinking is crucial for successful decision-making. Their study identified the research niche on human behavioral modeling with an emphasis on the coordination among stakeholder groups in different fields. Despite being unable to truly reflect on realistic situations, human behavioral models can still assist decision-makers in understanding social systems. However, the models that are developed solely based on social and physical science are usually fragmented in their fields, rely on qualitative analysis, or are difficult to incorporate into quantitative models. For models with agents to behave more realistically, one must expand their study scope to incorporate the theories in social science domains (such as psychological and cultural studies). Limited research was able to accomplish this task (Bharathy, 2006).

In terms of complexity among available DST, ABM is more robust at detailed micro-level simulation than qualitative studies, yet less dependent on sophisticated mathematical logic than some quantitative models, such as system dynamics. This methodology can simulate global emergent patterns/social consequences by setting up only individuals' characteristics and behaviors. ABM is better at capturing the non-linear interactions between human behaviors based on various factors and the macro-environment through feedback effects and at explaining the collective outcomes resulting from a given set of interactions among individuals. So far, the primary use of ABM for policy decision support has primarily been in the fields of sociology, epidemiology, and urban planning (Bhandari & Hassanein, 2012; Bruch & Atwell, 2015; DeAngelis & Diaz, 2019; Groeneveld et al., 2017; Marsella, Pynadath, & Read, 2004).

The theory of innovation diffusion was developed to conceptualize innovation adoptions through communication channels over time, which are determined by individuals' personal and social characteristics in a social system, and the decision-making logic of individuals regarding the associated social changes (Rogers, 2010). ABM is advantageous at micro-level simulations that can account for the heterogeneity and autonomy of individuals during the innovation diffusion process to a greater extent in comparison to aggregate-level models. Kiesling, Günther, Stummer, and Wakolbinger (2012) conducted an extensive review of ABM applied in this theory, which has been used for two main purposes: To advance the theoretical development, and to forecast outcomes for decision support using empirical data. Similar to other simulation models, ABM has its limitations. To date, no ABM framework has been widely agreed on for innovation diffusion due to the diverse selections of sub-theories, parameters, and equations to interpret the adoption processes. The two major challenges are: the lack of capability in capturing opinion changes as models generally assume a binary decision switch from a non-adopter to an adopter with a presumption of global success as the outcome (V. K. Kandiah, Berglund, & Binder, 2019). Therefore, there is a research need to continue extending and revising the existing ABM framework to better simulate more realistic innovation diffusion, particularly water-related infrastructure due to the pressing issues highlighted in the background section of this article. Though different in prior aims, the use of ABM to assist in decision support for diffusing innovative water-saving technologies shares similarities in the general concepts with GSI technology diffusion in terms of the simulations and behavior rules. Therefore, studies conducted on innovation diffusion of water conservation were reviewed in this section as well (**Table 2.3** and **Table 2.4**).

A few studies have applied ABM to analyze isolated influences of certain demographic, household, social, and external factors on water conservation technology adoption. However, they failed to consider the potential simultaneous influence of these attributes on agents' acceptance of decision-making. One empirical-data-driven study argued that ABM was more favorable in simulating innovation diffusion than the Bass model and cellular automata for its greater capacity in incorporating heterogeneity of agents and explicit special relationships (Schwarz & Ernst, 2009). The statement was also supported by another study (Rasoulkhani, Logasa, Presa Reyes, & Mostafavi, 2018). Another study discovered a research gap in the observed disagreement between the overall numbers of the households that indicated their will to adopt certain water conservation technologies and the number of the populations that implemented said technologies. They suggested it could be due to the additional costs and motivation required to install these inventions into one's household. They used ABM to simulate the innovation diffusion process by the state transition approach as mentioned in the previous section. Their results shed light on the importance to consider various characteristics of the communities when developing intervention strategies for the effective adoption of water-saving technology by households such as income growth, water pricing structure, the cost of rebated programs compared to the affluence of the community, and social network connections (Rasoulkhani et al., 2018).

One study based in Germany (Schwarz & Ernst, 2009) adopted the integrated ABM approach to combine the theoretical aspects of innovation diffusion, social psychology, sociology, and decision theory to enhance the accuracy of realistic decision-making processes using an empirical study of diffusion of water-saving technologies. This model contributed to an advanced decision-making process during water-saving innovation diffusion. On a different aspect during the adoption process, few researchers have developed ABM models that can incorporate the dynamics between public adoptions that are affected by changes in demands for resources and services and infrastructure expansion. A study (V. K. Kandiah et al., 2019) approached the issue through an ABM framework, which simulated the perception changes in risks/benefits of water reuse during infrastructure expansion by incorporating the theory of risk publics to simulate the social networks. It overcomes several limitations of cognitive models and diffusion of innovation models because the risk publics theory is relatively more comprehensive in reflecting real decision-making compared to other existing theories in that it assumes definitive connections among agents who held similar opinions about the risk/benefits of a technology based on a social psychology approach. This work is one of the few that applied social psychology-based ABM in innovation diffusion for water reclamation among households and has the potential to be adopted for decision support for GSI implementation.

Note that the review in this study is limited to the research works conducted solely through ABM. However, there have been several studies that used hybrid simulation models as a decision support tool in water infrastructure management. For instance, Faust, Abraham, and DeLaurentis (2017) developed a hybrid quantitative system dynamics-ABM framework to investigate the water demand dynamics in shrinking cities. This type of hybrid model showed its advantages in capturing sophisticated socio-technical interactions within the human-infrastructure system through feedback loops compared to using ABM. On the other hand, simulations of cognitive biases using ABM have been explored on various types of cognitive biases, such as risk aversion, confirmation bias, motivated reasoning, and cognitive filtering within social science, and economy domains (Abbott & Hadžikadić, 2017; Cannella, Di Mauro, Dominguez, Ancarani, & Schupp, 2019; Demary, 2011; Geschke, Lorenz, & Holtz, 2019; Wang, Sirianni, Tang, Zheng, & Fu, 2020). These scholarly contributions can be substantially beneficial in driving insightful decision-support tools for GSI implementation that reflect realistic public opinions and actions.

Table 2.3 *Innovative strategy diffusion in water management using ABM (part I).*

Source	Simulation Objectives	Agents	Behavior Rules	Social Networks	Time Step	Platform
(Galán, López-Paredes, & Del Olmo, 2009)	Water consumption behaviors	Households	Reversible stochastic diffusion of opinions, Bass' model of innovation diffusion	Random graph	Three-month (10 years)	Java
(Haer, Botzen, & Aerts, 2016)	Flood risk communication strategies effectiveness	Households	Protection motivation theory	Stochastic with predefined connection rules	Yearly (7 years)	NetLogo
(V. Kandiah, Binder, & Berglund, 2017; V. K. Kandiah et al., 2019)	Adoption of water reuse measures	Households	Risk publics ABM framework	Small-World	Yearly (30 years)	Not specified
(Kotz & Hiessl, 2005)	Innovation processes in urban water infrastructure systems	Water supplier, water consumers, sewage system operator, technical components producer	Bounded rationality with utility functions	Simplified structured models	Yearly (50 years)	Not specified
(Montalto et al., 2013)	Spatiotemporal emergence of GSI	Residential property owners	Probability-based GSI adoption rules	Simplified structured models	Monthly (30 years)	NetLogo

Source	Simulation Objectives	Agents	Behavior Rules	Social Networks	Time Step	Platform
(Rasoulkhani et al., 2018)	Effect of various factors on residential water conservation technology adoption	Households	Innovation diffusion, affordability theory, peer effect	Various (random, distance-based, ring lattice, small-world, and scale-free)	Yearly (20 years)	AnyLogic
(Schwarz & Ernst, 2009)	Diffusion of water-saving innovations	Households	Innovation characteristics, Theory of Planned Behavior, lifestyles, decision theory	Small-World	Monthly (14 years)	Java
(Zidar et al., 2017)	GSI adoption optimization	Water utility, local community organizations, and property owners	Probability-based rules	\	Quarterly (30 years)	NetLogo
(Rasoulkhani & Mostafavi, 2018b; Rasoulkhani, Mostafavi, Reyes, & Batouli, 2020)	Assessments of the long-term resilience of water supply infrastructure	Users, agencies, wells, stressors, wastewater treatment plant	Bounded rationality and regret aversion, stochastic processes, consequential impacts of the other two agents	\	Yearly (100 years)	AnyLogic

Table 2.4 *Innovative strategy diffusion in water management using ABM (part II).*

Source	Calibration, Verification & Validation	Novelty/ Advantages	Limitations	Location
(Galán, López-Paredes, & Del Olmo, 2009)	Calibration with empirical data, face validation	Integrate geographical, cultural, and socioeconomic factors with ABM for decision support in water demand	Requires exhaustive efforts into interdisciplinary empirical validation, demands advanced expertise and computation power to embed GIS into ABM	Valladolid (Spain)
(Haer, Botzen, & Aerts, 2016)	Calibration with empirical data and sensitivity analysis	Simulates micro-level diffusion of information for flood risk communication	Requires sufficient empirical data to minimize uncertainty	Rotterdam-Rijnmond (Netherlands)
(V. Kandiah, Binder, & Berglund, 2017; V. K. Kandiah et al., 2019)	Calibration with historical data and sensitivity analysis, validation through comparing results from another model	Captures opinion dynamics and adoption decisions on water reuse innovations under various infrastructure expansion scenarios	Assumes several parameters of fixed values, simulates at the unitary household level, limited capacity in capturing opinion dynamic resulted from external factors	Town of Cary, NC

Source	Calibration, Verification & Validation	Novelty/ Advantages	Limitations	Location
(Kotz & Hiessl, 2005)	Not specified (theoretical development only)	Captures the transition patterns of water supply infrastructure influenced by interactions of multiple stakeholder groups	Lacks agent heterogeneity of simulated stakeholder groups, omits some relevant stakeholder groups	Not specified
(Montalto et al., 2013)	Calibration with historical data	Simulates micro-level spatiotemporal adoption rates of two GSI practices determined by physical compatibility and socio-economic factors	Requires expertise in collecting, characterizing, and modeling with the relevant data, the behavioral rules need further data collection to reflect the decisions made under various constraints and conditions	Philadelphia, PA
(Rasoulkhani et al., 2018)	Calibration with historical data, internal validation with sensitivity analysis, external validation through comparison with similar studies' results	Explored the influence of various social factors, social networks, and water policies on water conservation technology adoption under	Fails to capture all impactful demographic factors due to data limitations and potential feedback mechanisms through dynamic factors	City of Miami Beach, FL

Source	Calibration, Verification & Validation	Novelty/ Advantages	Limitations	Location
(Schwarz & Ernst, 2009)	Calibration with empirical data, validation with independent empirical data	Simulates the diffusion of water conservation technology among households (heterogeneous agents) based on two decision algorithms and driven by empirical data	Sensitive to the values set to categorize households based on lifestyles, model accuracy can be improved by adding other economic factors	Southern Germany
(Zidar et al., 2017)	Calibration with historical data	Simulates multi-agent simulation of GSI adoption based on physical compatibility and socioeconomic factors with undergoing synergistic infrastructure transitioning and ownership scenarios	Relies on numerous yet reasonable assumptions	Pint Breeze, PA
(Rasoulkhani & Mostafavi, 2018b; Rasoulkhani, Mostafavi, Reyes, & Batouli, 2020)	Internal verification through component verification assessment, external verification through tracing, calibration with empirical data, face validation	Provides insights on theoretical, computational, and practical decision support for water supply infrastructure resilience under various scenarios of sea-level rise and adaptation strategies	Omits the salinity fluctuation caused by overexploited freshwater aquafer, and other adaption solutions by households	Miami-Dade County, FL

2.4 Conclusions and Recommendations

The burgeon urbanization and rapidly increased impervious surfaces have led to the increment of runoff volumes and peak flows casting burdens on existing stormwater management infrastructure. Conventional gray infrastructure utilizes a centralized management approach to control stormwater through treatment facilities or direct discharge into receiving water bodies bypassing the treatment process. It is environmentally inadequate in modern societies as climate change has gradually intensified its impacts worldwide. On the contrary, GSI exploits decentralized natural processes to treat stormwater runoff at its source, which also provides additional benefits to the community contributing to urban resilience and sustainability. However, it still faces various barriers to GSI implementation in the US mainly due to existing presumptions that can lead to a lack of funding allocation. Conceptual frameworks are directing tools that can be used to standardize GSI project planning. There is an urgent need for inclusive decision support tools to better evaluate the perceptions of private landowners (homeowners and renters) of GSI to devise effective intervention strategies for encouraging GSI implementation. This can minimize the erroneous perceptions of GSI of the stakeholders, compared to the existing gray infrastructure. This paper made the first attempt to bring forth the connections between such social barriers to GSI implementation in the US and the potentially linked cognitive biases that had hampered rational decision-making, which few studies have set their research efforts on. The authors acknowledge the limitation of this review regarding the connections due to its novelty in relevant research fields applied in GSI adoption, particularly the three biases chosen in this review. Further interdisciplinary discussions are encouraged to strengthen the research efforts on this topic to drive evidence-based local data analysis in addition to systematic analyses of these cognitive biases among stakeholder groups.

On the other hand, despite their capacity in being able to address multiple criteria, the existing decision support tools omitted some common cognitive biases which could result in less effective strategy implementation as pointed out in an article (Xu et al., 2014). Various scholarly publications reached an agreement on ABM's robusticity in simulating individual-level decision-making processes. Thus, this paper reviewed quantitative analysis for decision support to promote innovative strategies in water management for long-term resilience. Yet there have been no ABM models developed to approach the well-recognized social factor-related biases in GSI adaptation using the social-psychological approach of innovation diffusion. Thus, we proposed a conceptual framework to bridge this disconnection as shown in **Figure 2.3**. In this framework, assumptions of the presence of biases could be safely made if differences are recognized between the empirical data on households' perceptions of GSI, thus the acceptance and adoption and simulated results using the common mathematic theories in a multi-agent model. To further advance the realistic simulation of socio-infrastructure systems such as GSI implementation processes, future efforts should be made to incorporate the complex opinion dynamics due to cognitive biases into advanced hybrid models to explore the interdisciplinary interactions on a broader scale that have not yet been well examined for implementing innovative strategies of water infrastructure systems.

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CHAPTER 3. ADDRESSING THE SOCIAL BARRIERS TO GREEN STORMWATER INFRASTRUCTURE IN RESIDENTIAL AREAS FROM A SOCIO-ECOLOGICAL PERSPECTIVE[2]

3.1 Introduction

Green stormwater infrastructure (GSI), a nature-based solution to stormwater control that emphasizes the benefits of the balance of ecological systems, is increasingly being adopted in urban areas to treat and manage runoff. It works as a complement to traditional gray infrastructure, such as drainage pipes, ditches, and culverts, and in many cases can be a better alternative to some conventional practices. However, considering the combined impacts of climate change on rainfall intensity and frequency, aging gray stormwater infrastructure, and growing urban populations, GSI adoption rates need to accelerate to contribute to more sustainable and resilient urban centers. In the US, many barriers to GSI's acceptance have been identified among communities, and economic factors are largely considered as the limiting influencers. Social aspects, such as institutional conflicts, responsibility distributions, and community buy-in also impact the adoption of GSI which consequently affect economic decisions for GSI (Barclay and Klotz, 2019; Carlson et al., 2014; Derkzen et al., 2017; Giacalone et al., 2010; Mason et al., 2019). Cognitive biases may interfere with the rational decision-making process (Acciarini et al., 2021; Klotz, 2011). This impacts community buy-in which is needed for voluntary GSI adoption on private property. Furthermore, Qi and Barclay (2021) identified several potentially relevant social barriers. Together with other challenges, these barriers contribute to the sluggish increase of GSI in recent decades in the US despite the rapidly rising research interest in stormwater management. Some cities, such as New York City (Elborolosy and Cataldo, 2020), Los Angeles (LA Sanitation & Environment, 2021), Philadelphia (Hsu et al., 2020), and Atlanta (EPA, 2020) have had higher GSI implementation rates than others. However, the pressing risks arising due to urbanization and climate change have left us with little room to continue the

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status quo (Kirkpatrick and Olbert, 2020; Pokhrel et al., 2020; WMO, 2020) in denying climate science (Wong-Parodi and Feygina, 2020) and in omitting long-term adaptive measures (Dedekorkut-Howes et al., 2021). Therefore, there is an urgent need to accelerate the progress in GSI adoption for stormwater-related disaster mitigation nationwide.

Despite the efforts invested into understanding the social environment's influence upon GSI implementation, few studies have been conducted to study the behaviors of individuals at the socio-ecological system level to identify the potentially most effective approach to increase social awareness and acceptance on a regional scale. It is important to tailor the presentation of this idea to residents for the successful diffusion of alternative techniques for stormwater management because GSI measure adoption on private properties is voluntary and not regulated in the U.S. To approach these social barriers, one should expand their scope to a bigger picture, examining the function of GSI in socio-ecological systems. Human activities rely on various essential ecosystem services provided by ecological resources, such as stormwater resulting from precipitation. These interconnections between human activities and ecosystem services form complex socio-ecological systems (Biggs et al., 2015). To effectively minimize the struggles that hamper stormwater infrastructure from being resilient in social-ecological systems (SES), proper knowledge sharing and/or social engineering should be woven into the agenda of adoption and innovation diffusion at the early stage, along with the implementation processes of the practice. In that case, the best practices could be instilled in all stakeholders' minds as the norms to minimize the social and economic setbacks.

Many theoretical frameworks have been developed to better understand such adoption behaviors (Meade and Islam, 2006; Peres et al., 2010). One prominent behavior theory is the theory of planned behavior (TPB). This theory delineates human's logical decision-making process, and it aligns with the study scope of this work because it takes into consideration the influence of socio-cognitive factors (i.e., subjective norms and perceived behavioral control) at the individual level (Wisdom et al., 2014). In addition, TPB has been a major attitude-based framework to understand environmental behaviors

(Drescher and Sinasac, 2021; Kaiser et al., 2005). It has been used to explain environmental intentions and behaviors, however, TPB still has the potential to be improved to simulate the problem of interest more accurately (Mancha and Yoder, 2015). Yuriev et al. (2020) conducted a comprehensive review on the use of the TPB to understand pro-environmental behaviors. A recent study used the theory of planned behavior to assess the GSI adoption behavior of residents in several Canadian neighborhoods with a series of statistical analyses including partial least squares path modeling. However, the model failed to find the significance of attitudes (Drescher and Sinasac, 2021). It might be difficult to use TPB to fully interpret environmental conservation behaviors where one's self-interest might be at least partially at odds with the interest of others. At the same time, the author of the theory itself acknowledged that there is a potential to expand TPB to add more predictors to better understand intentions and behaviors (Ajzen, 2020). This could lead to the consideration of cognitive biases. For example, the GSI measures designed to be resilient may not be as resilient as expected if end-users fail to comply with the instructions to follow the recommended maintenance protocols. Thus, the irrational judgment and decision-making of the general public also demand significant considerations, which have been more or less overlooked. The adoption of GSI measures is voluntary and cannot be required by regulations on private land. Therefore, residents have a crucial role in the GSI measure implementation decisions. There is a need to explore further this research focus to develop targeted strategies for GSI adoption in residential areas. The research question to be addressed in this study is:

1) How do residents of Mecklenburg County perceive GSI adoption?

2) What are the gaps between the understanding of the field experts of the perceptions of GSI adoption and the actual perception of the residents?

3) To what extent is the theory of planned behavior suitable to interpret residents' decision-making on the adoption of GSI measures in residential areas?

The objective of this study is to explore if cognitive biases can be considered in combination with the theory of planned behavior to better interpret public perceptions of GSI adoption in residential areas. This research aims to provide insights to local stormwater management authorities so that stakeholder engagement plans for GSI implementation in urbanized areas could be improved.

3.2 Methodology

3.2.1 Study Area

Mecklenburg County, North Carolina, located in the southeast United States was selected as the research area. It is the most population-dense county in North Carolina (United States Census Bureau, 2021) and is well-suited as the case study location. Transferrable insights from this research outcome can be used for future scenarios for the State's other urbanized counties, as well as urbanized regions across the United States. Mecklenburg County (**Figure 3.1**) is home to the state's economic center, the city of Charlotte, and is one of the metropolitan areas embracing influxes of population groups from various locations with diverse backgrounds (United States Census Bureau, 2021). This growing population generates rising burdens on the existing infrastructure systems, such as stormwater, due to continuous development. However, there is a growing recognition among the general population of the need to address the interconnected technical, ecological, and social challenges that are inherent in water systems (Ferguson et al., 2013). The annual average precipitation in the county between 2011 and 2020 was 120.14 cm (47.30 inches) where a gradual increase in extreme precipitation intensity can be observed over the years (NOAA, 2021). According to Malinowski et al. (2018), there is a strong correlation between water quality and imperviousness in a watershed. The impervious coverage rate in Mecklenburg County had increased to over 20% as of 2020 (Open Mapping Mecklenburg County GIS, 2021). Water quality impairment and site flooding have driven the efforts and investment into various GSI practices across the watersheds by the local regulatory agency CMSWS.

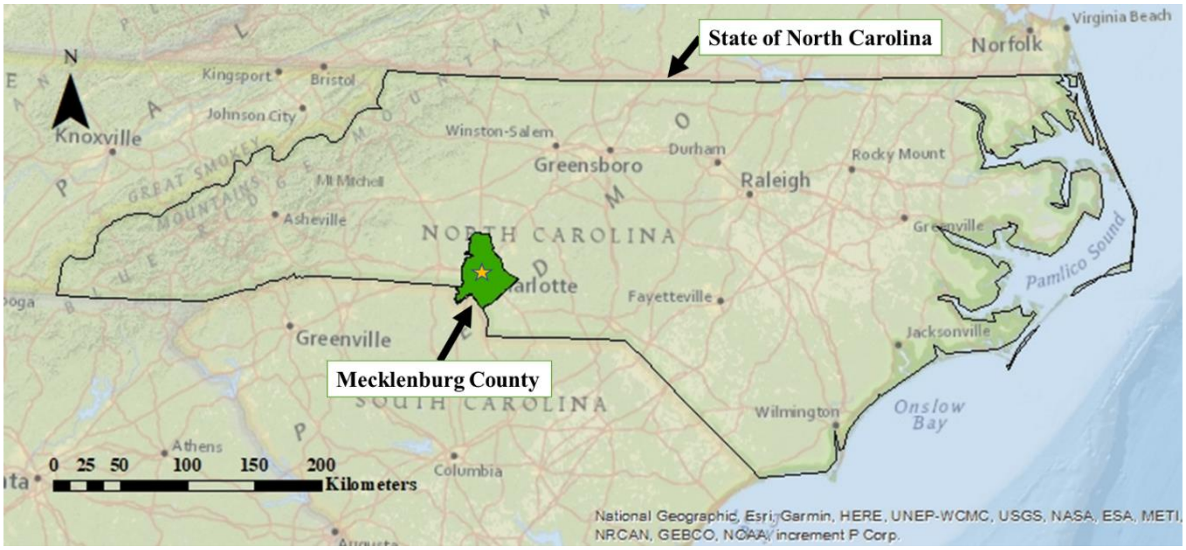

Figure 3.1 *Map of Mecklenburg County in North Carolina of United States of America. The estimated population as of 2019 is 1,110,356, and its estimated annual growth between 2010 to 2019 is 2.07% (Open Mapping Mecklenburg County GSI, 2021 and United States Census, 2021).*

3.2.2 Data Collection and Analysis

This work was mainly composed of two forms of human-subject studies with an approved Institutional Review Board (IRB) protocol, which included an online survey to gauge public opinions toward GSI and a series of semi-structured interviews with four representatives of major decision-making institutes/entities to learn about the logistics for GSI implementation in Mecklenburg County. The approximate duration of the interviews and the online survey questionnaires were 30 and 15 min, respectively. All identifiable information was handled per the data management best practices required by the IRB protocol. Interviews with regulatory agencies were included to gain additional insights, assess the consistency of the results obtained from the survey with the ones reported by the interviewees, and learn about the decision process within regulatory agencies (Persaud et al., 2016). A comparison between the aggregated answers collected from the interviews and the ones from the CMSWS survey was conducted to evaluate the inconsistencies and to explore the potential cognitive biases among residents under the assumption that the collective answers from the experts are relatively accurate and less biased. Additionally, the annual surveys and the associated reports conducted by the CMSWS on public opinions on stormwater management were inquired about and analyzed as supplementary reference data.

3.2.2.1 Survey Design

The survey was composed of twenty-seven questions progressing from asking about awareness of general water infrastructure and GSI, attitude towards GSI, adoptions of GSI, peer knowledge sharing regarding GSI, and demographic questions. The questions were curated based on past literature on assessing public opinions on GSI adoption (Coleman et al., 2018; Giacalone et al., 2010; Mason et al., 2019; Persaud et al., 2016) adjusted to fit into the theory of planned behavior (Ajzen, 1991). The questions were a combination of 9 multiple-choice questions, 9 seven-point Likert scale questions, 8 multiple-response questions, and an open-ended numeric question. The questionnaires were administered through the Qualtrics platform (Qualtrics, 2021). A prior pilot study was conducted on a group of 60 college students to refine the wording and sequence of the questions. In addition, brief and illustrative information was included to reduce non-sampling errors (Assael and Keon, 1982), helping participants understand the questions better and familiarize themselves with the terminology *GSI* given the diverse terminology used in the field. The authors worked to minimize sampling errors (Assael and Keon, 1982) by recruiting survey participants through several online-based social media platforms, such as LinkedIn, Instagram, Facebook, Nextdoor, and Reddit, based on feasibility and accessibility between February 16 to April 8, 2021. The participants were limited to Mecklenburg County residents aged 18 and above by using a screening question. In total, 642 completed survey questionnaires were collected. However, only 510 survey respondents were included in the final analysis because the rest skipped questions, rendering their responses non-representative to establish correlations among factors.

The statistics of the survey responses were processed through SPSS 27 (IBM, 2021). Frequency statistics were conducted on the categorical questions with nominal variables to examine the demographic characteristics of the samples (Q22-27) and to survey participants' opinions for future public engagement strategy development support (Q7, Q9, Q11-13, Q16, Q21). Five specific questions were selected as the direct predictors for each construct in the theory of planned behavior. The strengths of intention and perceived behavioral control on the behavior of GSI adoption were analyzed using multiple logistic regression. Next, the strength of attitude, subjective norms, perceived behavioral controls, and their respective indirect predictors on adoption intention were evaluated by multiple regression; the authors also tested the other potentially influential factors as the indirect indicators for attitude, subjective norm, and perceived behavioral control using multiple regression (**Table 3.1**).

Table 3.1 *Survey analysis framework (see detailed definition of each construct in Section 3.2.1).*

Construct	Variable Type	Direct Predicator [a]	Indirect Predicators
Attitude	Independent Variable	Acceptance level to new adoption of GSI practices (Q10)	Perceived importance of water infrastructure (Q3), Attitude toward GSI (Q8)
Subjective Norms	Independent Variable	Sense of peer pressure to engage in sustainable stormwater management behavior, such as GSI adoption (Q20)	Likelihood to share opinions on stormwater infrastructure (Q18, Q19)
Perceived Behavioral Control	Independent Variable	Familiarity with GSI (Q6)	\
Intention	Independent Variable/ Dependent Variable	Willingness to pay for GSI measure adoption (Q14)	Perceived competence of current stormwater infrastructure (Q5)
Behavioral	Dependent Variable	GSI adoption experience (Q15)	\

3.2.2.2 Interview Design

The interview questions were divided into two parts. The first part was administered to evaluate possible cognitive biases among residents, and the second part asked about the specific roles of each interviewed participant in the GSI implementation process. The latter was done to establish the weight of their responses to each question collected in the first part and to gain insight into their perspectives on effective stormwater management strategies. All interviews were conducted online via Zoom and audio recorded with consent for study purposes. Interviewees were recruited through the snowball method that uses the process of chain referral (Singleton and Straits, 2009). Interview transcripts from the audio recordings were analyzed in NVivo (NVivo, 2021) using qualitative coding methods (Saldana, 2015). First-cycle coding was done using the inductive approach to summarize the contents by themes that emerge from the data. Deductive coding was done for the second cycle to condense the transcript into two categories, including *adoption processes* (objective statements) and *opinions, attitudes, and behaviors* (subjective observations and self-reporting). During the second cycle of deductive coding, the pre-selected codes of five attributes from the theory of planned behavior (i.e., attitude, subjective norm, perceived behavioral control, intention, and behaviors) were used (Ajzen, 1991). Another set of independent coding was performed by a different researcher to minimize subjective biases and limitations. This theoretical framework based on the TPB established the connection between socio-cognitive factors and the individual-level decision-making process on innovation adoption. In addition, another theme of three codes was used to summarize the objective background information related to the influence of the institutions that the interviewees represent (i.e., current regulations, perceived challenges, and perceived solutions). These three codes emerged from the interview.

3.2.2.3 Other Documents

Two of the interview participants mentioned the annual public perception survey conducted by the CMSWS on stormwater management services provided by the institution. The reports were requested, and the comparable findings were analyzed in time series to better assess the reliability of this research, and to supplement the limitations of the survey sample selection conducted in this study. The limitation of using the existing reports' data was that the questions of this survey described in the report were not all directly aligned with those of the primary survey created for this study. Thus, only relevant questions and results from the CMSWS survey reports were used.

3.3 Results and Discussions

3.3.1 Survey Results

The demographic characteristics of the survey samples indicate that the majority of the participants were White (80.2%) males (62.8%) in the age group of 25–44 (76.3%) with at least some college (84.4%). Most participants lived in a single-family home (72%) of five members or above (75.1%) with a median household gross income range between $45,000 to $65,000. Both the participants' demographic characteristics and the most recent census data for the county are shown in **Table 3.2.**

Table 3.2 *The demographic of the survey participants compared with the 2019 census estimates.*

Demographic		Survey (%)	2019 Census Estimates[a] (%)
Age	18 to 64	98.1	85.0
	65 and over	1.9	15.0
Gender[d]	Female	37.0	52.0
	Male	62.8	48.0
Race[d]	White alone	80.2	57.3
	Black or African American alone	5.6	33.0
	Latino/Hispanic alone	7.8	13.8
	Asian alone	3.5	6.3
	Two or more races	0.2	2.5
	American Indian and Alaska Native alone	1.4	0.8
	Native Hawaiian and Other Pacific Islanders alone	0.8	0.1
Highest Education Level	High school graduate or higher	99.6	90.1
Household Size	Single	14.0	2.6[b]
	Two to four	10.9	
	Five and above	75.1	
Household Income Level	Less than $45,000	10.7	$71,932[c]
	$45,000 to $65,000	45.9	
	$65,001 to $85,000	25.9	
	$85,001 and more	17.5	

[a] Data retrieved from QuickFacts of Mecklenburg County from the United States Census Bureau (2021).
[b] Median household size.
[c] Median household income adjusted to 2021 dollars.
[d] The result for the choice 'other' is not shown to keep consistency with 2019 Census results.

The multiple-response questions (**Figure 3.2**) revealed that water conservation measures were the most common form of water-conscious activity the participants engaged in (72.2%). Participants preferred accessing GSI-related information through social media, publications, broadcast media, and the internet. Wanting to keep updated with the latest innovation was reportedly the primary deciding factor for opinion-forming toward GSI. The most expected benefit was minimizing non-point source (NPS) pollution in agreement with the study by Ureta et al. (2021) that showed that the public highly values ecosystem services from GSI such as water quality improvement and flood mitigation. NPS pollution in urban areas is usually the result of various anthropogenic sources, such as transportation waste, fertilizer and pesticides, and construction materials and this type of pollution can be exacerbated by flooding events (Petrucci et al., 2014). The participants expressed that having more reliable evidence of GSI's environmental benefits would motivate them more to adopt it. 70.4% of survey participants mentioned that they adopted small-scale GSI practices and/or gave financial support to larger-scale GSI practices. Of these adopters, 69.1% mentioned the reason for their adoption was environmental benefits. Different from the expected outcome, 62.5% of the survey participants expressed their concerns over long-term commitment in the form of maintenance costs, which outdid the concerns of capital investment (48.0%) where the long-term fees might only be a small fraction of the capital cost. This might suggest the existence of a status quo bias in combination with loss aversion where people show reluctance to change, particularly in financial aspects.

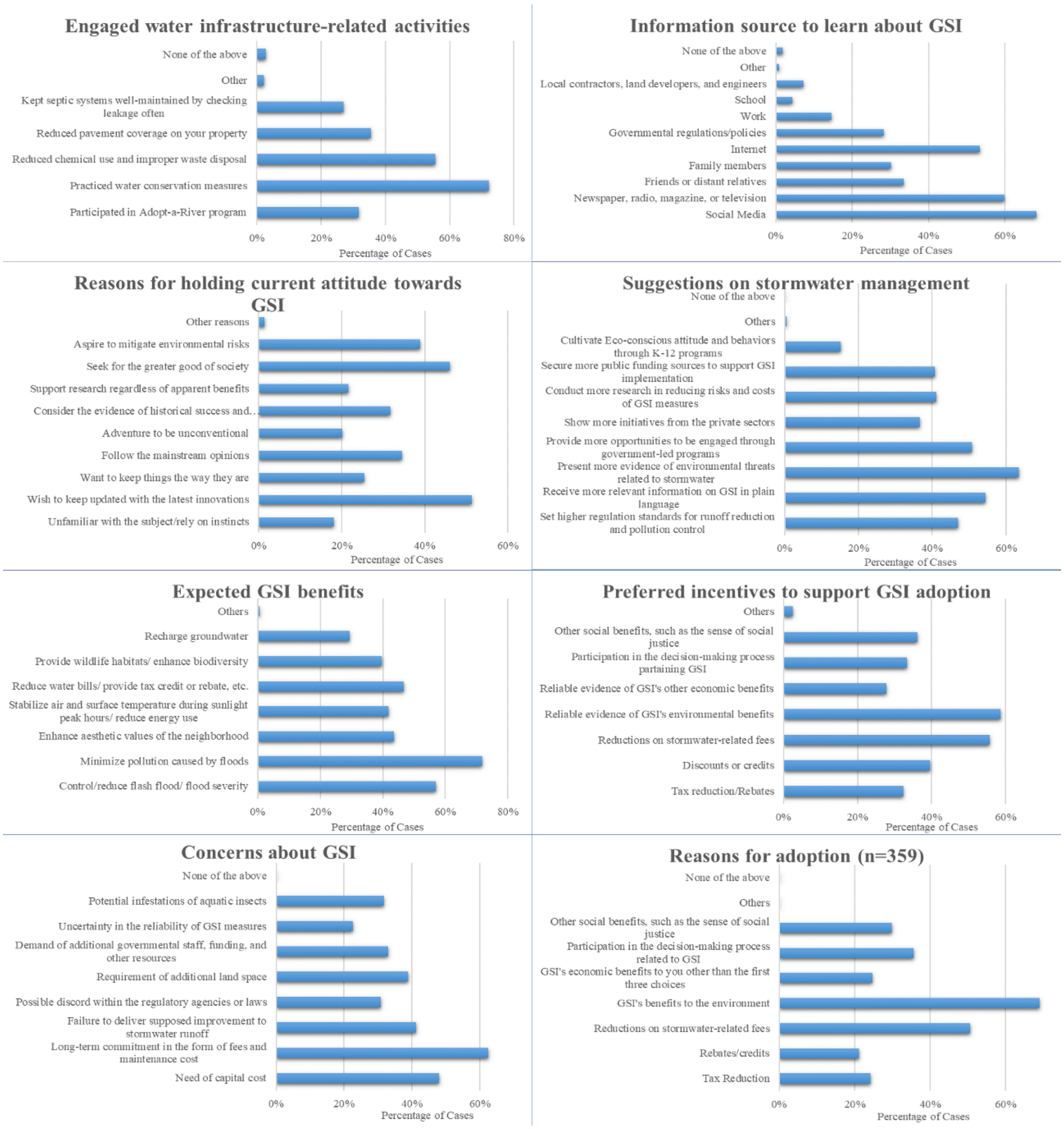

Figure 3.2 *Data synthesis of the annual report by CMSWS on residents' awareness of stormwater-related knowledge.*

The Likert-scale questions reflected a generally pro-environmental opinion of the participants, where the mean values were all at or above 5 on an ordinal scale of 1–7 with 1 indicating the most opposing, 4 the neutral, and 7 the most supportive opinion. This included the median value of perceived importance of water infrastructure in general, familiarity with GSI, current stormwater infrastructure's performance, self-reported attitude towards GSI, acceptance of GSI implementation near home, and likelihood to exchange opinions on GSI with both like-minded and those who had dissimilar opinions. In addition, those who identified as having already adopted or financially supported GSI practices expressed that they were likely (6 on the Likert scale) to recommend GSI to others. See details in **Appendix 3.3.**

Results from the logistic regression analysis are shown in **Table 3.3**. The calculated effect sizes using Cox and Snell R^2 ($R2CS$) and Nagelkerke R^2 ($R2N$) of the model were 0.14 and 0.19, respectively, with a p-value less than 0.001. Similar to R^2 for linear regression models, these two R^2 functions attempt to evaluate the predictive power of a model. This means that the model developed in this study moderately predicted the behavior. In this model, the perceived familiarity with GSI measures had a greater influence on the final decision of GSI adoption. In the multiple regression analysis, the best fitting with statistical significance ($p = 0.02$) was obtained using only the direct and indirect predictors of attitude (i.e., acceptance of GSI adoption, perceived importance of water infrastructure, and attitude toward GSI) on the intention to adopt GSI (**Table 3.4**). However, the prediction was still relatively weak ($R^2 = 0.04$, R^2 change = 0.02). It might infer that other factors could influence a resident's intention on adopting GSI measures, such as cognitive biases, which were usually not considered in most logical decision models.

Table 3.3 *The multiple logistic regression analysis results of the strength of willingness to pay and perceived familiarity resulting in the adoption of GSI measures among survey participants (n=510).*

Predictors	**B**[a]	**S.E.**[b]	**Wald** χ^2 [c]	**Sig.**[c]	**Odds Ratio**[d]
Willingness to Pay	0.000	0.000	10.759	0.001	1.000
Perceived Familiarity with GSI	0.514	0.093	30.468	0.000	1.672
Constant	-1.867	0.437	18.262	0.000	0.155

[a] B-coefficients. They are used to calculate the probability of an outcome happening using multiple predictor variables. For the B-coefficient of the constant (b_0), the greater it is, the higher the predicted probability of the outcome. For B-coefficients of the predictor variables, the positive and negative signs indicate the direction of the correlation, the greater the absolute value the more drastic the increase (or decrease) of the probability.
[b] Standard errors for B-coefficients.
[c] Wald $\chi 2$ and Sig. are the Wald Chi-Square test statistic and the corresponding p-value, respectively. It evaluates the relationship between the predictor variable and the probability of the outcome. The predictor variable is considered significant if the p-value is less than 0.05.
[d] The statistics that evaluate the level of impact of the input variables on the probability of the outcome. If the value is 1, it means that the predictor variable has no impact on the outcome's probability, whereas if it is greater than 1, the increment of the predictor value is associated with an increase in the outcome's

probability. If the odds ratio is less than 1, it means the increase in the variable is associated with a decrease in the probability of the outcome.

Table 3.4 *Results of the best-fitting multiple regression results.*

Independent Variable	Unstandardized Coefficients		Standardized Coefficients	t^d	Sig.[e]
	B^a	S.E.[b]	β^c		
(Constant)	12138.131	6995.480		1.735	0.083
Q3	-3018.276	1448.134	-0.125	-2.084	0.038
Q10	5284.452	1380.220	0.222	3.829	0.000
Q8	-3904.561	1703.549	-0.150	-2.292	0.022

[a,b,e] Same as mentioned in **Table 3.3**.
[c] Beta coefficients. They are standardized coefficients after standardizing all variables into z-scores where the mean is 0, and the standard deviation is 1, which makes it comparable among variables in terms of their influential strength on the predictors.
[d] Coefficient associated with Sig.

3.3.2 Interview Results

The first coding process followed an inductive method. This method used the keywords or summary phrases mentioned by either the participants or the interviewer with two major themes: adoption processes and organizational influence (objective statements) and attitudes and behaviors (subjective observations or self-reporting) with sixteen codes. The second coding process was conducted independently by two researchers to ensure consistency and validity. A codebook was created to define the pre-selected five codes (**Appendix 3.4),** according to the theme of the theory of planned behavior (Ajzen, 1991), subcategorized by their personal experience and their perception of the residents' experience. Any discrepancies between the two coders' results were resolved through open discussions to reach a minimum of 80% agreement as recommended by Saldana (2015). Selected examples of interview quotes can be found in **Appendix 3.2.**

3.3.2.1 Theory of Planned Behavior

a. Attitude

According to the theory of planned behavior (Ajzen, 1991), attitude is more subjective, reflecting personal liking and curiosity to gain relevant knowledge (i.e., a behavior's subjective utility (Kaiser et al., 2005)). Specific to the context within this study, the attitude was the subjective affinity to adoptions of GSI measures or motivations to gain knowledge about it or nature-based stormwater management solutions in general. In terms of the interview participants' personal opinions, three out of the four participants expressed a neutral or positive tone, such as "moderately" and "important", regarding the need of improving the current stormwater management regime via adopting GSI measures. When asked about the residents' attitude, the general responses were that it varied widely depending on the citizenry's residing jurisdictions and whether they lived in a flood-prone area. The latter was aligned with the finding by Ureta et al. (2021). Their study found that residents who had experienced flood-related impacts and who held high values on improving water quality through GSI were more likely to express support for GSI measures adoption. However, it was noted that the majority of the residents lacked interest in learning about GSI measures or were misunderstanding/unaware of them despite a slight upward trend observed over the years that was shown through more frequent phone call inquiries and engagement in public outreach programs. The adoption of larger-scale GSI measures was also considered cost-prohibitive; therefore, they hindered public acceptance. Conversely, the results from our survey showed a relatively positive direction where the participants expressed a mean attitude toward GSI measures in general and mean acceptance of GSI adoption of 5.43 ± 1.03 and 5.56 ± 1.13, respectively, on a 7-point ordinal scale with 1 as the lowest acceptance and 7 as the highest (**Appendix 3.3**). One study found that people who were given additional information held favorable perceptions and opinions toward GSI measures (Hu and Shealy, 2020). This could suggest that more emphasis on public education to enhance awareness of this type of stormwater infrastructure might be likely to raise residents' attitudes toward the adoption of the GSI measure.

b. Subjective Norm

Subjective norm is defined as "the perceived social pressure to perform or not to perform the behavior" (Ajzen, 1991, p. 188). Within this study's context, the subjective norm was whether people should adopt GSI measures based on the influence of others. The interview participants expressed their beliefs on the influence of the institutions/organizations of the higher hierarchy where initiatives were taken to disseminate relevant information. For example, national conferences could bring forth the importance of resilience-building in stormwater management, which leads to an amendment of existing policies for retrofitting or the creation of new ones for GSI measures. These policies would then be practiced by the local utility with caution to best fit the needs of the region. This could encourage local communities to incorporate GSI into their land development or redevelopment plans depending on the perceived priority compared to other factors, such as the rising influx of new residents within the county. News media coverage might also contribute to the recognition of sustainability-focused stormwater management approaches. The survey question asked about the perceived importance of peer pressure, yielding a relatively positive result where the mean was 3.45 with a standard deviation of 1.29 on a 5-point ordinal scale, which indicated the survey participants were more likely than non-participants to be the ones taking the initiatives to adopt GSI measures (**Appendix 3.3**).

c. Perceived Behavioral Control

Perceived behavioral control is a more objective judgment in terms of the person's familiarity with the GSI measures and the perceived feasibility to adopt them (Ajzen, 1991). It was worth mentioning that only one of the interviewees expressed extensive familiarity with GSI measures, including technical performance and maintenance procedures, which provided the most insights on the residents' perceived behavior control according to their experience. They mentioned that the physical separation and knowledge separation (i.e., the proximity to GSI measures and the exclusive knowledge of the technical experts) were some of the causes for the lower awareness and familiarity with GSI measures among residents. Our survey result observed a mean familiarity of 4.84 ± 1.19 on a 7-point ordinal scale with 1 as completely unfamiliar and 7 as extremely familiar, which meant most participants were somewhat knowledgeable about GSI measures (**Appendix 2.3**). In the external reports knowledge of stormwater management indicated that, though slow and fluctuating, there was an upward trend in the diffusion of relevant knowledge over the years (**Figure 3.3**). However, the knowledge diffusion may not solely result from the efforts made by the CMSWS (**Figure 3.4**).

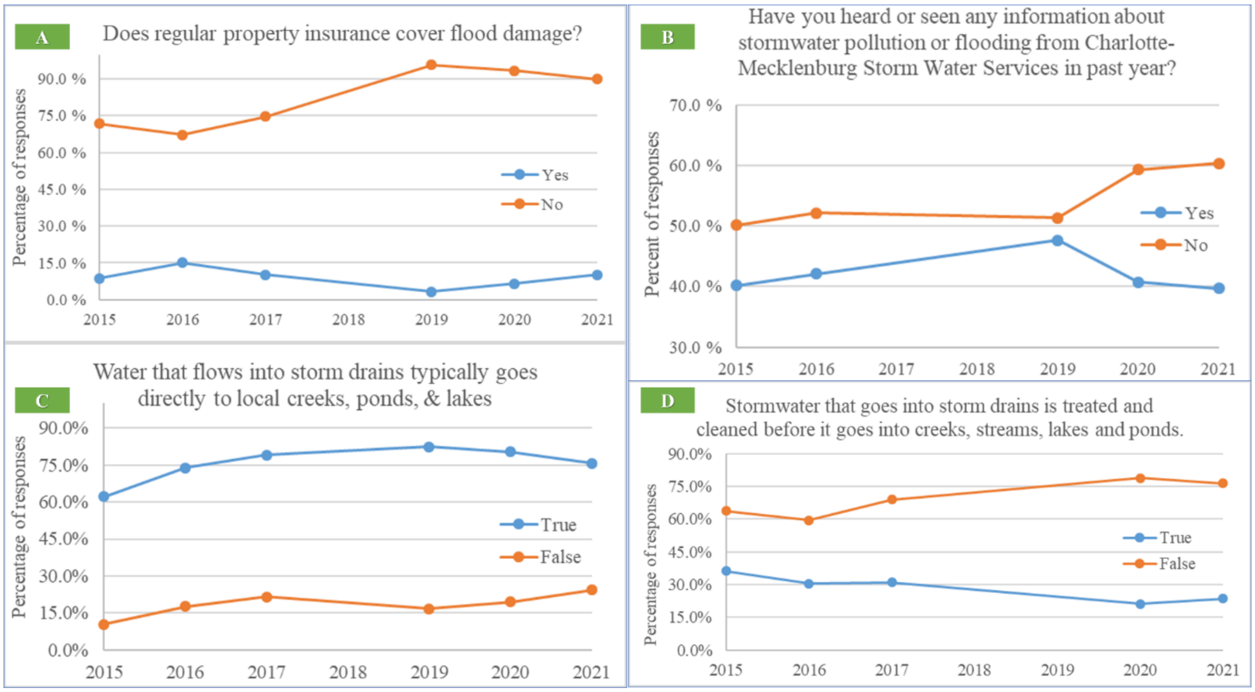

Figure 3.3 *Data synthesis of the annual report by CMSWS on residents' awareness of stormwater-related knowledge.*

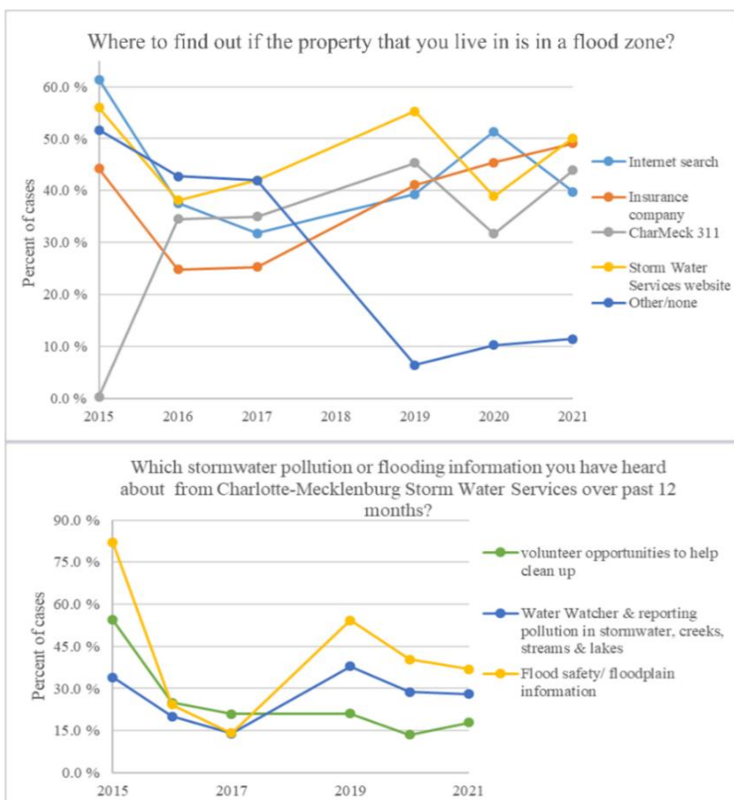

Figure 3.4 *Data synthesis of the annual report by CMSWS on sources that residents seek helps from with stormwater-related issues.*

d. Intention

In this study, the intention to perform the behavior is considered the motivational factor to consider/get GSI measures, not the motivation to learn about them in this study (Ajzen, 1991). In the survey, the intention was measured through a question of willingness to pay to adopt or financially support GSI. Five outliers were identified using the Z score method where a response with a Z-score outside the range of (-3.3) was considered an outlier. Thus, the median of $300.00 was used for this analysis with a standard deviation of $26,962.90 (n = 510). This substantially high standard deviation value corresponded well with the interviewee's statement that the attitude and intentions of residents varied vastly due to the influence of their affiliated jurisdiction, proximity to floodplains, and social background. At the same time, the results shed a positive light on the public's intention to adopt GSI measures. In Mecklenburg County, the cost of a rain barrel, which is commonly recognized as a highly cost-efficient GSI measure (Dallman et al., 2021; Yang et al., 2020), ranges from $105.00 (227-L) to $120.00 (303-L) each (MSWCD, 2021b). Three rain barrels (up to $360) would be more than sufficient in rain harvesting for a typical single-family house of 148 sq. meters (1597 sq. ft) in Mecklenburg County where the annual average precipitation of the past ten years was 120.14 cm (47.30 inches) (NOAA, 2021; Open Mapping Mecklenburg County GIS, 2021). The collected rainwater from rooftops can be used for gardening and other non-potable purposes, which reduces expenses on drinking water. Despite the potential for implementation here, information acquired from Mecklenburg Soil and Water Conservation District (MSWCD) showed that only 31 rain barrels were sold in 2018, 24 in 2019, and less than 20 sold since 2020 due to COVID-19 impacts ([Dataset]MSWCD, 2021a). These small numbers compared to the population in Mecklenburg may be because the rain barrel program is voluntary and is not well-known to the general public. Nonetheless, the MSWCD offers urban cost-share programs where they incentivize GSI adoption by reimbursing up to 75% of the allowable capital cost by the interested residents with a fixed upper limit (MSWCD, 2021c).

e. Behavior

In this study, behavior refers to the actual adoption or financial support of community GSI measures, including household-scale measures and neighborhood/community-scale practices, that primarily require financial support other than direct adoption. It was noticed that, except for one who had extensive knowledge of the technical aspect and had social exposure to people who had strong intentions of engaging in environmental-friendly behaviors, all interviewees did not adopt GSI measures at the moment the interviews were conducted. It suggested that it might be even more challenging for the residents to consider accepting these practices when they had much less knowledge and lived in communities under jurisdictions that had a lower priority on environmental issues, such as sustainable stormwater management. Despite the observed upward intake trend, the adopted GSI measures were mostly for meeting the state or local minimum requirements. Furthermore, many of the limited numbers of residents who had existing GSI measures on their property might not be aware of them, thus, there was a lack of clarity on their responsibilities for maintenance. On the contrary, in the survey administered for this study, the majority of the participants (70.4%) had adopted or financially supported GSI measures. This might be due to the limitation of our sampling strategy for the survey as it excluded potential participants who had no access to the internet or digital devices.

3.3.2.2 Perceived challenges and solutions for the regulatory agencies

In this section, statements from the interviewees were analyzed concerning their observations/perceptions of the institutions they represented. Through this process, two additional codes were generated: perceived challenges and perceived solutions. Upon studying in detail, these challenges and solutions could be categorized into 5 categories with 22 sub-categories (**Table 3.5**), many of which were aligned with the barriers reported in the literature (Dhakal and Chevalier, 2017; Pierce et al., 2021; Veiga et al., 2021; Zhang and He, 2021).

Table 3.5 *Perceived challenges and solutions regarding stormwater management within Mecklenburg County.*

Categories	Sub-Categories
Institutional Internal Constraints	Constrained Institutional Initiatives
	Limited Institutional Recognition
	Vagueness in Regulations
	No Strict Rules
	Low Institutional Capacity
	Lack of Focus
	Funding Sources
	Political Impacts
Existing Infrastructure	Limited Funding Capacity
	Lack of Technical Performance Assessment
	Aging Infrastructure
Economic Factors	Avoiding Long-Term Responsibility
	Cost-Benefit Analysis
Stakeholder Engagement	Lack of Trust
	Demographic Limitations
	Difficulty Accessing Relevant Information
	Lack of Clear Guidance
	Low Public Participation Attraction
	Lack of Relevant Information Sharing
	Limited Knowledge Transfer Among Practitioners
	Lack of Record Tracking
	Lack of Environmental Concerns
Uncertainties/Risks	Extreme Weather Events

In general, the interviewees expressed their efforts in an adaptive approach to managing stormwater within all Mecklenburg County jurisdictions. A promising solution observed by multiple interviewees was the initiatives adopted at the township level as shown in the town of Huntersville in Mecklenburg County, whereas the county-level regulatory agency had less power to upscale the adoption requirement above the towns. Another solution of a capital cost reimbursement program, though not well-known by residents, had successfully motivated several individuals to adopt GSI measures in residential areas. Furthermore, diverged options on the governance of stormwater management could be much more salient among different stakeholder groups (Cousins, 2017). Other common challenges mentioned include a lack of institutional capacity that was due to the limited staffing assigned to the public outreach and engagement programs.

However, these programs could be of significance to cultivate social capital, therefore encouraging the desired subjective norms (Green et al., 2012; Lim, 2018). Using an education campaign of a series of reverse auctions, Green et al. (2012) found a positive increase in GSI measures uptake by the residents. One minor challenge was the access to clear information regarding the residents' concerns. It was noticed that the websites set up for stormwater management within the county are usually collective, and residents are expected to locate the correct policies on the website within the town/city on their own properties (**Appendix 3.5**).

Nonetheless, literature has shown that promoting the use of e-government (online-based access to governmental information and services) could encourage trust in the government and a sense of responsibility (Tolbert and Mossberger, 2006). One study suggested that further efforts could be made by the regulatory institutions to cultivate positive attitudes toward GSI through enhancing public awareness and searching for GSI-related information and getting assistance with relevant programs online (Ozkan and Kanat, 2011).

Due to the scope of this study which was set primarily on enhancing the residents' adoption rate of GSI measures, the identified challenges and solutions for the other four themes are detailed in **Appendix 3.2**. Demographic limitations mostly referred to disposable income for GSI measure adoption, which could be both actual behavioral control and perceived behavioral control as it was influenced by how much stormwater management is being prioritized by the community (subjective norm) and to what extent people considered it necessary to adopt GSI measure (attitude toward the behavior). At the same time, other observed challenges, such as difficulty accessing relevant information, lack of clear guidance, low appeal to public participation, lack of relevant information sharing, insufficient implementation record tracking, and lack of concerns on environmental issues were considered as the major contributors to the forming of non-supportive subject norm and attitude. Thus, we recommend that regulatory agencies take innovative approaches to their existing knowledge diffusion strategies, considering the most observed cognitive biases to enhance residents' awareness of GSI measures first.

3.3.3 Discussions

As pointed out by the theory inventor, Ajzen (2011) acknowledged that the theory of planned behavior, though taking into consideration of normative and control beliefs of behaviors, did not explicitly incorporate the irrationality in human judgment and behaviors that might be already infused in these two constructs. However, it could be difficult to analyze behaviors quantitatively. There should be supplementary term (s) to directly measure irrationality. Some possible irrational behaviors are caused by cognitive biases, such as status quo bias, the anchoring and framing effects, and loss aversion.

Status quo bias that relies on heuristics links to people's preference to either not respond or behave the same way they have been regardless of the outcome of other options (Moshinsky and Bar-Hillel, 2010). In the context of stormwater management, this bias can be observed as the pro-gray mindset where the exclusive use of gray infrastructure is favored as a result of the accumulated familiarity (Dhakal and Chevalier, 2017). This mindset can be related to the problem within the provisioning domain which requires new inputs to create the resources for the new infrastructure systems. With benefits to consumers that cannot be directly measured compared to gray infrastructure, it is likely to observe such attitudes among residents. These attitudes can be attributed to brief development history in the U.S, lack of knowledge diffusion, and lack of comprehensive performance assessment of GSI in the context of the U.S. Additionally, stormwater infrastructure systems, in general, have been given less attention and have limited funding compared to other infrastructure systems (ASCE, 2021). Thus, it naturally stays unclear to the end-users how GSI differs from gray infrastructure.

Different from the pro-gray mindset is the anchoring and framing effects, both of which are caused by the way information is presented. The anchoring effect can influence consumer valuation that is subjective to the arbitrary pre-selected parameters set by the major decision-making authorities (Maniadis et al., 2014). The framing effect is the impact on decision-making caused by the way scenarios or information are presented to the targeted audience (Tversky and Kahneman, 1981). This effect can be partially observed in the synthesized results from the annual survey by Charlotte Mecklenburg Stormwater

Services (CMSWS) (**Figure 3.3 C and D**). Two questions that conveyed the same meaning but were framed differently were asked in the survey. However, the percentages of people who selected the correct answers were inconsistent. If used wisely, these two effects can assist in encouraging environmental-friendly behaviors by using layman's terms in public outreach messages and setting up higher default standards (Li et al., 2021; Shealy et al., 2016; Stillwater and Kurani, 2013).

Last but not least, loss aversion describes the over-proportioned fear of loss compared to the joy over the same amount of gain measured as a utility function (Kahneman et al., 1991). This attitude for GSI can arise due to the lack of understanding of the dynamic urban systems under the temporal limitations in the protection of the expected economic growth. This is in contradiction with the core concept of resilience building - to adapt and recover from external adverse influences. A meta-analysis study quantitatively estimated the effect of loss aversion and found that loss aversion was nearly a factor of two times more than the attraction of gain (Brown et al., 2021). In this study, it can be prominent due to the opposition to investing in GSI measures through capital cost and maintenance while being intentionally or unintentionally oblivious to the long-term benefits. This attitude can also be amplified by a lack of knowledge of the mechanisms within GSI systems. Loss aversion could hinder the adoption of GSI measures by residents and the destruction of the existing resources (i.e., the gray infrastructure). The consequence would interfere with the appropriation of funds for the updating or retrofitting of the existing infrastructure. Additionally, due to the difficulty in excluding unintended beneficiaries that negatively affect access equality and equity, this bias can also create hesitation in taking responsibility for maintenance, which therefore leads to lackluster contributions. On the other hand, loss aversion should not be confused with the precautionary principle, a guideline to propel preventive actions when human health or the environment is jeopardized.

The result of this work suggested a better approach to understanding the public's perceptions of GSI by considering these cognitive biases. Extending from this work is to modify current decision support tools that are specialized in providing sound multi-sector technical solutions (Kazak et al., 2018; Keyvanfar et al., 2021) to evaluate the overall most practical strategies that can meet social acceptance so that GSI measures can operate in favorable conditions on a long-term base. Another valid approach that can be taken at the same time is to propel the consistent use of terminologies that describe nature-based solutions, such as GSI, as it can ease the communication barriers across fields and accelerate the collaborations among researchers, practitioners, and politicians (Moosavi et al., 2021).

3.4 Conclusion and Recommendations

A case study using a combination of an online survey and interviewees was conducted to interpret potential barriers to GSI adoption through the theory of planned behavior. An inconsistency between the findings from the survey and the interviews was identified. It might be due to the limitation of the survey sampling strategy with an over-representation of a certain group of the population (in this case, millennial and middle-aged White males living in larger households with relatively lower income levels than the estimated County average in 2019) or occurrence of the self-reporting bias, which is common in survey-based studies (Rosenman et al., 2011). Another probable reason might be that participants may have misunderstood that paying mandatory stormwater administration fees is not a form of GSI adoption when responding to some survey questions. Logistic regression analysis and multiple regression analysis were conducted to evaluate the survey participants' adoption behavior. Only the attitude construct played a statistically significant role in minimally influencing the intention of an adoption behavior whereas perceived behavior control had a stronger effect on the actual adoption behavior, which suggested that subjective norms were less influential to residents of Mecklenburg County. This finding partially agreed with a similar study that found that subjective norms and perceived behavior control factors (e.g., resources in finance and time) were more determinate on residents' adoption behavior of small-scale GSI measures than personal beliefs and attitudes using several Canadian neighborhoods as the case study (Drescher and Sinasac, 2021). On the other hand, the study conducted by Paul et al. (2016) used an extended version of TPB, which added a new construct of environmental concerns, to explain purchase intention on sustainable goods ("green products") and found out that all but subjective norm significantly predicted such intention. It might suggest that subjective norm is a volatile term and could be highly subjective to the environment in which the population resides. The study suggested the addition of a new construct to account for cognitive biases in the TPB. Three major types of cognitive biases discussed in this paper include status quo bias, anchoring and framing effects, and loss aversion. The perceptual biases of residents in Mecklenburg County were evaluated and interpreted through the angle of urban socio-ecological systems. Cognitive bias, such as status quo bias, which is controlled by heuristics, could magnify this division among populations. When asked what made them form a certain attitude toward GSI, 25.5% expressed their desire to maintain a status quo and 18% mentioned they were either unfamiliar with the subject or opted to rely on instincts. Despite not being identified in this study, framing and anchoring effects can either mislead the audience or be harnessed to promote desired information as can be seen in Leadership in Energy and Environmental Design (LEED) rating systems and Envision frameworks (Dunford and Gillis, 2019).

The recruitment process of both interview and survey participants was somewhat limited due to resource constraints such as participant incentives and the study time frame; thus, the results may only reflect partial opinions toward GSI within the study area. The future work to address it could be through 1) the inclusion of the opinions from land developers, environmental consulting firms, and representatives from local Homeowner Associations (HOA); 2) diversifying the means of recruiting survey participants throughout the study area via phone calls, post mails, and other means.

As an applied practice of the precautionary principle in the context of environmental science, challenges to GSI could be approached by regulatory agencies by identifying possible Type III errors (problems that are ill-defined or ill-structured) in public outreach programs by attentively understanding the citizens' concerns and joining interdisciplinary efforts to provide tailored assistance (Kriebel et al., 2001). It could help encourage people's intention to adopt GSI measures gradually, which can be gauged by the willingness to pay, and eventually upscale the implementation rate within the county. For example, a study has explored the potential of public engagement of the younger generations through an intergenerational forum to a better understanding of the surrounding elderlies who may have been marginalized due to poor health conditions or low technological literacy, therefore preparing the future workforce to design effective and inclusive public outreach programs, bridging the generational gaps (Lee and Kim, 2017). Following this study, future studies can include quantitative modeling to explore the driven forces and resistance to GSI adoption in residential areas concerning community buy-in in collaboration with technical design and planning. In conclusion, effective knowledge diffusion regarding GSI is of utmost importance in reaching urban resilience. The insights from this work could be additionally adapted to small-scale innovative infrastructure technology adoption, such as energy-saving equipment, and food waste compost bins in urban regions.

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Appendix 3.1 Survey Questions Instrumented for the Study.

1. Please indicate the county of your primary residence in North Carolina.

    - A drop-down menu of the 100 counties of North Carolina[a].

2. What is the primary housing type of your residence?

    - Private homeowner (single-family home, townhouse, etc.)
    - Rental (apartment or dormitory, etc.)
    - Public housing (funded by not-for-profit organizations or government, etc.)

3. In your opinion, out of the five major physical infrastructure sectors (transportation, water - including wastewater and stormwater, waste management, energy and power, and recreation facilities), how important is water infrastructure?

	Not at all important	Unimportant	Somewhat unimportant	Neutral	Somewhat important	Important	Extremely important
Perceived importance	○	○	○	○	○	○	○

4. Which of the water infrastructure-related activities below have you engaged in in the past? Please select all that apply.

    - Participated in Adopt-a-River program
    - Practiced water conservation measures (such as rain gardens and barrels)
    - Reduced chemical use and improper waste disposal (such as fertilizers and pesticides used for lawn care; detergents and motor oil resulted from car wash; household chemicals and paints; and bacteria in pet waste)
    - Reduced the amount of pavement on your property
    - Kept septic systems well-maintained by checking leakage often
    - Other. Please specify ____
    - None of the above

5. Stormwater management is referred to as the efforts to reduce runoff resulted from excessive rainwater or snowmelt and control water pollution from non-point sources. Stormwater infrastructure is the physical measure to execute designed stormwater management strategies. How well do you think the current stormwater infrastructure is doing in terms of controlling stormwater runoff and associated water pollution?

	Very poor	Poor	Below average	Neutral	Acceptable	Great	Excellent
Perceived performance	○	○	○	○	○	○	○

6. Conventional stormwater infrastructure usually relies on gutters, pipes, and culverts to quickly divert runoff from roads. Another type of stormwater infrastructure, known as green stormwater infrastructure (GSI), mitigates stormwater runoff volume and controls water quality through natural processes such as infiltration and evapotranspiration. (Note that GSI is also commonly interchangeable as *stormwater best management practices (BMPs)*. To keep consistency and ensure clarity of this study, we will only use *GSI* throughout this survey.) Based on the short description of the two forms of stormwater infrastructure, what is your familiarity with GSI?

	Completely unfamiliar	Unfamiliar	Somewhat unfamiliar	Neutral	Somewhat familiar	Familiar	Extremely familiar
Your perceived familiarity with GSI	○	○	○	○	○	○	○

7. How have you learned about GSI? Select all that apply.

- o Social Media (Twitter, Facebook, Reddit, YouTube, etc.)
- o Newspaper, radio, magazine, or television
- o Friends or relatives
- o Family members
- o Internet

- o Governmental regulations/policies
- o Work
- o School
- o Local contractors, land developers, engineering consultants, etc.
- o Other platforms. Please specify. ____
- o None of the above

8. What is your attitude toward GSI regardless of your familiarity with it?

	Strongly opposing	Opposing	Somewhat opposing	Neutral	Somewhat supportive	Supportive	Strongly supportive
Attitude toward GSI	○	○	○	○	○	○	○

9. Based on what reasons did you make the choice in the previous question? Select all that apply.

- o Unfamiliar with the subject/rely on instincts
- o Wish to keep updated with the latest innovations
- o Want to keep things the way they were
- o Follow the mainstream opinions
- o Adventure to be unconventional
- o Consider the evidence of historical success and feasibility
- o Support research and development (R&D) regardless of apparent benefits
- o Seek for the greater goods for the society (human well-being, environmental protection, educational value, etc.)
- o Have personal values, beliefs, and/or worldviews
- o Aspire to mitigate environmental risks
- o Other reasons. Please specify ____

10. Please read this information before you move on to the next question.

The following examples are some commonly used GSI practices in Mecklenburg County.

Image and description sources:

Charlotte-Mecklenburg Storm Water Services. (2013). Charlotte-Mecklenburg BMP Design Manual. Retrieved from *https://charlottenc.gov/StormWater/Regulations/Pages/BMPDesignStandardsManual.aspx*.

USEPA. (2020). What is Green Infrastructure? Green Infrastructure. Retrieved from *https://www.epa.gov/green-infrastructure/what-green-infrastructure*

Bioretention: "shallow stormwater basin or landscaped area that utilizes engineered soils and vegetation to capture and treat runoff", can be used around parking lots and household backyards (Charlotte-Mecklenburg Storm Water Services).

Wet Ponds: "have a permanent pool, a temporary pool, and typically a littoral shelf with planted vegetation", typically seen in national parks (Charlotte-Mecklenburg Storm Water Services).

Grass Swales: "vegetated open channels that are explicitly designed and constructed to capture and treat stormwater runoff by limiting the slope in the direction of flow or within dry cells formed by check dams or other means", commonly used in the median of highways (Charlotte-Mecklenburg Storm Water Services).

Infiltration Trenches: "excavated trenches filled with stone aggregate used to capture and allow exfiltration of stormwater runoff into the surrounding soils from the bottom and sides of the trench", commonly seen along with sidewalks and around parking lots (Charlotte-Mecklenburg Storm Water Services).

Extended Dry Ponds: "a storage facility designed to provide water quantity control and some water quality control through detention and/or extended detention of stormwater runoff", usually placed near streams and lakes (Charlotte-Mecklenburg Storm Water Services).

Rainwater Harvesting: devices that collect and store rainfall from rooftops for non-portable reuse, typically used by households (USEPA).

If some of the described GSI practices were to be adopted by your community or on your property, how acceptable will they be to you?

	Extremely unacceptable	Unacceptable	Somewhat unacceptable	Neutral	Somewhat acceptable	Acceptable	Extremely acceptable
GSI Acceptance	○	○	○	○	○	○	○

11. What would you expect GSI to achieve the most if they were to be built in your community or on your property? Please select all that apply.

- o Control/reduce flash flood/ flood severity
- o Minimize pollution caused by floods
- o Enhance aesthetic values of the neighborhood
- o Stabilize air, building, and surface temperature during sunlight peak hours/ reduce energy use
- o Reduce water bills/ provide tax credit or rebate, etc.
- o Provide wildlife habitats/ enhance biodiversity
- o Recharge groundwater
- o Others, please specify ____
- o None of the above

12. What would concern you the most if GSI were to be built in your community or on your property? Please select all that apply.

- o Need of capital cost
- o Long-term commitment in the form of fees and maintenance cost
- o Failure to deliver supposed improvement to stormwater runoff
- o Possible discord within the regulatory community or laws
- o Requirement of additional land space
- o Demand for additional governmental staff, funding, and other resources
- o Uncertainty in the reliability of GSI measures

- Potential infestations of aquatic insects (such as mosquitoes)
- Others, please specify ____
- None of the above

13. What forms of incentive would motivate you the most to support GSI adoption in your community or on your property? Please select all that apply.

- Tax reduction/Rebates
- Discounts or credits
- Reductions on stormwater-related fees
- Reliable evidence of the benefits of GSI to the environment
- Reliable evidence of economic benefits of GSI to you other than the first three choices
- Opportunities to participate in the decision-making process on GSI installation in your community
- Other benefits, such as the sense of social justice
- Others, please specify ____
- None of the above

14. What is the maximum amount you would be willing to pay to install a GSI measure in your community or on your property?

Enter the amount in USD ____

15. Have you (including any of your household members) adopted or financially supported the adoption of any GSI practices?

- Yes
- No

16. For what particular reasons did you choose to adopt GSI practice(s)?

- Tax reduction
- Rebates/credits

- ○ Reductions on stormwater-related fees
- ○ GSI's benefits to the environment
- ○ GSI's economic benefits to you other than the first three choices
- ○ Opportunities to participate in the decision-making process on GSI implementation in your community
- ○ Other benefits, such as the sense of social justice
- ○ Others, please specify ____
- ○ None of the above

17. How likely are you to recommend GSI to others based on your own experience?

	Not at all likely	Unlikely	Somewhat unlikely	Neutral	Somewhat likely	Likely	Extremely likely
Likelihood to introduce GSI to others	○	○	○	○	○	○	○

18. How likely would you discuss stormwater infrastructure (or stormwater management in general) with others who <u>have similar opinions</u> to yours?

	Not at all likely	Unlikely	Somewhat unlikely	Neutral	Somewhat likely	Likely	Extremely likely
Likelihood to exchange opinions	○	○	○	○	○	○	○

19. How likely would you discuss stormwater infrastructure (or stormwater management in general) with others who <u>have different opinions</u> than yours?

	Not at all likely	Unlikely	Somewhat unlikely	Neutral	Somewhat likely	Likely	Extremely likely
Likelihood to exchange opinions	○	○	○	○	○	○	○

20. To what extent do you think you have to follow suit when people around you engage in sustainable stormwater management, such as GSI adoption?

- Will not influence me at all
- Not until the vast majority I know are doing so
- Not until around half of the people I know are doing so
- Will feel pressured after noticing a few people doing so
- Always the first one to participate and to encourage others to follow

21. Do you have any suggestions on what aspect(s) of stormwater management should be improved in Mecklenburg County?

- Set higher regulation standards for runoff reduction and runoff-induced pollution control
- Receive more relevant information on GSI in plain language
- Present more evidence of environmental threats related to stormwater
- Provide more opportunities to be engaged through government-led programs
- Show more initiatives from the private sectors, such as land developers and engineering consulting firms
- Conduct more research efforts in reducing risks and costs of GSI measures
- Secure more public funding sources to support GSI implementation
- Cultivate Eco-conscious attitude and behaviors through K-12 public school programs
- Others. Please specify ____
- None of the above

22. What is your household size?

- Single
- Two to four
- Five and above

23. What is your gender?

- Male
- Female
- Non-binary / third gender

24. Which age group are you in?

- 18 to 24
- 25 to 44
- 45 to 64
- 65 and over

25. What is the highest educational degree you have received?

- None
- High school diploma
- Some college or Bachelor's, etc.
- Graduate (Master's or Ph.D., etc.)

26. What is your race?

- White
- Black or African American
- Latino/Hispanic
- Asian
- American Indian and Alaska Native
- Native Hawaiian and Other Pacific Islander
- Two or more races
- Others

27. What is the estimated gross income level of your household?

- Less than $45,000

- $45,000 to $65,000
- $65,001 to $85,000
- $85,001 and more

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[a] If ‘Mecklenburg’ is not selected, the survey terminates itself without proceeding to the next question.

Appendix 3.2 Synopsis of the Perceived Challenges and Solutions Stated by Interviewees.

Theme	Sub-Theme	Perceived Challenges	Perceived Solutions
Institutional Internal Constrains	Constrained Institutional Initiatives	"We've done research on [green stormwater infrastructure] and we support them, but we don't have as much an impact (as the state)."	"We are trying to work more directly with [surrounding jurisdictions within the county]. We're sort of exploring those opportunities, right now, especially for things that are a little bit smaller and therefore we would be a little bit more cost-effective for some of the smaller things [...] As a district, we have a great relationship with the city, county and we have a well-developed stormwater utility. … Because they have such a robust program, they're knowledgeable."
	Limited Institutional Recognition	"People don't know [our district] exists [even if] we have been around [...] since 1963. [Not] a fraction of the county even knows who we are."	"We did send out postcards to, I think, about 600 people who had open requests for stormwater services. [...] It did not get us enough response. We need to figure out a more targeted outreach. […] But working with a board, where we have turnover over time, and everybody's got other full-time careers and things that can be a little bit tricky for us to figure out like the best way to do that. A lot of what we do is the word of mouth or referrals."
	Vagueness in Regulations	"Interpretation [of state law and administrative codes] can vary widely on the same requirement. I'd say that there are conflicts that are real or perceived in different requirements. [...] You may interpret something in a manner that makes it feasible."	"I think [...] if there are two laws conflicting [between the ones created by the state-level and the federal-level agencies], then we bring them to the attention of the lawmakers and try to get them to craft the code in a manner that there's enough room in interpretation, there's enough latitude so that both the standards could be met."

Theme	Sub-Theme	Perceived Challenges	Perceived Solutions
	No Strict Rules	"[Regarding the penalties for not adopting GSI measures or performing proper maintenance] none that I know of. Once a person moves into a property, those items are already there."	"I do think that we have to modify our current approaches regarding stormwater management. There's the design, implementation, the performance, the evaluation, and then the redesign (process circle). I think, as long as we are meeting our targets… and embracing the value of our surface water resources.
	Low Institutional Capacity	"We are understaffed, especially for the size of the county that we're in, the number of issues that are out there that could be addressed with our programs. [...] A lot of times we need engineering support, and we share the state engineer that we work with 33 other counties. It takes a long time. That's probably part of why we don't always do as much as we could in terms of the need that's out there and people who might be willing to do it. For us, capacity building is going to be our biggest challenge, rather than changing the way we approach actual stormwater BMPs.	"I do think that we have to continually modify our approach regarding stormwater management and continue to put information out there."
	Lack of Focus	"We're not looking at whether somebody meets the criteria [for our cost-share programs] that they were required by law to meet or, due to a violation or something like that. [...] We don't have enough resources to [prioritize certain regions]."	"We did, at the beginning of our cost-share program, give higher priority to watersheds that are more impaired. [...] We haven't, recently, had enough competition to where we're super honed in on [the most impaired watersheds] because we have sufficient funding right now with the staff that we have available to be able to address most of the issues that rank high enough to qualify for our programs. We write a strategic plan every year for our state programs."

Theme	Sub-Theme	Perceived Challenges	Perceived Solutions
	Funding Sources	"[Our district] doesn't work for the county. The county is generous with the funding they give us as the city of Charlotte. However, we don't quite belong to them. It's not the same for us to [ask for funding from the County]."	"If you ignore stream restoration work and alongside that, we might try to implement something. And we'll try to go for grants like Clean Water Management Trust Fund grants, or other money, to enhance projects that we're already doing."
	Political Impacts	"I feel like sometimes environmental quality issues tend to fall along these lines where if you're liberal you believe in environmental quality and if you're conservative you think that we should exploit all of them to our own benefit."	"I think that anything we could do to soften the political ideology attached to things like the stormwater management regime would probably be a benefit in the long run. so that would be my only suggestion."
Existing Infrastructure	Lack of Trust	"We had a lot of interests in our program, but we also had a lot of people who thought we were going to come to landscape their yards."	NA
	Limited Funding Capacity	"When you get into things that are in a true floodplain, where you're talking about like a FEMA floodplain, the level of permitting and, risk, and studies that have to go into that are typically kind of cost-prohibitive for us to be able to do [with our cost-share programs]."	"[Our district] at least in North Carolina is unique in that we, along with probably a couple of other entities, are able to put public money on private land without an easement. Our urban cost-share program [...] has funding from the city of Charlotte […], and from Mecklenburg County [...]. We have funding currently from the Clean Water Management Trust Fund […], but there are restrictions on which practices we can do. We have had an EPA section 319 grant for that. Before, we've also had other EPA grants. [...] We've applied for other grants. We could continue to look for other grants and may expand the funding. That is allocated and managed directly by our board with input from our

Theme	Sub-Theme	Perceived Challenges	Perceived Solutions
			partners in terms of what we do with the funding, but we have set practices that are included in that program."
	Lack of Technical Performance Assessment	"I think there's so much research still to be done that. […] You're still studying and learning and trying to figure out especially with new [GSI] practices on how effective they are, how effective they are over time, rates of failures, and things like that."	"The performance [monitored at] the inlet and the outlet, and the pollutant loads coming and pollutant loads leaving the actual infrastructure."
	Aging Infrastructure	"I know the [stormwater infrastructure] systems are getting overwhelmed pretty frequently as we get these heavier rainstorms."	"The [cost-share] program is new. […] We've realized recently that there's a niche for some of these smaller stream projects that are probably like where we can have the most impact, rather than paying for rain barrels and cisterns and things like that. Those are not bad things but are probably not the best use of our limited funds in terms of the impact that we can have."
Economic Factors	Avoiding Long-Term Responsibility	"But I don't think that they understand that if we implement many LID techniques, especially if we take care of them on a municipal level, this is going to improve water quality and reduce flooding but at a real cost to the community. That cost in the future is billions of dollars. No one wants to hear that or is prepared to understand the ramifications of that number because it is a staggering number.	"I think that the utility is key in shaping the direction [of stormwater management]. I think that they have a key role to play and that their influence in that role is largely responsible for most of the general knowledge that is in our citizenry is the essence at this time. I think that it is essential that the utility continues to exercise that role and learn from the previous attempts or previous campaigns. We implement, refine, educate, and implement again. You just keep going through that cycle and hopefully getting better each time."

Theme	Sub-Theme	Perceived Challenges	Perceived Solutions
	Cost-Benefit Analysis	"I don't know that we have any incentive. But we did, at one point, do a pilot BMP Program. The initiative would say that we will pay for half the cost to install a BMP on their property. But I don't think anyone signed up.”	"Not every municipality around us offers the same services the CMSWS does. That means that comes down to the fee money that they're able to collect from the number of impervious surfaces. But it's not even an option, and some counties around us only work on public land. If you get to the point where your house is falling and that they probably will come in and try to address it. But we're able to address those things before it gets to that point."
Stakeholder Engagement	Demographic Limitations	"My experience has been less of people who didn't necessarily want to do something good, more so was it feasible [with sufficient disposable income].	NA
	Difficulty Accessing Relevant Information	"I know our website can be confusing about [relevant stormwater management policies]. Even if you look at our website, sometimes the contact person might have a CharlotteNC.gov email address, and sometimes the contact person might have a MecklenburgNC.gov. That's why. It just depends on the program and the jurisdiction and how everything is set up."	"We do an annual public opinion survey, our resident survey. We ask them to have heard of our messages, what they thought of our messages, how they would like to receive information about that kind of thing."

Theme	Sub-Theme	Perceived Challenges	Perceived Solutions
	Lack of Clear Guidance	"My experience has been less of people who didn't necessarily want to do something good, more so was it [...] people don't understand that the stream is their responsibility. […] There's a lot of misunderstanding on some of those things sometimes as to what exactly they mean or what their purpose is."	"I tried to keep it as simple as possible. I think there are technical terms that get outside of the realm of what most people understand. I think that the way we try to explain things to people, we try to be pretty clear and pretty concise."
	Low Public Participation Attraction	"We have monthly advisory committee meetings that are open to the public. And then we rarely get public comments on that."	"We do try to go into those sorts of [public outreach] events, and interface with the public there, answer questions, and raffle off a rain barrel to get people to come to talk to us."
	Lack of Relevant Information Sharing	"We interact with the public, but we don't talk about [GSI]. We talk more about stormwater pollution, volunteer programs, and educational presentations that we do at the school. […] I don't deal with residents who are having things built on their property."	NA
	Limited Knowledge Transfer Among Practitioners	"My experience with especially dealing with stream stuff is that a lot of people have a lot less understanding in the field than I would think that they would. [Some engineers that work with us] may understand more of the efficacy from a data perspective, but the hands-on application is not as well understood as I would sometimes expect."	NA

Theme	Sub-Theme	Perceived Challenges	Perceived Solutions
	Lack of Record Tracking	"Larger BMPs […], I don't know how well they're providing people with the information that they need. [...] [The individual may not be required], but the community probably needs to know more about what happens if it starts to fill in [etc.]. Those are things that I don't know if it's necessarily that they're not given that information at the beginning, or if it's like the telephone game over time of people move in and out of the community, and somebody transfers the words over to the next person, and then by the time you're done, they have no idea whether it was a stormwater BMP or an old farm pond because nobody's got any reference to that. I think that's probably more of an issue that has been in for a while now."	NA
	Lack of Environmental Concerns	"[Some residents] think 'I've got my own yard now, what does it matter if my dog wastes stay in my yard', or 'I've got my own yard, now I want it to be pretty, so I'm going to use these chemicals as much as I want without considering that the fertilizers in runoff can cause problems in their downstream BMPs or that their dog waste might contribute to high bacteria levels in stormwater runoff. It's a lack of understanding."	"The town of Huntersville [has a higher adoption rate because it] has more work invested in green infrastructure."

Theme	Sub-Theme	Perceived Challenges	Perceived Solutions
Uncertainties/ Risks	Extreme Weather Events	"We have had issues where we have had 50-year storm events come in the day after we installed the project, more than once, which are the sites not prepared to handle that because it was just installed the day before."	NA

Appendix 3.3 Descriptive Statistics of the Likert-Scale Questions.

Variables	N	Min	Max	Mean	Std. Deviation
Perceived Importance of Water Infrastructure	510	3	7	5.61	1.12
Perceived Performance of Stormwater Infrastructure	510	1	7	4.90	1.07
Perceived Familiarity with GSI	510	1	7	4.84	1.19
Attitude toward GSI	510	3	7	5.43	1.03
Acceptance of GSI	510	1	7	5.56	1.13
Likelihood to Exchange Opinions with Similar	510	1	7	5.38	1.12
Likelihood to Exchange Opinions with People of Dissimilar Opinions	510	1	7	4.96	1.31
Likelihood to Introduce GSI to Others based on Personal Experience[a]	359	3	7	5.55	1.02
Peer Pressure[b]	510	1	5	3.45	1.29
Adoption Experience[c]	510	0	1	0.70	0.46

[a] It is a follow-up question to survey participants who expressed existing adoption experience.
[b] It is on a 5-point ordinal scale with 1 as not impacted by peer pressure at all and 5 as always taking the initiative to motivate others.
[c] It is a binary variable with 1 indicating adoption, 0 indicating no adoption experience.

Appendix 3.4 Coding Results.

Codes	Number of References	Agreement Between Coders (%)	Qualitative Summary (N=4) – Global Patterns	Corresponding Survey Results – Local Behaviors
Attitude	61	96.01	The general responses were that the public's attitude varied widely depending on the citizenry's residing jurisdictions and whether they lived in a flood-prone area.	A mean attitude of above 'supportive' toward GSI measures in general and mean acceptance of GSI adoption (5.43 ± 1.03 and 5.56 ± 1.13, respectively)
Behavior	22	99.39	It might be challenging for the residents to consider accepting GSI practices who have little relevant knowledge and live in communities under the jurisdictions that had a lower priority on environmental issues	The majority of the participants (70.4%) had adopted or financially supported GSI measures
Intention	13	98.96	The attitude and intention of residents varied vastly due to the influence of their affiliated jurisdiction, proximity to floodplains, and social background.	The median and mode of willingness to pay were $300 and $100, respectively
Perceived Behavioral Control	32	96.30	The physical separation and knowledge separation (i.e., the proximity to GSI measures and the exclusive knowledge to the technical experts) were some of the causes for the lower awareness and familiarity with GSI measures among residents.	Our survey result observed a mean familiarity of 'somewhat knowledgeable' (4.84±1.19)
Subjective Norm	20	96.08	The institutions/organizations on the higher hierarchy ladder have greater influence on taking initiatives to disseminate relevant information, encouraging local utility and then communities to follow. News media coverage might also have contributions.	The survey question asked the perceived importance of peer pressure, yielding a relatively positive result, indicating the survey participants were more likely to be the ones taking the initiatives to adopt GSI measures (3.45 ±1.29 on a 5-point ordinal scale)

CHAPTER 4. MODELING THE ADOPTION OF GREEN STORMWATER INFRASTRUCTURE CONSIDERING COGNITIVE BIASES[3]

4.1 Introduction

Traditional gray stormwater systems in urban areas are progressively strained due to physical deterioration and rising demands associated with urbanization. Additionally, intensified and more frequent rainfall events that result in increased flooding in some areas show the inadequacies of solely depending on conventional gray stormwater infrastructure to mitigate these impacts. Green stormwater infrastructure (GSI), a nature-inspired engineering solution, has emerged over the past three decades to address contemporary stormwater management concerns by mitigating stormwater runoff quantity and quality at its source. Studies have shown that GSI systems promote natural infiltration, evapotranspiration, retention, and reuse of on-site stormwater while providing additional socio-ecological benefits to local watersheds and reducing energy consumption for water treatment due to higher demands and more rigorous water quality regulations (Lennon, 2015; Pabi, Amarnath, Goldstein, & Reekie, 2013; Spatari, Yu, & Montalto, 2011). However, GSI is still underutilized in some urban areas, particularly on private properties, due to several barriers such as funding limitations, institutional barriers, cultural barriers, lack of engagement, and cognitive barriers (Dhakal & Chevalier, 2017; Johns, 2019; Qi & Barclay, 2021).

Considering these barriers, especially lack of engagement and cognitive barriers, there is a need to further understand residents' decisions to implement GSI on their property. This understanding can lead to the design of more effective intervention strategies that promote GSI adoption and implementation on a wider scale in residential areas and private property. Thus, this work aims to model the adoption of GSI measures in residential areas by incorporating the cognitive biases of residential-based adopters. To study the impact of cognitive biases on GSI adoption, this work is framed by the theory of planned behavior and uses agent-based simulation to model and test the selected cognitive biases' impact.

[3]At the time of ProQuest submission, this article was under consideration and undergoing review by Elsevier's Journal of Environmental Management.

4.1.1 Cognitive Biases and Green Stormwater Infrastructure Development

Cognitive biases are the departure from standards of logic and accuracy, which reflect how the mind comprehends the world (Haselton, Nettle, & Murray, 2015). Simply stated, biases can deter people from making optimal decisions. Therefore, there is a need to consider cognitive biases when designing engineering decision support tools for public engagement strategies, particularly for public projects with constrained resources and budgets, such as stormwater infrastructure projects. Often in the case of environmental concerns short-term personal gains may be insignificant or even intangible for those in the wider community; but long-term, community-wide gains are usually much stronger. Human behavior conceptualization in recent theories challenges the fallible assumption of rationality with various psychological and sociological factors (Anebagilu et al., 2021). Thus, the study of cognitive biases in environmental decisions warrants further research to determine their impact on human behaviors regarding environmental issues.

The two cognitive biases being studied for this work are status quo bias and loss aversion. Status quo bias may occur for many reasons, which challenge the well-established rational decision-making theory, such as other cognitive misconceptions including loss aversion (Samuelson & Zeckhauser, 1988). This seminal work highlights two patterns of status quo bias: the status quo is less favored when the alternative options are more appealing to individuals; and the more alternatives, the more likely the individual will maintain the status quo. On the other hand, loss aversion stems from the asymmetrical valuation of utility between losses and gains where the decision makers are much more sensitive to the losses compared to gains (Tversky & Kahneman, 1991). Because of this, loss aversion can contribute to the status quo bias. Using rain barrel purchase as an illustrative example, if the cost of a barrel is $40, the person with a strong degree of loss aversion would feel the loss stronger after the purchase compared to which from the gain of earning an equal amount in benefit as an expected reward. Thus, there may be a preference to keep the status quo, which is the original state of not owning a new rain barrel.

These biases are recognized in the literature and studied in the context of GSI to address decision-making towards its selection and adoption (Dhakal & Chevalier, 2017; Hu & Shealy, 2020, 2022). In a study by Carlet (2015), 20% of the interviewees pointed out the lack of community support and outreach as a barrier to GSI. Also, their findings showed that a lack of interactions with GSI information could lead to status quo bias. They further stated that only focusing on raising awareness through policies and campaigns or having a positive attitude will not spur substantial behavioral changes. Attitudes and actions are difficult to change if the performance and values of GSI cannot be directly measured and communicated (Chaffin et al., 2016). Addressing the status quo and loss aversion bias can help to break down cognitive barriers to GSI.

4.1.2 Theory of Planned Behavior

One framework that conceptualizes bounded rationality in human behavior is the theory of planned behavior (TPB) (**Figure 4.1**). This theory utilizes background information surrounding the behavior that is easier to obtain through methods such as local interactions and surveys (Ajzen, 1991; Anebagilu et al., 2021). In addition, TPB has been extensively studied on behavioral achievements that yield apparent and perceptible benefits to individuals and was proven its overall predictive validity. A recent study applied TPB using collected survey data to evaluate the installation of GSI in residential areas, and its results revealed that social norms and perceived control behaviors had a greater impact on residents' decision-making regarding GSI implementation in the studied area (Drescher & Sinasac, 2021).

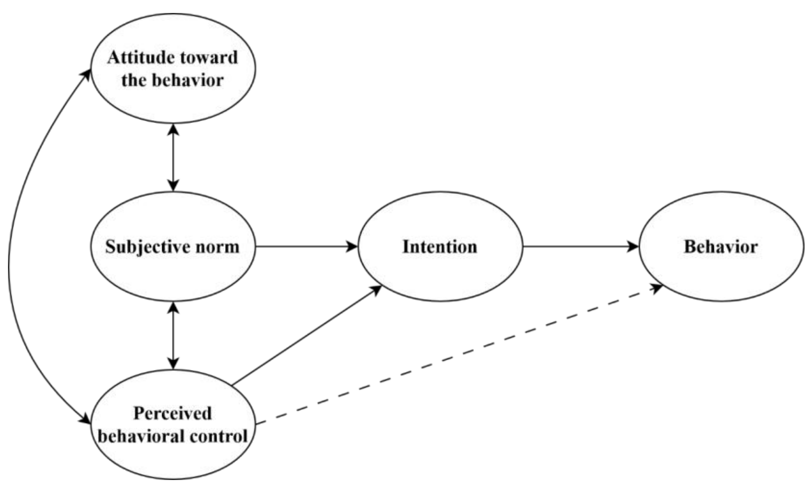

Figure 4.1 *Theory of planned behavior (Ajzen 1991, pg. 182).*

However, as mentioned by the author, TPB still has the potential to be further improved (Ajzen, 2020). The finding in the work by Caffaro, Roccato, Micheletti Cremasco, and Cavallo (2019) showed that subjective norms were less relevant to farmers' decisions to adopt agroforestry practices compared to attitude and perceived behavioral control. It might suggest that TPB needs to be modified based on context. Furthermore, it might require adaptation for behaviors related to environmental issues which provide less short-term observable benefits. This can be supported by the empirical data in the work by Gray (2021), which extensively analyzed the cognitive and perceptual barriers in GSI decision-making.

By design, TPB indirectly incorporates distortions in people's thinking patterns for decision-making. However, it still poses a challenge to quantitatively study the populations' behaviors when assessing individuals' values in each of the constructs potentially interfered with by survey bias (Kormos & Gifford, 2014). By explicitly incorporating the cognitive bias factors into the TPB model, it can, to a certain degree, compensate for biases that are commonly observed in human subject studies. The empirical human subject studies based on which behavior models including TPB are derived may be subjected to many errors, especially self-report bias. Given these types of models are commonly used to inform social policies, failure to address these errors could negatively impact the effectiveness of such policies. However, it could be financially inhibitive to most research entities studying pro-environmental behaviors to administer survey studies that minimize these errors to the greatest extent where the financial burden is perpetually stressed in the literature (Koller, Pankowska, & Brick, 2023). This work explicitly considers two possible biases to cost-effectively compensate for these survey-based errors.

4.1.3 Agent-Based Modeling for Behavioral Simulation

Among all simulation models, agent-based modeling (ABM) is advantageous for its capacity to simulate individual-level actions without the intervention of a central force. When used together with established behavioral theories, ABM is suitable for simulating human behavioral patterns (Jager & Mosler, 2007), such as the adoption of GSI measures. A review of the application of ABM in sociology has revealed that ABM has enhanced the existing sociological modeling theorization; that it has made it easier to analyze how social structures influence human behavior; and that it has generated insights on how social structures and individual behavior interact (Bianchi & Squazzoni, 2015). As demonstrated in Montalto et al. (2013), ABM was used in the GSI-based study as it has the capacity to 1) predict trends and 2) the flexibility to explore diverse relationships between different types of agents. The latter can support the testing of the validity of theories on certain phenomena/behaviors, investigate the probable intervention strategies, develop simulations that combine social science theories and physical systems, and therefore provide insights as decision support for major decision makers.

There have been several studies that applied ABM in the context of water, wastewater, and stormwater management. A simulation study by Zidar et al. (2017) using ABM concluded that the participation of private landowners is significant in contributing to the long-term reduction of combined sewer overflows. The study showed that tailored GSI implementation strategies by land use types might be essential to achieving sustainable redevelopment. Brown et al. developed an ABM model focusing on the economic aspect of long-term GSI adoption in response to incentives for private property owners (2021).

4.1.4 Research Questions

The objective of this study is to model GSI adoption in residential areas by accounting for cognitive bias barriers of those residents. This work applies a human behavior-centered approach to quantitatively consider this barrier and its impacts through ABM. The model presented gives a foundational framework based on TPB to extend quantitative assessments of barriers to GSI adoption and implementation. The model can be modified and expanded to account for the impacts of other barriers in this context. For instance, additional barriers to GSI adoption such as governance and resource barriers can be added to this model, and/or the “agents” or decision makers can be an alternative group, such as those who make institutional or design decisions. Overall, the understanding developed in this research study can help the appropriate authorities develop corrective actions to cognitive biases of GSI and accelerate community buy-in. To fulfill the study objective, the research questions that directed this study are:

1. How do the status quo and loss aversion cognitive biases impact the GSI adoption trajectory in residential areas over a 10-year timeframe?

2. How does the percentage of initial adopters affect the long-term adoption trend of GSI in residential areas?

The model is applied to a case study with locally sourced data that adjusts the model parameters for better reflection on the regional GSI adoption patterns. The simulation shows the adoption behavior of residents on GSI practices in general, using the survey and interview data acquired in a case study. The simulated agents are households within Mecklenburg County whose behaviors are modeled using TPB.

4.2 Methodology

4.2.1 Study Area

Mecklenburg County, sitting on a roughly 550-square-mile piedmont region, contains 33 sub-watersheds. It has a population density of approximately 2,130 per square mile with an impervious surface coverage of roughly 16% as of 2021. The predominant residential land use is single-family homes (**Figure 4.2**). The stormwater best management practices (BMP, an umbrella term for both structural and non-structural stormwater management practices where a portion of structural BMPs are considered GSI practices) show that within residential areas, the most applied GSI measures are sand filters. This data was obtained via the Charlotte Mecklenburg Stormwater Services (CMSWS), the local stormwater agency. Although there is no information on the implementation of rain gardens or rainwater harvesting systems available, the sales records of recent years indicate that some entities or individuals within the county have started utilizing rain barrels (even though the entities might also include commercial/industrial organizations). The data collected for this case study was through an online survey detailed in the work by Qi and Barclay (2022) with a total sample size of 510. The key summary of the dataset used in this study is shown in **Table 4.1**. All items in the table, except the willingness to pay and the impact of peer pressure, were evaluated through Likert-scale questions on a 1-7 scale with a least likely/least favorable as 1 and most likely/most favorable as 7.

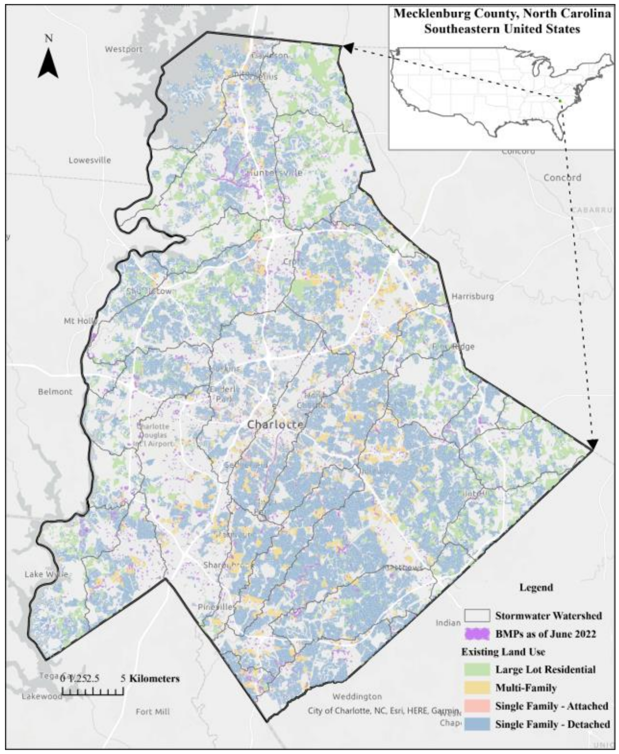

Figure 4.2 *Locations of structural BMPs in residential areas in Mecklenburg County, NC.*

Table 4.1 *Survey statistics.*

Survey Question	N	Mean	Median	Std. Deviation
Water infrastructure importance	510	5.61	6	1.12
Perceived familiarity with GSI	510	4.84	5	1.19
Perceived stormwater infrastructure performance	510	4.90	5	1.07
Attitude toward GSI	510	5.43	6	1.03
GSI acceptance	510	5.56	6	1.13
Likelihood to exchange opinions with similar	510	5.38	5	1.12
Likelihood to exchange opinions with dissimilar	510	4.96	5	1.31
Peer pressure impact[a]	510	3.45	4	1.29
Likelihood to introduce GSI to others[b]	359	5.55	6	1.02
Willingness to pay, $[c]	510	3352.21	300.00	26962.93

[a] Impact of peer pressure was measured on a 1-5 scale with 1 representing least susceptible to peer pressure and 5 as extremely susceptible to peer pressure.
[b] This question was only given to those who indicated existing GSI adoption experience.
[c] Willingness to pay was measured in dollar amount that each survey participant would like to pay for GSI development.

4.2.2 Model Construction

The purpose of this model is to simulate the adoption behaviors of Mecklenburg County residents for household-scale GSI practices or the communal GSI they can support financially. The novelty of it is that it incorporates cognitive biases into the behavior rules to better simulate the adoption process, therefore, better reflecting the realistic adoption patterns. These insights generated can be referenced by local regulatory agencies to design targeted public outreach programs. Scalco, Ceschi, and Sartori (2018) stressed the necessity of statistical analyses to evaluate the applicability of TPB to the behavior under study before constructing the model. Following that, statistical analyses are needed to establish the weights of each antecedent of intentions. The parameter setup within the model is derived from the survey results using logistic regression. The economic aspects taken into consideration in this model are as follows. A technical report estimated the capital and annual O&M costs of several types of GSI (**Table 4.2**). Other cost estimates considered in this study are tabulated in **Table 4.3.**

Table 4.2 *Estimated costs documented in the technical report (Climate Interactive, 2015, pg. 12-13).*

	Estimated Cost, $/sq. ft or unit cost	**Annual O&M Cost, $/sq. ft or unit cost**	**Annual O&M Cost, $/sq. ft or unit cost (comparable)**
Bioretention	21.00	11297.78	4836.26
Rain Barrels	148.20	3.71	-
Cisterns	6175.00	123.50	-

Table 4.3 *Cost estimates associated with disconnected downspouts, rain barrels, and cisterns.*

	Annual Estimate
Water harvesting (for outdoor irrigation)	
Annual precipitation, in	36.62[a]
Single-family surface, sq. ft	1597.3[b]
Rainwater capture, gal	36441
Portable water saving as water fee, $	21.42[c]
Reduced potable water use per household	
Energy saved on water treatment, kwh	52.22
Electricity rate, $/kWh	0.11
Energy saving, $	5.74
Captured rainwater - potable water saving, gal	27199
Annual energy saved on water distribution, kwh	43.52
Annual energy saved on water distribution, $	4.79
Total Annual Savings Estimates, $	**31.95**

[a] NOAA (2022), https://www.ncdc.noaa.gov/cag/county/mapping/31/pcp/202201/12/value

[b] Mecklenburg OpenMapping (2022)
[c] City of Charlotte, https://charlottenc.gov/Water/RatesBilling/Pages/CLTWRates.aspx

The agents being modeled are households living within Mecklenburg County. The behaviors of agents are based on TPB. The equation to determine adoption behavior is based on the original theoretical framework and the adapted formula in Chu and Chiu (2003):

$$B \cong w_1 AT + w_2 SN + w_3 PCB + w_4 BI + LA + SQ \qquad \textbf{Eq. 1}$$

Where *B* is the realization of the behavioral achievement, *BI* is the intention toward said behavior, *SN* refers to the associated subjective norms to the studied behavior, *AT* is the individual's attitude toward the behavior, and *PBC* is the perceived behavioral control over the behavior. The additional parameters *LA* and *SQ* are the loss aversion and status quo biases, respectively. The values are the modifiers to adjust the weights of each TPB construct, the actual values of which are derived from the online survey and interview of the case study. However, the data has its limitation that the survey results were not fully representative of the whole population within the county as commonly reported in the literature using survey instruments where the sampled participants are highly biased to white mid-age pro-environment highly educated adults. Interviews were only carried out with governmental agencies, no commercial/industrial practitioners. There are no weights for the cognitive biases because these two factors are set up in the model in such a way that they carry the uncertainty and the value of which are varied in experimental scenarios.

The Bass diffusion model adapted by Kiesling, Günther, Stummer, and Wakolbinger (2012) was utilized for the knowledge diffusion stage:

$$n(t) = (p + q\,\frac{N_{(t)}}{M})\,(M - N_{(t)}) \qquad \textbf{Eq. 2}$$

where *N(t)* is the number of adopters by time t, *M* is the total targeted population, n(t) is the transition rate of adopters from the entire population, p reflects the external influential factors, such as advertisement, and q indicates the internal influential factors, such as word-of-mouth.

The cognitive biases considered in this study, namely status quo bias and loss aversion, are determined quantitatively based on literature. For the status quo bias, the extensive work by Samuelson and Zeckhauser (1988) revealed that the option framed as the status quo is 17% higher than the alternative.

Thus, a triangular distribution with a min of 0, a max of 1, and a mode of 0.17 was used in the simulation in the baseline scenario. In the realm of economics, the irrationality in decision-making was demonstrated in a prominent work (Kahneman & Tversky, 1979) with the support of empirical data which, therefore, proposed a new theory named Prospect Theory (Tversky & Kahneman, 1992). The concept of loss aversion used in this study is primarily based on Prospect Theory, which highlights, in real-life human decision-making, the tendency to make judgments based on comparative gains or losses from a reference point rather than the final result and that greater emotional impact is linked to losses compared to the equivalent amount of gains (Polach & Kukacka, 2019). Given this work primarily focuses on the actions of non-adopters, thus, the reference point of gain versus loss is at the origin of the coordinate plane of the two domains. The equations were adapted from Pruna, Polukarov, and Jennings (2020) as

$$u = \begin{cases} nv * lambda, & nv < 0 \\ nv, & nv \geq 0 \end{cases} \quad \textbf{Eq. 3}$$

where *u* is the satisfaction associated with the GSI measure to be adopted and *nv* is the net economic value associated with the GSI measure.

$$p(loss\ aversion) = \begin{cases} -\frac{u}{WTP+u}, & u < 0 \\ 0, & u \geq 0 \end{cases} \quad \textbf{Eq. 4}$$

where p (loss aversion) is the probability of the person having loss aversion and WTP is the willingness to pay the person indicated for GSI measures.

The general logic within the model is shown in **Figure 4.3**. Given the primary focus of the model is to simulate the decision-making process of those who have not adopted or financially supported GSI development, the fraction of the existing adopters is separated (lime green block). The first decision branch the simulated population goes through is whether they are aware of GSI measures. If they are not, this sub-group will inevitably go through the process of knowledge learning (such as public engagement or peer pressure) which is quantitatively modeled by the innovation diffusion theory (light gray block). The remaining group that indicated a greater level of understanding of GSI and those who have effectively gained familiarity during the learning process will enter the second decision branch where they self-evaluate whether they intend to adopt GSI measures. If the intention level is below neutral, it indicates this portion of the population will resist the adoption (dark red block), and the only approach to change their mind will be the influence of the word of mouth from the existing adopters (lime green block). Those who indicate strong intention will make the final decision to adopt GSI measures based on TPB (yellow block) where the decision likelihood (to be either adopter or resistor) is further affected by the potential cognitive biases including status quo bias (influenced by the nature of the GSI alternatives compared to the current situation) and loss aversion (influenced by the economic potential of the alternative to be chosen). The verification of the model is achieved by internal sensitivity analysis. Given its exploratory nature, the model is only semi-validated through face validation in terms of the general adoption trend with field experts or knowledgeable individuals as from the interviews reported in the same study where the survey was conducted (Qi & Barclay, 2022).

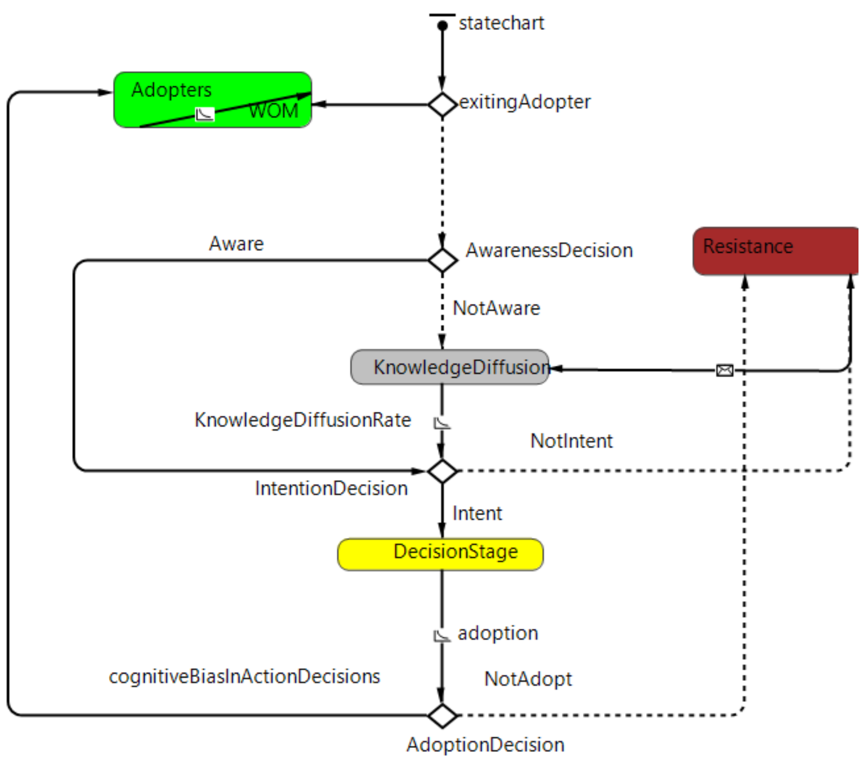

Figure 4.3 *Concept Development and Articulation Stage.*

4.3 Results and Discussions

The following figures reveal the simulated patterns of the adoption process. Various experiments were explored for a 10-year (3,650 days) simulation period. The experimental scenarios and the corresponding results are described in this section. To consider cognitive biases, a range of values based on the literature was used for the status quo bias and the loss aversion bias. A baseline scenario was first created using a population of 500 in which 38% are GSI adopters at the beginning of the simulation and no cognitive biases were activated.

The first experiment was to test the impact of the percentage of initial adopters (**Figure 4.4)**. Three values were tested for the percentage of initial adopters: 38% based on the survey result (left), 10% (center), and 0% initial adopters (right). It was noticeable that the adoption rate increased steadily when no cognitive biases are activated and after 3,650 run days, nearly 100% have become adopters regardless of the percentage of existing adopters unless it is close to none. It is most likely because the fewer the existing adopters, the lower likelihood of information diffusion through word of mouth according to the innovation diffusion theory.

A

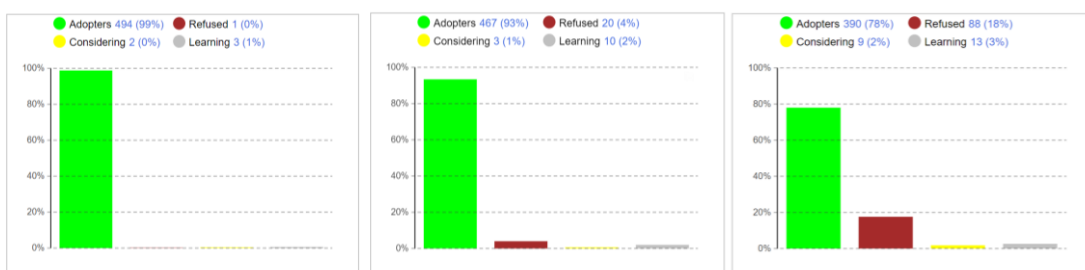

Figure 4.4 *The breakdown of residents' behaviors at the end of the 10-year modeling time. Experiment A: 38% initial adopters (left), 10% initial adopters (center), and 0% initial adopters (right).*

The second experiment evaluated the impact of the prevalence of the status quo bias with the status quo bias likelihood probability of 7%, 17%, and 27% from left to right in **Figure 4.5-B.** The range for the status quo bias parameter of 0.07-0.27 is based on the literature that there is a 17% difference between the likelihood of a person choosing the status quo and the alternative option in various tested scenarios (Samuelson & Zeckhauser, 1988). Similarly, the strength of loss aversion among the simulated population was tested in the third experiment with the parameter Lambda of 1.5 (left), 2.25 (center), and 3 (right) (**Figure 4.5-C**). The range for the loss aversion parameter lambda of 1.5-3 was chosen because 2.25 is the baseline value established in Tversky and Kahneman (1992).

The results showed that both status quo and loss aversion negatively affected this transition process with loss aversion showing a much stronger impact. Acosta, Smith, and Kreinovich (2021) pointed out that the non-linearity in behavioral achievement can be explained by status quo bias and it could aim in associated strategic planning. Similarly, loss aversion can also be accounted for to interpret the patterns in empirical experiments (Abdellaoui, Bleichrodt, & Paraschiv, 2007). The simulated results showed similar patterns reported in these studies. Status quo bias is fundamentally inherent to individuals, meaning it is driven by internal factors, whereas loss aversion is impacted by the economic reference point set by the person (i.e., the personal assessment of the benefit-cost ratio as the result of the behavioral action).

Figure 4.5 *The breakdown of residents' behaviors at the end of the 10-year modeling time. Experiment B: with low (left), average (center), or high status quo bias (right) only. Experiment C: with low (left), average (center), or high loss aversion (right) only.*

The fourth experiment explored the patterns of adoption at the end of the modeling time due to different combinations of the two cognitive biases in various strengths. In **Figure 4.6–D,** the chart on the left was generated using a combination of low status quo bias and low loss aversion whereas the one on the right was the result of a combination of high status quo bias and high loss aversion. The combination of the two biases was further explored (**Figure 4.6–E**) using a combination of low loss aversion and high status quo (left) or a combination of high loss aversion and low status quo (right). The number of adopters at the end of the modeling time reduces significantly when both status quo and loss aversion are present at a high level. Both biases reduce the probability of an individual performing the behavior. Thus, it is sensible that the adopter rate is much lower at the end of the modeling time when both are present at a high level.

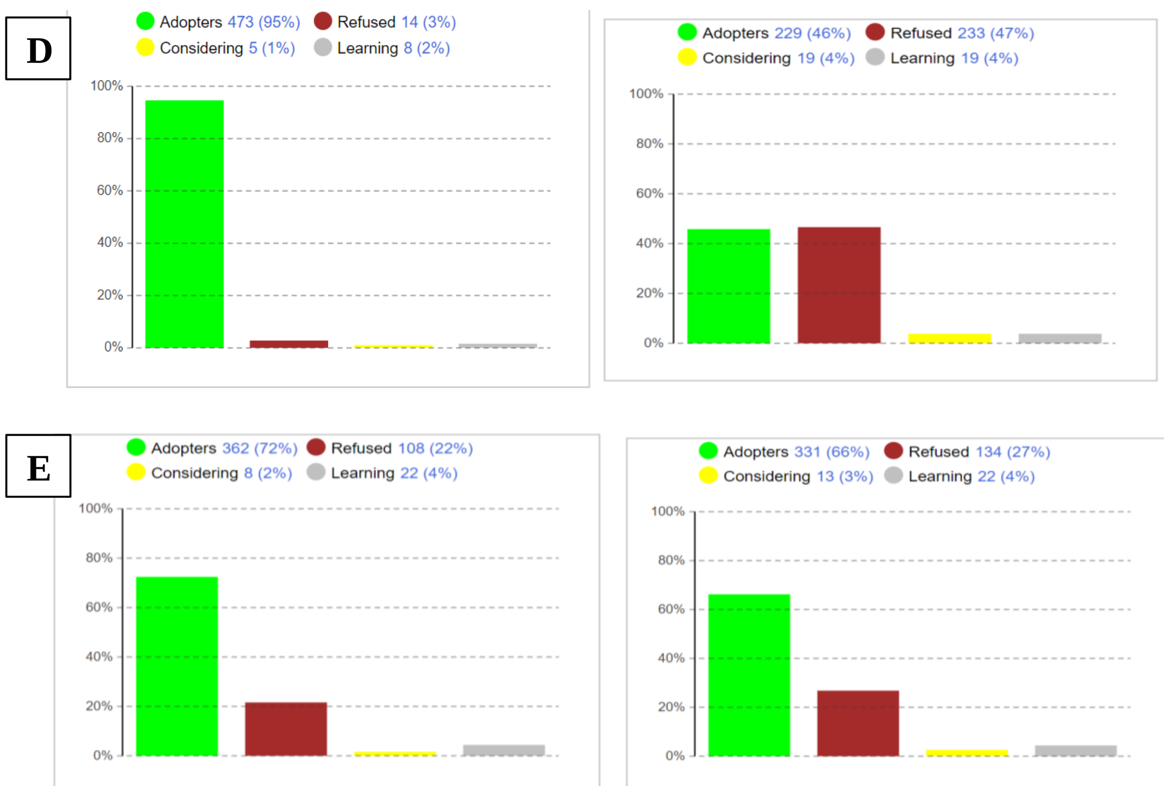

Figure 4.6 *The breakdown of residents' behaviors at the end of the 10-year modeling time. Experiment D: with a combination of low status quo bias and low loss aversion (left) or a combination of high status quo bias and high loss aversion (right). Experiment E: with a combination of Low loss aversion and high status quo (left) or a combination of high loss aversion and low status quo (right).*

From the time-series plot (**Figure 4.7**), it can be observed that the number of adopters at the end of the simulation is the highest in the baseline scenario and the lowest in the scenario where both biases are set to elevated levels. It reflects that it will overestimate the number of adopters over time using the assumption of rational behavior. This study showcases the potential impact of irrational decision-making due to cognitive biases in voluntary pro-environmental behaviors such as GSI.

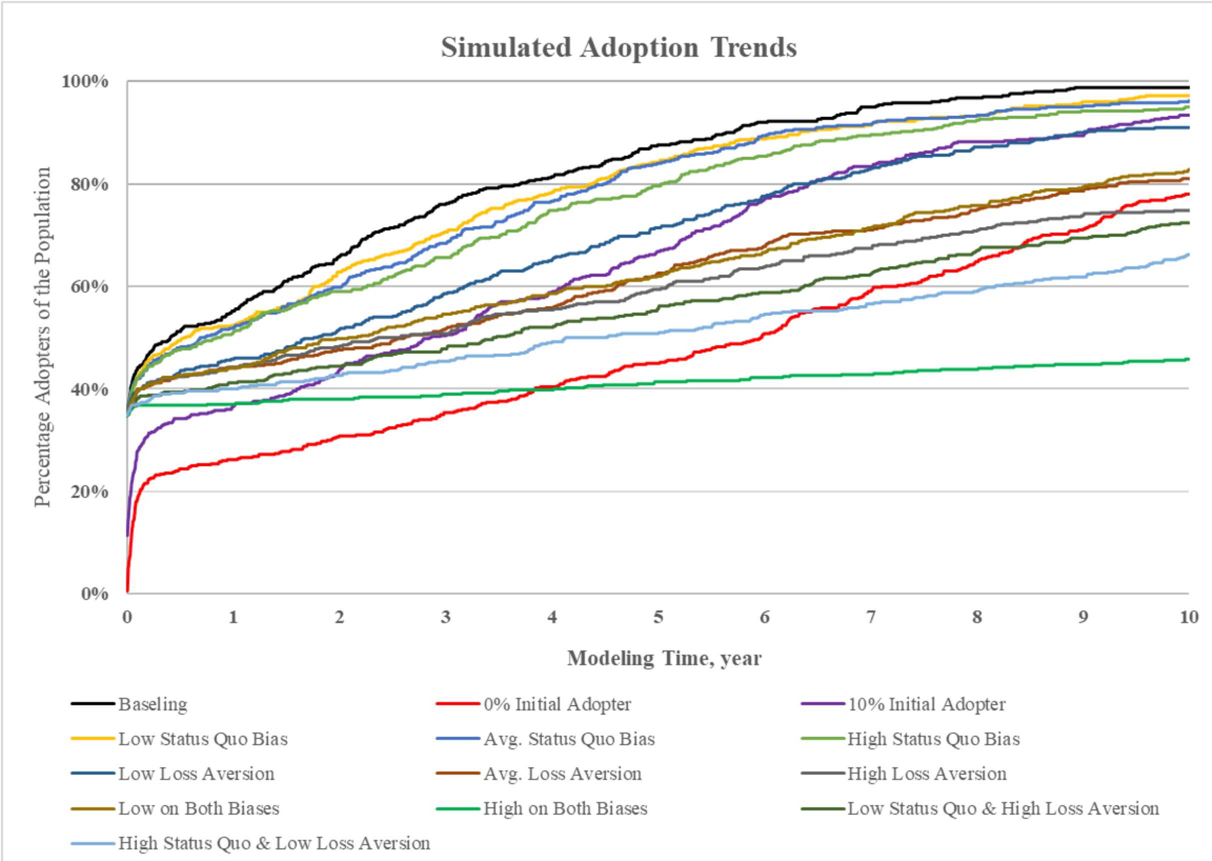

Figure 4.7 *The simulated trend of the adopters in time series.*

The simulation results showed that the prevalence of adopters at the initial stage can influence the time to achieve certain adoption rate goals when it is at the extremely low end. When present alone, status quo bias regardless of strength or low loss aversion did not significantly reduce the adoption rate at the end of the simulation time (less than 8% lower than the baseline scenario). However, the percentage of adopters after 10 simulation years only slightly increased (11%) when both cognitive biases are high among the population. These observations can aim in future voluntary-based GSI implementation planning in residential areas. It was suggested that more alternatives could lead to a higher tendency to remain the status quo (Samuelson & Zeckhauser, 1988). Therefore, to minimize this bias, the residents should only be provided a limited number of practical GSI options. Additionally, the framing effect, if incorporated properly into the public engagement strategies for general stakeholders, may also motivate individuals to participate in pro-environmental behaviors as demonstrated in a study on civil engineers (Shealy, Klotz, Weber, Johnson, & Bell, 2016).

4.4 Conclusion

GSI is an engineered solution for sustainable stormwater management in modern urbanized areas. However, being embedded within a socio-technical context, GSI faces variable practical barriers. A survey study showed that the residents' perception of GSI being ineffective was significant in influencing their intention to adopt GSI practices in addition to the geo-demographic factors (Ureta, Motallebi, Scaroni, Lovelace, & Ureta, 2021). It is of the essence to find alternative funding mechanisms. Stormwater is only regulated for water quality on the federal level; it is mostly up to the local government to mitigate flooding issues, in addition to managing public engagement. Limited financial support calls for a sustainable approach to economically increase GSI implementation. One potentially cost-efficient approach is through effective public engagement by maximizing voluntary GSI adoption in non-regulated areas. Self-sponsored adoption by residents may provide sustainable financial support to GSI, amending the impacts such as the risk of flooding and disturbance to local ecosystems caused by increasing climate change impacts and increasing impervious surfaces in highly urbanized areas. One of the less explored barriers is cognitive biases.

This study takes the research niche to devise a preliminary decision support tool that connects the social and technical aspects involved in GSI implementation in residential areas. TPB is a behavioral theoretical framework that highlights the intricate relationships among intentions, behavioral control, and behavioral achievement, where the behavior would be influenced by intentions to the extent that one has behavioral control and would rise in response to behavioral control to the extent that one possesses the intention. Despite TPB being a well-established behavioral theory, it may have limitations when analyzing pro-environmental behaviors where self-report bias is prominent. By incorporating the common cognitive biases in decision-making, this study aims to compensate for self-report bias in the simulation process.

The limitations of this study are that: the survey used in the case study was conducted via online methods only and the demographic characteristics of the participants do not fully reflect those of the population thus limiting the validity of the model; it appears to the authors that the overly positive adoption rate gathered through the survey might be due to the misunderstanding of the definition of 'adoption' in the context or due to nonresponse bias (Deming, 1944; Suchman, 1962); limited validation was conducted due to lack of long-term record of GSI implementation on private properties, thus record management should be encouraged through voluntary self-reporting for rigorous model validation. This work highlights some of the challenges prevailing in surveys that make it difficult to quantitatively simulate GSI adoption behaviors based on TPB. In addition, structural equation modeling (SEM) is a commonly used collection of statistical techniques for survey-based human subjective study in place of logistic regression. It can simultaneously analyze complex relationships among unobservable variables (i.e., the five key elements in the TPB framework) in its entirety using the manifest variables (i.e., the survey questions that are designed to quantitatively measure the unobservable variables) (Ullman, 2006). Future work should incorporate SEM in conjunction with the cognitive biases used in this study to quantitatively analyze the relationship between self-report bias and these cognitive biases in terms of environmental behavior. Finally, other relevant biases may be included in the quantitative analysis using ABM.

The results brought preliminary insights into how the prevalence of initial GSI adopters may support faster region-wide adoption and how cognitive biases may limit the adoption rate when many are present at the same time. Future research efforts should aim at further minimizing 'errors' in survey-based studies. Admittedly, the most valid method is to conduct a though survey such that the characteristics of the participants can adequately represent the target population. However, it will require a considerable amount of time, labor, and cost. One potential alternative approach to reduce nonresponse bias (or sampling mortality) due to lower education levels or lack of interest in the subject matter is to gather public opinions through big data. This can be achieved through a tailored public engagement maneuver that gathers public opinions and feedback. Other future work can incorporate additional biases and barriers in the modeling process to reflect the impact of a range of barriers more closely.

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CHAPTER 5. CONCLUSIONS

The main objective of this dissertation is to explore the social factors that are inhibiting GSI implementation in regions that are in elevated risk of flooding yet low in GSI usage. Despite the efforts in the planning and performance evaluation of GSI, the social barriers may pose as the limiting factor to GSI from becoming widely adopted. This dissertation delves into some of the possible root causes of social barriers. The results were reported and discussed in the respective sections of each article in the previous chapters. This chapter summarizes the conclusions drawn from these results that address the knowledge gaps in the current literature, their applications in a wider scope, inherent limitations in the development of the dissertation, and recommendations for future research.

5.1 Research Contributions

There are three main contributions of this dissertation corresponding to the three sub-objectives including 1) A survey of literature on challenges in GSI implementation and identification of the ones associated with potential adopters in residential areas; 2) The identification of the perceptual biases that are prominent in the case study area through quantitative survey analysis, in comparison with the recognized barriers in the literature. Also, this research established the correlation between the barriers and the economic, geological, and cultural background of the region; and 3) The discovery of the root causes from the angle of socio-ecological systems: how green infrastructure as public goods/ common pool resources can hinder its development in the study area by building upon the existing adoption and diffusion model. It paves the foundation for a comprehensive understanding of the root causes of such barriers and the leverage points for alleviation if used in conjunction with system dynamics. This approach may mitigate potential misinterpretations of Green Stormwater Infrastructure (GSI) among stakeholders compared to conventional gray infrastructure systems. Decision-making in the realm of environmental management can have profound consequences in the long run. Thus, in the context of GSI, there is a need to determine the most cost-efficient approach for highly urbanized areas to enhance sustainability and resilience.

The first study highlights the relationship between social barriers to GSI implementation in the United States and the associated cognitive biases that may impede rational decision-making, an area that has received limited research attention. Despite their ability to address multiple criteria, current decision support tools overlook certain prevalent cognitive biases, which, as indicated in a scholarly article, could lead to less effective strategy execution. There is an immediate need for improved assessment of private landowners' perceptions of GSI in order to develop efficient intervention approaches that encourage GSI implementation. Concurrently, numerous academic publications have concurred on the robustness of Agent-Based Modeling (ABM) in simulating individual decision-making processes. Consequently, this study also examines quantitative analysis for decision support with the aim of fostering innovative water management strategies that ensure long-term resilience.

The subsequent study emphasizes comprehending public perceptions of GSI in residential contexts and the impact of these perceptions on residents' adoption behaviors. This research serves to bridge the divide between modeling and practical implementation regarding the adoption and diffusion of innovative environmental solutions. The study provides a better understanding of the true perspectives and concerns of the stakeholders before establishing the simulation models that are beneficial to the pursuit of the resilience of the practice using a case study of Mecklenburg County in North Carolina.

Lastly, as a continuation of the previous work, the third takes the research niche to devise a preliminary quantitative decision support tool that connects the social and technical aspects involved in GSI implementation in residential areas. Additionally, despite TPB being a well-established behavioral theory, it may have limitations when analyzing pro-environmental behaviors where self-report bias is prominent. By incorporating the most common cognitive biases in decision-making, this study aims to compensate for self-report bias in the simulation process.

5.2 Implications of Research

Preserving clean potable water requires a global collaborative effort, which can be achieved through efficient practices, such as implementing GSI in urban areas which can also contribute to the reduction of runoff-related traffic delays and safety threats. The use of GSI can help restore diminishing groundwater levels and mitigate surface water pollution. Consequently, fostering a sense of shared responsibility and commitment to sustainable practices is essential in overcoming the challenges for the adaptation of infrastructure, which may be subject to free riding and overuse. By raising awareness, providing education, and encouraging cooperation among various stakeholder groups, it could accelerate the widespread adoption of GSI and other environmentally responsible measures.

Drawing upon Mecklenburg County as a case study, **Table 5.1** illustrates that, as of 2019, merely a small portion of land has been allocated for sustainable stormwater management in comparison to impervious surfaces. Consequently, it is imperative to address the possible future severity of runoff by proactively incorporating suitable green infrastructure measures to enhance resilience and sustainability in the swiftly expanding urban environment. The insights from this research hold significant benefits for the residents of the Charlotte region, as they can aid in more informed decision-making for GSI implementation. The contribution of this work is drawing attention from both academia and practitioners in terms of long-term planning for sustainable infrastructure development in residential areas where governmental incentives are limited. Furthermore, it facilitates improved data collection on residents' opinions of GSI over time, allowing the refinement and validation of the proposed simulation model to improve accuracy. Simultaneously, the survey can serve as a consistent means of public education and engagement, working to bridge the knowledge gap. This dissertation lays the groundwork for identifying potential conflicting decision-making patterns related to eco-friendly behaviors, specifically focusing on small-scale GSI in residential properties. Such insights are crucial for securing resident financial support for stormwater management, thereby alleviating pressure on already stretched federal resources.

Table 5.1 *Impervious coverage and GSI implementation statistics in Mecklenburg County as of 2019.*

Category	Area, acre	Percentage
Mecklenburg County	3.50E+05	100%
Impervious Cover	7.30E+04	20.83%
Residential	2.00E+04	5.63%
Commercial	3.20E+04	9.23%
Pavement	2.10E+04	5.98%
GSI Coverage	1.20E+03	0.34%

While this dissertation primarily utilizes Mecklenburg County as the study area to demonstrate its relevance, it is undeniably applicable to comparable urbanized regions within the US. This research carries significance for the stormwater sector across the nation, as it aids in identifying effective strategies for public engagement and acceptance of GSI, sustainable runoff control, and drought management methods. Nevertheless, the extent of perceptual barriers resulting from cognitive biases varies across states due to diverse cultural dynamics, distinct climate and topographic characteristics, and other potentially related factors. Consequently, it is crucial to consider local perspectives in assessing the impacts of these cognitive biases on GSI implementation and to develop simulation models that accurately represent local conditions. Ultimately, the procedures employed in this research (i.e., public opinion surveys compared with preconditioners' observations and the subsequent simulation model refinement) can be incorporated into strategic frameworks for sustainable infrastructure management, especially in situations where financial resources are constrained.

5.3 Limitations

The author recognize the inherent constraints in conceptualizing this dissertation in relation to the cognitive biases given its innovative nature within the pertinent research domains applied to GSI adoption, The limitations of this research include the following that 1) our survey was limited to online participants who identified themselves as residents of Mecklenburg County, therefore there is a survey bias that certain demographic groups were less sampled; 2) the survey instrument used in the study did not specifically differentiate the types of GSI and forms of GSI adoption behaviors (financial support through stormwater fees and adoption of physical GSI) we intended to survey opinions on; and 3) The simulation models are restricted for explorative purposes only whereas future work should include economic measures if more comprehensive datasets are available.

5.4 Recommendations for Future Research

This work lays the foundation to bring forth long-term planning for stormwater management in urbanized regions using hybrid multi-agent decision support tools. Such a model can incorporate multiple agents of 1) groups who have rights to adopt GSI measures - private landowners, commercial property owners, and the government that controls public lands, 2) GSI as resources that are assessed through operational conditions, 3) legislation that enacts, modify, or abandon relevant regulations that shape the direction of GSI adoption, and 4) practitioners that construct and perform GSI maintenance but are subject to budget and staff restrains set by legislative entities and landowners support. The vision is for a hybrid model that uses agent-based modeling to connect these agents, system dynamics to quantify GSI conditions, and discrete event modeling to manage the actions of practitioners. Furthermore, additional exploration of the impact of knowledge transmission to subsequent generations and the effects of information fatigue may also warrant consideration. This work has the potential to can be extended to counter the possible cognitive biases to the ones that can help support GSI adoption as demonstrated in the literature with the modified Envision rating system using anchoring effect (Shealy et al., 2018). Last but not least, promoting additional interdisciplinary dialogues is strongly recommended to bolster research endeavors on this subject, facilitating evidence-driven local data analysis alongside systematic examinations of these cognitive biases among various stakeholder groups.

DECLARATION OF GENERATIVE AI IN SCIENTIFIC WRITING

During the preparation of this dissertation, the author used ChatGPT by OpenAI (https://openai.com/blog/chat-gpt/) in order to enhance the readability of the writing. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

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