

ABSTRACT

Title of Dissertation: Persisting Social Vulnerability, Stormwater Infrastructure, and Planning for Flooding and Resilience in Washington D.C.

Minkyu Park, Doctor of Philosophy, 2024

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While Green Infrastructure (GI) has gained prominence in addressing climate change, particularly in flood prevention and other associated benefits. Limited empirical studies have explored its spatial distribution and temporal changes in relation to the whole stormwater infrastructure. This dissertation investigates the intersection of stormwater infrastructure, social vulnerability, and urban flood management strategies in Washington, D.C. The dissertation is composed of three studies. The first study employs geospatial exploration to assess the equitable allocation of stormwater infrastructure, considering historical discriminatory sewage services. Regression models reveal significant disparities in stormwater infrastructure distribution among communities with varying levels of social vulnerability, highlighting the inequitable distribution within urban areas. The study contributes valuable insights for stormwater management planning in the context of climate-related challenges.

The second quantitative study focuses on the spatial and temporal evolution of GI distribution in Washington, D.C., utilizing spatial panel data analysis. Unlike previous cross-sectional

snapshots, this study captures temporal trends in GI distribution in relation to social vulnerability. The findings, with potential implications for evidence-based policies, shed light on the evolving patterns of discriminatory distribution of GI and its relation to persistent social vulnerability.

The third study employs an Environmental Justice (EJ) framework to critically analyze the urban flood management initiatives in Washington, D.C., specifically examining the Flood Task Force (FTF) action plan. The study uncovers limitations and potential exacerbations of place vulnerabilities within current plans through qualitative coding. This research contributes to the ongoing discourse on achieving more equitable and resilient urban flood management in the city, emphasizing the need for environmental justice considerations.

The thorough examination of stormwater infrastructure, social vulnerability, and the initiatives of the DC Flood Task Force uncovers a tripartite phenomenon: 1) uneven distribution of stormwater infrastructure is influenced by social vulnerability, 2) temporally widening the gap in infrastructure among communities, and 3) overlooking social vulnerability and the unfair allocation of stormwater infrastructure in planning or policies could intensify place vulnerability.

Persisting Social Vulnerability, Stormwater Infrastructure,
and Planning for Flooding and Resilience in Washington D.C.

by

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Chapter 1: Introduction

The escalating challenges posed by climate change have propelled Green Infrastructure (GI) to the forefront of urban planning and environmental management. Recognized for its multifaceted advantages, GI encompasses a range of elements such as permeable pavements, green roofs, and urban forests. GI not only aids in carbon sequestration, thereby reducing greenhouse gas emissions, but also bestows additional benefits, including urban cooling and enhanced biodiversity (Pamukcu et al., 2021). Also, these natural and semi-natural components serve as powerful tools for stormwater management, playing a crucial role in flood prevention.

In the United States, the official recognition of GI in the Water Infrastructure Improvement Act of 2019 marks a significant step toward promoting stormwater management and mitigating environmental impact. This legislative acknowledgment reflects a shift from centralized stormwater systems to hybrid systems that integrate green and gray infrastructure (Porse, 2018). This transformation responds to the urgent need to adapt to the escalating frequency and intensity of precipitation events driven by global climate change. By combining GI with traditional gray infrastructure, a new hybrid system emerges, offering a comprehensive approach to address the challenges posed by climate change.

However, despite the growing popularity of GI in addressing urban challenges, its implementation has revealed inequities across communities. The benefits that GI promises for urban environments, including water quality enhancement and flood prevention, are not uniformly distributed. The communities poised to benefit the most

from GI often have the least access to it (Heckert and Rosan, 2016). Studies by Baker et al. (2019), Chan and Hopkins (2017), Mandarano and Meenar (2017), Lim (2017), Porse (2018), and Wolch et al. (2014) have demonstrated significant variations in access to GI based on factors such as racial minority status, income levels, and educational attainment. These findings underscore a new equity issue within infrastructure development, particularly concerning environmental justice. The implementation of GI, despite its promise, may unintentionally exacerbate existing disparities in society, emphasizing the need for a comprehensive examination of the relationship between social vulnerability, stormwater infrastructure, and flood planning.

The literature on environmental justice and social vulnerability indicates the intricate connections among social vulnerability, infrastructure settings, and planning.

Hendricks and Van Zandt's (2021) theoretical framework posits that infrastructure acts as a mechanism perpetuating environmental injustice and amplifying social vulnerability in everyday life and during disasters. The unequal distribution of infrastructure, driven by factors such as race, ethnicity, gender, and class, results in certain groups receiving insufficient protection due to social discrimination and exclusion from decision-making processes. While the Hendricks and Van Zandt's (2021) framework and other models of social vulnerability suggest that social vulnerability influences the uneven distribution of infrastructure, existing studies in the GI and environmental justice literature do not comprehensively measure overall social vulnerability when investigating infrastructure distribution and capture the mismatch between urbanization, gray, and green infrastructure. Empirical measure of

social vulnerability and analysis on the gray and green stormwater infrastructure distribution are necessary to reassess this conceptual relationship. Additionally, models of social vulnerability should be reorganized to identify the persistent attribute of vulnerability and to confirm whether the relationship between social vulnerability and infrastructure evolves over time. Previous theories posit that social vulnerability can change, while disaster and GI literatures suggest that vulnerability status may persist. The disaster case studies, Bolin and Stanford (1998) and Bullard and Wright (2009) illustrate how social vulnerability can be perpetuated, leading to continuous unsafe conditions and deepening a place's vulnerability. The theoretical explanations of GI implementation mechanisms presented by Lim (2017) and Mandarano and Meenar (2017) suggest that new stormwater infrastructure may continue to be concentrated in specific communities. The idea that social vulnerability may persist suggests a gap in understanding the dynamics and outcomes of social vulnerability in changing infrastructure settings. However, no published study has explored the temporal and spatial interrelationships among social vulnerability, infrastructure settings, and planning, and how these elements influence the overall vulnerability of communities (so called 'place vulnerability' in Cutter's (1996) study).

If social vulnerability persists, changing infrastructure settings may discriminate against previously vulnerable communities through inequalities in infrastructure management and planning processes. This results in environmental injustice with disparate protection across communities. Synthesizing previous models of social vulnerability, a new framework based on the that of Hendricks and Van Zandt's

(2021) assumes that social vulnerability perpetuates, creating a cyclical process with a discriminatory planning practice. In this cycle, socially vulnerable status, discriminatory planning, and infrastructure distribution reinforce each other, deepening the vulnerability of previously marginalized communities over time.

Given the importance of addressing the gaps and synthesizing the critical insights from existing literature, it becomes imperative to examine the overarching research question: What is the relationship between social vulnerability, stormwater infrastructure distribution and planning, and flood planning? This inquiry necessitates a reevaluation of the unequal distribution of GI through a comprehensive analysis that scrutinizes the mismatch between social vulnerability, urbanization, and the integration of gray and green infrastructure. Furthermore, an examination of the relationship between social vulnerability and the new type of stormwater infrastructure, GI, distribution in time flow is essential. Finally, an analysis of how flood planning accommodates the needs of socially vulnerable populations and addresses disparities in stormwater infrastructure distribution will provide insights into the evolution of vulnerability and inform future strategies for mitigating these challenges.

Thus, in this dissertation, my study tackles three research inquiries through three interconnected papers: 1) Are there significant disparities in the allocation of sewer pipelines and green infrastructures among communities with different levels of social vulnerability?; 2) Has the distribution of GI in Washington DC shown a tendency to concentrate more in communities with higher racial majorities and greater wealth?; and 3) Do the Flood Task Force's (FTF) action plans and their underlying plans

address issues of vulnerability from an Environmental Justice perspective?

Collectively, this set of research shows the need for a continued environmental justice research agenda that addresses the joint effort of stormwater management and planning for flooding and the mitigation measures to improve urban and community resilience.

In the first study, “Socially vulnerable people and Stormwater infrastructure: A geospatial exploration of the equitable distribution of gray and green infrastructure in Washington D.C.”, I tackle the underexplored dimensions of stormwater infrastructure distribution, focusing on Washington, D.C., and considering its historical context of discriminatory sewage services. The literature emphasizes the need to explore its distribution in relation to social vulnerability and gray infrastructure like sewer pipelines, but the distribution of GI, sewer pipelines, and their relationship with social vulnerability remain underexplored. Through a set of regression models, the research explores potential disparities in the allocation of stormwater infrastructure among communities with varying levels of social vulnerability. The study contributes insights into the relationships between stormwater infrastructure, social vulnerability, and urbanization. The findings shed light on the inequitable distribution of stormwater infrastructure within urban areas and offer implications for stormwater management planning, particularly in the context of climate-related challenges.

The second quantitative study, “Persistent Social Vulnerability in Washington D.C. Communities and Green Infrastructure Clustering”, specifically focuses on the temporal evolution of GI distribution in Washington, D.C. Unlike prior studies that

rely on cross-sectional snapshots, this study adopts a novel approach utilizing panel data analysis. Despite the critical importance of understanding how GI distribution evolves over time in relation to social vulnerability, only a few studies captured the temporal trends or change of GI distribution. The research aims to provide a comprehensive understanding of how these patterns evolve by delving into the temporal dynamics of GI distribution. The findings of this study have implications for evidence-based policy recommendations, particularly in fostering equitable distribution strategies that ensure socially vulnerable communities benefit from the positive impacts of GI.

The third study, “Navigating Stormwater Inequity: An Environmental Justice Analysis of Flood Management Strategies in Washington, D.C.”, critically examines the urban flood management initiatives in Washington, D.C. Applying an Environmental Justice (EJ) framework and qualitative coding, the study analyzes the action plans of the Flood Task Force (FTF) and the underlying plans, including plans of stormwater management and climate change. By uncovering limitations and potential exacerbations of social vulnerabilities within current plans, the study contributes to the ongoing discourse on achieving more equitable and resilient urban flood management in the city.

The study aims to reassess the complex relationships among social vulnerability, infrastructure distribution and planning, and flood planning. Its primary objective is to understand how the transformation of infrastructure, driven by market forces, exacerbates the vulnerability of already socially vulnerable communities, thereby deepening their risk to flooding. By examining the disparities in stormwater

infrastructure and vulnerability, the research highlights the importance of integrating equity considerations into flood planning, infrastructure management, and resilience strategies. It challenges the conventional view of vulnerability as merely a transient state and argues for a more nuanced understanding that acknowledges the persistent gap between social vulnerability and place vulnerability.

Chapter 2: Theoretical background

2.1. Environmental Justice

Literature addressing Environmental Justice raises critical questions regarding the equitable distribution of environmental benefits and burdens. For instance, Bullard (1993) has demonstrated that communities of color and low-income communities experience a higher spatial concentration of pollutants, marking a significant environmental burden. Conversely, research by Grove et al. (2018) corroborates the tendency for facilities providing environmental benefits, such as parks and green spaces, to be located predominantly in affluent or predominantly white communities. More recently, discussions on the spatial distribution of infrastructure have taken on an Environmental Justice perspective, revealing that the siting of facilities providing either environmental benefits or burdens correlates with demographic factors such as income and race. These studies pivot around the distributional aspects of Environmental Justice, questioning whether environmental benefits or burdens are equitably dispersed across space. However, the concept of Environmental Justice extends beyond mere distributional issues.

Environmental Justice seeks to alleviate environmental burdens across all human activities, striving for environmental conservation and social justice through the fair application of environmental benefits and the mitigation of environmental destruction. This perspective takes a global stance, considering the welfare of future generations (Schlosberg, 2007). Expanding on this, Schlosberg (2013) argues that Environmental Justice has broadened its scope to include non-human entities,

encompassing issues of climate change and sustainability. According to Schlosberg (2007), Environmental Justice comprises four simultaneous dimensions: first, distributive justice among social groups within a society; second, distributive justice between developed and developing countries at a global level; third, justice between current and future generations; and fourth, justice between humans and non-human nature.

The advocacy for Environmental Justice began with grassroots activists in the United States during the 1980s and has since been supported by numerous academic studies and governmental environmental policies (Cho, 2013). Challenging traditional environmentalism and mainstream movements, the Environmental Justice movement has sought alternative environmental knowledge and practices (Di Chiro, 1996). It links environmental issues to race, class, and gender, providing critical insights for Environmental Justice, such as the rejection of society-nature divisions, the importance of urban environments, the integration of various social movements, and crucially, the connection between social justice and Environmental Justice (Park, 2006). The movement's influence has spread across the United States, notably affecting the environmental policies of the Clinton administration (Cho, 2013).

Furthermore, the Environmental Justice movement has spurred both empirical and theoretical research into environmental justice and injustice. Since the early 1990s, a surge in studies, books, and special journal editions has highlighted severe environmental injustices, such as the uneven placement of pollutant-emitting plants and environmental facilities, disparities in protection against environmental hazards, and discriminatory impacts of toxins and contaminants (Bullard 1993, Hofrichter,

1993). While Bullard (1993) have identified race as a primary factor in environmental injustice in the United States, introducing the concept of environmental racism, others argue for the importance of considering class and gender as additional factors of environmental injustice (Heiman, 1996).

On the other hand, David Schlosberg's (2004; 2007; 2013) contributions in the early 2000s significantly expanded the Environmental Justice framework by articulating three core dimensions: distributional equity, procedural equity, and recognitional equity. This comprehensive approach broadened the scope of EJ beyond its initial focus on the fair distribution of environmental burdens and benefits, as follow:

- **Distributional Equity** involves ensuring that no single group of people, especially vulnerable communities, bears an unfair share of negative environmental impacts. This principle addresses the core of environmental injustice, emphasizing the need for equitable access to natural resources and protection from environmental harm.
- **Procedural Equity** underscores the importance of inclusive and democratic processes in environmental decision-making. It advocates for the meaningful participation of all affected communities in the formulation, implementation, and enforcement of environmental policies and regulations. This dimension emphasizes transparency, accountability, and the empowerment of communities to influence decisions that affect their environment and health.
- **Recognitional Equity** focuses on acknowledging and valuing the diversity of communities affected by environmental decisions. It calls for the respect of

cultural differences, the rectification of historical injustices, and the inclusion of diverse perspectives and knowledge systems in environmental governance. Recognitional equity is about ensuring that all voices are heard and respected, particularly those that have been historically marginalized or silenced in environmental discourses.

In the evolution of the Environmental Justice concept, David Schlosberg's three-dimensional framework provides a lens and concept that can be applied in my study to critically examine and understand the complex interplay of environmental justice issues within the specified research context. Schlosberg's comprehensive approach, which emphasizes distributional equity, procedural equity, and recognitional equity, enables a multifaceted analysis of environmental injustices that goes beyond traditional considerations of environmental distributional impacts. By incorporating these dimensions, the study aims to uncover deeper insights into the systemic nature of environmental injustices, exploring not only how environmental benefits and burdens are distributed among different communities but also how decisions regarding environmental issues are made and whose voices are heard or marginalized in these processes.

2.2. Models of Social Vulnerability

Various models have developed from the conceptualization of Chambers (1989) and the model of Watts and Bohle (1993), sharing that social vulnerability is multidimensional. The Pressure and Release model by Blaikie et al. (2004) explains vulnerability with four components; “root causes, dynamic pressures, unsafe conditions, and hazards”, and it dichotomizes the interaction between natural disasters and a series of social processes that make people vulnerable. This means that disasters originate from the intersection of two or more social and natural factors. Thus, the model is explained by two parts: the ‘Pressure’ part indicates a process in which vulnerability is born, named ‘the progression of vulnerability’, and the ‘Release’ part conceptualizes the actions for reducing the disaster impact and vulnerability. The Pressure and Release model’s “Pressure” is made up of the "Root causes", "Dynamic pressures", and "Unsafe conditions". These three components individually and jointly contribute to vulnerability. The root causes indicate people's limited resources and power and the surrounding economic and political system determining those limits. The "Dynamic pressures" indicates not only intertwined economic and political ideologies but also a particular temporal economic condition like the great recession that determines an individual’s or group’s preference or activities (Blaikie et al., 2004). In other words, the social vulnerability, which this study is debating, is made through the root causes and the dynamic pressures. The unsafe conditions depend upon people’s well-being level and the gaps between individuals, households, and communities. The conditions including locations dangerous to disasters, unsafe

building and infrastructure characteristics, and the lack of building code for safety are the forms in which people's social vulnerabilities take shape in space and time.

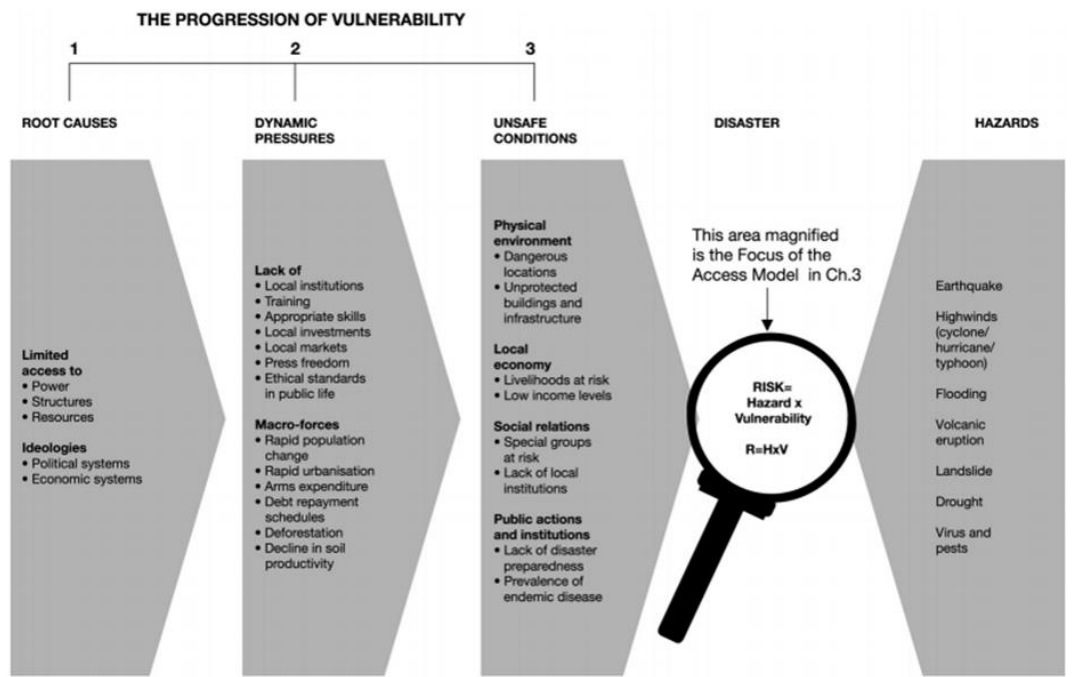


Figure 1 The Pressure and Release Model (Blaikie et al., 2004)

However, the Pressure and Release model is only a static description of social vulnerability and does not show how social vulnerability changes. This is because the authors suggest this model as an analytical tool and exaggerate the separation of risk from social processes to highlight the social causes of a disaster. In the model, the concept of vulnerability does not presuppose the persistent characteristic of social vulnerability. The authors just add descriptions that social vulnerability is subject to change depending on the change of the three components of the “Pressure” part in the model, illustrating the cases in which social vulnerability could decrease with the application of more appropriate building techniques or increase with rapid

urbanization. Also, with the Access model dealing with interaction between vulnerability and hazards, the authors argue that social vulnerability may decrease due to individual efforts or changes in social or political settings that could affect individual asset and resource management. However, when the authors explain the dynamic pressure, they assume that the economic and political systems tend to intensify the existing socio-economic marginalization. This assumption implies that the process by which the root cause creates the unsafe conditions could be an enduring cycle, but Blaikie et al. (2004) do not provide a firm description of how social vulnerability changes or perpetuates over time.

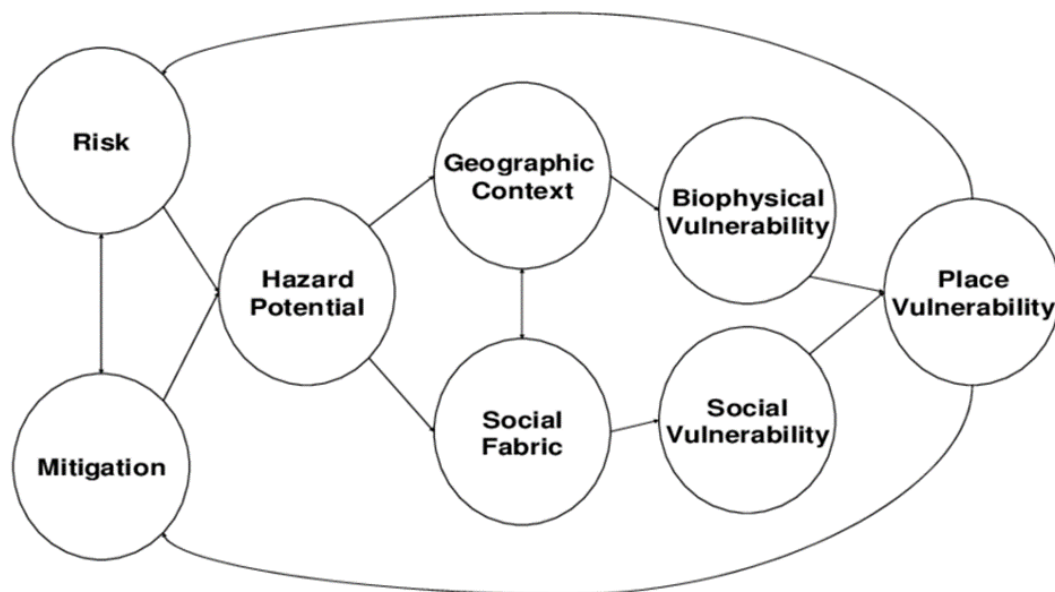


Figure 2 The Hazard of Place Model of Vulnerability (Cutter et al 2003)

Cutter's (1996) Hazard of Place model shows that interactions between human society and the environment produce place-specific vulnerability, and the hazard potential of a certain place is decided by the interaction of hazard risk and the related mitigation measures. People set their geographic context, such as proximity to the ground zero of disasters and elevation of the settlement, to cope with the hazard potential. The result of this spatially modified hazard potential is the biophysical vulnerability in her model. The hazard potential is adjusted not only by the geographic setting but also by the social fabric of the people. The social fabric includes a broad range of characteristics of society, including demographics and its distribution, wealth, people's experiences and perceptions of disasters, and the built environment. The socially created aspect of the hazard potential is a social vulnerability in the model. Both biophysical and social vulnerability interact and produce an entire vulnerability of a place. Cutter (1996) and Cutter et al. (2003) link place vulnerability to risk and mitigation to explain how social, biophysical, and place vulnerability can change over time. The linkages expressed in the model show how the "Place vulnerability" changes over time as changes in risk or application of mitigation measures, which are based on the current place vulnerability, change hazard potential, which in turn changes social and biophysical vulnerability, and finally leads to altered place vulnerability. Cutter (1996, p 536, 537) simply describes that "risks can be attenuated with good mitigation or they can be amplified by a poor or nonexistent mitigation practices" and shows that the social and place vulnerability can be adjusted.

2.3. Segregation

On the other hand, the residential segregation process shows that the socio-economic status of communities has been perpetuated in the United States by producing separate housing, education, and other public services for marginalized people. The persistent discrimination on race and class has placed communities of certain races or classes on enduring socio-economic marginalization so that communities cannot overcome their poverty and powerlessness. Menedian et al. (2021) prove that, in 169 out of 209 US metropolitan areas with a population of 200,000 or more, the phenomenon of clustering by race was more severe in 2019 than in 1990. Their report, *The Roots of Structural Racism*, notes that residential segregation is exacerbating racial inequality and making the lives of African Americans and Latinos worse off as it differentiates their educational, medical, and safety public services. Massey and Tannen (2015) also corroborate that the 52 metropolitan areas had shown racial segregation from 1970 to 2010, and Lichter et al. (2012) show that about 30% of poor people live in places in which poverty is highly concentrated over time. Given the empirical proof of long-lasting segregation, people who have lived in socially marginalized areas would attend low-quality public schools and tend to get lower education attainment, which in turn leads to lower incomes again (Massey and Tannen 2015; Menedian et al 2021).

The segregation links people's socioeconomic status to the built environment and makes difference in infrastructure. Studies on transportation (Grannis 1998; Jones and Armanios, 2020) show that transportation infrastructure has more significant impacts on marginalized people by constraining people's movement in terms of travel speed

and routes. Readon et al. (2008) find that transport infrastructure, including street networks and public transport, is responsible for the way segregated communities are distributed throughout cities. As infrastructure inequity causes the gap between communities, the communities' race or income could also affect differences in infrastructure. Since the 20th century, racial discrimination and segregation have led to communities of color with concentrated poverty and disinvestment causing deterioration of public services and the blight of communities (Massey, 1990). In the shadow of structural racism, people in segregated communities may be educated in underserved schools, be exposed to rampant crime, and to environmental pollution that interferes with their daily lives. Under the influence of this disinvestment related to infrastructure, the existing inequalities and injustices in cities can be perpetuated.

The explanations and empirical evidence for residential segregation show the gap between socio-economic statuses is widening. It also shows that the disparities in the built environment and infrastructure are also increasing, depending on the gap in socio-economic status and under a discriminatory social structure to certain classes and races. These accounts of residential segregation implicate that social vulnerability, as a capacity to respond to disasters, can perpetuate over time. Socially vulnerable individuals or communities may be relatively more critically affected in disaster situations, and the social structures that made them vulnerable may put them into more vulnerable conditions, discriminating against support for protective measures or recovery after a disaster. The literature on disasters, particularly regarding Environmental Justice by Bullard (2009), shows how socially vulnerable communities become more vulnerable as they experience disasters.

2.4. Disaster and marginalized people

The marginalization term is not fully interchangeable with social vulnerability. Personal wealth and race/ethnicity are inevitably crucial indicators of social vulnerability, but they cannot represent overall social vulnerability. Although the disaster literature says that socio-economic statuses including gender, wealth, age, and disability are general components of estimating social vulnerability (Aldrich and Benson 2008; Anderson et al 2007; Enarson 1998; Fothergill 1998; Fothergill and Peek 2004; Peek and Stough 2010), social vulnerability is not decided by only one indicator. It is hard to say that marginalized communities that are poor and of racial minorities are necessarily more socially vulnerable, given that the other wealthier and white communities consisting of female-headed households or retired populations could also be vulnerable.

However, the disaster literature shows a correlation between the marginalization of people and their social vulnerabilities, proving that 1) the marginalized communities of racial minorities, the below-poverty level, and female-headed households benefit less from negotiating or qualifying for getting public financial resources partly because of their low language skills and education level (Bolin 1985; Bolin and Stanford 1991; Morrow, 1997) and 2) racial minority communities are excluded from disaster recovery processes because of their lack of political representation and institutional discrimination (Morrow 1997; Phillips 1993; Prater and Lindell 2000,).

The Hurricane Katrina case shows that marginalized African American communities have been socially vulnerable in New Orleans. Hurricane Katrina was a massive hurricane that hit the southeastern United States in late August 2005. The hurricane caused a lot of damage to people and property over a wide area, and the damage was concentrated in New Orleans (Congleton, 2006). Bullard and Wright (2009) show that flood damage occurred intensively in the neighborhood where the proportion of Black population accounted for 75 to 100% based on the Census 2000. Also, they illustrate how vulnerable African American communities have been placed in flood-prone areas. The geographically flood-prone black neighborhoods were established right after the Civil War (Bullard and Wright 2009). During this period, the rapidly growing African American population had difficulties finding homes and jobs because many of them were liberated from slavery, and as a result, they settled in back swamps of the Mississippi River or the "battures" that is "the area on the riverside of the artificial levee without flood protection" (Bullard and Wright, 2009). After the communities were divided at the time, the Black and White settlements have been segregated throughout the long urbanization of New Orleans (Bullard and Wright, 2009). This process, by which poor and powerless people settle in geographically flood-prone areas and suffer more damage, not only shows the progression of vulnerability in which the vulnerable status of communities or individuals leads to "Unsafe conditions" as described in the Pressure and Release model, but also demonstrates that inequity forms social vulnerability (Cutter et al., 2003).

The Katrina case also shows that social vulnerability leads to an unequal distribution of infrastructure and persists over time. Right after Katrina, the Army Corps of Engineers spent \$4 billion in the budget to improve or replace the levees, flood gates, and stormwater pump stations (Bullard and Wright, 2009). However, this mitigation measure did not reinforce levees to prevent flooding in New Orleans East, which has the highest percentage of Black population (Bullard and Wright, 2009). Also, neighborhoods whose people are mostly Black such as the Ninth Ward and Gentilly had little increased flood protection while predominantly white and affluent neighborhoods got relatively more levee protection (Wright, 2011). With regard to this unequal levee protection, Bullard and Wright (2011, p.39) argue that “institutionalized racism has influenced policy that discriminates in ways that better serve the white and more affluent population and communities.” Moreover, Wright (2011) says that Blacks in New Orleans were excluded from the recovery initiative after Katrina due to institutional constraints and their economic conditions. As a result, the socially marginalized and poor Black population of New Orleans is left vulnerable to future flooding once again (Bullard and Wright, 2009). Based on the Pressure and Release model, the levee case of New Orleans proves that the root causes and the dynamic pressure influence the decision-making process to mitigate the risk of a disaster, and, in doing so, to spatial inequality of mitigation measures. The vulnerable communities became vulnerable again through the "good" mitigation measures reducing risks, which Cutter (1996) mentioned. In other words, the case shows vulnerability may be deepened by infrastructural inequity.

2.5. Social vulnerability and stormwater infrastructure

The literature focusing on the inequitable distribution of stormwater infrastructure systems including gray and Green Infrastructure (GI) is gradually growing from the environmental justice perspective. Porse (2018) reveals that sociodemographic indicators in Los Angeles, CA, such as the proportion of renter households and unit land cost, have a negative correlation with the density of stormwater infrastructure while engineering and hydrologic parameters like imperviousness and runoff coefficient in the region are important factors in estimating urban stormwater planning. Also, Baker et al. (2019) show that the density of above-ground GI in Portland, OR, negatively associates with the median income of communities. Wendel et al (2011) prove that the disparities in access to green infrastructure are existing in Tampa, Florida, and Ferguson et al. (2018) verifies that high income and dominantly white neighborhoods have better access to green infrastructures in the United Kingdom.

Only a few studies explain what factors are causing the inequitable distribution of green stormwater infrastructure. The first factor is the planning mechanism (Dunn 2010; Mandarano and Meenar, 2017). GI implementation approach has a range of policy approaches, but the most common approaches are public investment, regulation through building permits, and utilizing incentives to encourage the private sector's voluntary implementation (Dunn, 2010). According to Mandarano and Meenar (2017), all three common approaches link the community capacity to the GI's unequal distribution although the public investment approach is relatively free from the market forces making a kind of entry barrier in GI installation, compared to the

other two approaches. Public investment is a method of utilizing public land. Specifically, in the case of GI, it needs a site for the implementation near the point source of stormwater runoff. However, an agency implementing GI may have a small portion of the implementation site, so GI implementation by public investment may inevitably need collaborations between many stakeholders such as transportation authorities and communities (Wendel et al., 2011). If the concerned communities do not have enough capacity to serve as effective partners, the GI implementation would slow down or be hampered. Thus, even if public investment through a collaborative approach brings about its successful implementation, its success could be concentrated in only affluent communities.

The other policy approaches through regulation and voluntary implementation using incentives could also shut out marginalized communities. GI-related regulation generally mandates its implementation in local redevelopment projects and individual buildings' reconstructions or renovations (Dunn, 2010). This type of implementation does not discriminate whether they are affluent or poor, but the redevelopment process could lead to gentrification-induced displacement. Gentrification is a common byproduct of redevelopment in communities of color (Essoka, 2010; Shin, 2009). Thus, if the probability of gentrification and its negative effects are not controlled, GI implementation through mandatory regulation could be only for the renewed affluent communities. On the other hand, encouraging the voluntary participation of landlords through incentives is the approach most closely associated with unequal infrastructure distribution because it inevitably relies on individuals' or

communities' financial capacity more than the collaborative public investment approach does.

In terms of voluntary implementation, a few studies reveal the clustering of GI around specific neighborhoods and why this clustering occurs. Lim (2018) describes the phenomenon of clustering of GIs as “a process of information dissemination”. This process explains that information diffusion in a community or within adjacent communities makes people imitate others' choices and activities (Jaffe et al., 2002; Lim, 2018). Based on this logic, Lim (2018) statistically proves that GI implementation location is determined by the previous implementation. Also, Green et al. (2012) analyzed the adoption of voluntary rain garden initiatives and proved that voluntary rain garden adoption is spatially clustering near previous program participants. These findings could be universally valid beyond GI implementation, given that information diffusion between neighbors of environment-related behaviors, such as installing solar panels and recycling waste already identified (Hopper and Nielsen, 1991; Rode and Weber, 2016). However, the process where information is diffused across communities is associated with the communities' socioeconomic characteristics. Low-income areas isolate residents from social networks and deprive the broader community of the neighborhood's human potential (Sanbonmatsu et al., 2011). Also, poverty has hampered people to become part of wider social networks (Matthews and Besemer, 2014).

The current GI implementation mechanism of collaborative public investment, mandatory implementation through redevelopment, and voluntary participation could

keep marginalized communities out of it, leading to unequal distribution of GI. In all three approaches, community capacity is vital in GI implementation. Evans et al. (2015, p.212) say that “community capacity is the combined influence of a community’s commitment, resources, and skills that can be deployed to build on community strengths and address community problems and opportunities.” Given the definition of community capacity, low community capacity may indicate powerlessness, poverty, and racial minority in general, and these are primary factors making up social vulnerability. The explanation of this biased distribution of GI corresponds to the Pressure and Release model and disaster case studies, which show that socially vulnerable status leads to unsafe conditions.

Meanwhile, GI implementation is increasing to complement existing pipeline systems and reduce flood risk (Baker et al., 2019; Pose, 2018). Based on the findings and explanations of the current GI distribution, it can be predicted that the GI distribution will continue to be discriminatory to certain races and classes. However, this prediction contradicts the description of the Hazard of Place model presented by Cutter (1996). According to Cutter (1996), GI should play a role in reducing place vulnerability as a mitigation measure to reduce the flood risk of specific places. However, this mitigation measure puts potentially socially vulnerable groups at greater risk due to the implementation mechanisms excluding certain classes and races, which could increase their place vulnerability. It is difficult to say that the Hazard of Place model adequately describes the relationship between social vulnerability and infrastructure in continuous time flow. In addition, the Pressure and Release model fails to account for the relationship between this temporally persistent

relationship between social vulnerabilities and infrastructure. It is necessary to revise existing models of social vulnerability.

2.6. Summary

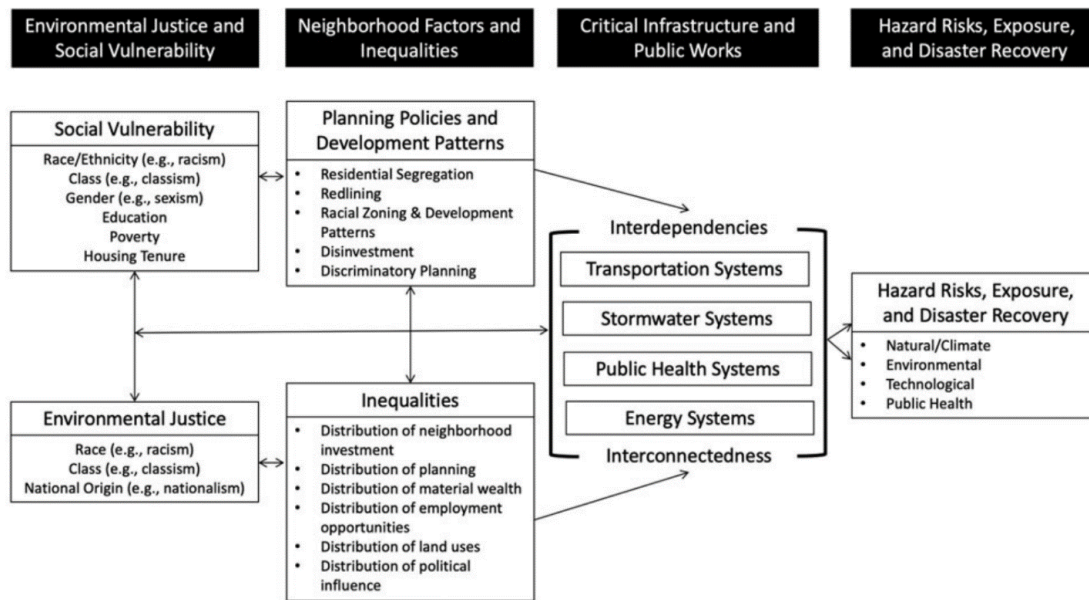


Figure 3 Theoretical Framework of Hendricks and Van Zandt (2021)

The above literature on environmental justice and social vulnerability indicates the close relationships between social vulnerability, infrastructure setting, and planning. As in the theoretical frameworks of Hendricks and Van Zandt (2021), infrastructure plays a role as a mechanism that diffuses environmental injustice and furthers social vulnerability both every day and during disaster events. According to Hendricks and Van Zandt (2021), the unequal distribution of infrastructure is a kind of outcome of environmental injustice or the progression of social vulnerability. Because of race,

ethnicity, gender, and/or class, certain groups of people receive less protection from infrastructure through restrictions on access to resources under social discrimination or exclusion in the decision-making process or urbanization processes. In turn, the societal distribution of infrastructure protection can affect not only daily environmental conditions but also the overall vulnerability to disasters, and thus create disparate impacts from weather extremes (Hendricks and Van Zandt, 2021).

On the other hand, empirical studies, including those by Baker et al. (2019) and Porse (2018), have investigated the distribution of green and gray infrastructure, revealing socioeconomic disparities. These findings offer tangible evidence of the theoretical framework proposed by Hendricks and Van Zandt (2021), yet also highlight gaps, such as the need for a more comprehensive measurement of social vulnerability. The relationship between social vulnerability and infrastructure needs to be identified again. Although the "Pressure and Release model" of Blaikie et al., (2004) and the framework of Hendricks and Van Zandt (2021) suggest that social vulnerability drives the unequal infrastructure setting, the previous studies of GI literature (Baker et al., 2019; Chan and Hopkins, 2017; Hendricks, 2017; Mandarano and Meenar 2017; Porse, 2018) do not measure the overall social vulnerability of communities when they investigate the distribution of infrastructure protection or benefits. They show socioeconomic indicators of race or income are related to the infrastructure distribution, but those few indicators cannot represent the overall social vulnerability of communities. Rygel et al., (2006) point out that white communities of elderly people could be more socially vulnerable than communities of color living in residentially segregated areas. should be considered in conjunction with the

distribution of gray infrastructure, as the primary function of GI is to supplement it (Porse, 2018). Therefore, the relationship between social vulnerability and infrastructure should be re-examined using empirical measures of social vulnerability, alongside an assessment of both gray and green infrastructure, to corroborate the previously suggested conceptual relationship.

Also, the models of social vulnerability need to be reorganized to identify the attribute of vulnerability that could be persistent over time and confirm whether the relationship between social vulnerability and infrastructure works over time. The previous theories and models explain that social vulnerability can change over time (Blaikie et al., 2004; Cutter, 1996; Cutter et al., 2003), whereas the disaster literature describes that the vulnerable status perpetuates (Bolin and Stanford, 1998; 1999; Bullard, 2008; Peacock et al., 2001; Wright 2011). Bullard and Wright (2009) describe in the Katrina case that social vulnerability of the African-American communities in New Orleans have perpetuated, and led to unsafe conditions continuously in time flow, which as a result deepens the place's vulnerability. As in the above section of 'Social vulnerability and stormwater infrastructure', the description in the book of Bullard and Wright (2009) shows that protective infrastructure may not be evenly applied to all communities because the long-standing social structure that is discriminatory to certain races and classes affect the decision-making process in which policies for good mitigation measures are made and the site for it is decided. In addition, the theoretical explanations of the GI implementation mechanisms presented by Lim (2017) and Mandarano and Meenar (2017), the market-based approach and the information diffusion phenomenon

indicate that the new type of stormwater infrastructure may continuously be concentrated in specific communities. If social vulnerability perpetuates, the changing infrastructure setting may discriminate against previously socially vulnerable communities, as an outcome of socially vulnerable status, through inequalities of infrastructure management and planning processes, and as a result, the distribution produces environmental injustice with disparate protection across communities.

Synthesizing the previous models of social vulnerability, a part of the theoretical framework of Hendricks and Van Zandt (2021) is modified as below (Figure 4) under the assumption that social vulnerability perpetuates. In the initial stages of this modified Pressure and Release (PAR) model, the socially vulnerable status of specific groups manifests within macro-scale institutions or cultures, as elucidated by Blaikie et al., (2004). In this preliminary context, discriminatory planning and policies that target particular races or classes are instituted, aligning with the tenets of the Pressure and Release model and corroborating the observations of Bullard and Wright (2009). Socially marginalized individuals often grapple with systemic discrimination, economic hardships, and limited access to resources, placing them in a position of heightened vulnerability.

The ensuing economic disparities, discrimination, and other social factors generate pressures compelling individuals to seek places where the cost of living may be lower, often without due consideration for the associated risks of disasters.

Consequently, socially marginalized individuals may settle in areas characterized by underdeveloped infrastructure. Limited economic resources and discriminatory

practices constrain their choices, directing them toward locations with inadequate facilities and services.

Once this initial stage is established, the status of social vulnerability becomes entrenched, as evidenced by literature on segregation (Massey and Tannen, 2015; Menedian et al., 2021). Residents in segregated areas frequently attend lower-quality schools and may face diminished educational opportunities, leading to reduced income levels. This engenders a cyclical pattern where low income reinforces social vulnerability, particularly making these communities more susceptible to disasters due to their limited resources. This perpetuation of social vulnerability is notably pronounced among ethnic minority populations, characterized by higher poverty rates, lower household incomes, and diminished educational attainment. Such a state of social vulnerability is intricately linked to unsafe conditions, including disparities in stormwater infrastructure. The first sub-essay elucidates the connection between social vulnerability and the disparities in stormwater infrastructure, contextualized within the historical backdrop of Washington, D.C.

Introducing the element of time in the cycle of segregation into the PAR model, the socio-economic status of socially vulnerable individuals may persist, perpetuating the pressures that place them in unsafe conditions over time. Despite efforts to implement mitigation and adaptation measures in response to disasters or changing environmental conditions, there is a risk of inadvertently perpetuating discrimination against socially vulnerable populations. Implementation of these measures may unintentionally favor more affluent groups, exacerbating existing disparities. The planning and policies guiding these measures may be exclusive, with approaches that

are market-friendly and reliant on private sector funding sources. The second sub-essay demonstrates the widening gap in the implementation of the new protective measure, GI, among communities, with persistent social vulnerability serving as a driving factor behind this disparity.

Moreover, within the intricate fabric of decision-making and planning processes, a nuanced concern arises. Socially vulnerable individuals, classified as such, face heightened susceptibility due to systematic exclusion or a disconcerting lack of recognition. This phenomenon underscores the gravity of procedural and recognitional inequities, as articulated in Schlosberg's environmental justice theory (2007). The failure to acknowledge and integrate socially vulnerable populations into the decision-making framework not only perpetuates their marginalization but also amplifies their exposure to various environmental risks and challenges. This will be addressed in the third sub-essay.

Consequently, a question on the relationships between social vulnerability, infrastructure distribution, and planning, and flood planning is comprehensively re-explored. The unequal distribution of infrastructure may widen the preexisting gaps in vulnerability, rendering communities that were already socially vulnerable even more susceptible. Without rapid urbanization or redevelopment leading to significant demographic and societal changes, this cycle persists within the confines of a discriminatory social structure. This potential conclusion illuminates the intricacies of dynamic vulnerability, demonstrating how vulnerability is not a static condition but one that is constantly evolving. Highlighting the feedback loops between social vulnerability, infrastructure disparities, and place vulnerability, the theoretical

framework developed in this study sheds new light on the attributes of dynamic vulnerability that persist over time and space (Figure 4).

This thesis represents a progress in the discourse on dynamic vulnerability, challenging the prevailing notion that vulnerability is merely a transient condition easily mitigated by immediate interventions. It delves into how vulnerability is shaped and sustained by complex social and environmental conditions, thus offering a nuanced narrative that emphasizes the complexity and enduring nature of vulnerability. Although the widely recognized Disaster Resilience of Place (DROP) model by Cutter et al. (2008), and subsequent research utilizing this model (Jones, 2021; Lianxiao et al., 2022; Riyadh et al., 2023), acknowledge that vulnerability can evolve over time, they mainly focus on illustrating how vulnerability and resilience are influenced by mitigation and preparedness efforts around disaster events, without delving into the specific conditions that determine whether vulnerability increases or decreases. However, such technocratic studies often overlook how mitigation and preparedness efforts can inadvertently widen the existing vulnerability gap or create new forms of disparity, particularly neglecting the potential adverse impacts on disadvantaged communities. Olsson (2022) critiques this emphasis on technical solutions, highlighting its tendency to ignore systemic failures and social processes that contribute to vulnerability among disadvantaged communities. This highlights the need for resilience and vulnerability models to incorporate a deeper understanding of vulnerability's evolving nature. My research addresses this critical gap by revealing the complex interplay between societal vulnerability, infrastructure distribution, and flood planning. This dissertation introduces an original framework that captures the

enduring complexities of vulnerability, addressing a critical dimension often overlooked by existing vulnerability and resilience models.

This dissertation advocates for a paradigm shift in resilience planning and policymaking towards more inclusive and equity-centric strategies. It emphasizes that beyond merely responding to immediate disasters and weather extremes, there is a critical need to proactively address the underlying socio-economic and environmental conditions that perpetuate vulnerability across communities. Specifically, by highlighting how disparities in stormwater infrastructure contribute to a potentially increased risk of flooding, the dissertation underscores the importance of considering long-term vulnerabilities, especially those rooted in injustices faced by socially vulnerable communities. It calls on planners, engineers, and policymakers to reconceptualize their efforts, moving towards approaches that genuinely reduce vulnerability and ensure equitable resilience against climate-induced challenges. This approach advocates for a holistic framework that not only prepares and responds to immediate disaster scenarios but also mitigates the entrenched vulnerabilities, ensuring a just and sustainable future for all communities. Such a reconceptualization is imperative for crafting more effective, just, and resilient solutions to the challenges posed by climate change and urbanization. It compels a critical examination of the policies and practices that perpetuate vulnerability, thereby fostering a more resilient and equitable future. In essence, this dissertation not only contributes to a deeper understanding of the persistent nature of social vulnerability but also catalyzes a shift towards more inclusive and justice-oriented resilience and adaptation strategies.

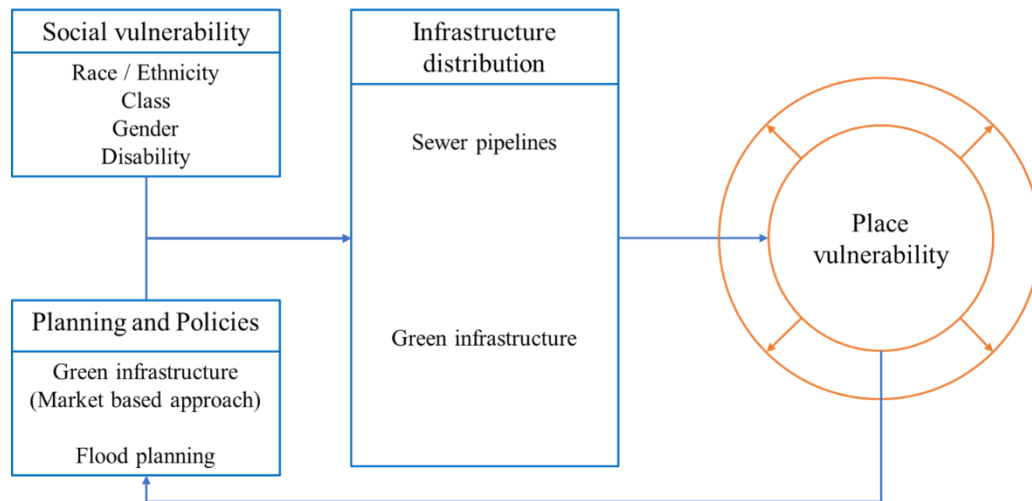


Figure 4 Theoretical Framework

Chapter 3: Study area

3.1. Data accessibility and the case for Washington, D.C.

To rigorously explore the interplay among social vulnerability, stormwater infrastructure distribution and management, and flood planning—while also shedding light on the temporally expanding vulnerability gap across communities—it is imperative to access comprehensive datasets encompassing both sewer pipelines and green infrastructure. This need arises from the ongoing transformation of stormwater management systems, which traditionally relied solely on gray infrastructure, towards the integration of green infrastructure advancements. Although socioeconomic data for U.S. cities is readily available through census records, access to critical infrastructure data, such as sewer pipelines or power supply grids, is often restricted due to security concerns. While certain studies (e.g., Baker et al., 2019; Porse, 2013; 2018) have examined pipeline distribution or density, the datasets employed remain confidential, reflecting the sensitive nature of such information.

Washington, D.C. distinguishes itself as an exceptional case where comprehensive stormwater infrastructure data—encompassing both gray stormwater pipeline (Figure 5) and green infrastructure (Figure 7)—is publicly accessible. This unique availability is facilitated through the District's proactive data transparency initiatives, such as the provision of pipeline data via ArcGIS Online through the official D.C. government account and the regular updates of GI data through the OpenData DC platform. OpenData DC represents a significant governmental effort by the District of Columbia to ensure the accessibility of its data to the public. The singular provision

of complete stormwater infrastructure data by Washington, D.C., positions it as the only viable study area for this research. This exclusivity underscores the necessity of focusing the study within this jurisdiction, enabling a comprehensive examination of the relationships and dynamics at play. Thus, the selection of Washington, D.C. as the study area is not merely a matter of convenience but a strategic decision driven by the unique availability of critical, otherwise inaccessible data essential for advancing understanding in this domain.

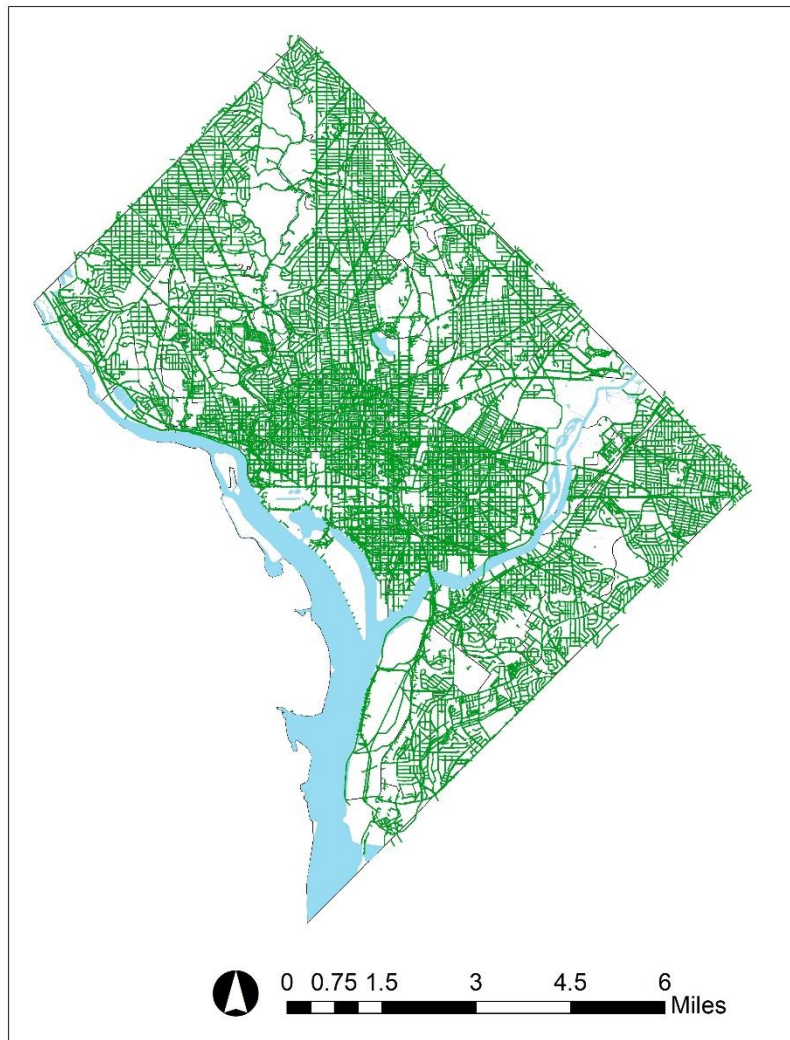


Figure 5 Sewer pipelines in Washington D.C.

3.2. GI growth in its implementation Washington, D.C.

Washington, D.C., exemplifies a leading model in the global arena for its dedication to GI initiatives. Between 2010 and 2020, the city saw an annual expansion of approximately 2,000 GIs (Figure 6), culminating in a total of 22,756 installations by the end of 2020. The district categorizes GIs into 32 types. The information regarding these types is presented in Table 1. This explosive increase in the number of installations indicates that the stormwater infrastructure in Washington, D.C., has been undergoing a significant transformation. The data availability on annual installations also facilitates an analysis of the temporal changes in GI expansion. Such temporal analysis of GI distribution can provide insights into whether the gap in infrastructure equity is widening. The total number of GI installations in Washington, D.C., signifies a density of approximately 333 installations per square mile or about 129 installations per square kilometer by the end of 2020.

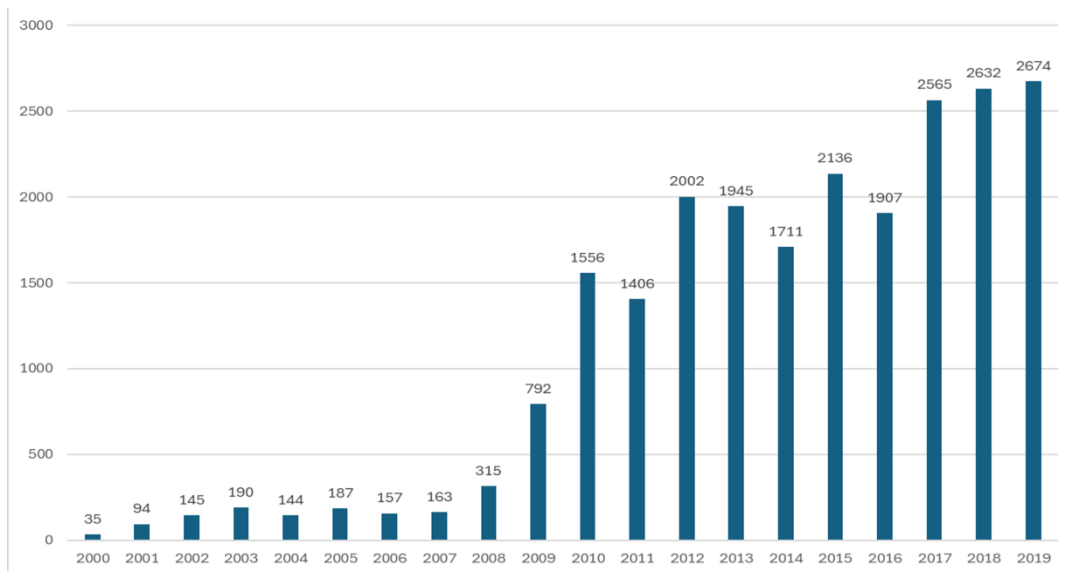


Figure 6 Annual GI increment in DC

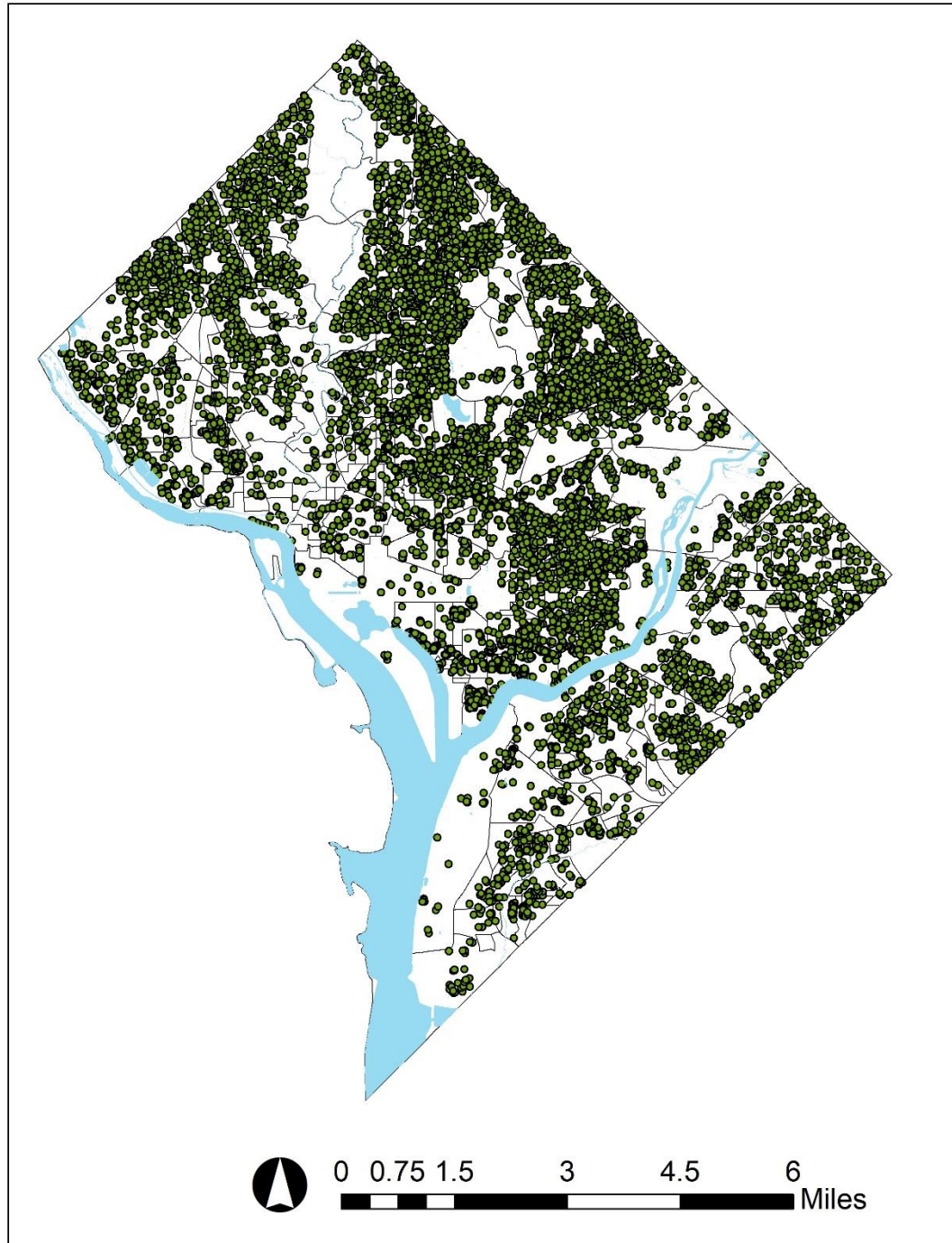


Figure 7 GI distribution as of 2020.

Table 1 GI types as of 2020

GI type	Count	Proportion
Bay scaping	1,909	8.4%
Bioretention	1,024	4.5%
Dry swale	101	0.4%
Engineered tree pits	156	0.7%
Extensive green roof	642	2.8%
Grass channel	47	0.2%
Green roof	547	2.4%
Impervious Surface Removal	1	0.0%
Infiltration	575	2.5%
Infiltration basin	14	0.1%
Infiltration trench	218	1.0%
Intensive green roof	370	1.6%
Open Channel	10	0.0%
Permeable pavement	846	3.7%
Permeable pavers	350	1.5%
Pervious concrete	81	0.4%
Porous asphalt	89	0.4%
Rain Barrel	5,100	22.4%
Rain Garden	1,031	4.5%
Rainwater harvesting	1,391	6.1%
Residential rain garden	18	0.1%
Rooftop storage	2	0.0%
Simple disconnection to a conservation area	16	0.1%
Simple disconnection to a pervious area	392	1.7%
Simple disconnection to amended soils	12	0.1%
Stormwater planters	152	0.7%
Streetscape bioretention	139	0.6%
Traditional bioretention	736	3.2%
Tree planting	6,583	28.9%
Tree preservation	195	0.9%
Wet Swale	5	0.0%
Wetlands	4	0.0%
	22,756	100.0%

Presently, the city is advancing seven key programs, including the DC Clean River Project and River Smart Homes, spearheaded by three main agencies: the Department of Energy and Environment (DOEE), the District Department of Transportation (DDOT), and the District of Columbia Water and Sewer Authority (DC Water). While there is no unified entity for the planning and execution of GI programs, efforts like DC Water's Long Term Control Plan (LTCP) and the DOEE's Total Maximum Daily Load (TMDL) implementation plan are pivotal in harmonizing various GI efforts. These plans are instrumental in identifying underutilized areas for GI placement, thus enhancing the coordination of voluntary and community-led GI projects (DC Water, 2002; DOEE, 2022; Lim, 2018).

Moreover, despite the distinct GI programs managed by DOEE, DC Water, and DDOT, there exists a unanimous commitment to a shared definition and objective for GI. This consensus is detailed in the Stormwater Management Guidebook and elaborated on the websites of DC Water and DDOT website (DC Water n.d.; DDOT n.d.; DOEE, 2020), positioning GI as a comprehensive strategy for urban areas to manage stormwater effectively. This approach not only aims to alleviate the burden on sewer systems and reduce water pollution but also to safeguard communities from floods. The collaborative vision extends the impact of GI beyond stormwater management to encompass environmental, social, and economic benefits, with DC's GI initiatives including technologies such as rooftop gardens, permeable surfaces, and bioretention facilities.

In terms of implementation, Washington, D.C. adopts a multifaceted approach to GI, leveraging public funding, regulatory mandates in construction permits, and

incentives for voluntary participation (Dunn 2010). Despite these efforts, the primary motivations for GI adoption in the city are redevelopment and new construction projects, along with voluntary contributions (Lim 2018). However, this strategy raises concerns regarding the equitable distribution of GI installations, suggesting that, over a decade, GI deployment may favor more advantaged communities, potentially leading to disparities in access to GI benefits across different neighborhoods.

3.3. Historical context and infrastructure in Washington, D.C.

On the other hand, prior models of social vulnerability recognize the infrastructure and built environment within communities of varying economic statuses as having social dimensions or implications (Blaikie et al., 2014; Cutter, 1996; Cutter et al., 2003) This suggests that the models interpret physical infrastructures not just in terms of their material existence or functional purposes but also in relation to their social impacts and meanings. In wealthier or poorer communities, the nature, quality, and distribution of infrastructure and built environments reflect and influence social structures, dynamics, and inequalities. This understanding points to the interconnectedness of physical and social realms, highlighting how infrastructure can embody and perpetuate social values, disparities, and vulnerabilities.

Washington D.C.'s history as the “Chocolate City” and its role as a case study area can indeed illustrate that physical infrastructures extend beyond their material existence and functional purposes to embody significant social impacts and meanings. The moniker “Chocolate City” historically referred to Washington D.C.'s majority

African American population and the rich cultural identity that shaped the city's social fabric. This demographic and cultural context provides a nuanced backdrop against which the interplay between physical infrastructure and social dynamics can be explored.

In analyzing Washington D.C.'s infrastructure within this context, I could examine that the accessibility of infrastructure or public service reflect social inequalities in its history. Incorporating the historical context of Washington, D.C., particularly focusing on the experiences of African American communities such as Barry Farm and Deanwood, significantly enriches the study of social vulnerability and infrastructure distribution. This historical examination reveals that systemic racism, manifested through policies like Black Codes, Redlining, and discriminatory education and housing policies, has deeply influenced the spatial and social fabric of the city. These policies not only shaped the economic opportunities available to Black residents but also determined the quality and accessibility of critical infrastructure and public services within their communities. The stark disparities in infrastructure development and maintenance between historically Black communities and their White counterparts in D.C. reflect broader patterns of social inequality and vulnerability. Barry Farm and Deanwood, historically Black communities, experienced the delayed or inadequate provision of essential services such as sewer pipelines, electricity, and water supply, which show the material consequences of racial discrimination (Anacostia Community Museum, n.d.). The historical context of D.C., particularly the experiences of its African American residents, offers invaluable insights into the ways in which infrastructure and social vulnerability are mutually

constituted. The detailed description regarding the historical context in Washington D.C. and the associated story of infrastructure gap across communities are introduced in Chapter 4.

In sum, the selection of Washington, D.C., as the study area is grounded in its rich historical context, marked by racial segregation, discrimination, and the ongoing struggle for social and infrastructural equity. This context provides a critical foundation for examining the contemporary challenges of stormwater management and social vulnerability, making D.C. an exemplary case study for this research.

Chapter 4: Socially vulnerable people and stormwater infrastructure: A geospatial exploration of the equitable distribution of gray and green infrastructure in Washington D.C.

Abstract

Green Infrastructure (GI) has gained recognition for its pivotal role in climate change mitigation and urban resilience. Increasing body of literature revealed the distribution of GI from environmental justice. Given the role of GI, the distribution should be explored with social vulnerability and gray infrastructure like sewer pipelines. However, the distribution of GI, sewer pipelines, and their relationship with social vulnerability remain underexplored. This research addresses these gaps by examining the allocation of stormwater infrastructure in Washington, D.C., considering its historical context of discriminatory sewage services. The study investigates whether disparities exist in the distribution of sewer pipelines and green infrastructure among communities with varying levels of social vulnerability. By adopting a comprehensive approach that integrates GI, underground pipelines, and social vulnerability indices, this research aims to enhance our understanding of inequitable stormwater infrastructure distribution within urban areas. The analysis reveals significant insights into the relationships between stormwater infrastructure, social vulnerability, and urbanization, offering valuable implications for stormwater management planning. This research contributes to the field of environmental justice and urban planning by shedding light on the complex interplay between infrastructure

allocation, community vulnerability, and the urgent need for equitable stormwater management in the face of climate-related challenges.

4.1. Introduction

Green infrastructure (GI) has been steadily gaining recognition and popularity due to its multifaceted advantages in tackling the challenges posed by climate change. GI comprises various elements, including permeable pavements, green roofs, and urban forests, which function as highly effective tools for stormwater management and play a pivotal role in climate change mitigation. These natural and semi-natural components not only aid in carbon sequestration, thereby reducing greenhouse gas emissions but also bestow additional benefits, such as urban cooling and the promotion of enhanced biodiversity (Pamukcu et al., 2021). By doing so, it equips cities with the necessary tools to better adapt to and manage the intricate and evolving impacts associated with our changing climate. Pamukcu et al. (2021) illustrate that GI not only enhances the resilience of urban environments but also fosters sustainable urban development. GI represents a holistic approach to address climate change challenges, offering a suite of benefits that extend far beyond environmental stewardship and significantly contribute to building more resilient and sustainable urban landscapes (US EPA, 2015).

In the United States, GI is officially defined as measures that involve filtering and absorbing stormwater at its source, as stated in the Water Infrastructure Improvement Act of 2019. This legislative recognition aims to promote GI in managing stormwater

and mitigating its environmental impact (The Water Infrastructure Improvement Act 2019). Porse (2018) argues that there is a noticeable shift from centralized stormwater systems to hybrid systems that incorporate both green and gray infrastructure, and this transformation reflects a heightened awareness of the urgent need to adapt to the escalating frequency and intensity of precipitation events driven by global climate change. Integrating GI with traditional gray infrastructure, such as sewer pipelines and pumping stations, new hybrid systems of stormwater infrastructure emerge, offering a multifaceted approach to addressing the increased intensity and amount of precipitation posed by climate change. Constructing this hybrid systems for stormwater management serves not only the traditional objective of diminishing urban flood risk but also brings about supplementary ecological and social advantages, including pollution mitigation. (Baker et al., 2019; Pataki et al 2011, Porse 2013; 2018)

With the popularity of GI, a growing body of literature from the environmental justice perspective has empirically demonstrated that the distribution of GI has closely associate with certain socio-economic factors, such as income and race. For instance, Baker and colleagues (2019) demonstrated a negative correlation between the density of above-ground green stormwater infrastructure in Portland, Oregon, and the median income of local communities. Wendel et al (2011) found disparities in access to green infrastructure in Tampa, Florida, while Ferguson et al. (2018) explore that higher-income and predominantly White neighborhoods in the United Kingdom tend to have better access to green infrastructures. Moreover, a few studies not only highlight the existence of these inequitable patterns but also delve into the mechanisms behind the

clustering of GI in wealthier communities. Lim (2017) employed the information diffusion theory to explain the distribution of voluntary GI implementation. Mandarano and Meenar (2017) pointed out that the current GI programs and policies in the US necessitate community capacity in voluntary participation, public investment, and regulation in GI implementation. Additionally, Park (2023) showed that GI implementation in Washington, D.C. has consistently clustered in wealthier communities throughout the 2010s.

While the existing body of GI literature from an environmental justice perspective has primarily focused on examining the unequal allocation of benefits and the distribution of GI in various areas based on the socioeconomic characteristics of communities, it is also crucial to highlight the disparities in sewer pipelines, as well as those in GI. This is because GI serves as a complementary component to traditional gray stormwater infrastructure, as emphasized by Baker et al. (2019) and Porse (2018). Porse (2018) argues that GI should be strategically located in areas where sewer pipelines are lacking, particularly in regions where more sensitive populations, such as children and the elderly who may be more vulnerable to environmental hazards, reside. This suggests that the distribution of GI and sewer pipelines should be considered together. On the other hand, in Park's study (2023), a social vulnerability index was integrated into the analysis of GI distribution, taking into account the manifold benefits of GI in various weather extremes, such as urban heat events and heavy rainfall. This approach is equally applicable when examining the distribution of the pipelines, as they are a critical component of urban infrastructure responsible for collecting, transporting, and treating sewage and wastewater, playing essential roles

in ensuring public health and sanitation. Measuring social vulnerability may provide a more comprehensive understanding of the needs of different communities. Therefore, it is essential to consider the distribution of gray and green infrastructure together and measure and utilize the social vulnerability index when exploring their distribution.

There is a noticeable research gap in exploring the interplay between GI distribution, sewer pipeline distribution, and the social vulnerability of communities. Only a few studies have investigated the relationships between the two (e.g., GI and sewer pipelines, GI and socioeconomic factors, or pipelines and socioeconomic factors). For instance, Baker et al. (2019) scrutinized the distribution of GI across communities in Baltimore, Maryland, and Portland, Oregon, along with several sociodemographic factors. However, they treated the distribution of the pipelines as an independent variable for analyzing GI, separate from socio-economic factors, despite applying an environmental justice perspective. Pallathadka et al. (2022) examined how GI is distributed to identify opportunities for urban planners to improve environmental equity when deciding where to locate GI concerning the risk of pluvial floods, but the authors did not connect the GI distribution with gray infrastructure. In a different context, Porse (2018) delved into the distribution of sewer lines in relation to sociodemographic factors, identifying areas of heightened interest for potential GI investments based on the disparities in sewer lines in Los Angeles, California, but he did not analyze the GI distribution. Nevertheless, there exists a dearth of comprehensive studies that have jointly examined the distribution of GI, underground pipelines, and the social vulnerability of communities. Such an approach will

contribute to a better understanding of the current environmental injustices and community vulnerabilities in the face of climate-related events.

My research aims to bridge this empirical gap by investigating the distribution of stormwater infrastructure consisting of pipelines and green infrastructure and its relationship with socially vulnerable status of communities. Thus, the research explores and provides answers to the following research questions: Are there significant disparities in the allocation of sewer pipelines and green infrastructures among communities with different levels of social vulnerability in Washington, D.C.? In doing so, the research strives to contribute to a more comprehensive understanding of inequitable stormwater infrastructure distribution within urban areas and presents empirical research results for future stormwater management-related planning.

The figure below presents a theoretical framework illustrating how this section of the study was conducted (Figure 8). It demonstrates how social vulnerability influences the distribution of stormwater infrastructure—including sewer pipelines and green infrastructure—and thereby leads to the occurrence of place vulnerability gaps across different communities. This article is organized as follows. First, Washington, D.C.'s historical context is described as the study area. In that section, I also describe the public service and sewer pipeline in the city's discriminatory ambience. Section 4 focuses on presenting the methodology adopted and specifics about the data used. Section 5 shows the main results obtained in the regression analysis, and section 6 presents findings based on the correlations between GI and the social vulnerability index, including the influence of urbanization, stormwater infrastructure and planning

implications. Thereafter, I discuss limitations, future research directions, and conclusions.

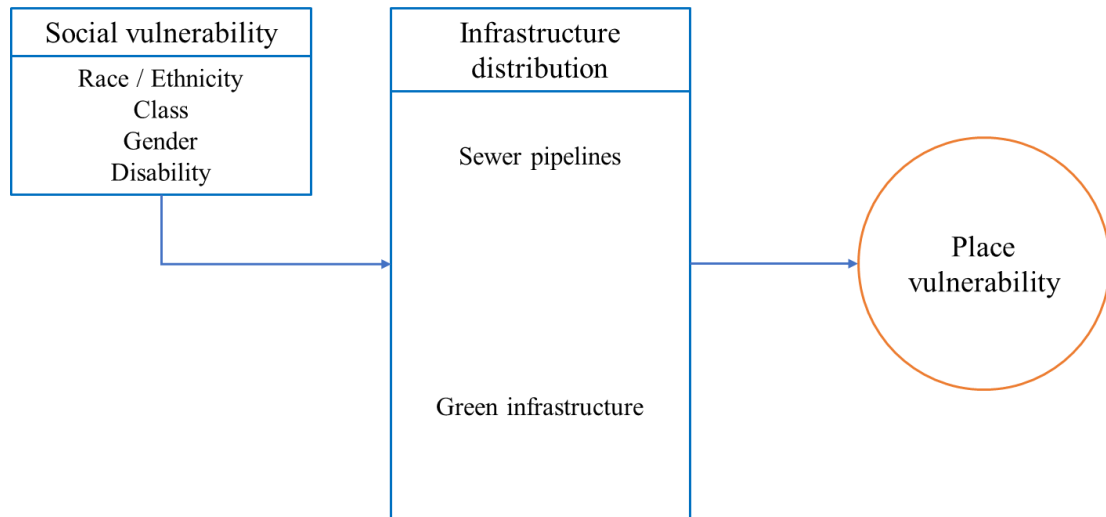


Figure 8 Theoretical framework for the distribution of stormwater infrastructure.

4.2. Literature review

Infrastructure distribution can be uneven across communities due to various factors. The Pressure and Release (PAR) model proposed by Blaikie et al. (2014) plays a significant role in understanding this disparity. The model identifies political, economic, demographic, and historical factors that influence the distribution of resources, leading to varying degrees of vulnerability among communities during disasters. According to the PAR model, economically or politically marginalized communities are often disproportionately affected by the uneven distribution of resources and infrastructure and face restricted access to essential services and resources due to discriminatory policies and development practices. As a result, government intervention in these communities is often given low priority, perpetuating their vulnerability. Disinvestment and exclusion from market-based development approaches exacerbate infrastructure disparity (Hendricks, 2017). These communities are left with inadequate infrastructure and limited access to basic amenities, making them more susceptible to the impacts of disasters. The PAR model explains why economically or politically marginalized communities reside in hazardous locations or buildings. These locations often lack proper infrastructure and protective measures, making the residents more vulnerable during disasters. The model's global application indicates that this issue is not limited to specific regions but can be observed worldwide.

Disaster literature has also shown that discriminatory policies and development patterns have influenced the location and outcomes of marginalized communities and subsequently excluded these communities from pre-disaster protective measures or

post-disaster investment (Bullard and Wright, 2018; Hendricks and Van Zandt, 2021). Oliver-Smith (1999) argues that cumulative underdevelopment patterns, subsequent racial marginalization and associated poverty, and anti-democratic development influence the differential vulnerability of communities. In New Orleans, studies shows that practices of segregation limiting location choice have led African American communities to settle in flood-prone areas that have incurred more damage during disasters. They also have been excluded from the protective measures that whiter and wealthier communities were granted (Bullard and Wright, 2011). In Houston, TX, neighborhoods located outside of floodplains with more Black and Hispanic residents experienced greater degrees of flooding during 2017's Hurricane Harvey, as a result of racial residential stratification (Smiley, 2020). These theoretical and empirical descriptions imply that marginalized communities, as a result of discriminatory policies and development patterns, have access to less safe housing, infrastructure, or built environment.

Similarly, a growing body of Environmental Justice literature focusing on the distribution of stormwater infrastructure, which delivers flooding mitigation and other benefits, empirically demonstrates that certain socio-economic factors are closely correlated with the distribution of stormwater infrastructure. This can also be seen in Porse (2018), which reveals that higher values of sociodemographic indicators in Los Angeles, CA, such as the proportion of rental households, correlate with lower capacity of stormwater infrastructure. Another example is Mandarano and Meenar's work (2017) that found a negative relationship between minority-populated areas in Philadelphia, PA, and the location of GI, with the authors tying the inequitable

distribution of it to market forces. For Baker et al. (2019), the density of both grey and green infrastructure is negatively associated with the median income of census tracts. These studies collectively suggest that GI is inequitably distributed from the perspective of Environmental Justice (EJ).

From the perspective of justice, while the correlation between socio-economic factors and social infrastructure is important, it is also crucial to view the distribution of infrastructure from a disaster perspective as well, considering that disasters can further highlight the existing injustices and inequalities within society. In the planning and practice of disaster responses, decision makers place importance not only on specific socio-economic factors, but also on the overall social vulnerability of a community or individual because this concept represents the ability to respond to disasters and determines policy priorities for disaster-related planning (Flanagan et al. 2011). By looking at how the distribution of storm-water infrastructure functioning to prevent major and minor floods is correlated with social vulnerability, I can identify and differentiate prioritized communities for assistance in planning for flood events.

Although there are no consistent metrics set for the social determinants that affect disaster vulnerability, the Social Vulnerability Index (SoVI) is widely utilized to represent the relative ability of a community or city to prevent human suffering in disaster events (Cutter et al., 2003). Social vulnerability literature has identified some common dimensions of social vulnerability, - such as income and poverty, race and ethnicity, and education level, - that differentially affect a community's impact from a given disaster context (Van Zandt et al., 2012). In addition to the commonly used factors of class and race, other root causes such as gender, age, or disabilities are also

crucial to consider (Enarson 1998; Fothergill 1998; Aldrich 2008). Social vulnerability is more accurately described not by one or two factors, but by a range of characteristics acting collectively. In this way, social vulnerability indices attempt to capture the cumulative effects of past discriminatory practices through surface level indicators of current conditions (Hendricks and Van Zandt, 2021).

Based on the empirical findings from stormwater infrastructure literature (Baker et al., 2019; Mandarano and Meenar, 2017., Porse, 2018) from the EJ perspective and the theoretical description of social vulnerability, this study hypothesizes that the comprehensive social vulnerability leads to the unequal distribution of stormwater infrastructure. Therefore, this study corroborates the previous social vulnerability theories saying that socially vulnerable communities have access to less safe infrastructure to cope with potential floods in a quantitative way, and the research question is whether the distribution of stormwater infrastructure in Washington DC is correlated with social vulnerability.

4.3. Study Area - Washington, D.C.

Geographically, the District of Columbia (DC), location of the capital city of the United States, is adjacent to the northern edge of the Potomac River and located between Maryland and Virginia states (Figure 9). To enhance city sanitation and flood protection, traditional pipelines construction began around 1810. Tarr (1984) notes that sewer pipelines in the United States have been planned and constructed to be of sufficient size and shape to carry storm runoff and human waste since the 1850s, but it remains uncertain whether the existing underground pipelines in DC can accommodate the significant changes in the above-ground urban environment that have occurred since the systems were constructed. In the 1960s, the Municipal Separate Storm Sewer System (MS4) was built to cover parts of the residential areas in DC's Northwest and Southeast regions, with the aim of safeguarding the water quality of the Potomac and Anacostia rivers. Recently, the city has been using GI to complement its aging stormwater infrastructure, generating additional social, economic, and environmental benefits (DC Water n.d.; DOEE, 2020).

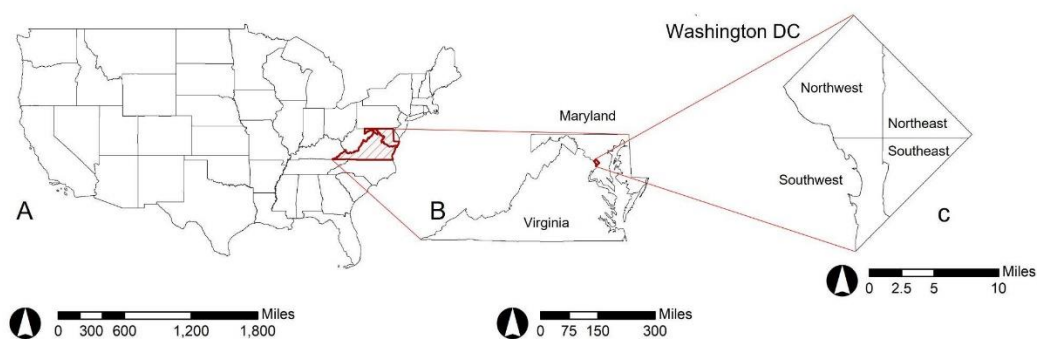


Figure 9 United States(A), Washington DC and surrounding states(B), and DC Quadrants(C)

4.4. The historical context in DC and two Black communities and their pipelines

DC is a demographically divided city - based on the 2019 American Community Survey (ACS) data (Figure 10). The divided demographics in DC reflects the historical context. Washington, D.C. has a historical backdrop dating back to the mid-19th century, marked by segregation and disinvestment. In the 1840s, the Black Codes prohibited freed Black individuals from owning and operating businesses, creating a clear disparity in economic opportunities (Kijakazi et al., 2016). In 1862, the DC government's decision to compensate White slave owners while neglecting compensation for formerly enslaved Black individuals further exacerbated disparities in wealth accumulation.

The discriminatory practices extended into the realm of education. During the 1860s, tax allocations for public education hindered the social development of Black residents in DC. The educational disparity between Black and White students, both in terms of facilities and quality, widened with the passage of a law known as "An Act providing for the education of colored children in the cities of Washington and Georgetown, District of Columbia" in 1862 (Gillette 2006; Kijakazi et al 2016). This law restricted funding for Black schools solely to taxes collected from Black individuals, leading to significant funding disparities. In 1863, the allocation for Black schools amounted to a mere \$410, while that for White schools reached \$65,000 (Kijakazi et al., 2016). These disparities had ripple effects, affecting income, employment opportunities, and even contributing to elevated crime rates associated with unemployment. Despite some advancements in educational policy within DC,

notably with the enactment of the Public Education Reform Amendment Act in 2007, which led to improved academic achievements for Black students (Sarah, 2021), the substantial gap in educational attainment between racial groups still persists.

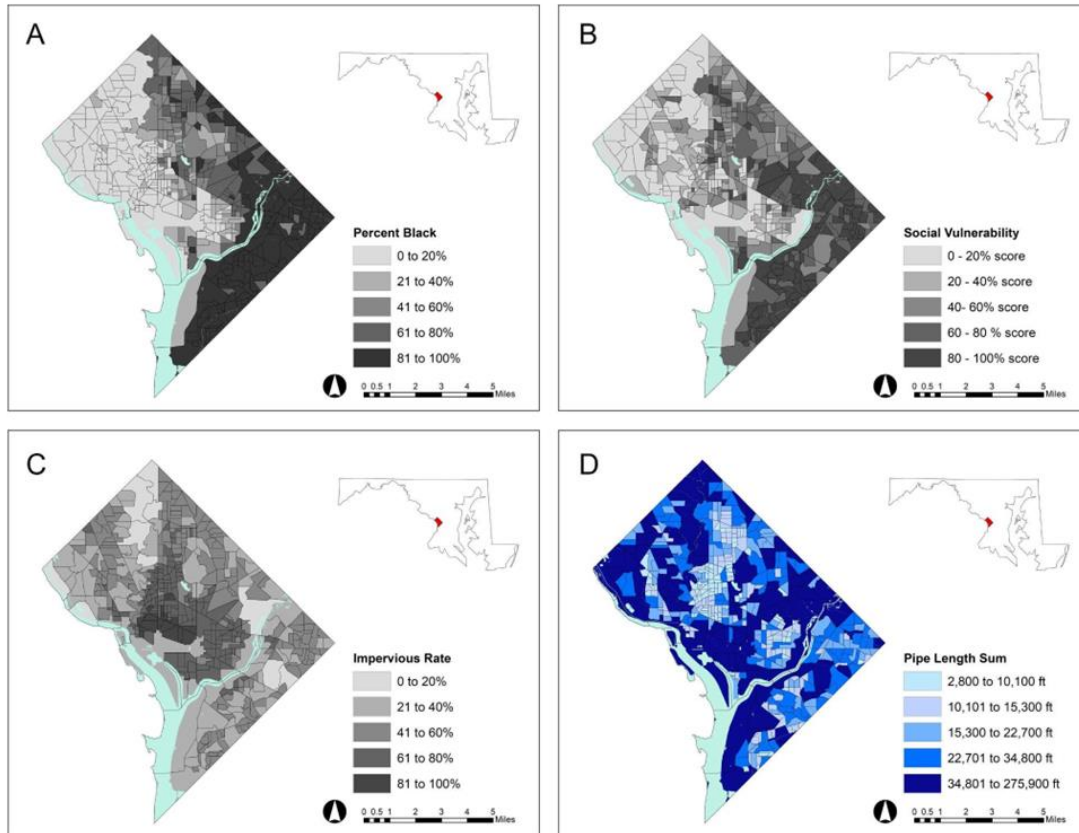


Figure 10 Spatial characteristics of variables (A: Racial composition of census block groups, B: SoVI distribution, C: Imperviousness surface distribution, and D: Sum of underground pipe length by census block groups)

During the 1930s, the Home Owner's Loan Corporation implemented a discriminatory practice known as Redlining, which primarily targeted Black communities, making it exceedingly difficult for Black individuals to access mortgage loans and achieve homeownership. Since homeownership is a pivotal factor in wealth accumulation, Redlining significantly hindered the wealth-building opportunities for Black people (Shapiro, 2006). Rothstein's research in 2017 further underscores the impact of discriminatory housing policies. By 1960, the Federal Housing Administration had insured property values for Black neighborhoods in DC at less than one-seventh the value of homes in surrounding White neighborhoods, creating a substantial wealth gap between White and Black homeowners (Kijakazi et al., 2016). In the 1960s, Urban renewal began. DC's dominantly Black neighborhoods in Southwest DC were cleaned by eminent domain (Kijakazi et al., 2016; Zickuhr, 2018). More than 500 acres of the urban area have been cleared, including 1,500 businesses and 6,000 homes, and about 23,000 residents, mostly Black, were displaced with not enough compensation (Kijakazi et al., 2016). 95% of newly built 5,900 homes were for the upper-middle classes, and only 5 % of new homes were for the middle class (Zickuhr, 2018).

Kijakazi et al. (2016) argue that the African American community in Washington, D.C. has faced intentional barriers to wealth accumulation for more than two centuries, with many of these challenges being deliberately embedded in legislation. The DC Policy Center (2022) has examined persistent practices across various domains, including housing, workplaces, and the fines and fees system, which have hindered the advancement of communities of color and exacerbated existing

disparities. These deeply ingrained racially discriminatory context manifest significant disparities in demographics. According to 2017 ACS data, out of the 450 census block groups comprising D.C., 126 of these groups, with over 80% Black populations, are concentrated in Southeast D.C., while the majority of the 76 block groups, with over 80% White populations, are situated in the northeast quadrant. This spatial division between African Americans and White residents directly correlates with socio-economic disparities. The median household income for the 76 predominantly White census block groups averages \$152,900, more than three times the average for Black settlements. The median wealth of White households, standing at \$284,000, is approximately 81 times that of Black households, which have an average wealth of \$3,500, based on 2013 and 2014 data (Kijakazi et al., 2016). The average home value for African Americans is roughly 65% of the value of White-owned homes (Kijakazi et al., 2016). Moreover, the proportion of the population without a high school graduation in Black communities exceeds 15%, whereas in White communities, this figure is less than 2%. Alongside these ethnic and income disparities, significant differences exist in family composition, property values, and poverty levels between these two groups.

The Barry Farm and Deanwood: Tales of Infrastructure Disparities

The history of Barry Farm reflects the discriminatory ambiance of the city. Barry Farm is one of the historically African American neighborhoods in Southeast DC. At the end of the Civil War, the Freedmen's Bureau, officially known as the U.S. Bureau of Refugees, Freedmen, and Abandoned Lands, purchased a 375-acre plot of land from a White landowner who had recently owned enslaved individuals in 1867 (Cantwell, 1973). This acquisition marked the beginning of the evolution of Barry's Farm into a self-sustaining community inhabited by African Americans, both formerly enslaved and free-born (Amos, 2021). Barry Farm neighborhood developed into a vibrant community with rising Black entrepreneurs (Shoenfeld, 2019).

However, the neighborhood experienced not only discriminatory housing policies but also underinvestment in infrastructure. Throughout the 20th century, residents of Barry Farm faced ongoing shortages of essential services like electricity, sewage, water supply, pavement, and mail delivery, with some of these deficiencies persisting into the 1940s, as reported by the Anacostia Community Museum (n.d.). The statement is also confirmed through my pipeline dataset. Figures 11, 12, and 13 show that some of the African American residential areas in Barry Farm (circled in the figures) did not have access to sewer pipelines. It wasn't until 1940 that these residential areas were connected to sewer pipelines along all their boundaries, and the density of these pipelines increased by the 1960s and beyond.

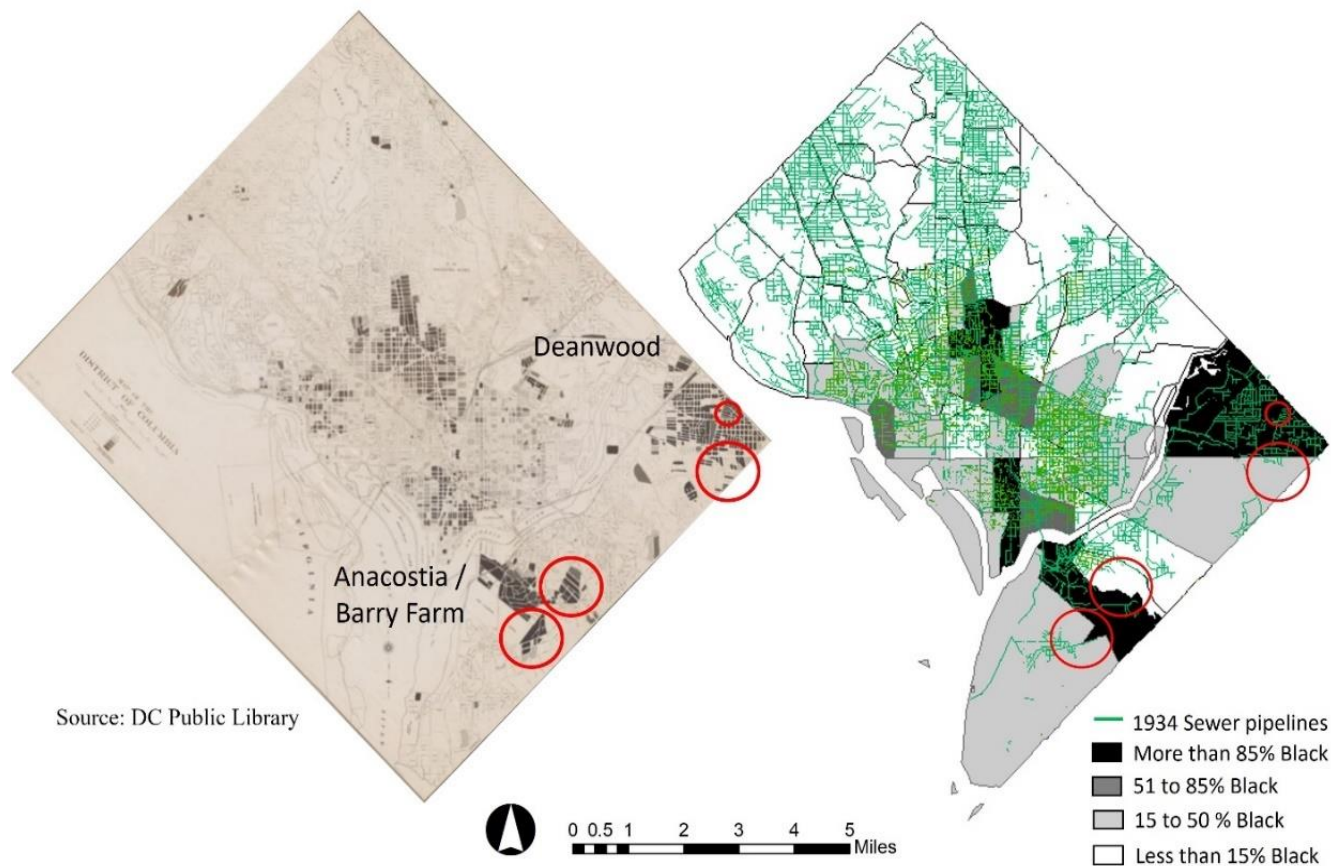


Figure 11 Black residential blocks and sewer pipelines in 1934. In the left map of 1934, the color of the blocks corresponds to the percentage of dwelling units. Completely black-colored blocks indicate that over 99% of the residents in that area are Black. In the right map, the base map is the US census tract map of 1930 and shows the racial composition. Completely black-colored tract means that over 85% of the residents in that area are Black. The green lines are sewer pipelines as of 1934.



Figure 12 Enhanced Visualization of Anacostia / Barry Farm and Deanwood

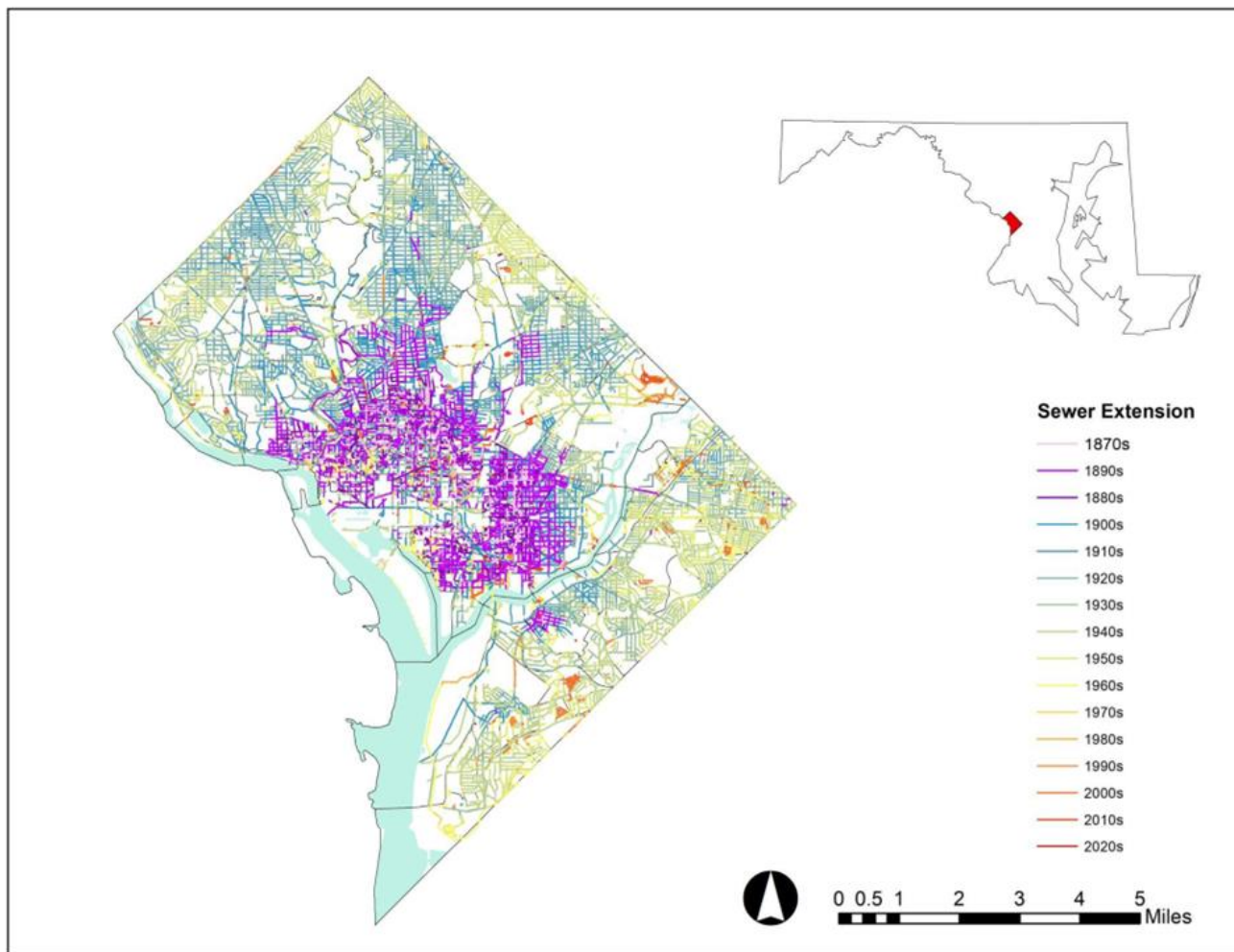


Figure 13 Historical sewer pipeline extension in D.C.

The 1950s and 1960s witnessed continued deficiencies in basic amenities and municipal disinvestment in the Barry Farm community. During this period, Black children in Barry Farm were compelled to attend racially segregated schools, often housed in aging and overcrowded facilities, while their White counterparts enjoyed access to newer, better-maintained schools (Shoenfeld, 2019). This discriminatory education policy was challenged in the case of *Bolling v. Sharpe* (1954), where Barry Farm residents played a significant role as plaintiffs. This case contributed to the Supreme Court's decision in May 1954 (*Bolling v. Sharpe*, 1954), which declared racial segregation in public schools unconstitutional (Shoenfeld, 2019). Furthermore, Anacostia Community Museum (n.d.) illustrates the activism of some groups of activists in Barry Farm during the 1960s. These activists worked to raise awareness of shared problems and engaged in community-led movements to address various issues, including policing, water infrastructure, and community programs. These efforts are closely tied to the availability and quality of public services in the neighborhood during that era (Anacostia Community Museum n.d.; Shoenfeld, 2019). Together, these descriptions provide valuable insights into the challenges the community faced concerning public services. According to Asch and Musgrove (2017), in the 1960s, over 12% of the city's African American households still had no running water, and more than 16% were without electricity.

Likewise, Deanwood, one of the District's oldest suburbs, has a history marked by historical discrimination. The neighborhood's housing development began in the early 1900s (Deanwood History Project Committee, 2005) and continued into the 1920s (MIT Digital Humanities Lab, n.d.). During this period, African American residents

in central DC were forcefully removed from alley dwellings and deemed inadequate residences (Asch and Musgrove, 2017). Many of these displaced Black residents had no choice but to relocate to the emerging Black communities in suburbs like Deanwood (MIT Digital Humanities Lab, n.d.). In racial discrimination of that era, when houses were being constructed in Deanwood, many did not have windows on the sides due to restrictions on the lines of credit provided to Black builders (Deanwood History Project Committee, 2005; Cultural Tourism DC, 2009). These lines of credit only covered essential building materials and not additional features like extra windows or basements (Deanwood History Project Committee, 2005).

As the Deanwood History Project Committee (2005) and MIT Digital Humanities Lab (n.d.) point out, the initial development of Deanwood was characterized as a self-sufficient community as a result of the city's lack of support. The homes of Black residents featured spaces for raising chickens and maintaining gardens to support their self-sufficient living (Cultural Tourism DC, 2009). The self-sufficient living, through raising livestock and gardening, was particularly necessary for Deanwood residents. During the majority of the early 1900s, Deanwood people lacked access to running water, and they either collected rainwater from their roofs or drew water from wells (Anacostia Community Museum n.d., MIT Digital Humanities Lab, n.d.). A lack of garbage collection and sewer systems for Black residents living east of the Anacostia River persisted until the 1950s (MIT Digital Humanities Lab, n.d.). As in Barry Farm, the figure 11 and 12 show that part of the lots in Deanwood did not have sewer pipelines in 1934. They raised pigs and chickens to manage everyday waste

and utilized organic waste from both humans and animals for their gardening (Cultural Tourism DC, 2009; MIT Digital Humanities Lab, n.d.).

4.5. Data and methods

4.5.1. Data

I obtained social vulnerability, landscape, and urbanization data from the District of Columbia government's Open Data DC website and the ACS at the census block group level. The underground grey infrastructure data was not available on the Open Data DC site, and was instead obtained from an open data source, ArcGIS online. Two owners are providing the same data of DC sewer pipelines. The pipeline data reliability was checked through comparison with Open Data DC storm sewer shed system data containing locations and attributes of storm sewer systems and Open Data DC MS4 storm sewer outfalls' location data. Using these available data, I organized a dataset containing 23 variables for further analysis concerning their relationship to stormwater infrastructure capacity, as seen in Table 2.

Stormwater infrastructure design must comply with a set of stormwater criteria, requiring provision of water quality volume, recharge volume, channel and overbank protection volume, and extreme flood volume (Maryland Department of the Environment, 2009). Calculating the criteria for a stormwater infrastructure design requires consideration of storm runoff coefficients and peak discharge rates that are determined by topological and geological settings, such as imperviousness, slope, and altitude of urban surfaces (Maryland Department of the Environment, 2009). Both the

quantity and quality of storm runoff could be sensitive to urbanization factors like population density and land use in urban stormwater management (Wang et al., 2017). This indicates that stormwater infrastructure construction should reflect not only landscape factors but also urbanization factors, such as land uses and densities of population and buildings. On the other hand, environmental justice perspective links the socially vulnerable status by class or race to unsafe conditions, such as dangerous locations and disaster preparedness, through the local institutions or urbanization process (Bullard and Wright 2009). From the environmental justice perspective, I hypothesize that stormwater infrastructure could also be associated with the social vulnerability of communities. Thus, as the below analytical framework shows (Figure 14), the independent variables are categorized into landscape data, urbanization data, and social vulnerability indicator data as in the green infrastructure papers (Baker et al., 2019; Chan and Hopkins, 2017; Mandrano and Meenar, 201; Porse, 2018), which investigate the relationships between green stormwater infrastructure and socio-economic factors.

For the analysis, I grouped variables representing the topography into the landscape subgroup. The urbanization subgroup was assigned population density, building related data, and dummy variables for either residential, commercial, or federal use based on the land use that occupies the largest area within each census block group. The variables in the socioeconomic subgroup are combined into the social vulnerability index which consists of 10 socio-economic variables, and this index was used in the analysis. The dependent variables for underground pipelines are the sum of pipe length and the sum of pipe plan view area within each census block group and

are proxies for the sewer pipelines' capacity (Table 2). These variables do not represent the exact capacity of the pipelines, since various factors such as diameter, slope, and material effect pipeline capacity, but they can act as a proxy in analyses of the distributions of stormwater infrastructures and sociodemographic factors (; Baker et al., 2019; Porse 2018). The area of sewer pipes was computed by multiplying the length of pipes by an assumed or specified pipe diameter. In cases where pipelines do not have associated diameter information in the database, I assumed a 2-foot diameter for the pipelines, a reasonable average pipe diameter for engineering practice (Porse, 2018). The dependent variable for above ground stormwater infrastructure is the number of GI in a census block group. A total of 450 census blocks were analyzed.

Table 2 Dependent and independent variables

Variable	Description	Unit	Source
<i>Dependent Variables</i>			
Pipeline length	Total length of sewer pipes in a census block group	foot	ArcGIS Online (Secondary data),
Pipeline area	Total area of sewer pipes in a census block group	square foot	DC STORM SEWER LINES by andrew.oetman@dc.gov_DCGIS, DCCR_admin
GI counts	The number of GI in a census block group		DC open data (as of 2023 Jan)
<i>Independent Variables</i>			
Building height		foot	DC open data
Building area	Sum of building floor area in a census block group	square foot	DC open data
Building age	Average building age in a census block group	years	DC open data
Impervious Rate	Proportion, Sum of Impervious surface area / Area of census block group	%	DC open data
Residential use	Dummy variable (If the largest area of a census block group is residential, the value is 1)		DC open data
Commercial use	Dummy variable (If the largest area of a census block group is commercial the value is 1)		DC open data

Federal use	Dummy variable (If the largest area of a census block group is federal, the value is 1)		DC open data
Average elevation	Average altitude above sea level of a census block group	foot	DC open data
Average slope	Average slope of a census block group	%	DC open data
MS4 system	Dummy variable (0: the census block does not include MS4 shed, 1: the whole area of a census block group have MS4 system)		DC open data
Population density	Population density	people / square mile	DC open data
Social Vulnerability Index	Sum of standardized value of 1) median house value, 2) median rent price, 3) median income, 4) percent of rent households, 5) percent of female householder, 6) percent of children (under 5yrs old), 7) percent of elderly people (more than 65yrs old), 8) percent of people with less than high school graduation, 9) percent of families below poverty level, and 10) percent of African-American population		ACS 2019 (5-year Estimates)

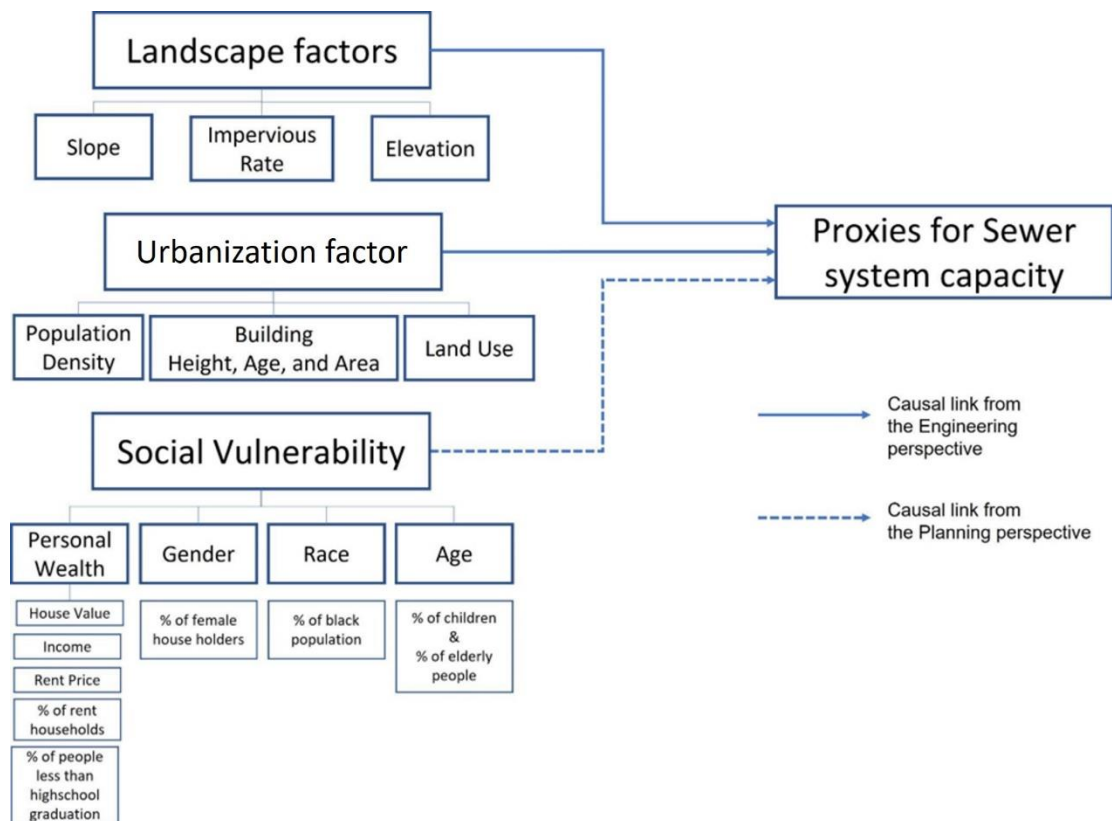


Figure 14 Analytical Framework

4.5.2. Methods

4.5.2.1. Social Vulnerability Index

I measured the social vulnerability of DC census block groups using an additive method adapted from Cutter et al.'s (2003) Social Vulnerability Index (SoVI) study. While Cutter et al. (2003) employed numerous indicators and proxies to construct the index, the approach focuses on four key indicators and their corresponding ten proxies (Table 2). These choices were informed by a review of disaster literature, which highlighted the significant impact of personal wealth, gender, race, and age on social vulnerability (Enarson 1998, Fothergill 1998, Morrow 1999, Fothergill and Peek 2004, Aldrich and Benson 2008, Peek and Stough 2010, Bolin and Kurtz 2018). The selection of these indicators may be subjective, but as Rygel et al. (2006) explain, the choice of pertinent indicators remains a subject of ongoing debate with no standardized approach in place. I standardized these ten variables using the mean and standard deviation and calculated their totals under the assumption of equal weighting, a methodology still utilized in the SoVI of the Centers for Disease Control and Prevention (Flanagan et al. 2011). A comprehensive summary of these indicators is available in Table 2.

3.5.2.2. OLS and Two-Stage Least Squares Regression for Endogeneity

Based on the compiled dataset, a regression model was used to investigate the relationships between a dependent variable, representing the capacity of stormwater infrastructure in a census block group, and explanatory variables, including landscape, land use, and the SoVI data. The linear model is used because of its

general suitability for testing unspecified causal relationships between dependent and independent variables, and the regression model is specified below (see equation 1).

$$\text{Pipeline capacity}_i = \beta_0 + \beta_1 \text{ SoVI}_i + \beta_2 \text{ Landscape Variables}_i + \beta_3 \text{ Urbanization Variables}_i + \varepsilon_{1i} \quad (1)$$

$$\text{GI capacity}_i = \gamma_0 + \gamma_1 \text{ SoVI}_i + \gamma_2 \text{ Landscape Variables}_i + \gamma_3 \text{ Urbanization Variables}_i + \varepsilon_{2i} \quad (2)$$

The equation 1 can be estimated by the Ordinary Least Squares (OLS) method. OLS is a common method to calculate the coefficients of linear regression equations that represent the relationships between dependent and independent variables. The term least squares refers to so-called minimum squares error. Linear regression was performed using the STATA program. A few independent variables with no statistical significance, such as the area and age of buildings and the industrial land use, could be removed through a backward stepwise regression to improve model fit. The three OLS models test the relationship between the three dependent variables –1) the total length and 2) intersection area of pipelines and 3) GI count- and the independent variables. The variables of total pipe length and area are log-transformed to modify their non-normal distribution to meet the one of OLS assumptions.

However, the above model (equation 1) might face an endogeneity problem, reverse causality bias (so-called simultaneity bias). Given the long time consumed to build the DC pipelines and the relationship between property value and the surrounding environment, it can also be said that the unsafe living environment has affected

property values and the economic characteristics of communities. Although Blaikie et al. (2014) and Cutter (1996) demonstrated that the socioeconomic factors of people determine the biophysical and built environment in their theoretical framework, poor infrastructure setting makes the community less safe and attractive to social capital investment (King et al., 2021) and makes an increasing gap in the built environment and the property values between communities so that the community attracts poorer people.

To solve the endogeneity issue in the regression model (equation 1), I had to make a new social vulnerability index. The social vulnerability index organized here includes economic indicators of income, house value, poverty status, and rent prices, these indicators could lead to the endogeneity in the regression model. Thus, the four economic indicators are excluded when the new social vulnerability index is built. Education attainment level, the proportion of female-headed households, and the percent of African American population are eliminated in the new index given the theoretical correlation between education, income, and wealth (Wolla and Sullivan, 2017), and the correlation test results between. Consequently, the new social vulnerability's role as an instrument variable consist of the proportions of children (under 5yrs old) population, elderly people (more than 65yrs old), and the renters. To ensure that the newly built social vulnerability index is an appropriate instrument variable, I utilized the pairwise correlation test in STATA and got acceptable results. The results showed that 1) the new index is significantly and highly correlates with the original index (the coefficient is 0.6233 and the p-value is 0.0000) and 2) the correlation between house value and the new index is significantly low (the

coefficient of -0.2786 and the p-value of 0.0000). The correlation test between the new index and other economic indicators of income and poverty level also shows the same pattern. These test results indicate that the new index is as a good instrument variable.

To handle the endogeneity issue in the regression process, I used Two-Stage Least Squares regression analysis via “ivregress 2sls” command in STATA. Two-Stage Least Squares (2SLS) is a statistical technique used to estimate the parameters of a linear regression model when the independent variables are endogenous, meaning that they are potentially correlated with the error term in the regression. The 2SLS method literally involves two-stage-estimation. In the initial stage, the endogenous regressors are estimated using a set of instrumental factors. An instrumental variable is a variable that should not be connected with the error term in the regression equation but is instead correlated with the endogenous regressor. This first stage regression is expressed as the equation 2. In the second stage, the estimated values of the endogenous regressors from the first stage are used in the regression equation as if they were known, rather than estimated. This is known as a "substitution" or "plug-in" approach (StataCorp, 2017). The OLS regression is then performed using these substituted values, along with the exogenous regressors and the dependent variable. The 2SLS method can estimate a wide range of linear regression models, including models with multiple endogenous regressors and models with lagged dependent variables. It is commonly used in econometrics and other fields where endogeneity is a concern, such as social sciences and public health. In summary, Two-Stage Least Squares is a statistical technique that allows for consistent estimation of parameters in

a linear regression model in the presence of endogeneity, by using instrumental variables to estimate the endogenous regressors and then substituting these estimated values into the regression equation.

Finally, to test endogeneity after 2sls estimation, I used the Durbin and Wu-Hausmann test through the “estat endogenous” command in STATA post estimation package. The null hypothesis of the tests is the same that the variable which is considered as endogenous could be regarded as exogenous, but the Durbin and Wu-Hausman tests for endogeneity differ in that the former use an estimate of the error term's variance based on the model supposing the variables under test are exogenous, while the latter use an estimate of the error variance based on the model supposing the variables under test are endogenous (StataCorp, 2017; Baum, Schaffer, and Stillman, 2003). Both estimates of the error variance are compatible with the null hypothesis that the variables under test are exogenous. Unlike the Wooldbridge's score (2010), these tests allow researchers to examine whether a subset or all the endogenous variables are exogenous (StataCorp, 2017). Also, I used “estat firststage” command to judge the explanatory power of the new index, based on the findings as arguments of Hahn and Hausman (2003), StataCorp (2017), Stock et al. (2002), and Stock and Yogo (2005). If I cannot reject the null hypothesis that the variable under examination is exogenous, I cannot treat the social vulnerability index consisting of both social and economic indicators as endogenous and estimate the regression (equation 1) with OLS method.

On the other hand, given the inherently spatial nature of data concerning sewer pipelines and green infrastructure (GI), a spatial model would ostensibly be more

fitting for estimation purposes than the Ordinary Least Squares (OLS) method. For example, the underground sewer pipeline system exhibits a tree-like hierarchy, where smaller pipes (akin to branches) feed into larger conduits (analogous to the trunk). This organization suggests that the sewer capacity—the volume of wastewater a sewer system can manage—of one area is intricately linked to that of its neighboring areas. Likewise, the distribution of GI appears to be influenced by the capacity of the community, potentially leading to spatial clustering, as evidenced by previous empirical studies (e.g., Lim, 2017). Nonetheless, despite the hierarchical, tree-like arrangement of sewer pipelines (wherein smaller pipes connect to larger ones), an area with smaller pipes may exhibit a total sewer capacity that surpasses that of an area with larger pipes. This indicates a non-linear relationship between the diameter of sewer pipes and the overall capacity of the sewer system in a given area. It implies that the efficiency or capacity of a sewer system is not solely determined by the size of its pipes but also by the configuration and interconnectivity of the system. Hence, although there is a general trend of capacities being interrelated among neighboring areas, there exist instances where the capacity of one area may not directly correlate with that of its neighbors. Consequently, owing to the challenges in calculating the precise capacity of sewer pipelines, the application of spatial models was deemed impractical for this study, leading to the adoption of the OLS method for estimation.

4.6. Results

Table 3 Two Stage Least Square Regression Results (The SoVI is instrumented)

sample size: 450

	Model 1		Model 2	
	Dependent variable: Total Length of Sewerlines R-squared: 0.5745		Dependent variable: Total Area of Sewerlines R-squared: 0.4491	
	Coefficients	p-value	coefficients	p-value
Social Vulnerability*	-0.012252	0.038	-0.020378	0.033
Building Height	0.013157	0.718	0.028163	0.633
Impervious Rate*	-0.945107	0.000	-0.824531	0.037
Slope	-0.094829	0.100	-0.052706	0.572
Elevation*	-0.056615	0.000	-0.149185	0.000
Residential use*	-0.161450	0.006	-0.334518	0.000
Commercial use	0.242277	0.066	0.081091	0.704
Federal use	0.265001	0.040	0.277956	0.184
Population density*	-0.000026	0.000	-0.000030	0.000
Constant*	11.485970	0.000	15.093580	0.000
Endogeneity test	Statistic	p-value	Statistic	p-value
Durbin score/chi squared(1)	0.522483	0.4698	0.041374	0.8388
Wu-Hausman/F(1, 439)	0.510303	0.4754	0.040366	0.8409

*Statistically significant at the 95 percent confidence level in both model 1 and 2

Regarding the endogeneity issue, the Durbin and Wu–Hausman tests explore the null hypothesis that the independent variable (the social vulnerability index here) can be regarded as exogenous. In the tests for both model 1 and 2, I cannot reject the null of exogeneity considering the p-values for the Durbin and Wu-Hausman tests are not significant. I can treat the social vulnerability index as exogenous. Also, even though

I follow the book of Wooldbridge (2010), the coefficient of the residual obtained from equation 2 does not show the significant p-values in the OLS regression of equation 1 with additional variable, the residual from the equation 1 estimation (0.465 in case of pipe length regression and 0.806 in pipe area regression). These insignificant p-values of the integrated Durbin-Wu-Hausman test indicate that the OLS is consistent. Thus, I estimate the model 1 and 2 with OLS method. The below table 3 shows the results from OLS estimation.

OLS models using the length and area of the underground pipelines as dependent variables show a common relationship between them and some independent variables, explaining 56.6%, 44.1%, and 29.6% of the total variance of the dependent variable. In the three models, impervious rate, average elevation, population density, and social vulnerability index showed statistically significant negative correlations with sewer pipelines, whereas the variables representing land use, average slope, and MS4 did not show the statistical significance in common. In other words, the analysis of my sample indicates changes in imperviousness, elevation, population density and social vulnerability are associated with stormwater infrastructure. A summary of results can be seen in Table 3.

In addition, when looking to the location of social vulnerability and sewer pipelines, models estimating the capacity of sewer pipelines show that DC's census block groups have less pipeline capacity as social vulnerability is higher (Figure 10 and 15). In other words, these three models show that the higher the average altitude, the higher the impervious rate, and the higher the population density, the pipeline capacity of the DC census block groups in terms of the landscape and built

environment. The analysis result of the model estimating the number of green stormwater infrastructure in the census block groups is also not very different from these. Although positively correlated with the average slope, DC's GI showed a negative correlation with impervious rate, building height, mean slope, population density, and social vulnerability.

However, one should be careful in interpreting the regression coefficients because of variable transformation used to meet the assumption of OLS and to relieve the issue of heteroscedasticity. To be specific, because the application of a linear regression model to the square root-transformed data causes uninterpretable regression coefficients (Gelman and Hill 2007; Pek et al., 2017), we cannot determine the magnitude of the influence of the square-rooted transformed variables on the dependent variable.

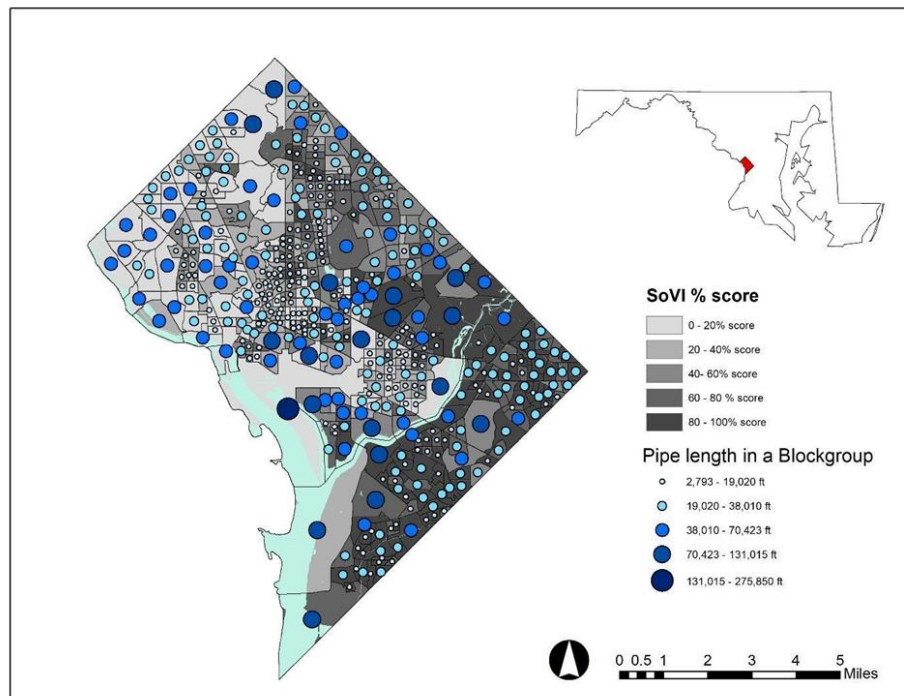


Figure 15 Correlation between the social vulnerability of communities and the sewer pipelines distribution

Table 4 OLS regression results

sample size: 450

	Coefficient	Standard Error	t statistic
Dependent variable: length of pipelines (Model1)			
F-statistic: 59.97 / p-value: < 2.2e-16			
Adjusted R-squared: 0.5661			
Constant*	11.5000	0.2090	55.0281
Impervious Rate*	-0.9520	0.2452	-3.8800
Building Height	0.0121	0.0369	0.3300
Slope	-0.0945	0.0581	-1.6262
Elevation*	-0.0604	0.0134	-4.5000
Residential use*	-0.1734	0.0614	-2.8241
Commercial use	0.2416	0.1332	1.8143
Federal use	-0.2715	0.1306	2.0801
MS4 sewer shed	0.0436	0.0590	0.7390
Population density*	-2.54E-05	1.91E-06	-13.2870
Social Vulnerability*	-0.0160	0.0039	-4.1239
Dependent variable: Area of pipelines (Model2)			
F-statistic: 36.45 / p-value: < 2.2e-16			
Adjusted R-squared: 0.4412			
Constant*	15.1034	0.3376	44.7330
Impervious Rate*	-0.8874	0.3960	-2.2408
Building Height	0.0249	0.0592	0.3711
Slope	0.0271	0.8754	-0.2890
Elevation*	-0.1442	0.0202	-6.6491
Residential use	-0.0285	0.0952	-2.8690
Commercial use	0.0105	0.1999	0.4987
Federal use	-0.2647	0.2015	1.2551
MS4 sewer shed	-0.1816	0.0887	-1.9050
Population density*	-3.06E-05	3.09E-06	-9.8872
Social Vulnerability*	-0.0169	0.0058	-2.6974
Dependent variable: The Number of GI			
F-statistic: 19.84 / p-value: < 2.2e-16			
Adjusted R-squared: 0.2955			
Constant*	11.5634	1.1870	9.7374
Impervious Rate*	-3.3203	1.3920	-2.3010
Building Height	-0.4280	0.2083	-2.0551
Slope	-1.0610	0.3299	-3.2160
Elevation*	0.2156	0.0762	2.8288
Residential use	0.2837	0.3487	0.8140
Commercial use	1.4360	0.7536	1.8977
Federal use	0.3459	0.7413	0.4670
MS4 sewer shed	-0.2099	0.3510	-0.6261
Population density*	-8.88E-05	1.09E-06	-8.1800
Social Vulnerability*	-0.0542	0.0220	-2.4620

*Statistically significant at the 95 percent confidence level

4.7. Discussion

4.7.1. Urbanization and stormwater infrastructure in Washington DC

Sewer pipelines and Urbanization

In Washington, D.C., the capacity of sewer pipelines reveals a negative correlation with population density and surface impervious rates (Table 4). This suggests that past and current development of the traditional sewer pipelines does not keep pace with continuing urbanization. The historical context of sewer system development in the United States is noteworthy. The construction of sewer pipelines commenced in the early 19th century with a primary goal of transporting and disposing of human waste and a secondary objective of mitigating flooding in human settlements (Peterson 1979; Tarr 1984). Notably, in the 1890s, Washington, D.C. took a significant step by introducing a Municipal Separate Storm Sewer System (MS4) (DC Water, n.d.). This innovative approach involved the construction of separate sanitary sewer systems for human waste and distinct storm sewer systems for managing stormwater (DC Water, n.d.). Tarr (1984) observed that sewer lines in the United States have been designed and constructed since the 1850s to accommodate the transportation of both human waste and storm runoff. However, it remains uncertain whether the existing underground sewer pipeline infrastructure in DC can effectively adapt to the substantial changes in the urban landscape that have occurred since its original construction. Through a new pipeline expanding project, Northeast Boundary Tunnel Project, the DC Water (n.d.) describes that the city's combined sewer system, established a century ago, is insufficient to accommodate the population growth witnessed over the past century.

Throughout its history, Washington, D.C. has undergone a transformation in population, with its numbers surging from under 100,000 residents in the mid-19th century to more than 700,000 today, according to the 2022 report by the US Census Bureau. This population growth has necessitated the development of a more urban infrastructure to support the expanding community. Urbanization, integral to this growth, involves the expansion of urban areas, resulting in a higher prevalence of impervious surfaces. As a consequence, the process of rainwater turning into runoff accelerates, reducing the time required for runoff concentration. This acceleration leads to higher peak discharges, often exceeding the capacity of the sewer pipelines to efficiently store and convey the increased flow (Bords, 2014; Olechnowicz and Weinerowska-Zahran et al., 2008). A critical factor in this scenario is the capacity of sewer pipelines, primarily determined by peak flow, which results from the flow cross-sectional area and flow velocity. As urbanization advances, stormwater runoff's peak flows and flow velocities increase, imposing a heavier load on the sewer pipelines. Zahran et al., (2008) explains that the changes in the above-ground built environment due to urbanization are expected to place additional stress on preexisting sewer pipelines.

Furthermore, changes in the urban environment due to urbanization appear to have manifested differently in White and Black residential areas, implying that the strain on sewer pipelines has also varied depending on the community. Zickuhr (2018) delineates how racially exclusionary housing policies and zoning from the late 19th and mid-20th centuries have contributed to disparities in housing density. For instance, the majority of White communities in Northwest DC are characterized by

predominantly single-family units, while Black communities in Southeast DC primarily consist of multifamily units. These differences in zoning and housing policies have had implications for housing density and segregation (Zickur, 2018), as depicted in Figure 16 and 17. Research on urban heat islands, which examines the history and distribution of impervious surfaces, has also revealed that segregationist practices tend to concentrate minority populations in densely populated neighborhoods with more impervious land cover (Jesdale et al., 2013). The concentration of dense development and the associated high impervious cover in Southeast DC might have resulted in larger peak flows and flow velocities through sewer pipelines, a consequence of discriminatory housing practices that have led to uneven increases in sewer load across communities.

Southeast DC's MS4 system, depicted yellow in Figure 13, was constructed in the 1960s and 1970s. Despite an overall decrease in population density across DC due to rising suburbanization rates since the 1970s (Rowlands, 2019), Southeast DC still hosts high-population-density communities. Through this analysis, I have discovered that densely populated communities have less sewer pipeline capacity. This negative correlation between current population density and sewer pipeline capacity indirectly underscores a disconnect between planning and infrastructure in the United States since the 1960s, as previously noted by Neuman and Smith (2010). However, further research is essential to fully comprehend the implications of the distribution of sewer pipelines in the face of future extreme weather events. There are lingering questions

about whether the planning and construction of the sewer pipelines at that time considered the potential for future increases in population density and urbanization.

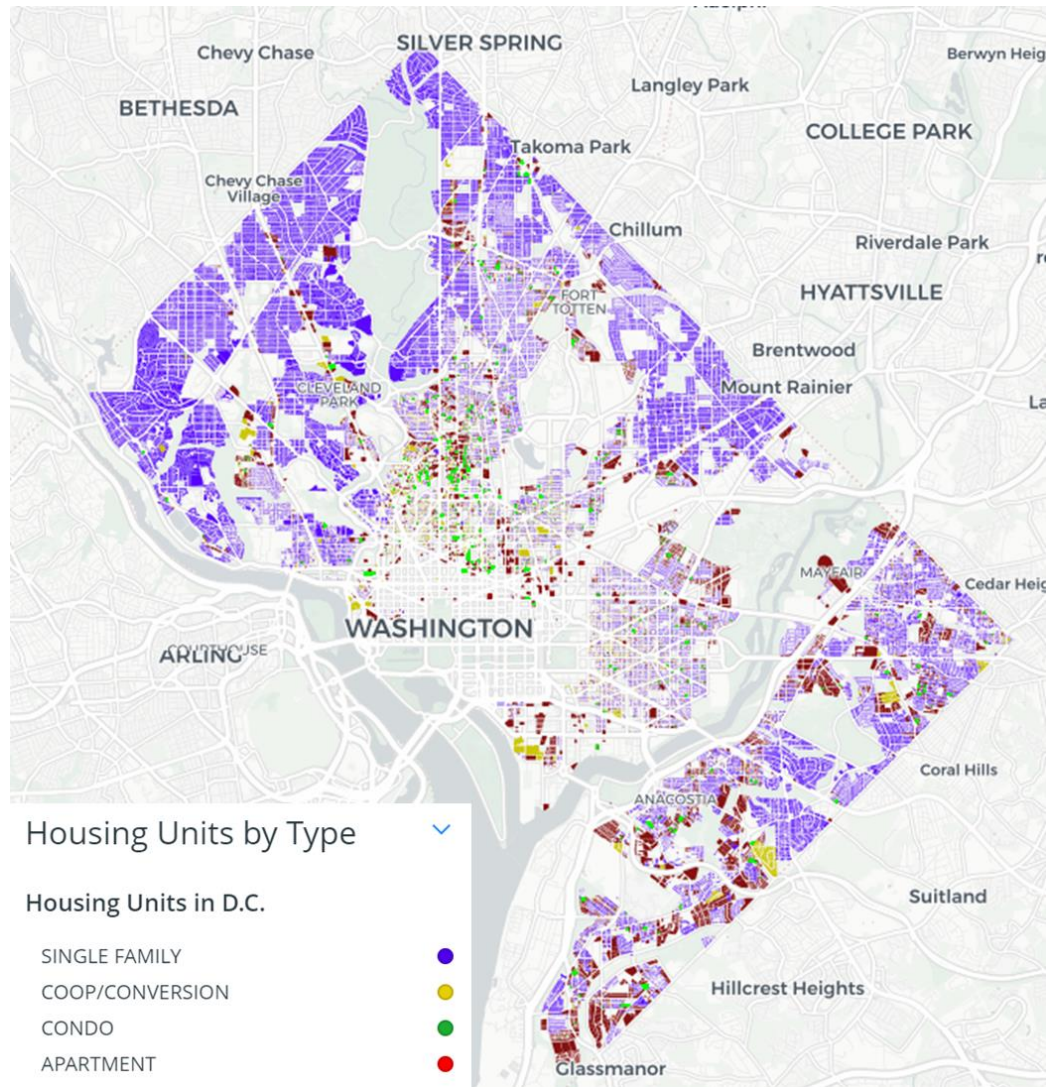
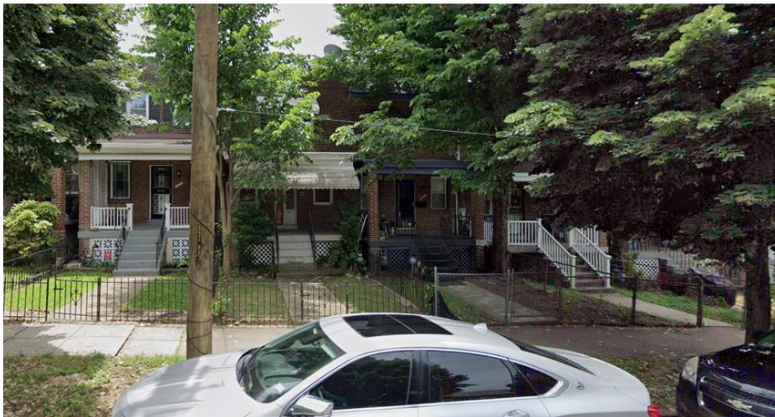


Figure 16 Housing units by type

Source: Data compiled by the D.C. policy center

Southeast

20 Danbury St SE / 1631 R St SE



Northwest

1949 Biltmore St NW / 6613 32nd St NW



Figure 17 Contrasting densities. The photos on the left, depicting Southeast DC, exhibit characteristics of denser housing, including smaller lot sizes and the absence of driveways. In contrast, the Northwest DC shows less dense, with larger lots, and individual driveways.

Source: Google Street View (Image capture: Sep 2022)

GI locations and Urban environment

On the other hand, the negative correlation between the number of GI facilities and the imperviousness rate and population density shows potential inconsistency between DC's practice and initiatives regarding using GI to supplement the existing sewer infrastructure's capacity. The Long Term Control Plan Modification for Green Infrastructure (2015) of the DC Water and sewer authority specifies that the GI in DC aims to reduce the scope of the traditional pipe system in controlling storm runoff and combined sewer overflows. The DC department of transportation and of energy and environment also clarify the same purpose of green infrastructure in DC (District department of transportation, 2014; Department of Energy & Environment 2022). In order for GI to effectively complement traditional stormwater infrastructure consisting of sewer pipelines and related components, such as stormwater pump stations, it must be strategically located in areas where there is a higher runoff volume and a lower density of traditional sewer pipeline infrastructure. Given that one of the intended purposes of GI programs is to supplement the capacity of traditional gray infrastructure, their success is compromised when GI is not primarily concentrated in densely populated and impervious urban areas. However, the results of my analysis indicate that both green and gray infrastructure are less prevalent in communities with higher population density and more impervious surfaces. This suggests that GI initiatives have not aligned with their fundamental purpose. Future research should further investigate this finding and the relationship between the distribution of gray and green stormwater infrastructure from the engineering perspective. The strategic

placement of green infrastructure in areas with high runoff volume and low density of gray infrastructure can help supplement the capacity of the existing system.

4.7.2. The Social Vulnerability Index and stormwater infrastructure relationships in Washington, D.C.

This analysis finds a statistically significant negative relationship between the social vulnerability index and stormwater infrastructure, suggesting that the communities most vulnerable to weather extremes are also the areas least served by DC's GI and sewer pipeline (Table 4 and Figure 15). Specifically, Southeast DC, with its high social vulnerability (Figure 10), contains residential areas predominantly occupied by African Americans who face economic hardship and social marginalization (King et al., 2022). This indicates that, due to limited access to resources, communities in Southeast DC may encounter greater challenges in dealing with various extreme weather events. As shown in Table 4 and Figure 15, socially vulnerable communities in Southeast DC have relatively low gray stormwater infrastructure capacity.

The interplay between social context, infrastructure distribution, and social vulnerability was well described in the past literature of disasters and social vulnerability (Blaikie et al., 2014; Bolin and Kurtz 2018; Bullard 2008; Bullard and Wright 2009), emphasizing the role of social inequity in perpetuating disparities in disaster preparedness and resilience. Existing social structures or processes can result in an unequal distribution of infrastructure, favoring certain classes or racial communities. The vulnerability that stems from the characteristics of the built environment, such as the level of growth or urbanization and the amount of

infrastructure, is in part the product of social and spatial inequity (Cutter et al. 2003; Watts and Bohle, 1993). More powerful people with easy access to resources may also have greater access to mitigation measures or proactive action to cope with hazards or crises, such that socially vulnerable people who are marginalized and impoverished have relatively greater exposure to hazards (Curtis, 2014; De Keyzer, 2019). This suggests that if social inequity is not resolved through granting more power and resource access to historically marginalized communities, the inequities in infrastructure and the built environment will not be resolved and will likely only grow.

The results support the argument that socially vulnerable communities can experience an exacerbation of their vulnerability due to the existing social structures that perpetuate discrimination in protective measures and restorative support based on social class and race, as Bullard (2008) highlights. The context of DC's stormwater infrastructure does not appear to be free from the potential for discriminatory social context, especially in light of the sewer pipeline extension and the analysis results specified above. As seen in section 3, the historically African American communities in Southeast DC, the Barry Farm and Deanwood, had history in which they are excluded essential public services including sewage, and the current distribution of sewer pipeline and GI look unfair given my analysis. It is important to note, however, that my study does not conclusively demonstrate that the unequal distribution of stormwater infrastructure in DC is solely the outcome of the continuous impact of the social processes causing inequity. This complex issue remains a subject for future research.

4.7.3. Infrastructure planning implications

Past discriminatory development and planning practices in DC, which concentrated high density housing and impervious surfaces in communities of color, likely were not accompanied by appropriate stormwater infrastructure development. This mismatch between urbanization and stormwater infrastructure might overburden the capacity of the sewer pipelines. The Long Term Control Plan (LTCP), which aims to manage combined sewer systems in DC, identifies specific areas where GI needs to be concentrated based on their simulation models (DC Water, 2002; 2015), which detects sewer sheds that are operating beyond their capacity. However, even if the DC Water and DC government pinpoint potential GI implementation areas, a disconnect between simulated GI locations and actual implementation may occur. The GI dataset, provided as open data by the District Government Website, reveals that private sector GI implementation exceeds, public GI implementation by approximately 41.95%. This situation aligns with Neuman and Smith's study (2010), which describes that the recent growth of the private sector in infrastructure planning leads to continuously escalating social inequity.

Moreover, the recent growth of the private sector in infrastructure planning may not be the sole reason for the current stormwater infrastructure equity issue in DC.

Mandrano and Meenar (2017) specify that the most common GI approaches, which encompass public investment, regulation, and property owners' voluntary implementation, can lead to disparities in the distribution of GI. This is primarily

because these approaches require a certain level of community capacity and engagement for successful GI implementation. They suggest that even when public investment is utilized for GI implementation, community capacity and active involvement are essential factors to ensure equitable and effective implementation. Focusing on all implementation types of GI approaches in DC, Park's (2023) study reveals a statistically significant relationship between the annual increase in GI from 2010 to 2019 and social vulnerability, whereby socially vulnerable communities have experienced a lesser increase in GI. His study shows that the disparity in GI across communities deepened in the 2010s. In addition to the implementation mechanism, Hendricks (2017) points out that a series of structural obstacles accumulated in planning and policies, such as inadequate funding, lack of political support for marginalized people, and the gap in the built environment originating from redlining, result in infrastructural disparities, making certain communities vulnerable. Addressing this equity issue in infrastructure demands a comprehensive planning approach that encompasses the entire infrastructure sector (Neuman and Smith, 2010). Planners need to adopt a multifaceted perspective that tackles these structural obstacles, fosters community engagement, and prioritizes the equitable distribution of stormwater infrastructure. It can be said that collaboration with engineers is also essential for planners to ensure a more resilient and just urban landscape in DC.

4.7.4. Limitations and Future Research Recommendations

Methodological limitations must be considered when evaluating the results of this study. First, for the purposes of this analysis, sum of sewer pipe length and sum of sewer pipe area were used as proxies for sewer line capacity. This representation can neglect interactions between factors like pipe slope and pipe material that are needed to determine exact pipe capacity, but has the potential to skew sewer line capacity estimates. Furthermore, this analysis does not consider the relationship between the sewershed area being served by a specific sewer line and the capacity of the pipe. Sewer line capacity was compared directly without normalizing for sewershed area, meaning that a large sewer line that was serving a large sewershed area and a large sewer line serving a small sewershed area were judged comparably, despite their differing functions. Future research should examine more closely the relationship between sewer line capacity and the sewershed being served.

Lastly, the comprehensive social vulnerability index calculated through the sum or average of indicators eases comparison across communities but has two inherent limitations. First, the assumption that each vulnerability indicator evenly contributes to the vulnerability may not fully represent the current social vulnerability. The second limitation is that the comprehensive social vulnerability index of the sum or average value necessarily hides the existence of extreme-valued indicators, without showing the distribution of the overall indicator values. In other words, the social vulnerability index of arithmetic sum or average is a tool for providing insights about communities' needs but should be further enhanced discuss the communities of special needs. In this sense, future research efforts might develop a social

vulnerability index more sensitive to variations between social vulnerability indicators that can reveal the social vulnerability of the community and its relationship to the built environment and infrastructure.

4.8. Conclusion

This study created models to describe the correlations between stormwater infrastructure and landscape, urbanization, and social vulnerability for 450 census block groups in Washington, D.C. The analysis result shows that stormwater infrastructure capacity proxies have a statistically significant correlation with some of the landscape variable and urbanization factors in three regression models (Table 3). This suggests that the expansion of the stormwater infrastructure system may not be keeping pace with above ground urbanization. The historically discriminatory social context in DC highlights that two African American neighborhoods, Barry Farm and Deanwood, had to endure a lack of essential services such as electricity, water supply, pavement, and sewage. Also, the past housing policies in DC have created denser African American residential areas in Southeast DC, which may result in high rates of impervious surfaces. The number of green infrastructure also negatively correlates with social vulnerability, keeping with previous findings that green infrastructure distribution in D.C. is biased towards the wealthier White communities (Park 2023), as indicated in the results. As communities with more underground sewer pipeline also have more green infrastructure capacity, my findings indicate that green infrastructure may not serve its intended purpose of complementing the traditional

sewer pipeline where most needed. These results also imply that unequal infrastructure distribution may be accumulating and increasing environmental injustice in D.C., exacerbating unequal vulnerability across the city. Results also point us to reconsider D.C.'s current GI programs, and the D.C. government needs to address the uneven infrastructure distribution from the perspective of environmental justice. In summary, this study underscores the pressing need for a comprehensive reevaluation of stormwater management and the urgent requirement for the D.C. government to rectify the uneven infrastructure distribution from an environmental justice perspective.

Chapter 5: Persistent Social Vulnerability in Washington D.C. Communities and Green Infrastructure Clustering

This chapter is a revised version of my paper published on October 2nd day 2023. Park, M. (2023). Persistent Social Vulnerability in Washington DC Communities and Green Infrastructure Clustering. Land, 12(10), 1868. <https://doi.org/10.3390/land12101868>. Drawing upon the original paper, the Data and Method section (5.3) and Discussion section (5.5.4) have been updated to add a literature review section, include a more detailed explanation of the methodologies employed, and articulate clearer methodological limitation.

Abstract

Cities worldwide are presently contending with the intricate task of formulating urban infrastructure that seamlessly blends sustainability and resilience to effectively tackle urgent challenges. An increasingly prominent strategy gaining swift traction is the deployment of green infrastructure (GI), heralding a multitude of advantages for the urban milieu. As a growing body of research highlights the emergence of a new equity issue in infrastructures from the perspective of environmental justice, it becomes evident that there is a significant gap in comprehensive studies investigating the combined temporal and spatial evolution of GI distribution. This research aims to address this gap by adopting a novel approach that explicitly considers the temporal dimension of GI distribution. Unlike previous studies that often rely on cross sectional snapshots, this study employs a panel data analysis, which allows for a comprehensive examination of how GI distribution evolves over time. The primary research question addressed in this study is whether GI distribution in Washington DC exhibits a propensity to concentrate within certain communities. This inquiry delves into the pressing concern of potential exacerbation of existing disparities through GI implementation. The study's findings may drive evidence-based policy

recommendations that foster equitable distribution strategies, guaranteeing that socially vulnerable communities reap the rewards of GI's positive impacts.

5.1. Introduction

In the ever expanding urban landscapes across the globe, the imperative to design urban infrastructure that not only addresses pressing issues but also stands the test of sustainability and resilience has taken center stage (La Rossa and Pappalardo, 2021). As urbanization continues to escalate, one approach that is rapidly gaining momentum is the implementation of green infrastructure (GI), which offers a myriad of benefits for urban environments. Among the numerous advantages of GI, one notable feature is its remarkable ability to enhance water quality by effectively filtering pollutants and contaminants from stormwater runoff. Serving as a cost effective alternative to conventional stormwater infrastructure like pipes and ponds (Heck 2021), GI serves to curtail stormwater runoff and prevent flooding, enhance air quality, support biodiversity through habitat creation, and increasingly addresses urban heat island effects in the context of escalating global temperatures (Balany et al., 2020; Kim and Song, 2019).

Despite the numerous benefits that GI offers for urban environments, its implementation has not been equitable across communities. Ironically, the communities that should stand to benefit the most from GI are often the least likely to have access to it (Heckert and Rosan, 2016). Extensive research has shed light on the correlation between socioeconomic factors and the availability of GI or GI in

different communities (Baker et al., 2019). Several studies have demonstrated that access to, or the density of, GI may vary significantly based on factors such as racial minority status, income levels, or educational attainment of the communities (Baker et al., 2019; Chan and Hopkins 2017; Lim 2017; Porse 2018; Mandarano and Meenar 2017; Wolch et al., 2014). The findings of these studies are particularly concerning as they highlight the emergence of a new equity issue in our infrastructures from the perspective of environmental justice. The implementation of GIs, a promising new type of urban infrastructure, might unintentionally exacerbating existing disparities in society, given that infrastructure serves as a mechanism that causes unequal effects on communities both in their daily services and in mitigating the adverse outcomes of environmental extremes (Hendricks and Van Zandt, 2021).

Several studies provide insight into the mechanisms through which certain socio-economic factors drive the disproportionate distribution of green infrastructures (GIs). Dunn (2010) and Mandarano and Meenar (2017) discuss the most common approaches to public investment, regulation, and incentives for property owners' voluntary implementation, each presenting its own set of challenges. These studies emphasize that all three approaches hold the potential to yield uneven benefits, with a particular impact on lower income residents and underserved neighborhoods. The reason for this lies in the limited capacity of such communities to effectively implement and maintain GIs. It's worth noting that the role of community capacity is pivotal in determining the success of public investment and regulatory mandates (Dunn 2010; Mandarano and Meenar, 2017). On a different note, Lim (2017) introduced the concept of information diffusion and applied it to the voluntary

participation of property owners in the implementation of GIs. This concept effectively illustrates the tendency of GIs to cluster in more affluent communities. This phenomenon arises from the finding that wealthier communities often possess more abundant resources and extensive networks, facilitating their superior access to and dissemination of information about GI programs (Lim, 2017). Consequently, these communities tend to be more actively engaged in GI initiatives. In essence, Lim's (2017) findings suggest that the unequal distribution of GIs remains an ongoing challenge.

However, previous studies that employed regression analysis with cross sectional data (Baker et al., 2019; Chan and Hopkins, 2017; Lim, 2017; Mandarano and Meenar, 2017; Porse, 2018; Wolch et al., 2014) did not determine whether this unequal distribution is persisting and, consequently, if the disparity between communities has deepened. Because of their methodological limitations, they just provide snapshots of a specific moment, capturing relationships between variables within a fixed timeframe. While valuable insights can be gleaned from cross sectional data, they fail to capture the intricate temporal trends and changes that may occur in GI distribution and its determinants.

GI programs are ongoing or being implemented as an equitable way to improve stormwater management and reduce the impacts of global warming in many places, and it indicates that the distribution of GI may continuously change. Neglecting GI development in socially vulnerable areas can lead to higher long term costs for both communities and governments. Without proper GI development, these areas may face increased health care costs, property damage, and infrastructure repair expenses due

to inadequate protection from environmental hazards. It is necessary to observe the temporal trends of GI distribution, considering that it can help 1) identify areas where additional investments in GI may be required to achieve more equitable distribution, 2) provide insights into the factors affecting the distribution, and 3) evaluate the effectiveness of policies and programs aimed at promoting the adoption of GI. To be specific, understanding the factors driving the adoption and the distribution of GI can help not only inform the development of more effective policies and programs of GI but also expect the future distribution.

Despite the critical importance of understanding how Green Infrastructure (GI) distribution evolves over time, only a few studies captured the temporal trends or change of GI distribution. Pallathadka et al. (2022) investigate the historical GI data and show changes in GI distribution. However, their analysis to test the correlations between socio demographic factors and GI density is based on cross sectional data, which means they did not reveal the temporal driving factors of the GI distribution. Although Lim (2017) employed the shuffle test method in his research and revealed that the previous GI location had an impact on the placement of new GI adoption in Washington DC, his findings on the factors driving the GI distribution are based on a cross sectional analysis using Geographically Weighted Regression, with a sample limited to voluntary participation in GIs, accounting for only about 12% of the total GIs as of 2020. Thus, spatial panel data analysis is necessary to identify the temporal trend of the whole GIs in Washington DC and find the factors that continuously affect the distribution. It is an essential tool for examining the dynamic relationships between changing infrastructures and the driving factors.

This research fills the significant gap by adopting a novel approach that explicitly considers the temporal dimension of GI distribution. Unlike previous studies that often rely on cross sectional snapshots, this study employs a balanced panel data analysis, which allows for a comprehensive examination of how GI distribution evolves over time. By utilizing panel data, I capture the dynamics and trends that cross sectional analyses may overlook, thus providing a more accurate representation of the changing landscape of GI distribution. Moreover, this study introduces a crucial and previously unexplored dimension by integrating a social vulnerability index into the analysis. While previous research has highlighted the unequal distribution of GI, my study goes beyond by assessing the relationship between socioeconomic characteristics and GI distribution over time, especially in the context of socially vulnerable communities. This innovative approach helps identify areas that are most in need of GI investment, ensuring that the benefits of GI are directed towards the communities facing the greatest challenges.

This research seeks to address the following research question: Has the distribution of GI in Washington DC shown a tendency to concentrate more in communities with higher racial majorities and greater wealth? It addresses a pressing concern regarding the potential exacerbation of existing disparities in GI. By investigating this question, this study has the potential to inform policymakers, urban planners, and community stakeholders about the fairness and inclusivity of GI implementation. The results could lead to evidence-based policy recommendations that promote more equitable distribution strategies, ensuring that disadvantaged communities benefit from the positive impacts of GI.

The figure underneath provides a theoretical framework demonstrating how this piece of the study was directed. It shows the temporal process in which green infrastructure, designed to complement existing gray sewer pipelines and alleviate environmental problems, is affected by market-based implementation mechanisms and social vulnerabilities, showing uneven growth depending on the communities, and further deepening the gap in place vulnerability between communities. This article is organized as follows. First, the next section focuses on presenting the methodology adopted and specifics about the data used. Next, I show the main results obtained in the spatial panel regression analysis, and present discussion based on the temporal correlations between GI and socially vulnerable status. Thereafter, limitations, future research directions and main conclusions are discussed.

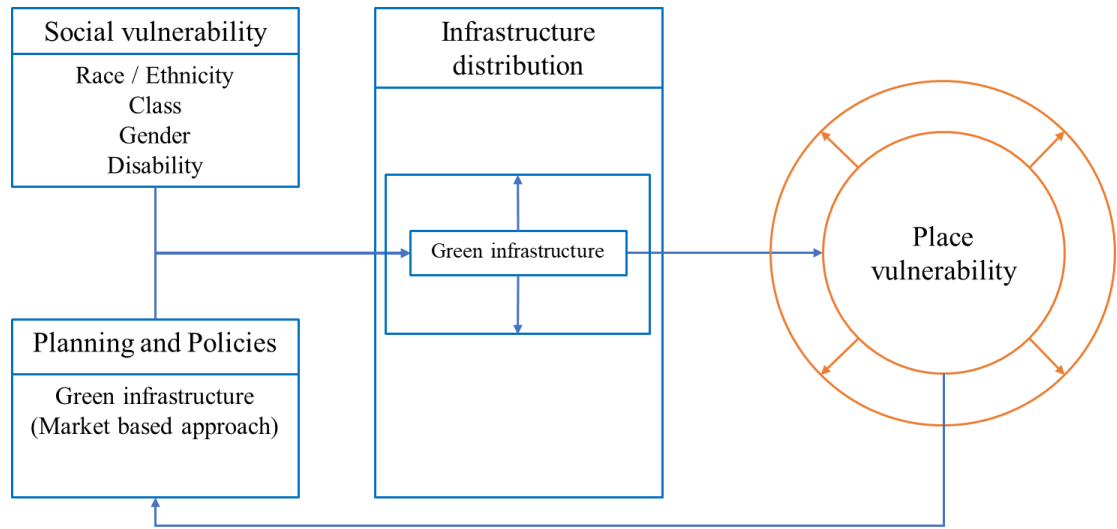


Figure 18 Theoretical framework for the widening gap of GI and place vulnerability

5.2. Literature review

The previous theories and models explain that social vulnerability can change over time (Blaikie et al., 2004; Cutter, 1996; Cutter et al., 2003), whereas the disaster literature describes that socially vulnerable status could perpetuate as in disaster cases (Bolin and Stanford, 1998; 1999; Bullard, 2008; Peacock et al., 2001; Wright, 2011).

The models focusing on improving vulnerability suggest that advances in building and civil engineering technologies, large scale demographic changes, and the application of climate change countermeasures can reduce it. The changes in vulnerability they discuss may entail changes in community attributes. Gentrification is an example. If we focus only on the geographic and socioeconomic attributes of a community over a long period of time, it can be seen that the vulnerability of the community at that location has definitely improved through gentrification process.

The brand new built environment may be more robust to disasters such as flooding or other climate events, and new people willing to pay for the new environment would have replaced the old inhabitants. However, in the absence of outside development pressure causing gentrification or large scale redevelopment, the community's attributes can be also maintained as the segregation process shows.

As noted earlier, the process of residential segregation in the United States has been instrumental in perpetuating the social and economic inequalities experienced by marginalized groups by segregating housing, education, and other public services. The persistence of discrimination based on both race and class has resulted in certain

communities facing long-standing socio economic marginalization, rendering it challenging for them to break free from the cycle of poverty and powerlessness. According to a recent study conducted by Menedian et al. (2021), there is compelling evidence that in 169 out of 209 US metropolitan areas with a population of 200,000 or more, the phenomenon of racial clustering was more pronounced in 2019 than it was in 1990.

Studies on disaster management have demonstrated that existing marginalized communities are often excluded from emergency response and recovery processes, which perpetuates existing inequalities. This exclusion can be driven by two main factors. First, marginalized communities may lack the capacity to access recovery assistance, as noted by Bolin and Stanford (1999). Second, inadequate recovery processes in which affluent communities get more support based on their pre disaster social network and political power can intensify preexisting inequalities, as highlighted by Peacock et al. (2001). These studies indicate that disasters can make socially vulnerable status perpetuate and exacerbate inequalities, both during and after emergency events.

Moreover, persistent socially vulnerable status within the social structures which create that condition can continuously influence the built environments. Research by Blaikie et al. (2004) suggests that socially vulnerable groups are more likely to face unsafe conditions when new infrastructure programs are not inclusive of racial minorities, genders, and people with disabilities, through their Pressure and release model. Although the model does not show the “progression of vulnerability” as a perpetuating process, the perpetuating relationship between socially vulnerable status

and infrastructure setting has been widely studied and documented in the literature of disaster and segregation (Bullard, 2008; Massey and Tannen, 2015; Menedian et al., 2021). This process is exemplified in Bullard's (2008) article of "unequal protection", which highlights the ways in which communities of color are systematically excluded from safe place and essential infrastructure like levee protection due to long-standing institutional racism and disinvestment. This article was clearly demonstrated in the aftermath of Hurricane Katrina, where white communities received greater levee protection than their minority counterparts. Similarly, Massey (1990) argues that the historical legacy of racial discrimination and segregation has resulted in the concentration of poverty and disinvestment in communities of color, leading to the deterioration of public services and the blight of these areas. Pulido (2017) also shows how structural inequalities and power imbalances produce and perpetuate racist and classist spatial arrangements in Southern California. Specifically, she highlights the ongoing processes of racial segregation, exclusion, and exploitation that have shaped the built environment in ways that are discriminatory towards low income communities and communities of color.

If the relationship between social vulnerability and infrastructure setting is temporally continuous, under the assumption that there is no demographic or institutional change, this relationship can also be applied to the currently expanding GI programs. Although the currently uneven distribution of green infrastructure across communities is a complex issue with multiple contributing factors. One key factor could be historical and ongoing patterns of discrimination and disinvestment in socially vulnerable communities, which have resulted in a lack of access to infrastructure,

including GIs. The uneven distribution of green infrastructure across communities may also be influenced by historical patterns of discrimination and disinvestment in socially vulnerable communities. The temporally continuous nature of this relationship, absent any significant demographic or institutional change, means that the same historical patterns of discrimination and disinvestment that have contributed to the unequal distribution of other infrastructure may also be influencing the distribution of green infrastructure, including GI programs.

In terms of GI distribution and the driving factor for it, Mandarano and Meenar (2017) discuss the most common approaches of public investment, regulation, and incentives for property owners' voluntary implementation, each with its challenges. They explain that these three approaches have the potential to produce uneven distribution of benefits because poor residents and underserved neighborhoods may not have the capacity to implement or maintain GI and the community capacity can play a key role in the public investment and regulatory mandates. That is, it can be inferred that GI may continue to be distributed unevenly over time if the capacity of urban neighborhoods to effectively install and maintain GI or act as partners for its implementation remains persistently unequal.

Numerous studies have demonstrated a significant correlation between socioeconomic factors and the location or accessibility of green infrastructure. For example, Baker et al. (2019) and Porse (2018) found that disadvantaged communities in LA, Baltimore, and Philadelphia are less likely to have access to green infrastructure than their more affluent counterparts. Similarly, Landry and Chakraborty (2009) reported that neighborhoods with higher median household

incomes had more tree canopy coverage than lower income neighborhoods. Another study by Boone et al. (2009) showed that neighborhoods with higher percentages of people living below the poverty line had lower levels of tree canopy coverage. The research conducted by Grove et al. (2014) in the Baltimore metropolitan area found that neighborhoods with higher levels of poverty had lower levels of tree canopy coverage and were more likely to be located in areas with poor air quality.

Conversely, studies such as those by Bolitzer and Netusil (2000) showed that higher income neighborhoods tend to have more green infrastructure amenities, such as parks and recreational areas. Furthermore, research by Wolch et al. (2014) suggested that income inequality may exacerbate the unequal distribution of green infrastructure in cities. Although these studies collectively indicate that socioeconomic factors play a crucial role in the location and accessibility of green infrastructure, and that disadvantaged communities are disproportionately affected, they do not only provide theoretical description on the persistent relationship between GI and socially vulnerable status and the empirical evidence on the relationship because they lean on the cross sectional data.

On the other hand, Lim (2017) explain the spatial clustering of voluntary GI participation in DC with information diffusion theory that describes how new ideas and innovations spread through a population over time. He points out that residents of affluent communities have greater access to information and resources that allow them to become aware of and evaluate the benefits of green infrastructure. Applying the theory to the voluntary GI programs, once residents become interested in green infrastructure and participate in the GI program, their neighbors may be more likely

to seek out information and resources and to adopt these practices. This may create a cluster of green infrastructure adoption within affluent communities, as residents share experiences with one another and influence each other's behavior in their stronger social networks and with greater access to information and resources. However, his analysis is limited only to the voluntary participation among the three common approaches and does not show whether the other GIs by public investment or regulatory mandates are also clustering in wealthy communities. Also, he uses the geographic weighted regression and Monte Carlo permutation resampling techniques, but these methods cannot provide evidence of whether the relationships between the distribution of GI and the driving factors may perpetuate over time.

While overall vulnerability can change over time, socially vulnerable status can also be perpetuated, both in disaster cases and daily lives through residential segregation. The historical disaster cases shows that marginalized communities are excluded from emergency response and recovery processes and that their poverty and powerlessness maintain. Historical patterns of discrimination and disinvestment in socially vulnerable communities have resulted in the lack of infrastructure and resources, unequal distribution of infrastructure, including green infrastructure. The distribution of GI may continue to be uneven if the capacity of urban neighborhoods to effectively install and maintain GI or act as partners for its implementation remains persistently unequal. I hypothesize that perpetuating socially vulnerable status have driven the clustering of GI in Washington D.C. By understanding the spatial and temporal clustering GI, this study will provide valuable theoretical insights into the dynamics that cause urban infrastructure systems to be unevenly distributed, which is crucial for

making cities more resilient to climate extremes. Also, this study can provide policy recommendations that can help address this newly developing inequity issue.

5.3. Data and Methods

5.3.1. Green infrastructure in Washington D.C.

Considering the array of options available in local strategies for executing Green Infrastructure (GI) programs, including public investment, the inclusion of regulatory mandates within construction permits, and the offering of incentives to encourage voluntary involvement (Dunn, 2010), Washington DC employs all three of these approaches. However, the predominant drivers behind GI adoption in DC are redevelopment and new construction initiatives, coupled with voluntary engagement (Lim 2018). Between 2010 and 2020, the annual count of Green Infrastructure (GI) installations increased by approximately 2,000, culminating in a total of 22,756 GIs dispersed across Washington, D.C. by the close of 2020.

Currently, about 7 programs, such as DC Clean River projects and River Smart Homes, are being actively implemented by the three DC agencies, including the Department of Energy and Environment, the District Department of Transportation, and the District of Columbia Water and Sewer Authority. Although a comprehensive planning and implementation agency for GI programs does not exist as a singular entity, DC Water's Long Term Control Plan (LTCP) and DOEE's TMDL implementation plan strive to integrate diverse GI practices, thereby formalizing voluntary and community-based interventions (Lim, 2018). The LTCP and TMDL plan for CSS(Combined Sewer System) and MS4 (Municipal Separate Storm Sewer System) sheds identify areas operating below capacity, specifying locations where GIs should be situated (DC Water, 2002, DOEE, 2022).

In Washington, DC, a significant wealth divide persists between White populations and communities of color, as highlighted by Kijakazi and colleagues in 2016. Their research uncovers stark racial and ethnic disparities in net worth, demonstrating how systemic racism and discrimination have fueled the existing wealth gap in the capital. In 2013 and 2014, the average net worth of White households in DC was \$284,000, which was 81 times more than the \$3,500 average net worth of Black households. Moreover, the average home value for Black families in DC stands at \$250,000, roughly two thirds that of White and Latino households, as reported by Kijakazi et al. (2016). The accompanying maps show the persistent socio economic differences between Northwest DC, predominantly White, and Southeast DC, mainly Black. Population density maps alone may not clearly show this disparity, but the DC Policy Center (2018) notes that in predominantly White areas of Washington, DC, local authorities often used zoning laws and other strategies to preserve neighborhoods with low density, single family homes, while encouraging the construction of apartment buildings in lower income areas largely inhabited by Black communities. These findings underscore Washington, DC's ongoing social vulnerability from 2010 to 2019, as depicted in Figure 19.

5.3.2. Data

The panel dataset used in this study was sourced from multiple data sources. The green infrastructure data was obtained from OpenData DC, which includes information on the location, type, and size of green infrastructure projects. The data was regularly updated, and the latest version, which was released in May 2022 and

includes a total of 22,756 GI projects, was used in the analysis. Using Geoprocessing in ArcMap, the annual increase in the number of green infrastructures was calculated based on this raw data. The National Land Cover Dataset provided information on imperviousness rates, which were used to calculate the average proportion of impervious surfaces in each census block group using the Zonal statistic tool. Socio economic indicators, including median income, median house value, median rent price, etc., were sourced from the American Community Survey (ACS).

The dataset for spatial panel regression comprises a 10-year observation of 450 census block groups in Washington DC. The dataset includes the annual increase in green infrastructure, landscape and urbanization proxies, 10 socio economic indicators, and a social vulnerability index consisting of the indicators (see table 5). The dependent variable is the annual increase in green infrastructure. The independent variables are the social vulnerability index, which measures the social and economic characteristics of the population living in each census block group, consisting of the 10 socio economic indicators of a census block group. These indicators include median income, median house value, median rent price, the educational attainment level representing the proportion of people without a high school degree, the proportion of households living below the poverty level, the proportion of renters, and the proportion of female headed households. The analysis unit for this study is the census block group. Census block groups are often preferred over census tracts for analyzing community characteristics because they provide a finer level of geographic detail. According to the United States Census Bureau, a census block group is a "statistical subdivision of a county that is a combination of

blocks, having a population of 600 to 3,000 people" (U.S. Census Bureau, n.d.). The dataset is perfectly balanced panel from 2010 to 2019 and observing 450 census block groups in DC. Having a balanced panel dataset allows for the examination of changes that occur over time within each census block group. Some null values in the ACS data have been replaced with the median value.

The control variables are the landscape and urbanization proxies, which include building age, imperviousness rate, average surface slope, and average elevation. These variables provide insights and details about the built environment. They represent factors that possess the potential to influence the placement of green infrastructure, particularly in light of its functions, such as mitigating pluvial flood risks and alleviating urban heat island effects. The selection of these variables aligns with the analysis models from the existing literature on green infrastructure (Pallathadka et al., 2022; Baker et al., 2019; Porse, 2018; Mandarano & Meenar, 2017; Chan & Hopkins, 2017), which has examined both the cooling effects and the distribution of green infrastructures within different communities. Additionally, guidance from a Maryland design manual has informed this selection (Maryland Department of the Environment, 2009).

Table 5 Variable list and the sources

Variable	Description	Unit	Source
Annual increase of GI	Annual Increase in the Number of GIs in a Census Block Group		DC open data
Building area	Sum of building floor area in a census block group	square foot	DC open data
Building age	Average building age in a census block group	years	ACS 2010-2019 (5-year Estimates)
Impervious Rate	Proportion, Sum of Impervious surface area / Area of census block group	%	The National Land Cover Dataset 2016
Average elevation	Average altitude above sea level of a census block group	foot	DC open data
Average slope	Average slope of a census block group	%	DC open data
MS4 system	Dummy variable (0: the census block does not include MS4 shed, 1: the whole area of a census block group have MS4 system)		DC open data
Population density	Population density	people / square mile	DC open data
Social Vulnerability Index	Sum of standardized values of 1) median house value, 2) median rent price, 3) median income, 4) percent of rent households, 5) percent of female householder, 6) percent of children (under 5yrs old), 7) percent of elderly people (more than 65yrs old), 8) percent of people with less than high school graduation, 9) percent of families below poverty level, and 10) percent of African-American population		ACS 2010-2019 (5-year Estimates)

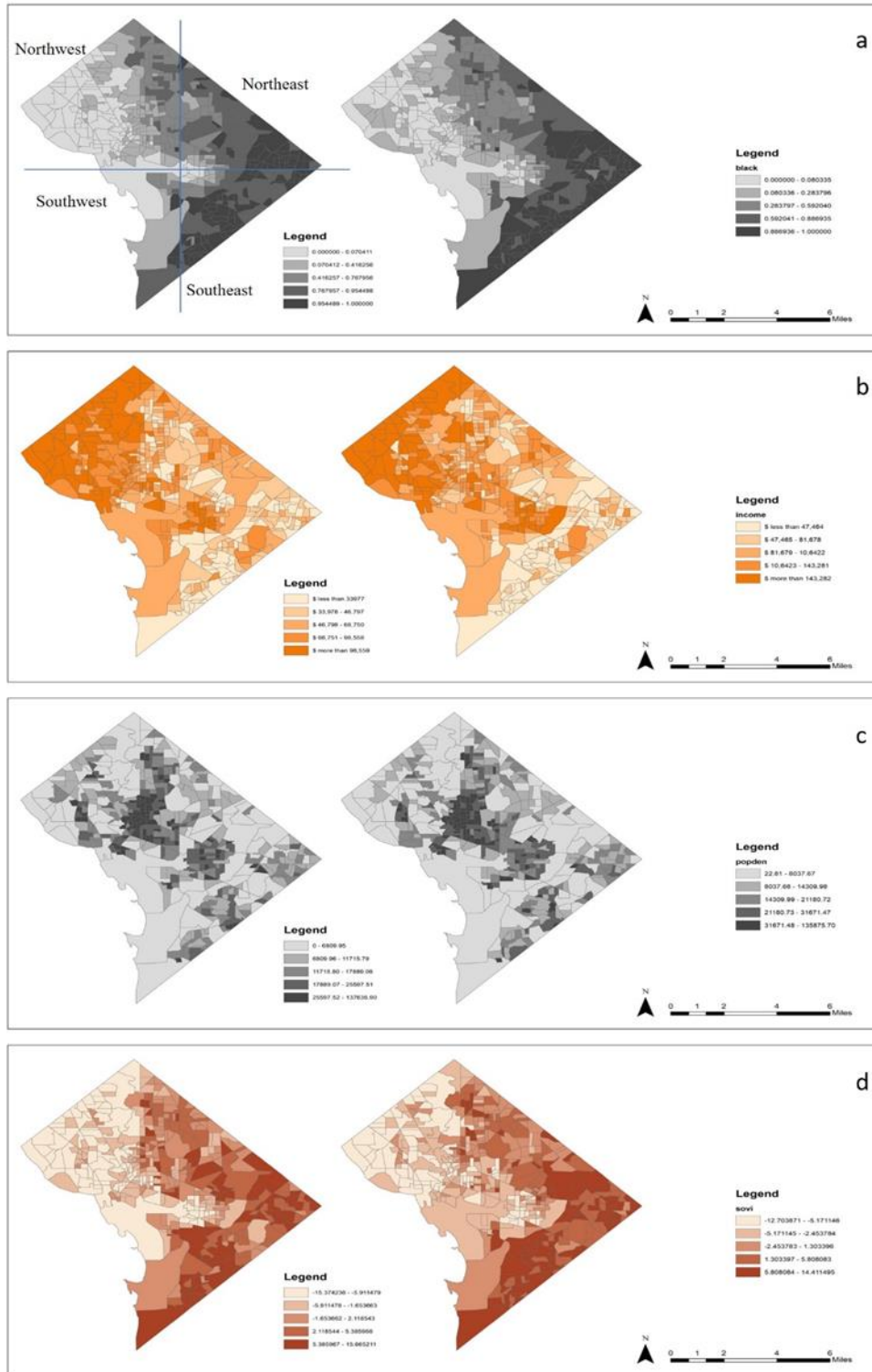


Figure 19 Persistent Socioeconomic Disparities in Washington D.C. The maps above illustrate that socioeconomic disparities in racial composition (a), income (b), population density (c), and community social vulnerability (d) have endured in the city from 2010 to 2019. Specifically, the gap between the communities of North-west and Southeast is evident. Washington DC is organized into four administrative geographical quadrants (a).

5.3.3. Social Vulnerability Index (SoVI)

Although numerous vulnerability indicators appear in the literature on social vulnerability, there is no specific standard for which indicators are most significant for social vulnerability. Social vulnerability studies often use a diverse set of proxies for their indicators, with different studies using different proxies for the same indicators (Rygel et al., 2006). Based on these practices for determining SoVI and the available data provided by the ACS, I chose 4 social vulnerability indicators of personal wealth, gender, race, and age, and 10 common proxy variables representing the indicators from the disaster literature (Aldrich and Benson 2008; Bolin and Kurtz 2017; Enarson 1998; Fothergill 1998; Fothergill and Peek 2004; Peek and Stough 2010), as seen in Table 5.

The choice of these four social vulnerability indicators—personal wealth, gender, race, and age—alongside ten common proxy variables, stems from several key considerations. Firstly, an individual's income and assets play a crucial role in enhancing their ability to prepare for and recover from climate related extremes or disasters, a point underscored by Cutter et al. (2003). Furthermore, Fothergill and Peek (2004) highlight that poverty in the United States amplifies vulnerability to natural disasters due to factors like geographical location, housing conditions, construction quality, and social exclusion. The role of education is also significant in this context. Individuals with lower levels of education, as described by Morrow (1999), frequently encounter practical and bureaucratic challenges when dealing with disaster preparedness and recovery processes while people with higher educational

backgrounds generally have better access to and make more effective use of information related to hazards. Meanwhile, children and the elderly emerge as particularly vulnerable groups during disasters due to their limited coping capabilities, as evidenced by Aldrich and Benson (2008) and Peek and Stough (2010). Minority status compounds vulnerability, with racial and ethnic groups facing elevated risks due to social and economic marginalization, as well as real estate discrimination, as documented by Bullard and Wright (2009), Cutter et al. (2003), and Morrow (1999). Finally, Enarson (1998) and Fothergill (1998) shed light on how women in female headed households often shoulder primary caregiving responsibilities, a circumstance that can curtail their involvement in income generating activities and community based disaster preparedness initiatives, ultimately making evacuation and seeking shelter during disasters more challenging for them.

I standardized the 10 variables using the mean and standard deviation for each variable. All standardized scores were then summed under the assumption that each proxy contributes equally to the overall vulnerability of the block group, similar to the approach taken in the study by Cutter et al. (2003).

5.3.4. Spatial clustering of green infrastructure

In order to assess the spatial clustering of green infrastructure in Washington D.C., I utilized the Local Moran's I with queen contiguity based spatial weight matrix and the hotspot analysis. The analysis was conducted using ArcMap 10.5 software. In addition to Moran's I, I used an optimized hotspot analysis tool to further confirm the

clustering of GI in Washington D.C.. Hotspot analysis is a spatial mapping and analysis method that focuses on identifying clusters of spatial phenomena, which are typically represented as points on a map, and it was conducted using the Getis-Ord Gi* statistic (Esri, n.d.). The Getis-Ord Gi* statistic was developed by Getis and Ord (2010) as an extension of the standard spatial autocorrelation statistic, Moran's I. The Gi* statistic measures the degree of concentration of a variable within a defined neighborhood, taking into account both the intensity and spatial pattern of the variable.

In the hotspot analysis, I choose “count-incidents-within_fishnet-polygons” option. It allows me to aggregate point data into a grid of equally sized rectangular cells called a fishnet. The tool then counts the number of point incidents that fall within each cell of the fishnet grid. I set the cell size of 500 ft by 500 ft. The chosen cell size of 500 feet by 500 feet results in an area of 250,000 square feet. The area of census block groups in DC varies from 335,347.62 to 122,896,846.26 square feet, making it evident that the analysis cell size is smaller than the census block group area. By setting a smaller analysis cell size, the potential averaging of data within each block group can be reduced, providing a more accurate representation of the specific location of GIs and enabling more precise analysis of their clustering.

5.3.5. Spatial panel regression

Spatial panel regression is a statistical method used to analyze panel data where both spatial dependence and time dependence are present. It extends the standard panel

regression by incorporating spatial autocorrelation and heterogeneity in the data. I used “spgm” function of “splm” package in R to estimate spatial panel data models using the Generalized Moments (GM) estimator. The generalized moments (GM) estimator has two advantages over the maximum likelihood approach; the first advantage is that the GM estimator's consistency is not affected by whether or not the errors follow a normal distribution., and the second advantage is that the calculation of the is straightforward, even for extremely large samples (Bell and Bockstael, 2000; Kelejian and Prucha, 1999). To be specific, the accuracy of eigenvalue calculations for matrices up to 2,000 observations using sparse and full matrix routines available in MATLAB is also unconfirmed (Bell and Bockstael, 2000). Also, the GM estimation is a flexible method that can be used to estimate a wide range of models, including those that suffer from endogeneity (Millo and Piras, 2012). Considering these advantages and the fact that the panel dataset in this study is a balanced panel with 4,500 observations and makes the spatial weight matrix consists of 450 census block groups, GM estimation would serve as a good alternative to the maximum likelihood estimation method.

In the spatial panel data set, except for the social vulnerability index, population density, and building age, most variable representing landscape factors and urbanization factors are time invariant. This indicates that the fixed-effect model cannot be estimated because there is no variation in the explanatory variables within each individual observation. In this case, the random-effect model is the only feasible option. The random-effect model assumes that the unobserved heterogeneity that affect the outcome variable are uncorrelated with the independent variables, including

the time invariant variables. This assumption allows the random-effect model to capture the unobserved heterogeneity among the individuals in the sample and estimate the average effects of the observed variables on the outcome variable. To statistically detect random effects empirically, I used Lagrange Multiplier tests using “splm” package and its “bskttest” function. The tests are commonly used to detect random effects and correlation (serial or cross sectional) in panel data models (Milo and Piras, 2012).

The random effect spatial lag model is a variant of the spatial lag model that incorporates individual level random effects into the model. This model is used to analyze spatially dependent data that exhibit spatial autocorrelation and individual heterogeneity. In the random effect spatial lag model, the dependent variable is not only influenced by its own lagged value but also by the lagged values of neighboring units, as well as by unobserved individual level characteristics that are assumed to be spatially correlated. These individual level random effects capture the unobserved heterogeneity among the units in the sample, and allow for the estimation of unit specific effects that are not accounted for by the observed independent variables. The general form of the random effect spatial lag model can be expressed as:

$$y_{it} = \rho \sum_{j=1}^n w_{ij} y_{it} + x_{it}\beta + \varepsilon_{it}$$

$$\varepsilon_{it} = a_i + u_{it}$$

Here, y_{it} represents the dependent variable for observation i at time t . ρ is the spatial autoregressive coefficient that measures the strength of spatial dependence among

observations. $\sum_{j=1}^n w_{ij} y_{jt}$ is the spatially lagged dependent variable, which captures the impact of neighboring observations on the current observation's value. w_{ij} is the spatial weight matrix that assigns weights to neighboring observations based on their spatial proximity. x_{it} is the independent variable for observation i at time t . β is a vector of coefficients that represent the effect of the covariates on the dependent variable. The second equation is the error equation, which describes the error term ε_{it} as the sum of two components: a_i and u_{it} . The a_i component is the unobserved time invariant heterogeneity, while the u_{it} component represents other unobserved factors, so called idiosyncratic error.

While the spatial lag model assumes that the dependent variable is influenced not only by its own lagged value but also by the lagged values of neighboring units, the spatial error model assumes that the error term in the model is spatially autocorrelated. In the random effect spatial error model, the dependent variable is a function of both the observed independent variables and an unobserved error term that has both spatially correlated and spatially uncorrelated components. The spatially correlated component of the error term is accounted for by the spatial weight matrix, which captures the spatial dependence among the observations. The spatially uncorrelated component of the error term is represented by the random effect term, which accounts for unobserved heterogeneity across spatial units. The inclusion of both spatially correlated and spatially uncorrelated components of the error term is a key feature of the random effect spatial error model. This allows for the model to capture both the spatial autocorrelation in the data as well as any unobserved factors that may be affecting the dependent variable. By accounting for both sources of variation, the model provides a more accurate estimation of the relationship between the dependent variable and the independent variables. The equation of this model is like below:

$$y_{it} = x_{it}\beta + \varphi_{it}$$

$$\varphi_{it} = \lambda \sum_{j=1}^n w_{ij} \varphi_{jt} + a_i + u_{it}$$

The first equation is the regression equation for the dependent variable y_{it} , where the dependent variable is a function of the independent variables x_{it} and an error term φ_{it} . Here, the second equation shows the spatially correlated component of the error. The λ represents the average level of spatial correlation between errors, given the spatial structure defined by the weight matrix w_{ij} . Thus, the second equation reflect that that the error term has a spatial autocorrelation with the error of the neighborhood.

I estimate both the random effect spatial lag model and the random effect spatial error model and compare their fit using model selection criteria such as the Akaike information criterion (AIC), the Bayesian information criterion (BIC) and the statistical significance of spatial parameters.

5.4. Results

5.4.1 Green infrastructure clustering

The interpretation of Univariate Local Moran's I depends on the sign of the index and the significance level of the test. The statistic of the spatial autocorrelation suggests that the pattern of GIs at census block groups is clustered. The Moran's Index is 0.371 with the z-score of 14.065, and the p-value is 0.001. Although it is difficult to say that there is a stronger clustering given that the value close to 1 indicates perfect

clustering, the probability that the observed clustering pattern is due to random chance is less than 1 percent as the critical value is greater than 2.58.

Additionally, the below cluster map (Figure 20) identifies areas where there is a significant spatial concentration of high or low values of a variable of interest, which can provide insight into the spatial patterns. The presence of a high-high (HH) cluster on the LISA Cluster map suggests that there is a spatial concentration of GIs in a specific area in DC Northeast and Northwest, where there are many GIs surrounded by neighboring areas with similarly high numbers of GIs. On the other hand, a low-low (LL) cluster in some communities in DC Southeast and around National mall indicates a spatial concentration of areas with less GIs, surrounded by neighboring areas with similarly low numbers of GIs. Overall, these patterns suggest that the concentration of GIs across DC varies across different spatial areas.

The optimized hot spot analysis also suggests that GIs in DC are clustering. If a z-score of G_i^* statistic returned for each data cell of 500 ft by 500 ft is statistically significant and positive, it means that there is a strong clustering of high values, also known as a hot spot. In such cases, the larger the z-score, the stronger the clustering of high values. Conversely, if a z-score is statistically significant and negative, it means that there is a strong clustering of low values, or a cold spot. In such cases, the smaller the z-score, the stronger the clustering of low values. Thus, the map output of the hot spot analysis illustrates that GIs are highly concentrated near the border of Northeast and Northwest and in the Northeast. Although the concentration of GI is also observed in Southeast DC, its size is much smaller than that of Northeast and Northwest DC. The hot spot that exists around the central part of DC is a different

point compared to the above cluster map. This reflects that analyzing the spatial clustering using Moran's I can distort information about the true location of GI clusters.

Both the Univariate Local Moran's I and the optimized hot spot analysis indicate that the pattern of GIs in DC is clustered. Although the two tools output different results regarding Southeast DC, the LISA cluster map identifies significant clusters in Northeast and Northwest, and the optimized hot spot analysis also shows that the GIs are highly concentrated in the same area of DC. These results suggest that the concentration of GIs across DC varies across different spatial areas.

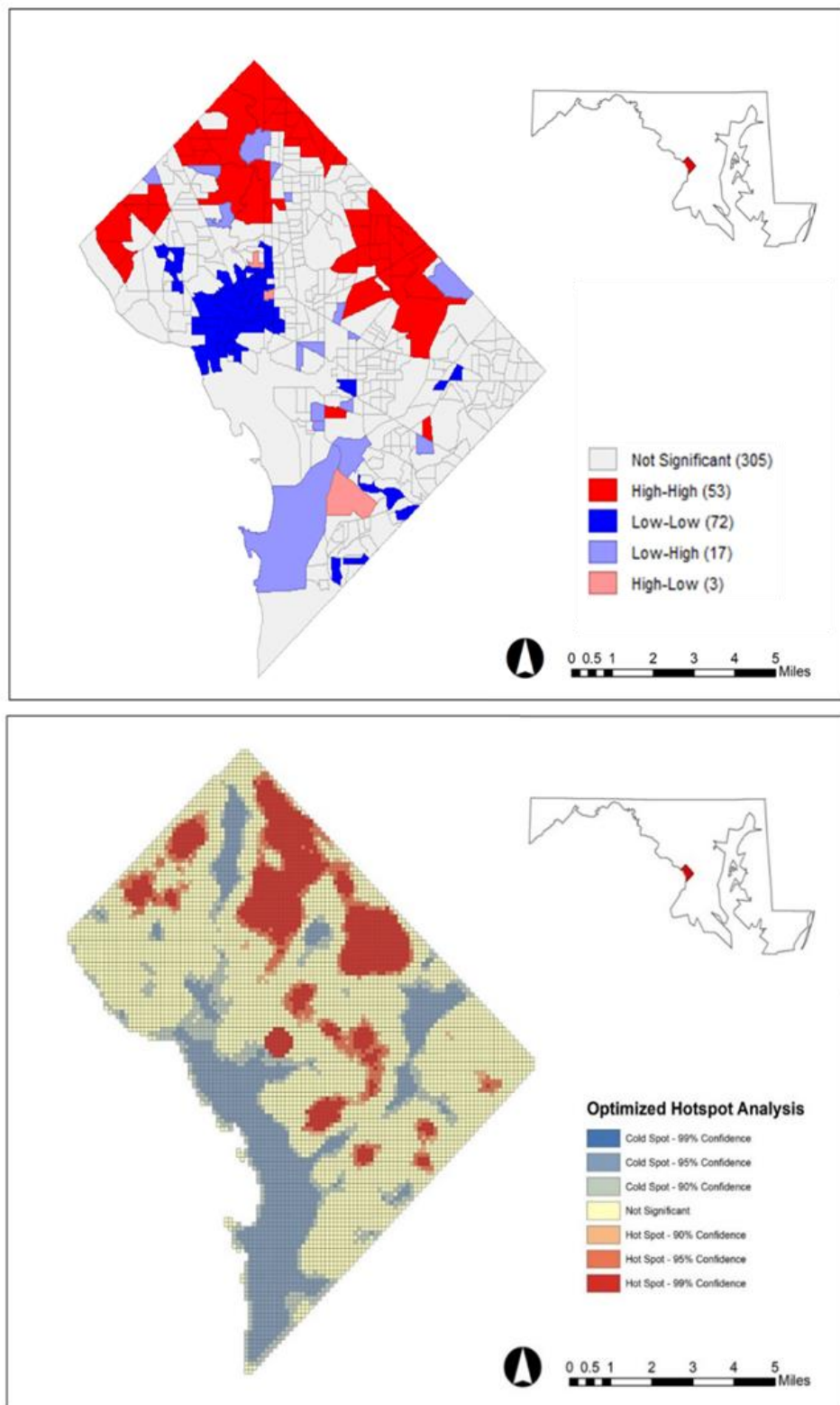


Figure 20 GI clustering in Washington, D.C.

5.4.2. Spatial panel regression results

Table 6 . Baltagi, Song and Koh LM test for spatial panel regression

Model	GIs' annual increase ~ sovi + popden + impvs + slope + elev	
Test		Statistic
SLM1	Alternative Hypothesis: Random Effects	48.853*
SLM2	Alternative Hypothesis: Spatial Autocorrelation	23.753*
LM*-lambda conditional	Alternative Hypothesis: Spatial Autocorrelation	11.556*

*: $p < 0.01$

The table above displays the Lagrange multiplier test results. The test includes SLM1, SLM2, and LM*-lambda conditional tests as proposed by Baltagi et al. (2003), which investigate the panel data regression model with spatial error correlation by combining ideas from two previous research strands. The output shows that the statistically significant LM1 test statistic. The SLM1 is for testing spatial autocorrelation in linear regression models with random effects (Baltagi et al., 2003), and thus the result indicates strong evidence against the null hypothesis of no spatial correlation in the model, in favor of the alternative hypothesis of random effects. Both SLM2 and the Conditional Lagrange Multiplier (LM*)-Lambda tests examine the presence of spatial autocorrelation in the specified regression model in which the dependent variable is cnt and the independent variables are sovi, popden, impvs, slope, and elev. Only with SLM2, researchers cannot exclude the possibility of incorrect inference when the “variance component” referring to the variability of the random effect is large (Millo and Piras, 2012). To address this issue, Baltagi et al. (2003) developed a conditional LM test that tests for the existence of spatial autocorrelation in the regression model while allowing for the possibility that the

variance component may or may not be zero. Based on both test results, I can reject the null hypothesis of no spatial autocorrelation and conclude that there is evidence of spatial autocorrelation in the model.

Table 7 Spatial panel regression results

		Number of observations: 4,500 Panel length: 10yrs Number of census block groups: 450		
Variable		Pooled OLS	Panel SAR	Panel SEM
Annual Increase of GI	SoVI	-0.011025***	-0.017741***	-0.020207***
	Popden	-0.000029527***	-0.000011272***	-0.000016773***
	Impervious	-0.96456***	-0.46629	-1.491***
	Slope	-0.42821***	-0.15351*	-0.32335***
	Elevation	0.14735***	0.031555	0.12163***
	Intercept	2.5074***	0.75368**	2.4722***
ρ (spatial)			0.8270***	
λ (Error)				0.3456
R square		0.1557	0.1560	0.1425
LM tests for spatial dependence	Lag	611.23***		
	Robust Lag	47.53***		
	Error	564.21***		
Robust Error		0.51679		
AIC		15818.42	14563.40	15888.23
BIC		15863.31	14621.11	15933.11

*: $p < 0.1$, **: $p < 0.05$, *** $p < 0.01$

The above table 7 shows the coefficients and statistical significance of a spatial panel regression model estimated using three different methods: Pooled OLS, Panel Spatial Autoregressive (SAR), and Panel Spatial Error Model (SEM). The analysis is based on a dataset with 4500 observations over a panel length of 10 years and 450 census

block groups. The dependent variable is the annual increase in GI, and the independent variables are the social vulnerability index, population density, the proportion of imperviousness surface, the average slope of the community, and the average altitude of the community.

The results of the “locally robust panel Lagrange multiplier test” for spatial dependence (Millo and Piras, 2012), which is based on the OLS estimation, show that there is strong evidence of spatial lag dependence, as the LM test statistic of 611.23 for spatial lag dependence has a very low p-value ($<2.2 \times 10^{-16}$). This suggests that the value of the dependent variable in each observation is spatially correlated with the value of the dependent variable in neighboring observations. Also, the locally robust LM test for spatial lag dependence supports this conclusion, with a statistic of a low p-value of 5.418×10^{-12} . On the other hand, the LM test for spatial error dependence also has a statistically significant value of 564.21, indicating that there is evidence of spatial error dependence in the data. This means that the errors in the regression model are not independent, but rather, are correlated with the errors in neighboring observations. However, the locally robust LM test for spatial error dependence, which accounts for spatial heterogeneity, does not support the presence of spatial error dependence, as the p-value is relatively high (0.4722). This may indicate that the spatial autocorrelation in the errors is not consistent across all observations, but rather varies locally.

Like these results, the coefficient of the spatial parameter ρ (spatial) is positive and statistically significant at the 1% level, indicating the presence of spatial autocorrelation in the data. On the other hand, the coefficient of the spatial parameter

λ (error) is positive but not statistically significant, suggesting that the spatial errors are not systematically related to the independent variables. Additionally, the AIC and BIC values show that the Panel SAR model has the lowest information criteria, and the r-squared value of the SAR is slightly higher than the other two models. In sum, the results from the Lagrange multiplier test and the estimation of regression models indicate that the Panel SAR model is the best model among the three in terms of balancing goodness of fit and model complexity. The Panel SAR model accounts for the spatial autocorrelation between dependent variables by incorporating a spatial lag of the dependent variable in the regression equation, which would improve the accuracy of the parameter estimates, considering that the coefficient estimates for the annual Increase in GI in the Panel SAR model are smaller than the Pooled OLS and Panel SEM models.

The results show that the variables representing social vulnerability and population density are negatively associated with the annual increase in GI, and the coefficients are statistically significant at the 1% level in all three models. This analysis is a kind of panel regression, which reveals that a statistically significant negative coefficient means that as the independent variable increases within each individual entity over time, the dependent variable tends to decrease. Thus, the relationship implies that communities with much socially vulnerable or higher population density had experienced lower increases of GI annually, from 2010 to 2009. Also, considering that the SAR model is the best, the significant spatial parameter ρ means that the annual increase in GI in one census block group is positively correlated with the annual increase in GI in neighboring census block groups. In other words, the results

suggest that neighboring communities' increases in GI are affected by the annual increase in GI within their neighboring communities. Also, consider that the coefficient estimates for the annual increase in GI in the Panel SAR model are smaller than the Pooled OLS and Panel SEM models.

On the other hand, while the coefficients of the proportion of imperviousness surface, the average slope of the community, and the average altitude of the community are significant in the pooled OLS and the panel SEM, their influence on GI is not directly observable in the panel SAR model. The estimated effects of these independent variables may be overestimated or biased due to unobserved spatial factors in the pooled OLS and the panel SEM.

5.5. Discussion

5.5.1. Social vulnerability and green infrastructure growth

The analysis results indicate that communities with higher social vulnerability have experienced relatively fewer advancements or developments in terms of GI compared to other communities. This could imply that disparities in GI investment or development have persisted or even worsened for socially vulnerable communities during the 2010s. In other words, the communities that are more socially vulnerable have not seen as much progress in terms of increasing their GI compared to communities that are less vulnerable. This link between social vulnerability and GI growth has led to an uneven clustering of GIs across communities in Washington D.C., which carries significant implications for vulnerable groups during extreme weather conditions. The lack of sufficient GI in socially vulnerable communities can hinder their ability to adapt to changing climatic conditions and cope with the adverse effects of extreme weather events. In scenarios involving pluvial flooding or excessive heat, these deepening unequal distributions of GIs can result in varying levels of protection for different communities. Consequently, the exacerbation of disparities in GI development could lead to increased health disparities, reduced quality of life, and heightened social and economic vulnerabilities for these communities.

This disparity in protection can further exacerbate existing inequities during environmental extremes, as observed in previous disaster cases. Bolin and Kurtz (2017), Bullard and Wright (2009), and Fothergill and Peek (2004) demonstrate that

individuals from groups already vulnerable before disaster experience relatively greater property damage and disproportionate support from societies during such events. This phenomenon intensifies the preexisting socioeconomic disparities among communities.

Examining the aftermath of Hurricane Katrina in New Orleans allows us to dissect the specific mechanisms through which unequal infrastructure protection can heighten vulnerabilities and perpetuate long-standing patterns of marginalization. This focused approach facilitates drawing vital parallels between the New Orleans case and the current study area, shedding light on broader implications for urban planning and equity. Bullard (2009) delves into how factors such as race, socioeconomic status, and place intersected with environmental concerns during and after the disaster. Before Hurricane Katrina struck, African Americans in New Orleans settled in areas that were relatively more vulnerable to flooding within a discriminatory context, ultimately resulting in greater flood damage for them. However, Bullard and Wright(2009) argues that institutionalized racism played a role in the post disaster processes of cleaning up, sheltering, providing housing, and levee protection. He asserts that they experienced discrimination during these processes. Specifically, this case illustrates how already vulnerable groups, once again, faced discrimination in protective measures of infrastructure after the disaster, ultimately placing them at greater risk once more. Bullard and Wright (2009) posits that the unequal protection from infrastructure in New Orleans can be traced back to historical, social, and political structures and institutions that have systematically maintained unequal access to resources and opportunities for disadvantaged

populations. Socially vulnerable groups could be excluded or unrecognized in decision-making processes related to protective infrastructure or mitigation measures, which can lead to increased vulnerability to disasters and climate change. This suggests that socially vulnerable people may experience the perpetuation of historical patterns of marginalization through disaster events and inequitable infrastructure settings.

It is important to note that measures aimed at mitigating or adapting to climate change can, ironically, result in unintended consequences that exacerbate vulnerability. While these ‘good’ measures are often conceived with the intention of alleviating risk and vulnerability (Cutter 1996), their practical impact may fall short of this goal if their distribution lacks equity, given that vulnerability is a relative concept (Cutter et al., 2003). Reckien et al. (2017) assert that adaptation and mitigation policies may disproportionately affect vulnerable populations when not adequately designed. Thus, the introduction and implementation of mitigation or adaptation measures should not solely center on enhancing overall social vulnerability reduction and resilience at a citywide scale. Instead, they must also encompass considerations of potential discrimination against vulnerable groups or the exacerbation of their vulnerabilities. In other words, infrastructure development addressing climate change and disaster challenges necessitates more than just technical solutions. It involves decision-making processes, policies, and social contexts that influence the implementation and distribution of these measures. The presence of infrastructural disparities in certain neighborhoods is not due to a single event, act of discrimination, or capital improvement project (Hendricks, 2017). Rather, these disparities result from a series

of entrenched obstacles woven into planning practices, policies, and implementation frameworks (Hendricks, 2017). I defer the investigation of this potential to be explored in future studies.

5.5.2. Higher density and green infrastructure

The findings derived from the analysis unveil a significant and noteworthy negative correlation between population density and the annual growth of green infrastructure (GI) in the context of Washington D.C. This association underscores the potential challenges that arise when attempting to introduce and expand GI initiatives within densely populated urban environments. The observed negative relationship suggests that higher population densities within the city are intertwined with constraints on the adoption and integration of green infrastructure, primarily due to limitations in available land and restricted space for implementation. These limitations can impede the effective implementation of GI programs, resulting in an intricate interplay between the pressing need for urban sustainability and the inherent constraints posed by dense urbanization. Exploring innovative strategies for integrating green infrastructure within densely populated areas becomes paramount. Designing adaptable and space efficient GI solutions that can thrive within the constraints of limited urban space holds promise for mitigating the challenges imposed by high population densities. Such strategies could encompass vertical greenery, rooftop gardens, pocket parks, and other creative approaches that optimize available space while enhancing urban livability and resilience.

Ferguson et al (2018), McConnachie and Shackleton (2009), and Wolch et al (2010), suggest that when investigating the reasons behind unequal green space access for certain racial groups, researchers are increasingly acknowledging that it is not just about any one factor in isolation. Rather, they are exploring how multiple elements converge to shape these disparities. Further investigation could delve into the potential ripple effects of the observed negative correlation. For instance, understanding how this relationship interacts with other socioeconomic factors, such as ethnicity and deprivation, could provide a deeper understanding of the complex dynamics underlying unequal green space access. This expanded analysis might shed light on whether certain demographic groups face compounded challenges due to the overlapping effects of multiple factors.

5.5.3. Green infrastructure clustering mechanism and policy implications

The spatial autoregressive panel model accounts for spatial dependence in this panel dataset by introducing a spatial lag variable that reflects the average value of the dependent variable in neighboring units. That is, the results show that GI's annual increase in a community is influenced not only by its own characteristics (here, social vulnerability and other independent variables) but also by neighboring communities' GI increase. This spatial dependence between communities in GIs in part corresponds to Lim's finding (2017) that the property owners' voluntary participation in GI implementation is influenced by the locations of previous installations. However, his research was limited to voluntary GI implementation by property owners, which

accounts for only 5012 of the total 33,813 GIs in D.C. as of 2022. Focusing solely on voluntary participation by property owners may not provide a complete picture of GI implementation patterns. A more comprehensive understanding of GI clustering is necessary to effectively address issues related to GIs and environmental justice. As Mandarano and Meenar (2017) noted, current GI programs in the United States, regardless of whether they are direct public investment, regulatory mandates, and incentives for voluntary implementation, require collaboration and engagement with communities and stakeholders and the capacity of communities, in terms of economic and political aspects, for effective implementation. Poor or racial minority communities often lack the capacity to get information about the incentives for GI, install GI on their properties, or engage in local decision-making processes, which indicates that GIs would cluster in wealthier and politically powerful communities as seen in the above results.

Promoting a more equitable distribution of GI has the potential to improve both capacity to weather extremes and social equity outcomes (2022). For more equitable distribution of GIs in D.C., planners and engineers in the D.C. government need to become conscious of the current distribution of GIs and analyze the potentials of the distribution in reducing stormwater runoff or urban heat island effect, prioritizing equitable distribution of GIs across communities. To be specific, given that the current GI implementation inevitably leans on market forces (Baker et al., 2019; Mandarano and Meenar, 2017), planners and engineers should also recognize that socially vulnerable people who lack social and economic resources can be excluded from the GI programs whether they are implemented by public or private and

promote community engagement and participation in the decision-making process surrounding GI programs.

The concurrent efforts of several government agencies, including the District Department of Energy and Environment, D.C. Water, and the District Department of Transportation, to implement GI programs in Washington, D.C. is commendable. Their GI programs are designed to achieve a broad spectrum of program goals and offer numerous benefits, including increased sustainability and resilience. However, despite these efforts, it is unlikely that the current implementation of GI programs will properly achieve any one of those goals with regard to environmental justice due to the uneven distribution of GIs across communities. A more comprehensive approach is needed that integrates GI programs with other environmental justice initiatives, such as affordable housing and public transportation, to address the underlying social and economic inequalities that perpetuate environmental injustices (Wolch et al., 2010). As suggested by Wolch et al. (2010), such an approach would be necessary to ensure that the benefits of GI are distributed equitably across communities, especially those that have been historically underserved. Therefore, a more holistic and integrated approach is needed to achieve true environmental justice and ensure that all communities in Washington, D.C. can reap the benefits of GI.

5.5.4. Limitation

There are several limitations in this study. In order to investigate the association between GI and independent variables, I utilized the count of GI units in each census

block group as a proxy for the multifaceted capacity of GI. This approach was necessary due to the absence of variables in the raw GI data that could effectively represent its diverse functions. While the raw data did contain a value indicating retention or storage volume associated with stormwater processing, this value solely represented the capacity linked to stormwater management by the GI. Additionally, a significant portion (approximately 9%) of the retention volume data had null values, rendering it unsuitable for use. However, relying solely on the count of GI facilities within a given census block group as a stand in for the true capacity of GI to manage stormwater or mitigate the heat island effect in that area might not accurately capture the complete extent of GI's capabilities.

GI is a heterogeneous form of infrastructure encompassing various types (such as bioswales, rain gardens, green roofs, and trees), which can be constructed in different sizes and locations within a given area. Bioswales, for example, are linear, vegetated ditches designed to concentrate and convey stormwater runoff while removing debris and pollution. Rain gardens, in contrast, are shallow depressions planted with native vegetation that temporarily hold and soak in rainwater runoff from impervious urban areas like roofs, driveways, walkways, parking lots, and compacted lawn areas. Green roofs, another form of GI, involve the establishment of vegetation layers on rooftops, offering benefits such as reducing heat island effects, insulating buildings, and contributing to stormwater management. Unlike ground-level GI forms, green roofs utilize often underutilized spaces in dense urban areas. The effectiveness of GI in managing stormwater runoff or mitigating extreme heat can vary based on these forms. Consequently, additional interdisciplinary research is imperative to determine

whether the distribution of GI considered in this study can genuinely represent the ability of communities' green infrastructure to effectively address diverse weather extremes at the infrastructure level.

Furthermore, it should be noted that this study's exclusive focus on Washington D.C. could be considered a limitation. While Washington D.C. serves as a suitable case study for exploring the connection between social vulnerability and GI distribution, its findings may not be directly transferable to other cities or regions due to the diverse programs being implemented for various purposes across different urban areas. The correlation between social vulnerability and GI distribution may exhibit variations in other urban locales, influenced by the distinct socioeconomic, environmental, and political factors that characterize each city. Similarly, the environmental and political considerations impacting GI distribution might diverge among urban regions, contingent upon localized policies, regulations, and stakeholder engagement. As a result, the applicability of this study's findings beyond Washington D.C. could be constrained. Researchers who seek to investigate the relationship between social vulnerability and GI distribution in alternative cities or regions must consider these variations and contextual factors during their study's design and analysis.

5.6. Conclusion

In conclusion, this study rigorously examined the relationship between social vulnerability and the annual increase in GI in Washington D.C. Through the

application of a spatial panel dataset and advanced regression models, Pooled OLS, Panel Spatial Autoregressive (SAR), and Panel Spatial Error Model (SEM) were tested. Among the models, the Panel SAR approach proved most effective in explaining the observed dynamics and it was established that socially vulnerable communities and areas with higher population density experienced comparatively lower annual increases in GI. The presence of spatial parameters further emphasized that the annual increase in GI in one census block group positively influenced the increase in neighboring block groups.

These findings underscore an enduring nexus between social vulnerability and the disproportionate growth of GI, leading to varying levels of vulnerability during extreme weather events. This uneven distribution perpetuates disparities, wherein communities endowed with greater social and economic capital experience augmented protection, while their more vulnerable counterparts confront heightened susceptibility. These results may illuminate the pivotal roles played by the planning mechanism, particularly its reliance on infrastructure privatization, and the subsequent implementation mechanism. The unequal provision of infrastructure protection can be traced back to entrenched inequalities in access to resources and opportunities for marginalized populations (2009). Additionally, a negative association between population density and the annual increase in GI highlights the challenges posed by limited space and competition for land use in densely populated areas.

Collectively, these findings underscore an urgent imperative to confront social vulnerability and champion an equitable distribution of GI. They accentuate the

integral role of comprehensive urban planning and engineering practices in the effective implementation of GI plans. It is essential for planners and engineers to recognize the potential absence of incentives and engagement opportunities for socially vulnerable communities. Advocating for an equitable distribution of GI presents a pathway to fortify sustainability and advance social equity (Wang et al 2019). To achieve this, planners should assess GI distribution through a lens of social vulnerability, thereby prioritizing communities in need. Moreover, the integration of GI with other environmental justice initiatives, encompassing affordable housing and public transportation, becomes imperative to ensure the even handed dispersion of benefits (Wolch et al., 2010). This study reaffirms the inescapable necessity for a comprehensive and integrated approach to secure equitable GI benefits across all communities in Washington, D.C.

Chapter 6: Navigating Stormwater Inequity: An Environmental Justice Analysis of Flood Management Strategies in Washington, D.C.

Abstract

As global warming escalates, cities worldwide grapple with more frequent and severe climatic changes. While urban areas, including Washington, D.C., are actively developing and implementing climate change action plans, a critical concern emerges – the tendency to overlook equity and justice considerations. Despite the District of Columbia's commitment to flood management and resilience, evidenced by the establishment of the Flood Task Force (FTF), disparities in stormwater infrastructure distribution reveal a significant social vulnerability within local communities. Applying an Environmental Justice (EJ) framework and a qualitative coding based on the framework, the study analyzes the FTF's action plans and their underlying foundations, including stormwater management, climate change planning. The research investigates whether the FTF effectively considers vulnerability issues from an EJ perspective. By revealing the limitations and potential exacerbations of social vulnerabilities within current plans, this research contributes to the ongoing discourse on achieving more equitable and resilient urban flood management in DC.

6.1. Introduction

Global warming is intensifying, causing more severe and frequent climatic changes and environmental disruptions around the world. Cities are increasingly taking action to address climate change by developing and implementing related plans and policies. However, a concerning issue is that these plans often overlook critical aspects of equity and justice (Heyen 2023). Various studies have highlighted this problem, demonstrating that references to social or environmental justice, equity, and inclusion are typically neglected in many cities' climate change action plans (Anguelovski et al., 2016; Bulkeley et al., 2013; Fitzgibbons and Mitchell, 2019; Meerow, 2019; Pratt, 2023;). Even when some consideration is given to social justice, it often focuses solely on distributional equity, neglecting other dimensions like recognition and inclusion in decision making process (Bulkeley et al., 2013; Collins and Niemeyer 2017; Fitzgibbons and Mitchell, 2019; Grabowski et al., 2022; Meerow et al., 2019; Schlosberg,). Prett (2023) and Meerow (2019) state that increasingly compelling evidence indicates that cities' efforts to combat climate change may worsen disparities and social injustices.

Washington D.C. (DC), like other global cities, stands at the forefront of climate change and flood management initiatives. The city's commitment to addressing flooding and enhancing resilience is demonstrated through a wide range of initiatives. Notably, the Office of the City Administrator has established a Flood Task Force (FTF) to proactively manage and mitigate flood risks. The FTF's primary objective is to develop strategies and plans aimed at reducing flood risks, enhancing stormwater management, and bolstering the city's ability to withstand extreme weather events,

including flooding. This collaborative effort involves various city agencies, departments, and organizations, including the District Department of Energy & Environment (DOEE), the District Department of Transportation (DDOT), the District Department of Public Works (DPW), and the District of Columbia Water and Sewer Authority (DC Water). The FTF comprised 13 District agencies and 15 dedicated federal and public agents who collaborated to formulate specific measures and subsequently released the final report, which provides an extensive account of the intricate endeavors undertaken over a span of 16 months. The final report includes a comprehensive set of 27 action plans, each aligned with the 9 action categories established by the City Administrator. To be specific, among the 9 categories, 3 categories are associated with stormwater infrastructure. Also, the FTF acknowledges that some action plans are informed by and connected to previous climate change-related planning efforts, such as Sustainable DC 2.0 and Climate Ready DC. Those planning documents explicitly incorporate the concept of equity as a central goal in their actions, demonstrating a genuine commitment to addressing social and environmental justice concerns alongside climate mitigation and adaptation efforts. The final report and climate change plans acknowledge the disproportionate impact of climate change and flooding on vulnerable communities and aim to prevent exacerbating existing disparities.

However, in DC, the disparity in the distribution of stormwater infrastructure is conspicuous, revealing a significant inequity concerning the social vulnerability of local communities (Park, 2023). As indicated by the studies above, the distribution of the overall stormwater infrastructure system in DC, including Green Infrastructure

(GI) and sewer pipelines in DC, exhibits inequity concerning the social vulnerability of communities. Socially vulnerable communities in DC have fewer sewer pipelines and less GI. Moreover, they consistently experienced lower annual GI growth compared to less socially vulnerable areas throughout the 2010s. This uneven annual increase suggests a deepening disparity in stormwater infrastructure distribution during the 2010s. The deepening gap in stormwater infrastructure distribution raises a potentially unfair situation which may result in disparities in the level of protection and resilience that different communities can access. This asymmetrical allocation of resources is accentuating existing societal disparities, leaving already vulnerable communities even more exposed to the ravages of flood events. These findings underscore the urgent need for a case study to analyze both the FTF's action plans and the underlying plans upon which the FTF's actions are based. Specifically, it is crucial to determine whether the FTF is taking into account the stormwater capacity disparities in vulnerable communities, the increasing disparities, and the special needs of the vulnerable communities given the disparities. Furthermore, the availability of open access data and comprehensive documentation on the FTF's website, as well as their transparent decision-making process available on YouTube, make DC an ideal case study candidate for analyzing the FTF's action plans and the underlying plans based on data accessibility.

Socially vulnerable individuals are frequently excluded from planning process or plans related to urban development and infrastructure projects (Meerow et al., 2019; Wang and Palazzo 2021). Even when their participation is ensured, in some cases, the inclusion of these communities may be more symbolic than substantive, resulting in

plans that may appear equitable on the surface but do not effectively rectify or prevent disparities in access, resources, and opportunities (Anguelovski et al., 2016). The Hurricane Katrina case, a historical example, brought heightened focus to the connection between flood planning and environmental injustice (Bullard and Wright 2009). This experience has revealed that post-disaster planning activities, such as the construction of new flood-protection measures and assistance to people who are affected by floods, can add another burden to already socially vulnerable individuals and thus results in a new type of injustice. The Hurricane Katrina case spurred increased research into the relationship between EJ and the policies and practices related to flood management (Wang and Palazzo, 2021). These studies from an environmental justice perspective raises concerns and provides evidence underscoring the importance of analyzing the action plans of FTF and its associated plans to ensure they align with principles of equity and justice.

Applying an Environmental Justice (EJ) perspective to analyze the plans related to the FTF is valuable, given that EJ encompasses three key dimensions of justice: procedural justice, involving the inclusion of all populations in environmental decision-making; distributional justice, addressing the placement of development in relation to historically disadvantaged communities; and recognitional justice, understanding that different communities may have unique vulnerabilities, needs, and relationships with their environments (Schlosberg, 2004). Thus, by utilizing these three dimensions of justice, the EJ lens can offer a robust framework for investigating not only the distribution issues of stormwater infrastructure but also the processes in which socially vulnerable individuals are often excluded or not represented in the

decision-making processes of plans created by the FTF, and the related plans provide a solid basis for the FTF's own planning efforts.

My study applies the EJ framework to analyze the FTF's action plans and the underlying plans upon which the FTF's actions are based, which include stormwater management, climate change planning, and flood management, and investigate whether Washington DC is learning from early critiques regarding the equity issues of infrastructure. While a few studies have developed the EJ framework to analyze what evidence exists regarding how different types of GI could contribute to addressing justice-related issues (Kato-Huerta and Geneletti, 2022) and to analyze how stormwater management plans perform (Wang and Palazzo, 2021), studies aiming to evaluate a comprehensive set of flood management from the EJ perspective are still lacking. Most studies assessing or analyzing flood management have an engineering focus, such as optimization or impact simulation (Hansson et al., 2008; Indrawati et al., 2017; Louw et al., 2019).

At the core of this study lies the research question: Do the Flood Task Force's (FTF) action plans and its underlying plans address issues of vulnerability from an Environmental Justice perspective? This question arises in response to the pressing concern of addressing the unequal distribution of stormwater infrastructure. The study seeks to enhance understanding of the underlying mechanisms contributing to the unequal distribution of stormwater infrastructure and exacerbating the overall vulnerability. By doing so, this study reveals how planning and policies may neglect the vulnerable people and the unequal distribution of existing stormwater infrastructure, potentially leaving socially vulnerable communities more susceptible

to flooding. In addition to the above studies that reveal the unequal distribution of stormwater infrastructure in relation to social vulnerability and the deepening disparities of green stormwater infrastructure, this study aspires to contribute to identifying the characteristics of persistent vulnerability to floods in socially vulnerable communities. As illustrated by the theoretical framework below, this chapter examines Washington, D.C.'s flood planning efforts, which are aimed at mitigating vulnerability disparities but fall short of achieving their objectives. The planning process is critically flawed, marked by an inadequate recognition of socially vulnerable groups and a prevailing market-based approach during the development phase. This raises concerns about its ability to effectively address the existing infrastructure gap.

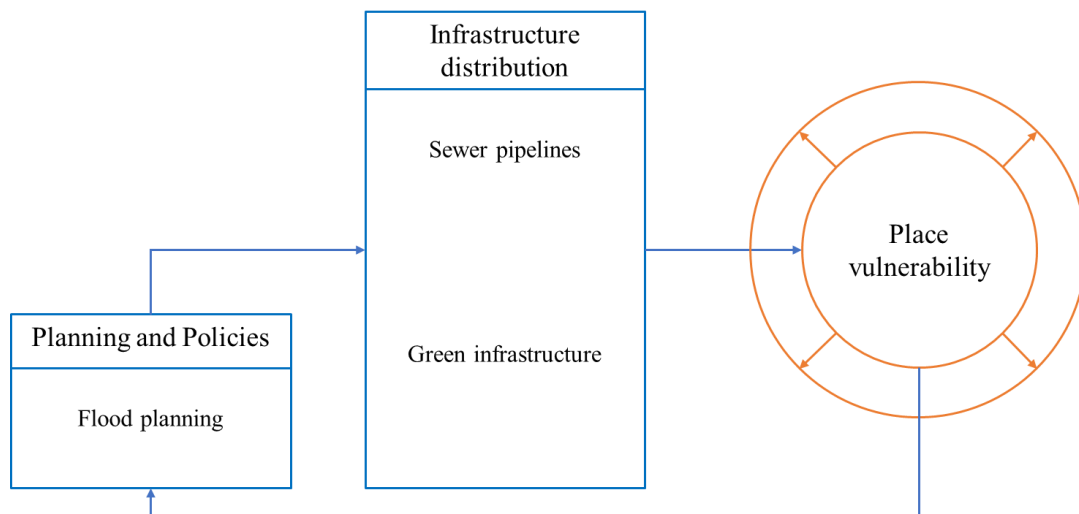


Figure 21 Theoretical framework for evolving place vulnerability through the flood planning.

6.2. Defining the environmental justice framework

Schlosberg's Environmental Justice (EJ) framework, developed in the early 2000s, is a significant contribution to the field of environmental justice. This framework expands the traditional concept of environmental justice, which originally focused primarily on distributional equity (fair distribution of environmental benefits and burdens) and broadens it to include two additional dimensions: procedural equity and recognitional equity (Schlosberg, 2004; 2007). Based on this widely accepted EJ definition by Schlosberg (Meerow et al., 2019), scholars have subsequently developed and tested planning analysis indicators grounded in the 'tripartite' EJ framework, which includes distributional, procedural, and recognitional equity dimensions (Kato Huerta and Geneletty, 2022; Wang and Palazzo, 2021). I also adopt this tripartite framework and describe the three dimensions of justice as follows.

Distributional equity

This dimension focuses on the equitable distribution of environmental benefits and burdens, ensuring that no group or community bears a disproportionate share of environmental harm. Lucy (1981) illustrates that the early legal rulings on cases of environmental injustice, especially those involving exposure to environmental risks, often relied on the concept of equality. This suggests that the legal system historically addressed environmental harm and unequal exposure to risks by treating everyone equally, without taking into account specific circumstances or disparities that could lead to environmental injustices. However, Distributive justice in the Schlosberg's description (2004; 2007) does not necessarily mean that every group or community receives the same share of environmental benefits and burdens. It emphasizes fairness

and equity, which may not always result in equal distribution. Instead, it aims to ensure that no particular group or community bears a disproportionate or unfair burden of environmental harm. Moreover, recent empirical studies examining the infrastructure distribution merely reveal the unjust situation in which low-income individuals or racially minority groups have limited access to benefits, without providing a clear definition of just distribution (Baker et al., 2019; Chan and Hopkins, 2017). On the other hand, Nicholls (2001) offers a different perspective or approach. She suggests that when assessing equity in the context of park access, it is more appropriate to define equity based on people's needs. According to Nicholls (2001), an equitable distribution of parks would be one that prioritizes and provides parks where they are needed the most to address the needs of the community effectively. Hecker and Rosan (2016) argue that distributive justice should be a need-based concept that takes into account factors like vulnerabilities and the specific context of the environmental issue. The need-based distributional justice may require targeted efforts to address and rectify existing disparities, with the goal of achieving a more equitable distribution of benefits and burdens, even if that means some groups receive more support or protection than others to compensate for historical or systemic injustices. So, while distributive justice seeks to achieve fairness, it doesn't necessarily mean an identical distribution for all; it aims to rectify imbalances and ensure that no group is unfairly burdened by environmental harm.

Procedural equity

Procedural equity is a critical aspect of environmental decision-making, with a specific focus on ensuring the inclusion of all populations, especially including

historically disadvantaged and marginalized groups (Schlosberg, 2004; 2007). This equity dimension places a strong emphasis on the importance of making environmental decision processes not only fair but also participatory and inclusive. It aims to address concerns related to the equitable and unbiased involvement of various communities in shaping environmental policies, plans, and projects. Procedural equity upholds the fundamental principle that individuals have the inherent right to be informed, participate actively, and have their voices heard in decisions that directly affect their environment. Of particular significance within this equity dimension is the emphasis on the adoption of green infrastructure within city policies. Researchers like Grabowski et al. (2023) apply the concept of procedural equity to green infrastructure planning, covering every aspect of the process, from how the plan is formulated, the design of green infrastructure, the execution of green infrastructure projects, to the assessment of their real-world effects. This emphasis on procedural equity fosters collaboration between scientific experts and local representatives from civil society, showcasing how diverse voices and perspectives can come together to shape sustainable solutions for urban challenges (Grabowski et al., 2023). In the context of resilience, the definition of procedural equity remains consistent. As described by Meerow et al. (2019), procedural equity is recognized as the fair and just involvement in decision-making procedures. This entails not only active public engagement in plan development but also initiatives to enhance ongoing public participation in urban governance. Moreover, it involves targeted outreach to marginalized communities that are often excluded from traditional public involvement mechanisms. By addressing these dimensions, procedural equity ensures a comprehensive approach to

environmental justice and the meaningful inclusion of all voices in shaping environmental policies and practices.

Recognition equity

Recognition equity, as a component of environmental justice according to Schlosberg (2004; 2007), addresses the importance of acknowledging and respecting the unique identities, values, and perspectives of different communities. To be specific, this equity dimension is associated to with the other two dimensions: distributional and procedural equity. Schlosberg's (2007) perspective highlights that recognition and distribution are not isolated dimensions but are interconnected. While distributional inequities can lead to injustices in access to environmental resources, it is often the lack of recognition that allows these inequities to persist. Communities that are not recognized may struggle to advocate for their fair share of resources, legal protections, and environmental benefits. The absence of recognition can undermine their ability to challenge distributional inequities effectively and perpetuate distributional inequities. Also, Schlosberg (2004; 2007) highlight that recognition equity, by acknowledging and respecting the identities and perspectives of different communities, supports procedural equity by creating a more inclusive and participatory decision-making process. While recognition is more prominently linked to distribution equity, its role in promoting procedural equity should not be overlooked within the broader context of environmental justice.

In the context of nature-based solutions in Europe, which supplement the traditional gray infrastructure and align with the concept of green infrastructure (GI) as in the US, Kato-Huerta and Geneletti (2022) argue that Nature-Based solutions are

integrated into complex socioecological systems. Recognitional equity “is fundamental when considering who gets to define suitable solutions, which voices, values, and perceptions are deemed relevant, and under which historical and cultural context these preferences and values are shaped (Kato-Huerta and Geneletti, 2022, p.123)”. Similarly, Meerow et al. (2019) stress the importance of recognizing historical context and addressing structural racism when investigating recognitional equity, underlining its fundamental role in achieving resilience.

6.3. Identifying analysis indicators

In drawing upon the three-fold environmental justice framework (Schlosberg, 2004; 2007), various studies have proposed a set of indicators to analyze urban resilience plans (Meerow et al., 2019), stormwater management strategies (Wang and Palazzo, 2021), and green infrastructure planning (Grabowski et al., 2023; Kato-Huerta and Geneletti, 2022). These indicators aim to identify planning challenges and provide specific guidance for planners. Meerow et al. (2019) present a 'tripartite framework' along with seven indicators to analyze ten resilience plans. Except for one indicator concerning economic resilience in distributional equity, their indicators reflect the fundamental aspects of the three equity dimensions clearly defined and easily comprehensible. My analytical framework is constructed upon theirs. However, their indicators are primarily crafted for resilience plan documents and do not include indicators for flood plan analysis. Additionally, when analyzing the procedural equity dimension, Meerow et al.'s (2019) sole indicator, "inclusive participation and

engagement," is too abstract to provide analytical criteria representing this dimension. Thus, I found it necessary to eliminate some indicators and introduce new ones to analyze content related to flooding.

In the context of analyzing indicators for stormwater management and flooding within the distributive equity dimension, Wang and Pallazzo (2021) and Kato-Huerta and Geneletti (2022) provide supplementary distributional equity indicators. For instance, Wang and Pallazzo (2021) argue that factors like the distribution of urban drainage network capacity and the concept of 'water logging vulnerability,' which refers to the degree to which an area or region is susceptible to the problem of waterlogging, are critical indicators for evaluating flood risk. On the other hand, Kato-Huerta and Geneletti (2022) identify maintenance characteristics as vital for distributive EJ indicators. This maintenance focus aligns with the engineering study of Rossi et al. 2022 and O'Donnell (2005) that employ simulation models to assess pipeline aging. They explain that incorporating these factors related to the distribution of vulnerable areas and infrastructure maintenance is essential in identifying flood prone areas. Consequently, I have incorporated these distributive equity indicators into my analytical framework.

While analyzing the participatory equity dimension, Meerow et al. (2019) relied solely on a single indicator, 'inclusive participation and engagement,' which is notably abstract and challenging to operationalize. This indicator was replaced with others to provide more detailed information about the participation process. For example, a collection of research endeavors (Gong et al., 2019; Wang and Palazzo 2021; Zafra-Calvo et al., 2017), employing evaluation criteria, establishes that enhancing public

consciousness, advocating for grassroots decision-making, and ensuring transparency in the process form the fundamental elements of public participation. Kato-Huerta and Geneletti (2022) also articulate that the principles of procedural EJ include “providing relevant information related to the project to all interested individuals, giving voice to all involved parties, and allowing a leading role for all communities.” These principles are supported by previous studies (Lopes and Videira, 2013; Yenneti and Day, 2015). As a result, I have subdivided the inclusive participation indicators into transparency, inclusion, and representation in participation.

Finally, a common indicator for analyzing recognitional equity is addressing issues related to vulnerable groups in the three plan analysis studies based on the EJ framework (Kato-Huerta and Geneletti, 2022; Meerow et al., 2019; Wang and Palazzo, 2021). Kato-Huerta and Geneletti (2022) and Wang and Palazzo (2021) emphasized the importance of identifying the spatial distribution of vulnerable populations and their specific needs in the policy formulation and planning process. Meerow et al. (2019) suggested that acknowledging a history of racism or discrimination and designing strategies to reduce the vulnerability of these groups are essential for achieving recognitional equity. I have incorporated these indicators into the recognitional equity dimension (See below Table 8).

6.4. Data and Method

6.4.1. Method

In analysis of the Flood Task Force's action plans and their underlying plans, qualitative coding method was implemented. I organized the below analytical framework with deductive codes that are derived from the above literature review defining EJ framework and identifying its analysis indicators. (Table 8). The indicators are utilized as the codes. In the analytical framework, the codes within each equity dimension have their description, and it is utilized to detect related contents in the dataset. For example, the framework shows how the code of “Equity of resource allocations” is described. The plans were subjected to a double review process to ensure no information was missed and to identify common themes associated with each indicator. In other words, the review process involved two separate rounds of review to minimize bias and increase the robustness of the findings. This approach helps enhance the credibility and trustworthiness of the research findings by reducing the likelihood of overlooking important details or misinterpreting data.

During these reviews, specific sections or passages pertinent to the aforementioned indicators were identified. When applying the indicator of 'acknowledgment of vulnerability,' particular attention was paid to identifying texts that explicitly acknowledged the presence of vulnerable populations in the plans. This included identifying sections that discussed who vulnerable individuals are, where they are located within the city, and what their specific needs are in coping with flooding or other weather extremes. Any sections that directly addressed these aspects

were considered as meeting the indicator's criteria. Once the sections corresponding to this indicator were identified, I copied and pasted them for subsequent analysis. This process was repeated twice to ensure thoroughness. Subsequently, the duplicated sections were inductively merged to generate a unified set of results that encompassed the content from the previously identified sections.

Table 8 Analytical framework for qualitative coding

EJ Dimension	Code (Analysis Indicator)	Description
Distributional Equity	Equity of resource allocations	Content explaining the unequal distribution of resources within the city or recommendations for allocating them more equitably
	Urban flood risk distribution	Content regarding spatial distribution of 1) the capacity of the urban drainage network or 2) the vulnerability to inundation.
	Maintenance of stormwater infrastructure	Content showing the differences in stormwater infrastructure maintenance across communities
Procedural Equity	Transparency	Content ensuring information available; it encompasses actively and comprehensively sharing information, decision rationale, and outcomes with the public and affected communities
	Inclusion	Content referring to the deliberate efforts made to ensure that all relevant communities and stakeholders, especially those historically disadvantaged and marginalized, have a meaningful and equal opportunity to participate in the decision-making process.
	Representation	Content describing the importance of having individuals who can effectively advocate for their interests and needs within the decision- making process.
Recognitional Equity	Acknowledgment of vulnerability	Content acknowledging the identities and locations of vulnerable individuals within the city and understanding their specific needs when dealing with challenges such as flooding and extreme weather events.
	Recognition of historical context	Content regarding past injustice or their consequences
	Recognition of discrimination resulting from structural racism	Content identifying the presence of systemic racism

6.4.2. Data

In September 2021, the Office of the City Administrator in DC established the Flood Task Force (FTF) with the goal of identifying policies and projects to enhance flood preparedness and resilience. The Task Force consisted of 13 District agencies and 15 dedicated federal and public partners who collaborated for 16 months to formulate the Action Plans, which detailed specific strategies and actions designed to enhance the District's resilience to flooding. These Action Plans were the result of 32 meetings and two public listening sessions, during which potential actions were discussed. The FTF recommended a total of 27 actions, which encompass such as

updating “flood maps to account for climate change and interior flooding, reinforcing and upgrading homes for increased flood resilience, install flood infrastructure, streamlining internal agency processes for flood-related permitting and complaint resolution, and introducing various measures to enhance the availability and affordability of flood insurance (DC Flood Task Force, 2023, p.2).”

These Action Plans and the 32 meetings serve as a vital primary data source for my analysis.

In addition to the FTF Action Plans, my analysis includes a set of references that played a significant role in informing and influencing the content of the FTF Action Plans. These references encompass various documents, reports, and studies related to flood risk management, climate readiness, and urban resilience, such as Resilient DC and Watts Branch Flood Risk Mitigation Report. These references offered valuable

insights into the information, knowledge, and guidance that contributed to the development of the FTF's action plans (DC Flood Task Force, 2023). Some of these references have been directly cited in the action plans, underlining their integral role in shaping the FTF's strategies and actions. To illustrate, the final report of the action plans describe that they are developed as an option to support the sustainability and resiliency plans of DC (DC Flood Task Force, 2023). The task force's meeting also indicates that the task force shares the concept of resilience and sustainability in the plans. To be specific, the action plans are developed based on the flood risk information and strategies from Climate Ready DC, Flood Risk Management Planning Resources, Report on Flooding and Stormwater, and Watts Branch Flood Risk Management Study.

My analysis includes an examination of two stormwater management plan associated with green infrastructure and other green infrastructure plans and programs. One of the action plans focuses on developing a comprehensive list of flood infrastructure, incorporating DOEE's green infrastructure strategies. The plan emphasizes the subsequent prioritization of projects based on various criteria, including geography, cost, timeline, and equity considerations, particularly for stormwater infrastructure with widespread implications across the entire city (DC Flood Task Force, 2023).

This highlights the critical need to assess the distribution of stormwater infrastructure in the action plan. Consequently, the analysis scrutinizes the stormwater management plans, specifically the DC Water's Combined Sewer System Long Term Control Plan (LTCP) and the DOEE's DC Consolidated Total Maximum Daily Load (TMDL) plan, both identifying potential green infrastructure locations. These plans identify

key sewer sheds that are under the capacity of gray stormwater infrastructure or need green infrastructures through simulation models, specifying areas where green infrastructure concentration was deemed necessary (DC Water, 2002; DOEE, 2022). Additionally, the analysis encompasses an examination of other green infrastructure plans in DC that play a role in shaping the overall distribution of green infrastructure. The relationship among these plans for analysis is illustrated in the figure below.

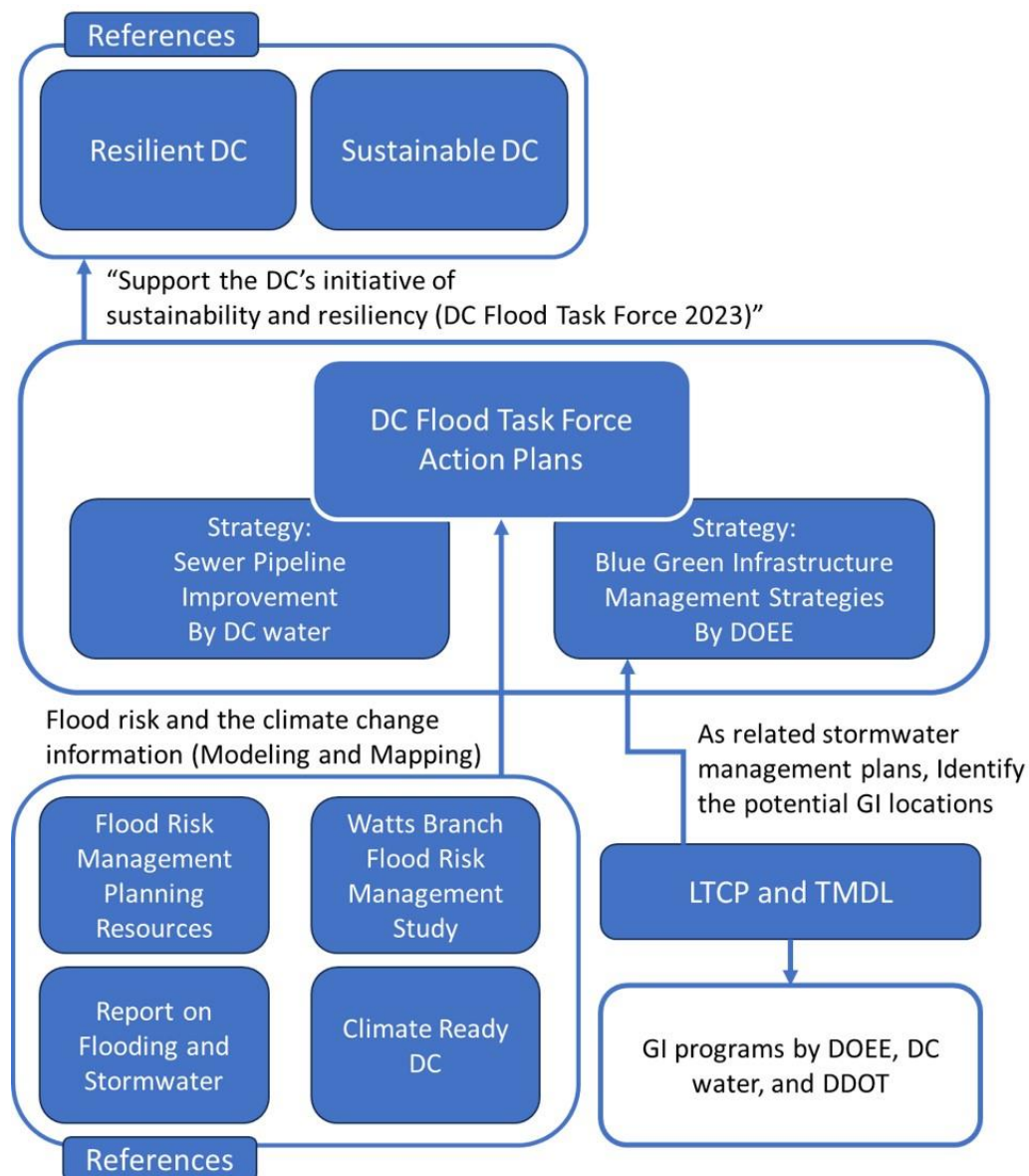


Figure 22 The relationship between the flood action plans and the underlying and related plans.

Table 9 Data for plan analysis

Action plans of the DC Flood Task Force, including their underlying and related plans		Agency	Goal	Source
DC Flood Task Force	DC Flood Task Force Action plans and the 32 meeting records	1.Office of the Deputy Mayor for Operations and Infrastructure (DMOI), 2.District of Columbia Water and Sewer Authority (DC Water), 3. District Department of Energy & Environment (DOEE), 4.Homeland Security and Emergency Management Agency (HSEMA), 5.District Department of Transportation (DDOT), 6.Office of Planning (DCOP), 7.District of Columbia Department of Insurance (DISB), 8.Office of Risk Management (DCORM), 9.Department of General Services (DGS), 10. Department of Parks and Recreation (DPR), 11.Department of Housing and Community Development (DHCD), 12.District Department of Public Works (DPW), and 13.Department of Consumer and Regulatory Affairs (DCRA)	Equitable protecting for residents and economy, and bolstering flood readiness	DC flood task force official website

	Flood Risk Management Planning Resources for Washington, DC	National Capital Planning Commission	Provide a summary of key flood risks in the National Capital Region and recent flood mapping	DC flood task force official website
FTF References	Watts Branch Flood Risk Management Study	DC silver Jackets Interagency Study	Identify and implement solutions to reduce flood risk around the District and to assist local communities in Ward 7	-
	Report on Flooding and Stormwater in Washington, DC	National Capital Planning Commission	Provided the requested information and potential action steps for reducing the flood risks around the national mall	-
	Blue Green Infrastructure-Cloudburst Management Strategies for the District of Columbia	Department of Energy & Environment	Detail the concepts of the green infrastructure as a crucial measure to cope with DC's flooding vulnerability	-
	Resilient DC	DC	Inclusive Growth, Climate Action, Smarter DC, Safety and Health of DC	-
	Sustainable DC	DC	Protect, restore, and expand aquatic ecosystems	-

	Climate Ready DC	DC	Organizing strategies to make DC more resilient to the future climate change	-
Stormwater Management Plan	Combined Sewer System Long Term Control Plan	DC Water	Mitigating the adverse impacts of stormwater runoff on water quality and the environment	DC water official website
	DC stormwater plan: Consolidated Total Maximum Daily Load (TMDL) Implementation Plan	DOEE	Mitigating the adverse impacts of stormwater runoff on water quality and the environment	DOEE official website
GI plans	River Smart Homes	Department of Energy & Environment	Reducing Stormwater Pollution from properties	DOEE official website -
	Stormwater management requirement	Department of Energy & Environment District of Columbia Municipal Regulations	Reducing Stormwater Pollution from properties and Storm runoff control	-
	Green Area Ratio	Department of Energy & Environment	Reducing Storm runoff and heat island effect and Improving air quality	-
	Clean Rivers - Green Infrastructure Projects	DC Water	Reducing Combined Sewer Overflows through integration of green and grey infrastructure	DC Water official website

Green Alley
Partnership

DC Water and District
Department of
Transportation

Reducing
Stormwater
Pollution from
streets, Storm
runoff control,
and landscaping

DDOT
official
website

6.5. Analysis results

6.5.1. Flood task force action plans

The 27 action plans, each falling into nine distinct categories, shared aim of addressing various aspects of flood risk management and mitigation in Washington, DC. These categories encompass 1) flood insurance, 2) flood damage repair, 3) floodproofing, 4) sewer line backups, 5) flood infrastructure, 6) regulations and permitting, 7) mapping and modeling, 8) planning and coordination, and 9) emergency response, collectively forming a comprehensive strategy to enhance flood resilience and community safety. These action plans pursue diverse objectives, such as increasing awareness of flood insurance programs, offering financial aid to low-income residents affected by water damage, improving regulations and coordination, enhancing floodplain management, and installing warning systems and sensors. Each action plan comprises four key components: an overview and implementation strategy that defines its goals, the background information explaining development of the action plan, a brief description of its support for vulnerable communities, and a summary of public feedback received during the review process. This approach ensures a multifaceted strategy to better prepare and safeguard the community, eliminating redundancy.

The analysis of the 27 Flood Task Force action plans, categorized into nine areas of focus, reveals a concerted effort to address flood risk management and mitigation in Washington, DC. These plans collectively aim to enhance flood resilience and community safety through a multi-faceted strategy. Key findings from the analysis, aligned with the established EJ framework, underscore the action plans' emphasis on

distributional and recognitional equity, highlighting the prioritization of vulnerable communities in the flood resilience efforts.

Distributional Equity:

The action plans demonstrate a strong focus on equitable resource allocations, particularly in reducing the financial burdens of flood insurance for low-income residents, notably in Wards 7 and 8, and in prioritizing infrastructure investments in communities most susceptible to flooding. Programs such as the Water Damage Remediation Grant and Insurance Programs are designed to provide immediate relief to affected residents, with a clear emphasis on low-income households. Similarly, floodproofing initiatives and the expansion of the Backwater Valve Installation Program underscore efforts to allocate resources where they are most needed, reflecting a distributional equity approach.

Recognitional Equity:

Recognitional equity is addressed through the acknowledgment of the vulnerabilities of specific populations and the incorporation of historical context and structural discrimination considerations into the action plans. The plans recognize the identities, locations, and specific needs of vulnerable individuals, integrating this understanding into flood mitigation strategies. For instance, updates to floodplain regulations and the enhancement of floodplain review processes are crafted with a keen awareness of the historical disinvestment in certain wards, aiming to mitigate added flood risks and recovery costs for these areas.

Procedural Equity:

While the action plans exhibit efforts towards transparency and inclusion, the limited frequency of public listening sessions suggests room for improvement in ensuring comprehensive community engagement in the decision-making process. The documentation of public feedback and the engagement strategy outlined in the action plans reflect an attempt to adhere to procedural equity, although the depth of public involvement remains an area for further scrutiny.

To encapsulate these findings concisely and align them with the analytical framework, a summary table can be introduced (Table 10). This table will map the action plan components to the EJ dimensions and indicators from the analytical framework, providing a clear and direct correspondence between methodology and findings.

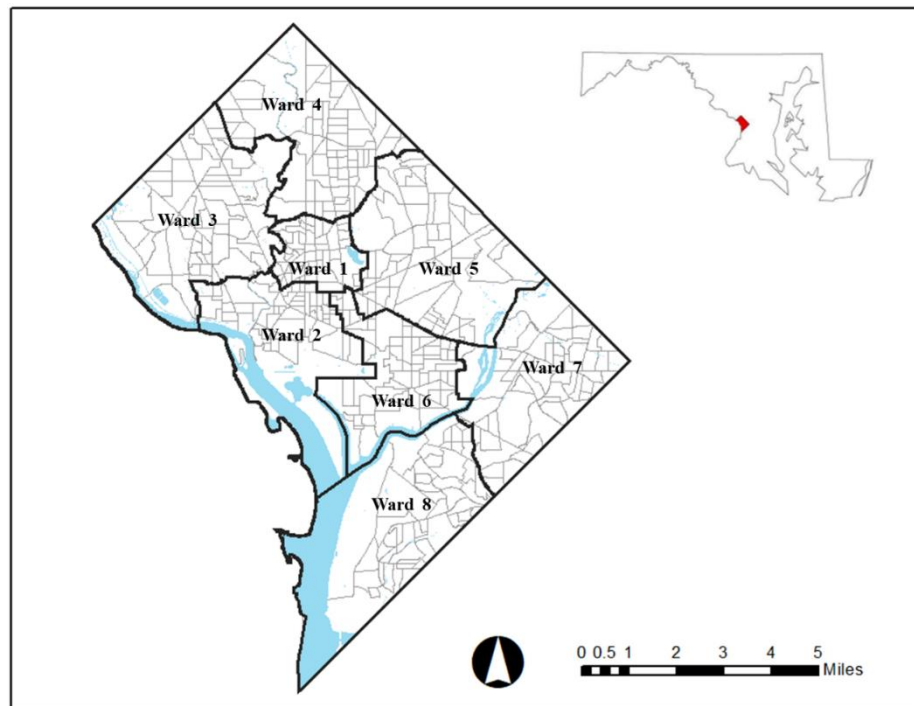


Figure 23 Wards in D.C.

Table 10 Summary of Findings Aligned with EJ Framework Indicators

EJ Dimension	Indicator	Action Categories	Findings
Distributional Equity	Equity of resource allocations	1) Flood Insurance, 3) Floodproofing, 6) Regulations, Legislation, Compliance, Permitting,	Plans aim to reduce flood insurance costs for low-income residents (e.g., Wards 7 and 8) and prioritize floodproofing and infrastructure investments in high-risk communities, addressing economic disparities.
	Urban flood risk distribution	4) Sewer Line Backups, 5) Flood Infrastructure,	Investments are focused on the most vulnerable communities within high-risk floodplains, and maintenance programs are aimed at areas with high deprivation indices.
	Maintenance of stormwater infrastructure	4) Sewer Line Backups	The "Expand Backwater Valve Installation Program" targets homes in disadvantaged areas, reflecting a commitment to equitable maintenance of infrastructure.
Procedural Equity	Transparency	General (across categories)	Efforts to share information, albeit with room for improved community engagement.
	Inclusion	General (across categories)	Some plans incorporate public feedback, but the limited number of public listening sessions suggests a need for more inclusive engagement.
	Representation	General (across categories)	Direct community representation in decision-making is less evident.
Recognitional Equity	Acknowledgment of vulnerability	7) Mapping and Modeling, 4) Sewer Line Backups, 5) Flood Infrastructure	Using social vulnerability indices to focus on highly vulnerable areas in flood insurance updates.
	Recognition of historical context	6) Regulations, Legislation, Compliance, Permitting	Floodplain regulations are updated with an awareness of historical disinvestment in certain wards, aiming to mitigate flood risks and recovery costs in these areas.
	Recognition of discrimination	General (across categories)	There is no direct reference to discrimination

In the context of the action plans described, equity is discussed in terms of how the actions prioritize and benefit vulnerable communities. This reflects a focus on the fair distribution of resources and support to those who are most affected by flood risks. Also, one aspect of equity emphasized in the document is the prioritization of vulnerable communities. Several action plans specifically target low-income residents and communities historically disinvested. For instance, in the first “flood insurance” category, the "Flood and Sewer Line Backup Insurance" action seeks to reduce the flood insurance’s high cost, primarily affecting low-income residents and those living in the floodplain, notably in Wards 7 and 8. The document highlights that "those wards contain 98% of all the single-family homes in DC’s 100-year floodplain (DC Flood Task Force, 2023 p.40)" This represents a distributional equity approach, focusing on reducing the financial burden of flood insurance primarily for those who can least afford it, as well as a recognitional approach acknowledging the identities and locations of vulnerable people and understanding their special needs.

The two equity categories are further emphasized in this category. The document discusses the "Water Damage Remediation Grant Program," which provides immediate relief and services to low-income DC residents affected by flooding. This program enables affected residents to address and reduce flood losses quickly, stay in their homes, maintain structural integrity, and address safety concerns. Also, the "Water Damage Remediation Insurance Program" aims to provide quick financial assistance to low-income residents with flood losses throughout the district, and the "Home Insurance Water Damage Mitigation Credits" was designed to help residents

in vulnerable communities reduce their insurance premiums and mitigate costly property damage claims. While these actions have broad benefits, it is noted that it may be especially useful for low-income communities, emphasizing the distributional equity aspect. The document explains that this action could assist low-income households by providing additional financial assistance toward purchase or installation, further promoting equity.

In the third “floodproofing” category, the "Flood Proofing Individual Homes and Facilities" highlights equity as a consideration in prioritizing funding. It notes that the program's initial funding would prioritize homes with the highest risk of flooding and those in historically disinvested communities, which often overlap. This approach embodies both distributive equity and a recognition perspective by ensuring that resources are allocated where they are most needed and where disinvestment has occurred. Likewise, the fourth category of “sewer line backups” further emphasizes the two equity dimensions of EJ. The "Expand Backwater Valve Installation Program" outlines “this would prioritize homes occupied by residents with limited income and in areas of the district with high Area Deprivation Index as defined by the Health Resources and Service Administration.” It also addresses the financial constraints that some residents may face by providing an option where plumbers directly bill DC Water, eliminating upfront costs for the homeowner. This approach aligns with distributional equity by targeting assistance toward individuals with limited means and with recognitional equity by identifying the extent of deprivation or disadvantage in DC.

The fifth and sixth category follow the same focus on the equity dimensions. The fifth “flood infrastructure” category action plan explains that many of the DC’s lowest-income areas are in the 100- or 500-year floodplains, making those with the least ability to withstand economic shocks the most vulnerable to flooding. The document states that this action will prioritize using DC's infrastructure dollars on communities vulnerable to flooding, thus addressing distributional equity. In the sixth "Regulations, Legislation, Compliance, and Permitting" category, the document addresses the update of floodplain regulations. It emphasizes that these regulations are crafted to protect residents living in floodplains while minimizing the financial impacts on the residents themselves. The document points out that Wards 6, 7, and 8 contain 94% of the structures in the 500-year floodplain, making it especially important to avoid adding flood risks and recovery costs to these historically disinvested areas.

Another action plan in the sixth category aims to improve floodplain review processes. By enhancing the efficiency of permitting within the Special Flood Hazard Area (SFHA), the document notes that this action would increase flood safety and reduce flood mitigation costs in the district's most vulnerable communities. The SFHA, known as the 100-year floodplain, includes many residential and commercial buildings in vulnerable communities. This action plan focuses on both distributional and recognition equity aspect by addressing the needs of these communities. Additionally, the document highlights the importance of collaboration between federal and district authorities in floodplain management. By coordinating

infrastructure projects and development, this action aims to help all district residents, especially those exposed to higher flood risk due to federal property.

The seventh category of “mapping and modeling” primarily focuses on recognition of equity, directly referencing social vulnerability index (SoVI) from the Centers for Disease Control and Prevention (CDC). In the update of flood insurance map, the document points out that “Each of the Census tracts bordering the Watts Branch floodplain in Ward 7 and the Oxon Run floodplain in Ward 8 is ranked as having a high or moderate-to-high level of vulnerability to disasters by the CDC SoVI. The median SoVI Score of Census tracts in Wards 7 and 8 intersecting 100-year floodplains is 0.829, while the district as a whole has a median SVI of 0.5029. Scores closer to 1.0 indicate higher vulnerability (DC Flood Task Force, 2023).” The action plans in this category prioritize equity by focusing on areas with high social vulnerability, thereby reducing the impact of flooding on vulnerable communities.

In the eighth category, 'Flood Mitigation Planning and Coordination,' several actions are introduced. These actions include updating the DC Silver Jackets Memorandum of Understanding (MOU), which addresses flood hazards and related issues, and improving the processes of the DC Drainage Committee, which is responsible for managing and enhancing drainage systems to ensure their effective operation in preventing flooding and associated issues. The action plans in this category are aimed at improving the working processes of the FTF, but the action plans specify that “By bringing in the perspective, resources, and knowledge of multiple agencies we can be more likely to respond to the varied needs of our community (DC Flood Task Force, 2023).” They emphasize the importance of involving multiple agencies to better

address the diverse needs of our community. This approach reflects the focus on recognitional equity.

In the final category, "Flood Emergency Planning, Response, and Recovery", the document discusses the implementation of a severe weather early warning system, which reflects both distributional and recognitional equity dimensions. This system allows residents to prepare for severe weather and flood events, reducing the financial and livelihood impacts of damage. The document emphasizes that this would profoundly impact low-income residents and residents in the floodplain in Ward 7 and 8 (DC Flood Task Force, 2023). Furthermore, updating emergency flood response procedures is discussed as an action plan that focuses on best practices to identify areas of improvement in flood response and relief protocols, particularly as they relate to vulnerable communities. This approach aims to strengthen the efficiency and effectiveness of flood response, demonstrating the commitment to equitable outcomes. The other action plan also introduces actions related to installing flashing warning signs and flood sensors. These measures provide critical flood warning systems to District residents, including those in socially and flood-vulnerable communities. The document underscores the importance of reaching historically overburdened populations and emphasizes the distributional equity aspect.

The 27 action plans primarily focus on distributional and recognitional equity by identifying and prioritizing vulnerable communities and their specific needs, reducing the expected disproportionate impacts of flood events, and ensuring that the benefits and protections provided by these plans are distributed fairly among different communities. The focus on equity is evident throughout the categories, from flood

insurance and damage repair to floodproofing, sewer line backups, and flood infrastructure. It carries through to regulations, mapping, coordination, and emergency response. The comprehensive strategy detailed in these action plans aims to bolster resilience and community safety.

On the other hand, the final report outlines the action plan development process as follows:

The Task Force began with initial ideas from agencies about what problems needed to be solved to reduce flood risk. Those ideas were discussed during Action Team meetings, and ultimately narrowed into a smaller list. Early in the process, the Task Force held Public Listening Session meetings in March 2022, to capture public input and feedback to address concerns and needs of residents and businesses. Throughout the process of developing Action Plans, public outreach and engagement continued to ensure the Task Force was on track to create plans that provided useful solutions. Action Teams incorporated ideas further refined by lead agencies and then presented them to the Task Force for open discussion. These plans went through an end stage review by District agencies, 30-day open public comment period, and agency edits were released for approval by the full Task Force (DC Flood Task Force, 2023, p.6).

This description, along with the action plans, highlights collaboration among lead agencies of action plans, the 15 consulting public partners, and other agencies in discussing, refining, and presenting initial ideas. However, the limited occurrence of public listening sessions (only twice), which in the development process suggests a constrained role for the general public in shaping these action plans.

The FTF has uploaded all the action plans whenever they developed them and the 33 records of the meeting in which DC government agencies and 15 consulting public partners discussed the action plans. This indicates that DC agencies have attempted to share information, decision rationale, and outcomes with stakeholders

and the public, partially aligning with the principles of procedural equity.

Nevertheless, the DC FTF does not provide any information about the public listening sessions both in the opened meeting records and action plans. Without details about the inclusion and representation factors in the decision-making process, it becomes challenging to analyze how the perspectives, concerns, and needs of the public were taken into account during the development of action plans. Only a few action plans, such as "Action 3.1 Flood Smart Homes," "Action 4.1 Expand Backwater Valve Installation Program," and "Action 4.3 Require Backwater Valve Installation in Codes," directly show that residents' opinions served as the 'input' for their plan development. However, they do not provide information about how these opinions are reflected or how there is interaction with the residents.

6.5.2. Action plans' references

The references for the action plans fall into two distinct categories: the first comprises reports offering technical insights into the mapping and modeling of flooding, while the second encompasses Washington, D.C.'s sustainability and resiliency initiatives that the action plans strive to bolster. The technical reports' group, which consists of the Flood Risk Management Resources for Washington, D.C., Report on Flooding and Stormwater in Washington, D.C., Watts Branch Flood Risk Management Study, and Climate Ready DC, focuses explicitly on revealing the distribution of urban flood risks from an engineering and technical standpoint. These reports delve into aspects such as the identification of flood-prone areas, utilizing tools such as projections, maps, and reports based on the numerous flood modeling. They primarily focus on showing the distribution of urban flood risks from the engineering and technical perspective.

However, Climate Ready DC takes a significant step in recognizing and addressing vulnerable populations through the creation of the 'Vulnerable Populations' map (DOEE n.d.). This map illustrates that vulnerability to flooding and heat events is unevenly distributed across the district, with Wards 7 and 8 identified “most vulnerable given high levels of unemployment, poverty, obesity, and asthma, as well as a large elderly population (DOEE n.d., p.7).” The plan also notes that “heat waves, storms and other disruptive events do not impact all neighborhoods equally, exacerbating existing inequalities and vulnerabilities (DOEE n.d. p.7)” and suggest

strategies to be taken for the vulnerable, such as “Improve emergency preparedness and planning for climate-related events with a particular focus on those most vulnerable (DOEE n.d., p.10).” Additionally, the Watts Branch Flood Risk Management Study represents distributive and recognitional equity dimensions by describing the distribution of inundation and acknowledging vulnerable communities. The study cites both the CDC Social Vulnerability Index (SoVI) and the Climate Ready DC plan, highlighting that communities along the Watts Branch floodplain in Ward 7 are rated as highly vulnerable, given both the comprehensive index and individual indicators. The study further emphasizes the unique character of these communities as a vital center of the DC African-American community and one of the areas susceptible to flash flooding.

On the other hand, the action plans specify that their efforts in developing the plan align with Washington, D.C.'s sustainability and resilience initiatives. The concepts of sustainability and resilience are equity-inclusive. As in Campbell's (1996) triangular model of sustainable development, which highlights divergent planning priorities such as growth, equity, and the natural environment, sustainability inherently incorporates and addresses issues related to equity. The social-ecological resilience emphasizes adaptive and transformative capacity, which indicates that the resilience concept pursues a transformation of the unsatisfied and undesirable status quo and share a pathway in which social equity is enhanced (Bene et al 2018). In DC's Sustainable DC and Resilient DC plans, these concepts embody the equity discussion.

Analyzing the equity theme in the Sustainable DC plan reveals a comprehensive and explicit commitment to addressing racial disparities and promoting equity. The plan acknowledges that communities of color in DC have been facing deep and persistent gaps in income, health, employment, and education. It emphasizes that while the city's prosperity has been growing, the benefits are not equally shared, with significant disparities in median household income between Black and white residents. The Sustainable DC plan explicitly states that racial equity is a critical component of a sustainable city. It emphasizes the importance of equity in housing, employment opportunities, and earning potential. The plan proposes specific actions, such as creating an Equity Impact Committee, developing an Equity Impact Assessment Tool, providing equity-focused training for government employees, and focusing community engagement on historically under-represented communities. To be specific, the commitment to equity is evident in the plan's short-term goals, such as the creation of an Equity Impact Assessment Tool. This tool aims to ensure that planning processes do not disproportionately impact any community, holding users accountable for equitable outcomes. The focus on racial equity is prioritized, recognizing it as a foundational aspect that must be addressed for broader social equity. In the other themes of the plan, such as climate, health, nature, transportation, and water, it emphasizes paying attention to the vulnerable population and areas in which vulnerable populations such children and the elderly are highly concentrated. The plan aligns with the indicators of distributional and recognitional equity, as it recognizes and addresses persistent geographic disparities, including differences in access to well-maintained green spaces, high-quality schools, and walkable

commercial areas. In distributional equity dimension, it emphasizes that less affluent areas often experience higher crime rates, mortality rates, lower income, and fewer amenities.

Moreover, The Sustainable DC plan partly aligns with the indicator of procedural equity as evidenced by its commitment to inclusive and participatory processes. For instance, in the words of the plan's creator, there was a conscious effort to ensure that "sustainability became inclusive of all residents," with initiatives such as the refocusing of events, partnership with community organizations, and adjustments in communication strategies to address the concerns of residents in all eight wards. According to the plan's development lead, these efforts have proven effective, noting that "the development of Sustainable 2.0 included far more racially and culturally diverse voices than ever before (p.3)." Moreover, during the planning of Sustainable DC 2.0, there was a deliberate shift in engagement strategies, focusing on populations historically excluded from sustainability planning. The plan acknowledges this shift, stating, "we have piloted new community advisory board structures such as the Equity Advisory Group in Far Northeast Ward 7 and a 100% Renewable and Equitable Cities project (p.14)." While not explicitly framed as procedural equity, the plan's commitment to transparency is evident in the mayor's statements like "I made sure my team was transparent in how we developed the plan and incorporated feedback from the public."

The equity theme in the Resilient DC plan reveals a robust commitment to addressing disparities and promoting equity, encompassing both distributional and recognitional equity dimensions. The plan emphasizes the fundamental role of equity in resilience,

recognizing that acute shocks often expose long-standing inequalities caused by chronic stresses. It also highlights the need for inclusive policies to correct historical wrongs rooted in institutional and systemic biases, recognizing that decades of structural and institutional racial bias have created persistent racial inequalities across communities in DC. This indicates that the plan covers procedural equity, as well as other two equity dimensions of EJ framework.

The Resilient DC strategy especially acknowledges that government, historically part of the problem, must now be part of the solution. Recent progress under Mayor Muriel Bowser's leadership includes historic investments in education and childcare, aiming to create pathways to the middle class for all residents. The plan identifies structural and institutional racial bias as a persistent issue and outlines explicit efforts to eliminate racial disparities. This includes community dialogues, training government employees to recognize and address bias, developing indicators to measure racial disparities, and formalizing an Equity Officers Community of Practice.

Moving forward, the plan outlines a vision to build a more inclusive and responsive government, establishing a robust feedback loop between engagement and decision-making. Initiatives include centralizing the oversight of strategic and policy plans, creating a consolidated application for benefits and programs, aligning employee performance plans with agency performance plans, and professionalizing engagement across the DC government.

6.5.3. Stormwater management plans-LTCP and TMDL implementation plan

DC Water's CSS LTCP (Combined Sewer System Long Term Control Plan) has purpose of controlling combined sewer overflows in DC, and the plan is called LTCP (DC Water, 2002; 2015). The LTCP simulation plays a crucial role in recognizing areas of need for stormwater management and water quality improvement within the Anacostia River, Potomac River, and Rock Creek. This assessment is based on the analysis of infrastructure capacity parameters and water quality parameters, including bacteria levels, dissolved oxygen, and nutrient concentrations. It assists in prioritizing and planning measures to enhance water quality and adhere to regulatory standards in these regions. In summary, the plan can identify key sewer sheds that are under capacity in terms of gray stormwater infrastructure, as indicated by their simulation models, and that may be susceptible to Combined Sewer Overflow (CSO), in which Green Infrastructure (GI) would ideally be concentrated.

In addition to the comprehensive simulation modeling, DC Water also made efforts to involve the public in the development of the LTCP. The goals were “to foster public awareness and facilitate public participation in the decision-making process to develop and select the final LTCP” (DC Water, 2002). The process encompassed several components, including public meetings, the creation of a stakeholder advisory panel, and a public information initiative (DC Water, 2002). The agency held four public meetings to educate the communities and gather their opinions on CSO-related concerns. Responding to the public's request during the initial meeting, the Stakeholder advisory panel was formed. This panel included 1) representatives from both local and federal government agencies, 2) regulatory bodies, 3) citizen groups,

and 4) environmental advocacy organizations, all of whom shared concerns regarding water quality issues in DC. Over the course of the participation process, twelve panel meetings were convened.

Furthermore, DC Water (2002) showed that the outreach effort included educational materials distributed in water and sewer bills, the creation of a dedicated CSO website, the compilation of a CSO mailing list, informative CSO newsletters, and the establishment of public information repositories. Following the release of the draft LTCP, nine community meetings were held to explain the program and collect public feedback. The DC Council and DC Water hosted public hearings on the draft, and utilized informational mailers, DC Water's website, and presentations to interested groups in order to solicit public input. The draft LTCP received extensive publicity, resulting in substantial feedback from the public. Notably, more than 2,300 comments were received on the draft (DC Water, 2002). The extensive feedback received from the public, the Stakeholder Advisory Panel, and various community engagement efforts resulted in a more refined and comprehensive LTCP. The final draft incorporated changes and strategies to better align with the needs and expectations of the communities affected by CSOs (DC Water, 2002). Public participation not only contributed to the plan's effectiveness but also ensured that it addressed environmental justice concerns and was more equitable in its approach.

The table below (Table 11) summarizes DC Water's detailed efforts for public participation. The CSS LTCP's public participation endeavor demonstrates an attempt to achieve procedural equity by engaging with a wide range of stakeholders and communities. While the LTCP has shown procedural equity through various public

engagement activities, there seems to be room for improvement in terms of recognitional equity, particularly in identifying vulnerable populations and ensuring their participation and representation. Incorporating recognitional equity efforts, such as tailored outreach, can enable the LTCP to more effectively address the concerns and needs of vulnerable communities and promote a more just and equitable decision-making process.

Table 11 LTCP's plan development that align with procedural equity indicators.

Analysis indicator for procedural equity		Strategies and Actions
Inclusion	Public Meetings	The plan included multiple public meetings that were advertised in local newspapers, on the radio, and through internet websites. This suggests an effort to reach a broad audience, including potentially affected communities.
Representation	Mail Notifications	A list of over 500 citizens and representatives of various groups was developed, and they were sent special notices of upcoming public meetings. This approach demonstrates an effort to engage with a diverse group of stakeholders.
Inclusion	Stakeholder Advisory Panel	The formation of a stakeholder advisory panel, which included representatives from government agencies, citizens' groups, and environmental advocacy groups, allowed for more frequent input and consultation. This panel approach supports a more inclusive decision-making process.
Transparency	Field Trips	Field trips were organized to provide stakeholders with a direct look at DC Water facilities and to learn from other cities' experiences. This promoted transparency and information sharing.

Representation	Diverse Representation	The stakeholder advisory panel consisted of representatives from various government agencies, citizen groups, and environmental advocacy groups, reflecting a diverse set of interests and backgrounds. This reflects an effort to recognize and include different perspectives.
Transparency	Information Dissemination	The distribution of educational mailers, newsletters, handouts, and public information depositories in various public libraries aimed to provide accessible information to a wide range of stakeholders.
Transparency	Presentations to Different Groups	Presentations were made to a variety of citizens', government, and environmental groups, which indicates an attempt to recognize and engage with different communities.
Transparency	Website and Online Information	Creating a dedicated website section for CSO issues and posting public meeting notices online suggests an effort to engage a tech-savvy audience while providing information access to those with internet access.

In the realm of Municipal Separate Storm Sewer Systems (MS4) sheds, the DOEE implements the Consolidated Total Maximum Daily Load (TMDL) Implementation Plan, also known as the DC Stormwater plan. The fundamental purpose of this plan is to exert effective control over stormwater runoff, prevent pollution, and safeguard water quality within the designated MS4 sheds. An integral component of the Consolidated TMDL Implementation Plan is its comprehensive approach, focusing on the identification, cataloging, and quantification of existing Green Infrastructure (GI) within the District. Recognized as Best Management Practices (BMPs)¹, these Green

¹ The EPA's application of the term BMPs in this context clearly encompasses GI practices, highlighting a comprehensive approach to stormwater management that utilizes the advantages of

Infrastructure elements are deemed crucial for achieving the stipulated load reduction targets outlined in the plan. The plan establishes a detailed database of existing Green Infrastructures, encompassing crucial information such as GI type, spatial locations, ownership, treated area, managed volume, and other pertinent data. A noteworthy facet of the Consolidated TMDL Implementation Plan is its commitment to identifying specific areas and the depth of stormwater volume retention needed within the District where BMPs, particularly GI, are concentrated (Figure 24). In essence, the plan not only serves as a strategic framework for stormwater management but also underscores the critical role of Green Infrastructure in achieving sustainable load reduction objectives, with a focused approach to specific geographic areas in DC.

The plan is primarily technical, consisting largely of data analysis and model development. However, the plan has a two page of public outreach section that engages not only key stakeholders but also the general public. The section outlines efforts to inform stakeholders and the public. It emphasizes informing stakeholders and the public about available data, maps, and methods for developing and implementing the plan. This suggests a commitment to transparency by providing information to the public. However, it lacks explicit information on maintenance disparities of existing stormwater infrastructure or the inclusion of vulnerable communities.

natural processes alongside traditional methods. Despite the distinct terminology, there appears to be no practical difference in their implementation within DC's policy framework. The BMP types identified by the DOEE in DC align with the GI types outlined in Table 1 above. Furthermore, the official dataset of GIs categorizes them under the column title 'BMP type,' with the DOEE referring to this dataset as BMP data.

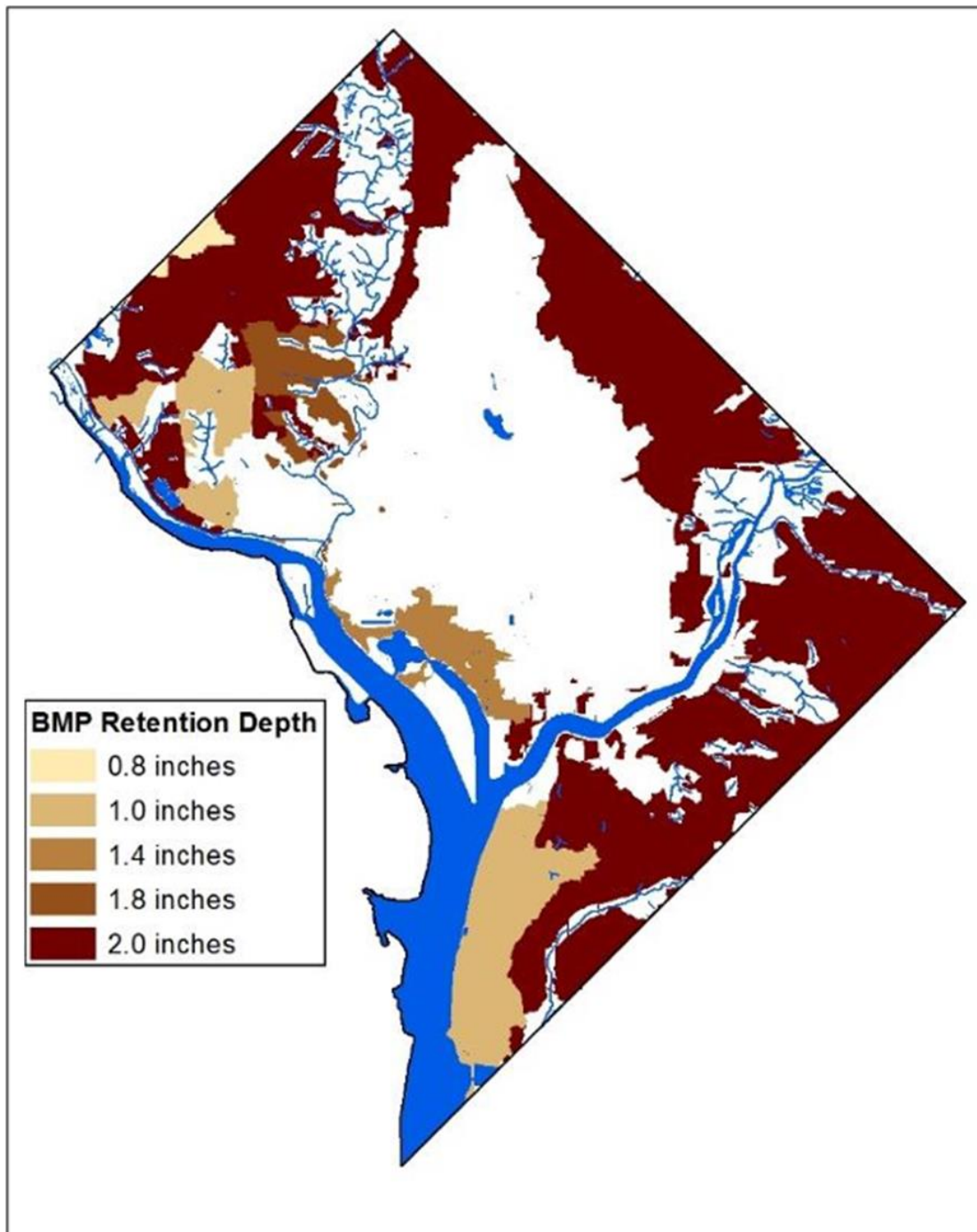


Figure 24 Spatial depiction of the required GI retention depth over the MS4 to meet all annual MS4 waste load allocations.

Source: DOEE 2016 Consolidated Total Maximum Daily Load (TMDL) Implementation Plan p 63.

6.5.4. Green infrastructure plans and programs

The governance of DC's stormwater infrastructure is divided between two lead agencies: the DC Water, responsible for Combined Sewer System (CSS) sheds, and the DOEE, responsible for MS4 sheds. The LTCP, alternatively known as the DC Clean Rivers Project (DCCR) implemented by DC Water, encompasses various projects aimed at controlling Combined Sewer Overflows (CSOs). Among these projects, green infrastructure (GI) plays a crucial role. GI initiatives, which involve nature-based solutions like permeable surfaces and vegetation, are integrated into the overall LTCP strategy. Additionally, the LTCP may include other measures like pumping station rehabilitations and a system of underground storage/conveyance tunnels. Together, these components work synergistically within the LTCP framework to address and mitigate CSOs, contributing to the overall water quality management efforts in DC.

As of 2023, DC Water's GI plan includes 9 projects: 1) Rock Creek Green Infrastructure Project B, 2) Downspout Disconnection Program, 3) Green Alley Partnership with DDOT, 4) Potomac River Green Infrastructure Project A, 5) Rock Creek Green Infrastructure Project A, 6) Green Infrastructure Design Challenge, 7) Irving Street Green Infrastructure Project, 8) A Drop's Life - The Sequel, 9) Clean Rivers Green Infrastructure Projects at DC Water Facilities. Among the 9 programs, A Drop's Life is a promotional video for the plan, and the Downspout Disconnection Program is a voluntary GI implementation program by property owners. Other projects are underway in the CSS sheds of the city center and being implemented by

DC Water. However, none of the associated GI programs' documents from DC Water address equity-related content.

The DOEE also considers GI installation as a significant strategy for controlling stormwater runoff. The agency's GI programs consist of three categories: the River Smart Homes program, the DOEE lead projects, and Regulations. The Regulations encompass stormwater management requirements for new construction and redevelopment projects exceeding 5,000 square feet. The Green Area Ratio is a zoning regulation setting criteria for landscape and site design. Its aim is to diminish stormwater runoff, enhance air quality, and contribute to a cooler urban environment. Additionally, as the agency lead GI projects, DOEE is implementing the Palisades Recreation Center Stormwater Retrofit Project in Northwest DC.

On the official website of River Smart Homes, the DOEE specifies that this program prioritizes equity by focusing on outreach and engagement in Wards 7 and 8, which are often considered underserved. By concentrating efforts in these areas, the program aims to address environmental concerns in communities that may face higher levels of pollution and limited access to green infrastructure. The DOEE is thus addressing environmental disparities and working towards creating a more equitable distribution of resources to mitigate stormwater runoff.

To be specific, the program additionally operates the Ambassador program. The River Smart Ambassadors are volunteers who undergo training and receive incentives and benefits, including \$250 stipend every 6 months for implementing GI and the annual maintenance service for their practices. These incentives are designed to

encourage community engagement. The Ambassadors not only promote the program but also play an educational role. They inform residents about the issues of stormwater runoff and provide information on how individuals can contribute to stormwater control of the city. The provision of resources, information, and support from River Smart staff further ensures that residents in underserved areas have the knowledge and assistance needed to participate in the program.

However, the River Smart Home is fundamentally a voluntary participation program for property owners. It is not mandatory or required; individual property owners can decide whether or not they want to be involved in the program. Except for the free shade tree planting, all other types of practice such as the rain barrel and garden are not free. Property owners need to pay a copayment of \$50 to install the rain barrel and \$ 100 per 50 sq ft rain garden. Considering that 26.6% and 34.2% of residents in Wards 7 and 8 live below the poverty line and struggle with food security (Vilakazi and Collins 2023), it could be questionable whether the cost of GI practices is affordable for the residents.

In summary, while both DC Water and DOEE identify potential areas for GI implementation in DC, the actual execution of GI projects are driven by a combination of regulations, voluntary participation by property owners, and agency-lead GI initiatives. The implementation seems somewhat opportunistic, with certain GI initiatives being carried out through regulatory measures and the voluntary engagement of property owners. As described in Chapter 4 above, this opportunistic GI implementation has resulted in an uneven distribution of projects across

communities, prompting questions about the equity issues of GI distribution despite the concerted efforts by DOEE.

6.6. Discussions

6.6.1. Advancing equity in the flood action plans

My analysis finds that the DC Flood Task Force (FTF) has focus on the distributional and recognitional equity in development of their 27 flood action plans of 9 categories. Specific measures, such as reducing the high cost of flood insurance, providing financial assistance for water damage remediation to socially vulnerable residents in Wards 7 and 8, and offering mitigation credits for insurance premiums, demonstrate a focus on alleviating the financial burden on those who are least able to afford it. Also, actions such as improving floodplain review processes and installing warning systems are designed to address the areas where vulnerable people are living, reflecting a recognitional equity approach. However, the results reveal crucial aspects that have to be considered and supplemented to get the specified goal of bolstering “flood readiness while equitably protecting the District’s residents and economy from the damage that floods can cause (DC Flood Task Force, 2023).”

In the array of the 27 action plans devised by the DC Flood Task Force, a notable subset comprises eight action plans intricately connected with flood insurance. This focus on insurance is consequential, as it designates flood insurance as the sole foundation of the entire flood damage recovery strategy for the Task Force. While recognizing the pivotal role of financial safeguards in mitigating flood-related losses,

the exclusive reliance on insurance mechanisms raises concerns regarding the recognitional equity. Specifically, socially vulnerable communities characterized by lower socioeconomic status may encounter challenges in procuring comprehensive insurance coverage.

The comprehensive nature of the flood insurance related action plans manifests in their multifaceted approach to flood insurance, ranging from reducing premiums through participation in FEMA's Community Rating System (CRS) program to providing remediation assistance and promoting preventive measures for homeowners and renters by offering premium discounts or enhanced coverage options. These measures involve providing incentives in the form of premium discounts or enhanced coverage options. Undeniably, the measures to reduce flood insurance premiums outlined in these action plans represent a beneficial step towards addressing the vulnerabilities of residents in Wards 7 and 8, who face a heightened risk of flooding, as explicitly outlined in the plans.

However, a critical facet remains unexplored – the affordability of the total cost of flood insurance, even with the proposed discounts, for vulnerable populations. This crucial consideration was conspicuously absent in the final action plans, even though it is evidenced by insights gleaned from the Residential Resilience Action Team Meeting held on April 12, 2022, subsequently released on YouTube. During this meeting, Dr. Carolyn Kousky, the Associate Vice President for Economics and Policy at the Environmental Defense Fund, introduced the concept of inclusive insurance. This innovative approach aims to provide suitable and affordable coverage to underserved populations. Dr. Kousky highlighted the potential scales at which

insurance can be procured, including micro insurance (tailored policies with lower premiums) and meso insurance (coverage secured by entities such as NGOs or city governments on behalf of residents), aiming to suggest more affordable insurance programs. Regrettably, the flood insurance-related action plans unveiled in June 2023 fall short of incorporating these considerations. Notably absent from these plans are provisions for inclusive insurance models that would have addressed the economic capacity of vulnerable groups. The lead agencies responsible for these action plans ought to have meticulously assessed the financial standing of these vulnerable groups, determining the extent to which flood insurance premiums would impose economic burdens. This oversight raises questions about the recognitional equity of the proposed flood damage recovery strategy. This issue is especially significant because flood insurance is the only one flood recovery measure for the DC Flood Task Force.

On the other hand, although maintaining and monitoring pipelines could be crucial in identifying flood-prone areas (Rossi et al., 2022), the finalized action plans and the meetings for this do not address this issue. In the Flood Infrastructure category (Category 5), the task force listed two sewer pipeline improvement projects: 1) Sewer Rehabilitation Projects and 2) Northeast Boundary Tunnel Project. DC Water has been performing the Sewer Rehabilitation Projects throughout DC and the Northeast Boundary Tunnel Project to address the mismatch between 100 years of urbanization and the 100-year-old combined sewer system in Northeast DC.

However, the data concerning sanitary sewer overflows (SSOs) in DC unequivocally underscores the imperative for targeted pipeline improvements, particularly in the socially vulnerable communities of Wards 7 and 8. The DC Water's open data reveals

that since 2013, a s total of 250 SSO incidents have been recorded, with Wards 7 and 8 accounting for a substantial 45.6 percent (114 events, see below chart). The U.S. Environmental Protection Agency (EPA n.d.) identifies aging pipelines, coupled with inadequate cleaning, repair, and operational practices, as prime factors contributing to pipeline failures and the resultant sanitary sewer overflows. This connection underscores the vital necessity of regular and strategic maintenance practices. Moreover, the EPA (n.d.) notes that SSOs may coincide with periods of intense rainfall or elevated water flow, potentially exacerbating flooding in susceptible areas. The intricate relationship between pipeline maintenance, SSOs, and flooding becomes apparent in this context. Aging infrastructure and insufficient maintenance not only contribute to SSO incidents but also create conditions that may amplify the impact of these overflows during adverse weather events. The potential for SSOs to occur concurrently with intense rainfall, as highlighted by the EPA, establishes a direct link between compromised pipeline integrity and increased risk of flooding. Understanding and addressing pipeline maintenance in Wards 7 and 8 is not merely an infrastructure concern but a crucial element in comprehensive flood risk management for these socially sensitive communities. The task force should have prioritized and addressed the potential challenges associated with pipeline maintenance in Wards 7 and 8, recognizing its pivotal role in mitigating SSOs and their cascading impacts on flooding in the region, but the listed pipeline improvement projects are not for the areas of vulnerable people.

From chapters 3 and 4, this study reveals that socially vulnerable communities in Wards 7 and 8 have less capacity for sewer pipelines and green infrastructure. They have experienced persistent social vulnerability and discriminatory increases in green infrastructure. Moreover, the SSO data reveal a potential gap in maintenance between socially vulnerable communities and those that are not vulnerable. Given these findings and the Hurricane Katrina case, in which vulnerable Black communities were excluded from flood response and recovery, finally exposing them to a larger flood risk (Bullard 2009), neglecting pipeline improvements in Wards 7 and 8 may exacerbate overall vulnerability disparities between communities. Considering distributional equity in environmental justice (EJ), this issue needs to be reconsidered by the task force.

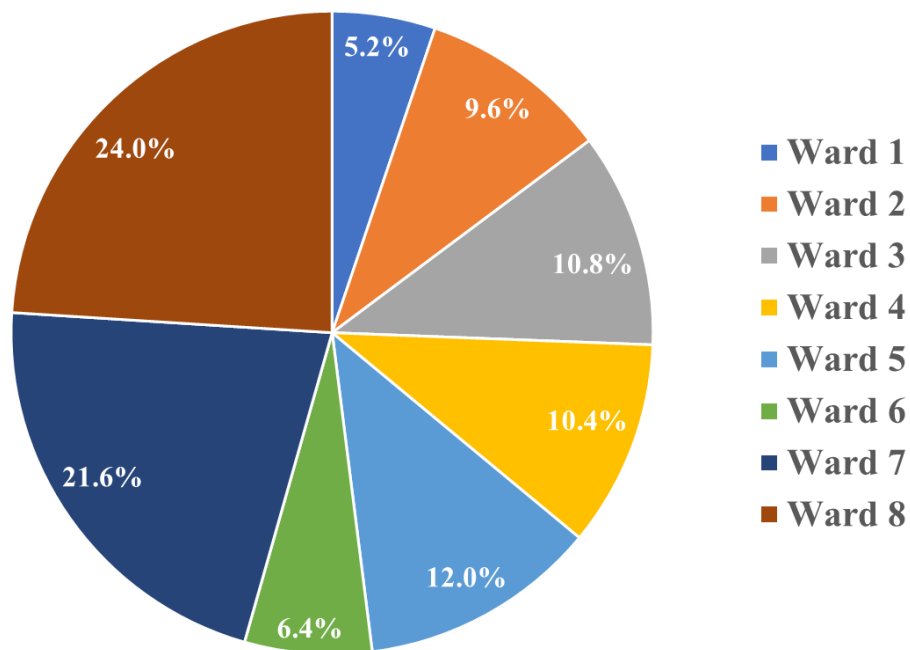


Figure 25 Sanitary Sewer Overflows in D.C., from 2013 to 2021

In addition to the complementary points of flood action plans, it is noteworthy that the Task Force exhibited a comparatively lesser emphasis on procedural and recognitional equity dimensions when compared to the prominent focus on distributional equity within the EJ framework. While the overarching sustainability and resilience plans underscore the importance of procedural equity, and the final report of action plans highlights their role as a supportive mechanism for these broader initiatives, questions arise concerning the effective achievement of procedural equity in the development processes of the specific flood action plans. The action team's approach, as reflected in their documented activities, reveals a limited incorporation of procedural equity considerations. Notably, the team conducted only two instances of public listening sessions throughout the planning and development phases. This aspect of the engagement strategy raises concerns about the inclusivity and representativeness of the decision-making process for crafting these crucial action plans. The scarcity of engagement opportunities may pose significant challenges in ensuring a comprehensive and diverse representation of the community's perspectives, potentially limiting the effectiveness of the flood action plans in addressing the unique needs and concerns of all resident groups. While the sustainability and resilience plans lay the groundwork for procedural equity, the translation of these principles into the specific development processes of the flood action plans warrants closer scrutiny. Enhancing the participatory nature of the planning procedures, such as increasing the frequency of public engagement sessions and incorporating mechanisms for soliciting input from underrepresented groups, could strengthen procedural equity dimension. This, in turn, would contribute to a

more robust and inclusive foundation for the implementation of the flood action plans, aligning them more closely with the overarching goals of equity in the final report.

Furthermore, while most action plans express support for vulnerable communities in Wards 7 and 8, a critical observation emerges when considering the absence of explicit attention to structural factors such as historical racism within the action plan development. As in studies of Bolin and Stanford (1998), understanding how structural factors have historically influenced the allocation of resources and protective measures in both flood response and recovery is paramount. Previous case studies by Bullard (2008) and Bullard and Wright (2009) have underscored the persistent impact of structural and historical racism on the improved but discriminatory levee protection and the supply of toxic FEMA trailers for Blacks after Hurricane Katrina. Incorporating a thorough examination of these factors into the action plan development process would enhance the achievement of recognitional equity by addressing underlying systemic issues. By acknowledging and actively mitigating the historical inequities embedded in the allocation processes, the Task Force can lay a more resilient foundation for the flood action plans, fostering a comprehensive and equitable approach to community well-being in the face of environmental challenges.

6.6.2. Challenges for integrating equity considerations into stormwater infrastructure management

Integrating equity considerations into stormwater infrastructure management poses significant challenges. The Flood Infrastructure Action Plan of the DC flood task force, categorized as the fifth, outlines a total of 32 infrastructure projects aimed at prioritizing budget allocations for vulnerable communities. Within this list, five projects fall under gray infrastructure, focusing on pipeline and pumping station enhancements, while 10 projects are dedicated to green infrastructure. However, the reliance on intricate calculations and simulations in managing stormwater infrastructure poses a major obstacle. The heavy dependence on quantitative estimation implies that the city's overall stormwater infrastructure, including location and maintenance priorities, does not adequately incorporate direct reflections of equity considerations even if the agencies get public opinions in the plan development process. Despite public participation through the LTCP, the predominant influence of modeling outcomes on the location, as indicated by the LTCP and mirrored in the TMDL implementation plan of the DOEE, further highlights the challenges in achieving equitable outcomes.

In light of the significant reliance on simulation models and complex calculations to determine the optimal locations for Green Infrastructure (GI) aimed at processing stormwater runoff, it is imperative to embed equity considerations into the final decision-making process for prioritizing stormwater management projects. While technical analyses provide essential insights into the physical and environmental feasibility of GI projects, integrating social aspects into decision-making ensures that

the benefits of such infrastructure equitably reach all segments of the community, particularly the most vulnerable. To this end, decision-makers should not solely rely on quantitative outputs from models but also incorporate qualitative assessments that evaluate the social impacts of proposed projects. This entails conducting thorough equity impact assessments for each project, taking into consideration factors such as the distribution of benefits and burdens across different communities, accessibility of the infrastructure, and potential displacement effects. The process should actively involve community stakeholders in identifying priorities and making choices that directly affect their lives and environments. Moreover, strategies for incorporating equity into decision-making processes may include weighted scoring systems that favor projects in under-resourced areas or the development of criteria that specifically assess the project's contribution to reducing social vulnerabilities. By systematically factoring in these considerations, the final prioritization of stormwater management and GI projects can more effectively address historical inequities and foster resilience in communities disproportionately affected by environmental issues. Adopting a decision-making framework that values both technical efficiency and social equity will not only enhance the effectiveness of stormwater management efforts but also promote a more inclusive and just approach to urban infrastructure development. This balanced approach recognizes that achieving sustainable urban water management requires solutions that are both technically sound and socially equitable, ensuring that all community members benefit from investments in GI.

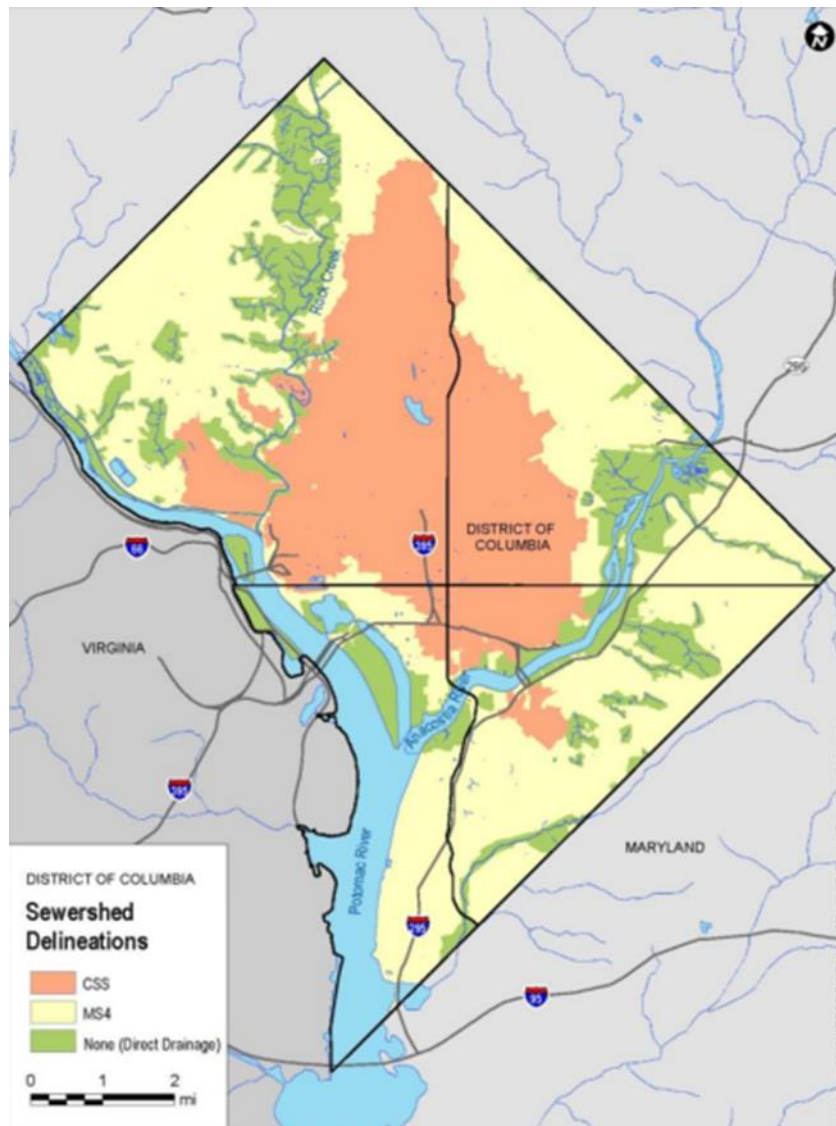


Figure 26 Combined Sewer System (CSS) area and Municipal Separate Storm Sewer System (MS4) area in D.C.

Source: DOEE 2016 Consolidated Total Maximum Daily Load (TMDL) p.1

Moreover, the governance system for stormwater infrastructure in Washington D.C. is marked by spatial and institutional divisions, which complicates the equitable management of stormwater infrastructure. While DC Water is tasked with managing the Combined Sewer System (CSS) in the city center, the Department of Energy & Environment (DOEE) oversees the Municipal Separate Storm Sewer System (MS4)

in the surrounding residential areas. Despite the distinct initiatives by DC Water for pipeline functionality improvement and DOEE's efforts to control storm runoff through Green Infrastructures (GIs) in their respective jurisdictions, a significant legal challenge emerges from the absence of explicitly designated responsibility for flood prevention across the entire city. This gap presents a barrier to devising a city-wide, integrated GI strategy that is essential for effective and equitable stormwater management.

The Clean Water Act mandates municipalities to manage stormwater runoff and reduce pollution, yet the specific allocation of duties concerning flood prevention remains ambiguous within the context of Washington D.C.'s divided governance model. This ambiguity complicates efforts to coordinate and implement comprehensive stormwater solutions that can effectively mitigate flood risks and distribute the benefits of GI equitably among all communities. To overcome these challenges and harness the full potential of GI for city-wide flood prevention, it is imperative to address these legal issues by clarifying responsibilities and fostering a more collaborative governance framework that bridges institutional divides and enables a cohesive approach to stormwater management.

As of October 25, 2023, DC Water and DOEE have implemented a total of 309 GI projects, strategically focusing on identifying optimal locations. In contrast, GI projects implemented through regulations and voluntary participation of property owners amount to 6,544. Remarkably, this reveals that the number of GI implementations not under the control of DOEE and DC Water exceeds those under their control by more than 20 times. Even if the other 3,853 GI projects from various

government agencies like DDOT and DGS are implemented to support the efforts of DOEE and DC Water, the private sector's GI implementation surpasses that of the public sector. These figures correspond to the empirical findings discussed in Chapter 4, indicating a widespread implementation of green infrastructure in the private sector and its contribution to inequitable increases across communities.

6.7. Conclusion

The stormwater infrastructure in Washington, D.C., aimed at preventing floods, including sewer pipelines and green infrastructure, exhibits an unequal distribution. Green infrastructure intended to complement the existing gray infrastructure shows an exacerbation of this unequal distribution over the past decade. Disparities in social vulnerability between communities persist, and the stormwater infrastructure, a significant factor in determining physical vulnerability, also reflects disparities among communities based on social vulnerability.

My analysis of the DC Flood Task Force clearly emphasizes equity in their action plans. However, they tend to focus on distributional and limited recognition equity, even though DC's resilience plan, supported by these action plans, explicitly acknowledges the necessity for inclusive policies and the rectification of historical wrongs stemming from institutional and systemic biases. In the discussion of environmental justice encompassing climate change and environmental pollution, Schlosberg (2004; 2007) describes that to properly recognize the diverse demands of socially disadvantaged groups who are politically underrepresented in the decision-making process, appropriate consideration of procedural and recognition equity is necessary. The DC Flood Task Force's action plans lack consideration for procedural equity. Moreover, the task force shifts flood recovery efforts to vulnerable individuals in Wards 7 and 8. Out of 27 action plans, 8 plans are related to flood insurance, constituting the entirety of measures for flood recovery of the task force. Considering that 26.6% and 34.2% of residents in Wards 7 and 8 live below the poverty line

(Vilakazi and Collins, 2023), these measures do not seem affordable to them, even with discounted insurance premiums.

The proposed improvements in green infrastructure and some sewer pipelines for flood prevention in the action plans are difficult to integrate operationally due to institutional constraints, making it challenging to concentrate them on the areas of vulnerable individuals. Instead, the disparities in flood prevention infrastructure could perpetuate or enlarge. The entire vulnerability is a relative concept, and the gap between socially vulnerable and non-vulnerable individuals seems to be growing. In the worst-case scenario of climate change, if historic Black communities in Ward 7 suffer flood damage, individuals without insurance will become even more socially vulnerable, as seen in the case of Hurricane Katrina.

Chapter 7: Conclusion

The first sub essay reveals a complex interplay between historical development, urban growth, infrastructure planning, and social vulnerability. The negative correlation between sewer pipeline capacity and population density, coupled with disparities in pipeline distribution between White and Black communities, highlights the need for a reevaluation of infrastructure planning in the face of urbanization. The mismatch between the existing underground sewer infrastructure and the substantial changes in population density and impervious surfaces suggests a disconnect between planning and infrastructure since the 1960s. The negative correlation observed in densely populated communities indicates a failure to anticipate and accommodate the increased demands on sewer pipelines, emphasizing the importance of considering future urbanization trends in infrastructure planning. The role of GI in supplementing traditional stormwater infrastructure presents another dimension. The analysis suggests an inconsistency in the distribution of GI facilities, with both green and gray infrastructure being less prevalent in densely populated and impervious areas. This raises questions about the effectiveness of GI initiatives in aligning with their intended purpose and calls for further research to understand the relationship between the distribution of gray and green stormwater infrastructure.

Finally, the significant negative relationship between the social vulnerability index and stormwater infrastructure highlights the inequities in infrastructure distribution. Vulnerable communities, particularly in Southeast DC, face challenges in dealing with extreme weather events due to limited access to resources and lower gray stormwater infrastructure capacity. The study aligns with past literature emphasizing

the role of social inequity in perpetuating disparities in disaster preparedness and resilience.

In the second sub essay, the observed correlation between higher social vulnerability and GI annual increase during the 2010s suggests persistent and worsening disparities. This has resulted in an uneven clustering of GIs across communities, with significant implications for vulnerable groups during extreme weather conditions. The lack of sufficient GI in socially vulnerable areas hinders their ability to adapt to changing climatic conditions and cope with the adverse effects of extreme weather events. This disparity in protection may lead to increased health disparities, reduced quality of life, and heightened social and economic vulnerabilities for these communities. To be specific, given the case of Hurricane Katrina in New Orleans, GI, as new type of flood protective measure, may exacerbate the gap of place vulnerabilities of communities and perpetuate long-standing patterns of marginalization through a flooding event. Moreover, the examination of the clustering mechanism of GI and its policy implications emphasizes the need for a more equitable distribution of GI. The spatial autoregressive panel model highlights spatial dependence in GI growth, indicating that neighboring communities influence each other. The study suggests that current GI programs, whether implemented by the public or private sector, may inadvertently exclude socially vulnerable people, leading to clustering in wealthier and politically powerful communities. To address this, planners and engineers need to be conscious of the current distribution of GIs and promote community engagement and participation in decision-making processes surrounding GI programs. Therefore, this research revealing spatial and temporal

change of GI and persistent social vulnerability shows the deepening gap of place vulnerability of DC communities.

On the other hand, the examination of the DC Flood Task Force's flood action plans and stormwater infrastructure management in Washington D.C. reveals both commendable efforts and significant challenges in advancing equity within the context of environmental justice. Firstly, the DC Flood Task Force demonstrates a commitment to equity in the development of flood action plans, particularly through measures aimed at reducing the financial burden on socially vulnerable residents. However, the exclusive reliance on flood insurance as the foundation of the entire flood damage recovery strategy raises concerns about recognitional equity, particularly in ensuring comprehensive coverage for lower socioeconomic communities. The oversight in incorporating inclusive insurance models, as suggested by experts, points to a potential gap in addressing economic capacity among vulnerable groups, raising questions about the recognitional equity of the proposed flood recovery strategy. Additionally, the lack of attention to pipeline improvements in socially vulnerable communities, despite evidence of their importance in mitigating sanitary sewer overflows and flooding, represents a notable gap in the flood action plans. Neglecting these improvements may exacerbate overall vulnerability disparities between communities. The focus on distributional equity needs to be reconsidered, with a greater emphasis on procedural and recognitional equity dimensions. In stormwater infrastructure management, challenges arise in integrating equity considerations, with a heavy dependence on quantitative estimation and modeling outcomes that may not adequately reflect the needs of vulnerable

communities. The governance system's spatial and institutional divisions contribute to the complexity, with DC Water and DOEE focusing on different aspects and facing challenges in achieving equitable distribution of green infrastructure.

In summary, the exploration of the relationships between social vulnerability, infrastructure, and flood planning has illuminated the intricate ways in which infrastructure distribution intersects with social inequities to exacerbate vulnerability. This dissertation substantiates the theoretical proposition that the unequal distribution of infrastructure—both green and gray—serves as a critical mechanism through which environmental injustice is perpetuated and vulnerability is deepened. Through its empirical analysis, this study reveals: 1) how social vulnerability influences the distribution of stormwater infrastructure—including sewer pipelines and green infrastructure—and thereby leads to the occurrence of gaps in place vulnerability across different communities; 2) how the transformation of stormwater infrastructure is affected by social vulnerability and market-based implementation mechanisms over time, further deepening the gap in place vulnerability across communities; and 3) the process by which the planning process can be flawed, marked by an inadequate recognition of socially vulnerable groups. Therefore, as demonstrated in the previously presented theoretical framework in section 2.5, a series of case studies in Washington D.C. reveals a cycle in which the persistent gap in social vulnerability leads to an unequal distribution of infrastructure, which in turn exacerbates the existing disparity in vulnerability, making already socially vulnerable communities even more vulnerable.

This dissertation may contribute to the current discussion on vulnerability and green infrastructure policy as follows.

- Contemporary research on vulnerability

In recent years, the spotlight in environmental sciences and urban planning has shifted towards unraveling the complexities of 'dynamic vulnerability.' This paradigm acknowledges vulnerability not as a static condition but as a dynamic and evolving phenomenon shaped by a myriad of interconnected factors. Scholars have intricately explored the temporal dimensions of vulnerability, meticulously studying its transformations over time in response to urbanization, climate change, and socioeconomic shifts. While recognizing the significance of dynamic vulnerability, a parallel imperative arises to scrutinize the perpetuating attributes of vulnerability within communities. Through a series of case studies in Washington D.C., this dissertation shows how vulnerability gap across communities grow. The analysis of relationship between the spatial and temporal distribution of stormwater infrastructure, social vulnerability, and flood planning unveils a persistent cycle of vulnerability. Neglecting social vulnerability and perpetuating the inequitable distribution of stormwater infrastructure through planning or policies, as illuminated in the analysis, holds the potential to amplify place vulnerability.

- Equity as a central tenet for urban resilience

The findings on perpetuating vulnerability accentuates the importance of a holistic approach to resilience—one that goes beyond addressing immediate concerns to encompass the underlying issues that perpetuate vulnerability over

time. In the pursuit of resilient and sustainable cities, the equity dimension emerges as a central tenet. Recent advancements in research emphasize that genuine resilience cannot be achieved without addressing the root causes of social disparities (Morrow et al., 2019). Planners are urged to prioritize the equity issue inherent in the perpetuation of social and place vulnerability, particularly in the realm of resilience and infrastructure planning.

- Toward equitable Gray and Green Infrastructure planning

To effectively address the deepening vulnerability gap and promote resilience in stormwater infrastructure, a paradigm shift in policies and practices is imperative. First and foremost, the findings suggest a critical reassessment of market-based approaches to stormwater infrastructure. The dominance of the private sector in GI implementation, as highlighted by the dataset, underscores the escalating social inequity associated with market-driven planning.

Therefore, a fundamental policy implication is to move away from market-centric models and adopt strategies that prioritize equitable distribution over profit-driven implementation.

Breaking down perceived disciplinary barriers is another crucial aspect of policy reform. Planners, engineers, and decision-makers must unite in a concerted effort to prioritize vulnerable communities. The disparities in stormwater infrastructure planning necessitate a holistic and integrated approach that transcends traditional disciplinary boundaries. This collaborative effort is essential to address structural obstacles, foster community engagement, and ensure the equitable distribution of stormwater

infrastructure. By dismantling disciplinary silos, a more comprehensive strategy can be formulated to bridge the deepening vulnerability gap and create a resilient urban landscape that prioritizes the needs of the most vulnerable.

The challenge of aging infrastructure in the United States offers critical insights for nations like South Korea, which faces similar issues. Over a century old, U.S. infrastructure now significantly impedes daily life and economic growth due to its deterioration. In tackling this, both federal and local U.S. governments have explored varied strategies, including securing funding and engaging private capital. However, this study highlights the considerable drawbacks of relying on private capital for infrastructure renewal.

South Korea's infrastructure, aimed at connecting regions and transitioning from an agrarian society to an industrialized and modern one, is going to confront the inevitable aging challenges as observed in the U.S. These challenges are amplified by demographic declines and an economic slowdown, increasing the burden of maintaining aging infrastructure. While South Korea is now extensively debating the use of private capital for infrastructure development, the Washington D.C. case warns of the potential to exacerbate inequalities between urban and suburban areas and among different communities.

In South Korea, the growing divisions along racial, ethnic, and socio-economic lines between urban and rural areas signal emerging forms of inequality. The recruitment of workers from developing countries to support labor in rural industries has

introduced new cultural and social dynamics, highlighting a growing socio-economic divide within the Korean population. It has been a generation since workers from third-world countries were recruited to bolster the labor force in primary and secondary industries within rural areas. These international workers and their second-generation Korean descendants are integrating into various aspects of Korean life, including military service. Their significant contribution to the economy of provincial cities is undeniable, but their engagement in low-income jobs in Korean rural areas led to economic gap between urban and rural areas. Also, the integration of these diverse groups led to new racial or religious tensions.

This context of social transformation emphasizes the risks tied to relying on private capital for maintaining aging infrastructure or introducing new models like GI. Such approaches may deepen access disparities to essential services, as shown by the case of Washington, D.C., where infrastructure inequality has intensified regional and racial divides.

Infrastructure plays a foundational role in ensuring public safety, enhancing quality of life, and supporting economic progress. The importance of equitable access to infrastructure for all is underscored by the development of modern sewer systems and the enactment of key legislation like the Housing Act in the U.S., responding to urgent societal needs. These efforts have led to a more desirable residential environment than in the 19th century. Yet, with climate change introducing new and more severe natural disasters, it's imperative to question whether advancements in infrastructure, such as GI and IT-enhanced urban systems, are making life safer for all communities or excluding some. The escalating environmental challenges demand a

reevaluation of the base line of our life qualities and development approaches for infrastructure. The decisions made today in deferral or country scale will significantly impact the livability and inclusivity of their cities for future generations, given the long lifespan of infrastructure. It's crucial to prioritize initiatives that not only rejuvenate the physical environment but also strengthen social cohesion, ensuring that progress encompasses all community members equitably.

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