EXAMINING THE IMPACT OF NATURE-BASED SOLUTIONS ON FLOOD VULNERABILITY AND LOSS IN SMALL URBANIZING REGIONS: A CASE STUDY OF THE PHILADELPHIA METROPOLITAN AREA

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ABSTRACT

Nature-based solutions (NbS) are becoming increasingly popular in cities around the world; however, such efforts have not been widely incorporated into analyses of urban flood vulnerability nor the total population and property loss of flooding to date, except for a few studies that examined the effectiveness of green infrastructure or only wetlands in flood regulation. The proposed research sought to understand if the existing pattern and composition of NbS can mitigate flood vulnerability and loss of flooding in one of the fastest urbanizing regions in the United States, the Philadelphia Metropolitan Area. This research made key contributions to our understanding of how urban areas can grow without exacerbating flooding and inequity.

First, a systematic mapping was conducted to reveal the most common spatial metrics of NbS that mitigate urban flooding in countries around the world. These findings identified important research areas for urban geographers, policymakers, planners, and civil engineers. This review indicated that the effectiveness of NbS varies spatially based on land use/land cover, climatic, and other contextual factors. The results indicated that the location, distribution, and arrangement of NbS may have different impacts on runoff mitigation and flood loss. Also, flood hydrology was the most common topic addressed, and the spatial configuration of NbS, especially connectivity was consistently identified as an important factor in flood regulation.

Second, the potential of NbS as a flood loss mitigation tool in one of the fastest-growing and flood-prone counties of Pennsylvania, Montgomery County, using the Generalized Linear Model (GLR) and Geographically Weighted Regression (GWR) techniques was examined. The findings partially contradicted previous research by revealing an unexpected relationship between NbS quantity in floodplains and expected annual loss. Findings also demonstrated that lower-sized and disconnected patches of NbS in floodplains in some dense urban areas effectively reduce total losses from flood events. Third, the spatial coincidence between the density of NbS and flood vulnerability within eight neighboring urbanizing regions situated in Montgomery County was analyzed by using the Local Indicator of Spatial Association (LISA). The results of LISA identified regions of concern characterized by elevated flood vulnerability scores and reduced concentrations of two tree canopy types as well as shrubs and grasses. Taken together, these results emphasize the significance of strategically integrating and improving NbS, especially in areas grappling with distinct flood-related issues. It also emphasized the potential for significant enhancements in flood resilience and mitigation policies thoughtful urban planning and the adoption of NbS.

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CHAPTER 1
INTRODUCTION

Flooding constitutes a significant hazard, impacting millions of people on a global scale. Over the past decade, direct flood-related damages in the US have incurred a staggering $99 billion in costs and resulted in more than 1,000 fatalities, with a discernible upward trajectory in flood-related losses over time (NWS, 2022). Given that numerous cities are situated in river floodplains or coastal regions, urban areas are often susceptible to flooding. In fact, roughly one-eighth of urban land within the United States falls within high-risk flood zones, impacting nearly a quarter of a million individuals residing in these areas (Qiang, Lam, Cai, & Zou, 2017; Wing et al., 2018). However, it's important to note that the drainage systems and flood mitigation infrastructure in many cities have not been designed to accommodate the expected urban flooding hazards induced by climate change (Mohtar et al., 2020). This lack of adaptation potential raises the possibility of technological risks for these urban areas (Chang et al., 2021).

This research sought to understand if the existing pattern and composition of nature-based solutions (NbS) can mitigate flood regulation in one urbanizing region in the United States. This research aims to answer the question "*how can urbanizing areas can grow without exacerbating the risk of flooding and inequity?*". NbS such as trees, urban parks, wetlands, green roofs and etc. are becoming increasingly popular in cities around the world, however, such efforts have not been widely incorporated into analyses of urban flood vulnerability or loss to date, except for a few studies that examined the effectiveness of green infrastructure or only wetlands in flood mitigation (e.g., Fahy & Chang, 2019; Cheng et al., 2021; Kim et al., 2021). Most research regarding the impacts of NbS on flood regulation has been done from hydrological perspective, and less is documented from geographical lens. Due to the close spatial linkages among regional towns and their surrounding areas and river basins, the existence and proportion of vegetated areas and their spatio-temporal dynamics can be different from other high-density areas. The type and extent of NbS impact on urban hydrology and flood regulation in these areas may be subtle and unpredictable. Nonetheless, the implications for the larger watershed are important to understand from both hydrological and regional geography perspectives. This study contributed to current hazards geography and its related streams: climate change adaptation (CCA), spatial planning, and disaster risk reduction (DRR), social and biophyscial vulnerability research by examining the spatial dynamics of vulnerability/loss and NbS pattern in small growing regions.

This research developed a novel analytical framework that integrates landscape ecology, climate vulnerability (social and biophysical vulnerability), and environmental justice perspectives to analyze the potential of NbS for flood regulation in the context of urbanizing regions in the Philadelphia Metropolitan Area. The spatially explicit and empirical framework developed in this study provided a normative tool for cities undertaking spatial planning for climate resilience and sustainable development. The results of this study highlighted the impact of NbS composition and configuration on flood regulation, who and where benefits from NbS in small urbanizing regions, and how can we maximize the efficacy of NbS for flood regulation. Using a combined systematic mapping, GIS, spatial statistical modeling approaches, this study investigated the following questions.

- What is the state of knowledge on how the spatial factors of NbS impact flood regulation?
- To what extent have NbS mitigated flood loss at a regional scale in the Philadelphia Metropolitan Area?
- How does NbS relate to flood vulnerability?

Out of these research questions have emerged the three papers of this dissertation. The **first paper** study analyzed the relationship between spatial factors of NbS and flood regulation through a systematic mapping of 52 peer-reviewed articles. The results of systematic mapping indicated that the general topic is gaining popularity among multiple environmental disciplines due to the growing climate and urbanization threats in urban areas. It showed that five spatial dimensions of NbS, including distribution, scale, area, configuration, and topography can be strategically manipulated to varying degrees to enhance their efficacy in providing flood regulation services within urban settings.

The **second paper** aimed to assess the potential of NbS as a means to mitigate flood-related losses in Montgomery County, Pennsylvania, which is known for its rapid growth and susceptibility to flooding. This evaluation used Generalized Linear Model (GLM) and Geographically Weighted Regression (GWR) techniques. The analysis integrated multiple datasets, including the National Risk Index dataset for river flooding, a 100-year flood zone layer sourced from the National Flood Hazard Layer (NFHL) provided by FEMA, as well as land use and impervious surface percentage data extracted from the 2019 National Land Cover Database (NLCD). Notably, this study's findings diverged from previous research, revealing an unexpected relationship between the quantity of NbS in floodplains and the anticipated annual loss. The results suggested that smaller, isolated patches of NbS in flood-prone areas within densely populated urban regions can effectively reduce the overall losses incurred during flood events.

The **third paper** offered valuable insights into the nuanced dimensions of flood vulnerability in eight small urbanizing regions situated within the Philadelphia Metro Area at a finer spatial resolution within both the 100-year and 500-year floodplains. The LISA analysis highlighted priority regions characterized by heightened flood vulnerability scores and a lower presence of two types of vegetated NbS: tree canopy and shrubs/grasses. This study provided actionable information that can guide the development and implementation of targeted strategies to enhance resilience against flooding in rapidly urbanizing areas.

Background and Significance

Nature-based Solutions for Climate Change

The importance of nature in tackling environmental, social, and economic problems is becoming more widely recognized (Faivre et al., 2017). Nature serves as a bulwark against the negative effects of climate change. Natural systems' structures, functions, and processes increase people's capacity for adaptation or climate resilience (Woroniecki et al., 2020). One of the novel framings of to use of nature to reduce the negative effects of climate change is the use of NbS which has increasingly gained traction in the last decade within the discourse surrounding sustainable and ecological urban planning and management (Frantzeskaki & McPhearson 2022). The World Bank first used the term “nature-based solutions” (NbS) in 2008 (World Bank, 2008) in the context of developing novel approaches to reducing and adjusting to the consequences of climate change while simultaneously preserving biodiversity and enhancing sustainable livelihoods (Eggermont et al., 2015). However, it was initially developed by European policymaker and practitioner networks, particularly through the International Union for Conservation of Nature (IUCN) in 2009, about climate change adaptation as well as biodiversity conservation and management (Dorst et al., 2019; Nesshöver et al., 2017).

The definitions that have often been referred to are the ones by the European Commission (EC) and the IUCN. The IUCN and the EC define NbS slightly differently, but they agree on one point: NbS are nature-based interventions that should address societal challenges. For the EC, NbS is understood as a way to address societal challenges with "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social, and economic benefits, and help build resilience". Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes, and seascapes, through locally adapted, resource-efficient and systemic interventions (European Commission, 2015). IUCN defines NbS as: "Actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits" (IUCN, 2009). Both definitions are related to the idea that NbS can result in a variety of advantages.

The closest term that is often used interchangeably with NbS in policy and research is green infrastructure (GI) (Kabisch et al., 2016). Benedict and McMahon (2001) define GI as "an interconnected network of green space that conserves natural ecosystem values and functions and provides associated benefits to human populations". GI refers to initiatives that combine gray infrastructure with eco-friendly practices to build hybrid systems that increase resilience to the effects of climate change. GI is similar to NbS in some respects and occasionally interchangeable, despite the distinction between “infrastructure” and “solution”. Nesshöver et al. (2017) conceptualize GI as an implementation of NbS with a clear infrastructural focus (Frantzeskaki et al., 2019). This means that GI specifically supports the connectivity concept by implementing a network of green/blue elements, while the focus of the NbS approach is on different solutions either distributed or connected, inspired by nature to tackle the complex environmental issue, adding more benefits to the latter. The clear solution orientation of the NbS concept and its capacity to incorporate a broader array of interventions and perspectives of “nature-based” than GI, further distinguishes it from GI, making it a useful tool for actors from many disciplinary backgrounds who want to address issues related to urban sustainability (Dorst et al., 2019). One key distinction lies in the fact that while GI prioritizes the interconnection of natural areas, the NbS approach is more open to encompassing "isolated" actions, such as the installation of a single green roof. The scale and interconnectedness of these actions significantly impact the extent to which natural elements can provide societal, economic, and ecological benefits, such as contributions to biodiversity (Savard, Clergeau, & Mennechez, 2000). Nonetheless, the incorporation of relatively standalone interventions can make NbS a more accessible option, particularly for entities less familiar with working in natural contexts, such as businesses opting to implement green roofs on their office buildings, or small grassroots community organizations.

NbS such as green roofs, green facades, trees, community gardens, urban forests, green infrastructure, wetlands, and unmanaged green sites is a relatively new notion used to support sustainable development and climate change adaptation in cities (Castellar et al. 2021; Frantzeskaki et al., 2019; Nesshöver et al. 2017). Well-planned NbS support a wide range of ecosystem services like enhancing biodiversity, water retention, flood mitigation, reducing urban heat, etc. at different spatial levels which are critical in resolving anthropogenic concerns and facilitating the planning of sustainable and resilient urban areas (Castellar et al., 2021).

NbS for Flood Hazard Mitigation

This research is informed by the flood-oriented human ecology lens of G.F. White in 1950s and his colleagues, R. Kates and I. Burton in 1970s. Vulnerability is a dynamic concept that varies among different spatial and temporal scales and can be assessed based on multi socio-economic and biophysical criteria in cities (Bigi et al., 2021; Cutter et al., 2008). The conceptualization of sustainable hazard mitigation by Mileti (1999) and hazard vulnerability components (resilience, exposure, and sensitivity) by Turner et al. (2003) and Integovernmental Pannel on Climate Change (IPCC)'s vulnerability conceptual framework (McCarthy et al., 2001) triggered this shift toward a more comprehensive and standard definition of hazard research in the third millennium with an evolution to the concept of socio-ecological systems (SES) and sustainability science. Over the two last decades, several studies have suggested different adaptation and mitigation policies to reduce the risk associated with urban flooding in complex SES. Flood mitigation can lower the likelihood and severity component (exposure) of a risk calculation through moderating vulnerability to flooding, while adaptation can lower the consequence component (sensitivity) through adjustments to actual or expected flooding; the two are complementary (Yohe & Strzepek, 2007; Fuller & Pincetl, 2015, Tomkins & Adger, 2005). Adaptation can be defined as "the longer-term and constantly unfolding process of learning, experimentation and change those feeds into vulnerability" (Birkmann et al. 2016, p. 196). Structured flood protection measures (e.g., dams, walls, and levees), early warning systems, nature-based solutions (e.g., wetlands, dunes, and waterfront parks), resilient land use planning, social protection, and risk finance instruments are all examples of effective adaptation to increased flood risk which can mitigate the negative impacts of climate change and population growth in the river or coastal cities (Jongman, 2018; Rainey et al., 2021). However, the success of these adaptation strategies depends on their abilities to promote equity, efficiency, effectiveness, and legitimacy factors over time and scale (Adger et al., 2005; Anguelovski & Corbera, 2022).

Following the growing concerns regarding global environmental and societal change, specifically over the last decade, redefining the relationship between nature, society, and technology, and mitigating the destructive human activities has been largely supported by approaches such as ecosystem services. Although green-oriented approaches such as NbS and green infrastructure are widely recognized as a viable complement to these approaches in both rural and urban settings, a trivial part of global spending on urban infrastructure goes towards them (Khatri, 2022; Seddon et al., 2020; Meerow & Newell, 2017). The terminology used to describe these approaches differs (e.g., natural infrastructure, natural climate solutions, or engineering with nature), but I use NbS as a unified umbrella and "bridging concept" thereby multiple terms such as green stormwater infrastructure (GSI), ecosystem-based adaptation (EBA), low impact development (LID), urban ecosystem services (UES), and water-sensitive urban design (WSUD) can allow to interface to highlight the compelling advantages these strategies offer in providing multifunctional solutions to pressing urban challenges under one term (Frantzeskaki & McPhearson, 2022; Hanson et al., 2020). NbS is supposed to be effective in regulating water-based ecosystem services, namely regulating services like flood and water flow regulation (Castellar et al. 2021). Multifunctionality and solution-orietned are two main principles by which NbS can contribute to ecosystem preservation, namely Ecosystem-based Disaster Risk Reduction (Eco-DRR) which has been put on the agenda of many countries' national and local policies (IUCN, 2020). Perhaps it is time to rethink the environmentally and socially deterministic paradigms of natural hazard and risk assessment, and to place more emphasize on transformations of SES through incorporating a new interconnection among social, ecological, and technological systems for vulnerability, ecosystem, and socio-ecological resilience assessment (Folke, 2006; Depietri, 2020; McPhearson et al., 2022; Chang et al., 2021).

NbS, which include adaptive management of ecosystems, contribute to flood vulnerability by providing water-related ecosystem services such as stormwater management and water purification. NbS can be considered as a strong tool to achieve transformative changes toward more sustainable and resilient pathways (Palomo et al., 2021). The concept is now being advocated in the U.S. policy debates through U.S. President Biden's Executive Order on NbS announced in April 2022 (U.S. White House 2022) and the U.S. NbS Roadmap released at COP27 in November 2022. It has been also highlighted by the most recent published reports from the Federal Emergency Management Agency (FEMA) "*Building Community Resilience with Nature-Based Solutions*" (2021) and the US Army Engineer Research and Development Center "*International Guidelines on Natural and Nature-Based Features (NNBF) for Flood Risk Management*" (2021) followed by "nature-based infrastructure" and "engineering with nature" as previous common approaches by the US Army Corps of Engineers (2013).

Nevertheless, flood vulnerability assessments have not focused on NbS. Thus, there is a need for research on the application of NbS as an effective adaptation tool in reducing flood vulnerability in urbanizing regions of the United States. However, there is very little knowledge about existing nature-based solutions and its effectiveness in small urbanizing regions (Maragno et al., 2018). To my knowledge, examining the impact of NbS has been restricted to the scale of individual and parcel-based GI, GSI, or green spaces on one hand and high-density areas in major cities on the other hand which results in limited studies investigating the flood risk and the potentiality of NbS at the scale of small urban areas (Conley et al., 2022; Browne et al., 2021). Furthermore, while evidence suggests that NbS can help with stormwater management, few studies look at how different types of NbS in varied contexts affect flood regulation and resilience. Human activities are causing huge changes in urban ecosystems which results in increasing the probability of urban flooding. This research did not only assess the correlation between NbS pattern with flood regulation, but it pushed forward understandings of how and where NbS affects flood vulnerability and loss in small urbanizing cities.

NbS and Flood Loss

Research on NbS for flood mitigation is growing (Razzaghi Asl & Pearsall, 2023). Studies show vegetated green infrastructure can reduce flood damage and enhance resilience (Kousky and Walls, 2014). Assessing flood damage through property losses based on insurance claims is common (Brody et al., 2017; Brody et al., 2012). Urban blue-green infrastructure, like stormwater control measures, can reduce property damage (Sörensen & Emilsson, 2019). However, limited exploration exists on NbS coverage's impact on property and population losses from flooding (Bhattacharjee & Behera, 2018).

Landscape ecology provides a valuable framework for understanding the intersection of NbS and flood dynamics (Gill et al., 2007). Some studies have examined NbS structure, including composition and configuration, with a focus on runoff management (Kim et al., 2021; Lee, 2020). However, NbS quality indicators like shape yield inconsistent results at different scales (Kim & Park, 2016; Peng et al., 2019).

Research also explores NbS placement within floodplain areas and its effects on flood-related losses. Sohn et al. (2021) found maintaining larger, irregular, scattered green infrastructure patterns can reduce per-capita flood damage costs in coastal Texas. Brody et al. (2017) emphasized the role of natural open areas in mitigating flood-related damages along the Gulf of Mexico. Still, there is a lack of evidence on NbS configuration (complexity and connectivity) and composition (size) and their impact on riverine flooding in the study area, highlighting the need for further research which has been addressed in **paper two**.

Theoretical Framework

To examine how NbS structure and flood regulation can be interlinked in case studies, this study is grounded in integrative environmental equity, landscape ecology, and climate vulnerability streams. While each literature discusses certain aspects of NbS planning and implementation, together it allows us to assess mainstream NbS functionality and distribution in small urbanizing towns from a more holistic perspective in a time where interlinked social, ecological, and technological innovations require multifunctional and transdisciplinary solutions.

Based on these premises, I construct a new theoretical NbS Flood Regulation framework based on the above three theoretical streams and generally accepted definitions and models (Fig. 1). First, to consider environmental equity, I used the concept of distributive justice of NbS. Second, having landscape ecology perspective, the most influential NbS structure (composition and configuration) indicators was recognized to be effective in **paper one** and then was spatially correlated with annual expected loss from flooding examined by using different spatial statistical techniques in **paper two**. Last, an integrated social and biophysical vulnerability assessment which is based on the vulnerability concept defined by the Intergovernmental Panel on Climate Change (IPCC) was examined including exposure, sensitivity, and adaptability (resilience) aspects in **paper three**. In this framework, I consider the human population and properties as the main subject exposed or affected by urban flooding rather than the ecological system as it is the case in most previous studies (Depietri, 2020). The vulnerability-equity-structure (VES) framework is used to develop a simple typology that defines three groups of attributes that support water regulation services of NbS in urban areas: A) structure (S) measuring spatial arrangement and diversity; B) equity (E) measuring spatial distribution; and C) vulnerability (V) measuring exposure, sensitivity, and adaptability to flooding. This provides a consistent framework to inform further research, analysis, and decision-making.

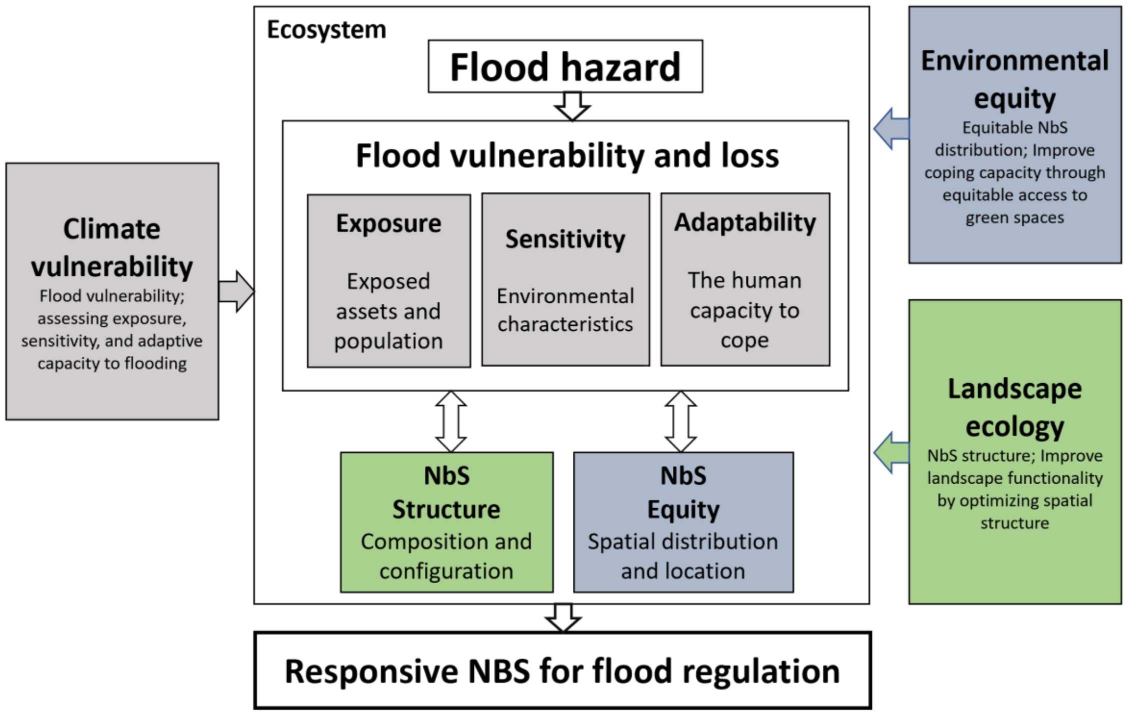

Figure 1. VES framework showing the elements and interactions that shape a responsive NbS for flood regulation in urban areas.

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CHAPTER 2
ARTICLE 1: HOW DO SPATIAL FACTORS OF GREEN SPACES CONTRIBUTE TO FLOOD REGULATION IN URBAN AREAS? A SYSTEMATIC MAPPING APPROACH

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Introduction

Floods are becoming more severe, lasting longer, and occurring more frequently because of changes in climate, rapid urbanization, and population growth globally (Tellman et al., 2021; Wing et al., 2022). By 2050, the population density in flood-prone coastal and riverine areas and megacities is predicted to increase by 25% with more than a billion people exposed to such flooding (IPCC, 2021). It is estimated that the extent of metropolitan areas vulnerable to flood threats will increase by 270% between 2000 and 2030, even without accounting for climate change (Güneralp et al., 2015). As several studies show, it is estimated that the flood damages are further exacerbated by climate change and land use/land cover (LULC) changes that replace vegetated areas with impervious surfaces, such as roads, roofs, and parking lots (Pattison & N. Lane, 2011; O'Donnell & Thorne, 2020; Venter et al., 2020; Zuniga-Teran et al., 2020). In most regions of the world, the degree of landscape change that is associated with urbanization is significant (Oke et al., 2017; Haas et al., 2015). Although traditional structural flood mitigation infrastructure (e.g., drainage systems) are effective in urban areas, their functionalities in the face of extreme rainfall events and increased development largely depend on the capacity and location of such systems, making complementary solutions such as vegetated areas important. To tackle such urban flooding challenges, implementing different types of urban green spaces (UGS) including urban parks, undeveloped open spaces, lawns, urban forests, green stormwater infrastructure (GSI), low impact developments (LID), water best management practices (BMPs), and water sensitive urban design strategies (WSUD) can increase natural capacity to adapt to climate change impacts (Ureta et al., 2021; Prudencio and Null, 2018; Araaf Tauhid & Zawani, 2018). As the findings of multiple studies show, many different types of UGS can maintain urban ecosystems and recreational services while decreasing the impacts of extreme precipitation and stormwater runoff (Kazmierczak & Cavan, 2011).

UGS, which refers to vegetated areas with trees, shrubs, or grasses in urban settings, contribute to a wide variety of water-related ecosystem services such as flood regulation, stormwater management, and water purification (Cilliers et al., 2013; Song et al., 2020; Graça et al., 2018). UGS can be used to control and regulate urban floods especially surface runoff reduction (Zölch et al., 2017; Liu et al., 2014). For example, urban wetlands and green roofs can regulate urban runoff by capturing stormwater (McPhearson et al., 2022). The impact of UGS on urban flooding control and mitigation in urban areas has been widely investigated in previous studies from different perspectives including technical (Yang et al., 2013), planning (Kim et al., 2021; Afriyanie et al., 2020), spatial (Baker et al., 2019), ecological (Zölch et al., 2017), social (Descher & Sinasac, 2020), economic (Sohn et al., 2021) and flood management (Ellis et al., 2021).

Additionally, the consequences of extreme weather such as storm surges, high tidal levels, and heavy rainfall in the river and coastal cities are greatly associated with an increase in impervious surface cover due to land-use change, making coastal, pluvial, and fluvial flooding more severe (Acreman & Holden, 2013; Kalantari et al., 2014). The failure of the urban drainage system also creates a unique form of flooding. Most rainfalls in cities will have to be drained using existing storm-water drainage systems because there is less land available for water attenuation and infiltration. However, when the amount of precipitation, and hence the volume of water, exceeds the area's drainage capacity, intense precipitation events can create floods. Rainwater begins to collect in places other than the drainage system, causing water to stagnate in low-lying areas (Jegatheesan et al., 2019). UGS are becoming important components of urban flood regulation systems, which simultaneously provide multiple benefits for human health, well-being, and biodiversity in cities as well. The vegetated and previous areas in urban areas have substantive roles in runoff reduction through the infiltration process (Berland et al., 2017). Several studies have been conducted on the runoff reduction and stormwater control functionality of different types of UGS in various contexts (Li et al., 2020; Liu et al., 2014). These studies suggest that UGS contributes to mitigating urban flood risk and stormwater management through 1) rainfall interception, 2) increasing the lag time between rainfall and runoff or water storage capacity, 3) evaporation from stored water, and 4) infiltration by soil (Kim & Park, 2016; Yang & Lee, 2021a; Sohn et al., 2021).

Increasing permeability in cities is one of the main reasons UGS can be effective in runoff regulation (Rezaei et al., 2019). The deterioration of the water cycle system is linked to an increase in impermeable surfaces in urban areas (Yang & Lee, 2021b). Imperviousness in urban catchments causes decreased infiltration capacity, increased surface runoff, increased soil erosion, and reduced base flow discharge, which increases the risk of flash floods and reduces the capacity for groundwater recharge. These repercussions are most likely where impervious surfaces are directly connected to urban streams, and they are linked to a variety of other factors such as land conversion pattern and past quality of converted land (Du et al., 2015; Schuch et al., 2017). By contrast, permeable surfaces such as UGS contain some kind of spaces filled with sand, gravel, or soil, which allows runoff to permeate into the underlying soil, reducing runoff and replenishing groundwater. Since it is difficult to include a considerable amount of green space in densely populated urban areas, the spatial arrangement and structural location of green spaces are critical to make optimal use of existing land from a landscape ecology perspective (Gill et al., 2007).

UGS infiltration capacity strongly depends on their biophysical and structural characteristics. Biophysical characteristics include natural attributes of plant species, health, and soil physical properties, and structural characteristics include shape, distribution, location, and connectivity (Gill et al., 2007; Kim et al., 2017; Yang et al., 2020). UGS structure has two major components: composition (the quantity and variety of UGS kinds, regardless of their spatial structure or organization) and configuration (the spatial aspect of UGS types such as arrangement, location, size, and connectivity) (Farina, 2000). From a landscape ecology perspective, the configuration, or spatial characteristics, of UGS, has an important impact on hydrological processes and runoff regulation (Zhang et al., 2019; Boongaling et al., 2018). Yet, the majority of previous studies have largely focused on the impact of different biophysical and compositional aspects of UGS, such as testing different combinations of types or analyzing the physical characteristics of vegetation species and pavements. Previous studies have also addressed how climate conditions and precipitation events affect UGS performance against flash or pluvial urban flooding (e.g., see Quagliolo et al., 2021; Alexander et al., 2019).

Although multiple disciplines have explored spatial factors relating to UGS and flood mitigation, these perspectives are disconnected and inconsistent, limiting a comprehensive understanding of the role of spatial factors. For example, some studies indicate that smaller and dispersed patches may have more runoff reduction (Liu et al., 2022; Yang & Lee, 2021a), while others indicate the positive impact of larger connected UGS on runoff reduction in an urban watershed (Li et al., 2020). To gain a comprehensive understanding of the expansive research field of flood regulation, we seek to highlight the role of spatial factors of UGS in this study. By using a systematic mapping approach, pertinent articles were identified, broad research trends were defined, key topics in flood regulation were summarized, and strong evidence for spatial factors was identified. This study also discusses knowledge gaps and suggests areas for further research.

Methods

This study developed a systematic map of the state of knowledge on the relationships between spatial factors of UGS and flood regulation. Inspired by Chausson and colleagues' (2020) research on nature-based solutions, this study followed the methodology proposed by James et al. (2016). Like systematic reviews, systematic mapping is a reliable, reproducible, and open scientific method for determining the literature that is currently available on a certain subject (Zhong et al., 2018). Systematic mapping is used to represent the scope of study in an area and pinpoint knowledge gaps and identify where future review work may be possible (Clapton et al., 2009). Systematic maps are not typically used to undertake a complete data extraction or critical evaluation of the pertinent research, in contrast to a systematic review. Instead, maps show the type, scope, and characteristics of research in a given field of study (Grant & Booth, 2009). This study conducted a systematic mapping of the spatial factors of UGS to identify the most common factors and their associated characteristics in different contexts.

The study's overarching research question and detailed sub-questions follow:

- What is the state of knowledge on the impact of UGS's spatial factors on flood regulation?
- Which flood regulation topics (e.g., hydrological, or financial) does the UGS literature address?
- Which spatial factors of UGS have been examined in the literature?
- What methodologies and trends have been used to investigate the impact of UGS on flood regulation?
- What are the knowledge gaps and the top priorities for future research?

Search Strategy

To find pertinent key terms, the search's scope was first decided. We determined that the information found using key search phrases included information on both flood regulation and spatial characteristics of UGS (location, distribution, configuration, and topography). We used two terms "flood" and "runoff" as indicators of flood regulation. In this review, the UGS refers to urban vegetated lands that fall under the category of nature-based solutions (NbS), green infrastructure (GI), low-impact development (LID), sponge cities, and sustainable urban drainage systems (SUDS). All different combinations of the above-mentioned keywords were searched using the Web of Science database as the search engine in the summer of 2022, with the search field set to "keywords" and "title" and the document type set to "article". No filter for the year of publication was used, hence the sample pulled from the database includes all publication years. Since some articles might have looked at a specific type of UGS (e.g., green roof) without directly referring to UGS at all, the second round of queries included "landscape" and two commonly used UGS types were added to the list: park and green roof. Separate search queries were used, each with a different two-way combination of (keyword/title category-related) search phrases as outlined in Table 1.

Table 1. Summary of results from scoping the study for search terms

	Search queries	
Round 1	Flood regulation terms UGS terms	(Runoff OR flood) AND (Green spac* OR Green infrastructure OR Nature-based solutions OR low impact development OR sustainable urban drainage system OR sponge cit*)
Round 2	Flood regulation terms UGS terms	(Runoff OR flood) AND (Park OR green roof OR landscape)[a]

[a] Search queries were restricted by only physical geography, forestry, and environmental studies fields in search engines.

Study Inclusion and Exclusion Criteria

Three steps in succession made up the inclusion procedure. The inclusion criteria were used to evaluate titles, abstracts, and full texts. Since the focus of the study is to detect spatial factors of UGS affecting flood regulation, the methodology section of each article was reviewed first to include or exclude the publication for the final mapping process. The following elements served as inclusion criteria:

- Scale: Studies examine UGS in urban areas
- Aspect: Studies address spatial structure, including distribution, configuration, topography, and location
- Type of UGS: All urban green elements including any specific type of vegetated lands

- UGS functionality: Any type of study that examined the economic and environmental capacity of UGS to reduce flood impacts.

Although there is a relationship between UGS structure and spatial factors, we excluded all studies that focused only on the composition of UGS, including but not limited to UGS types, plant species, and the number of patches or morphological factors (e.g., height).

Articles were also excluded if they did not focus on the spatial factors of UGS in the context of urban flooding. Excluded articles included: (1) spatio-temporal investigations of the effects of flooding on landscape and UGS change; (2) studies that emphasized runoff pollutants, quality, and nutrient cycling; (3) studies that investigated the large river basins and watershed scales without including any urban areas; (4) studies with a focus on technical/engineering, social (e.g., public attitudes), structural (e.g., size and shape), biophysical aspects (e.g., plant species, media types), climatic factors (e.g., rainfall intensity) and health indicators (e.g., water quality).

Coding Strategy

During the coding stage, information pertinent to the research questions and objectives was extracted from full texts. Since the relationship between UGS's different spatial arrangements depends on each city’s physical and environmental characteristics, we coded the specific metrics and features of each article (Table 2). Each sampled study included in database was categorized based on the associated codes: Bibliographic, geographic, study-specific, and topics. One row in an excel spreadsheet was set aside for each study. The same Excel spreadsheet was divided into columns for each variable, and counts were then performed to map out the general trends in the literature. Additionally, regarding the quality of articles, since we only evaluated articles from published peer-reviewed journals indexed in the Web of Science, we did not explicitly assess the quality of these articles. Additionally, critical evaluation is optional in systematic maps (James et al., 2016). We assumed that some level of quality control had already happened during the peer review process.

Table 2. Coding strategy used for collecting data from each study

Code category	Data collected
Bibliographic	Title, author(s), year, journal, study methodology, departmental affiliations
Geographic	Location of sample (country)
Study-specific	Sample UGS type, spatial metrics
Topics	Topics used in flood hydrology

Results

Search Results and Screening

Figure 2 shows the number of articles collected, screened, eliminated, and finally selected as final sampled documents for analysis during the steps of the systematic mapping. 2,135 articles and abstracts were initially identified, and 1,641 remained after duplicates were eliminated. 1,517 articles were disqualified in the first round of screening (at the level of the title and abstract). Two runs of full-text screening were conducted; the first resulted in the exclusion of 42, and the second pass resulted in the exclusion of an additional 30. The systematic map was completed by including and coding 52 academic articles based on the key spatial factors of UGS that affect flood regulation.

Country of Origin

A total of 52 articles contained research from a wide variety of regions (Fig. 2). Case studies were found in 11 countries including China (18), the United States (9), South

Korea (5), UK (4), Italy (3), Iran (2), Indonesia (2), Sweden (1), Netherlands (1), Germany (1), and Belgium (1). Also, five articles were conducted without considering any specific study area. Overall, more than half of the case studies were in China and the United States (27). Although these eleven countries were in different parts of the world, they were not uniformly distributed around the world. For example, the experiences of other low-to-high income nations, such as India, Vietnam, Pakistan, Bangladesh, Nepal, and Australia, which are regularly affected by flooding, were not included in these studies.

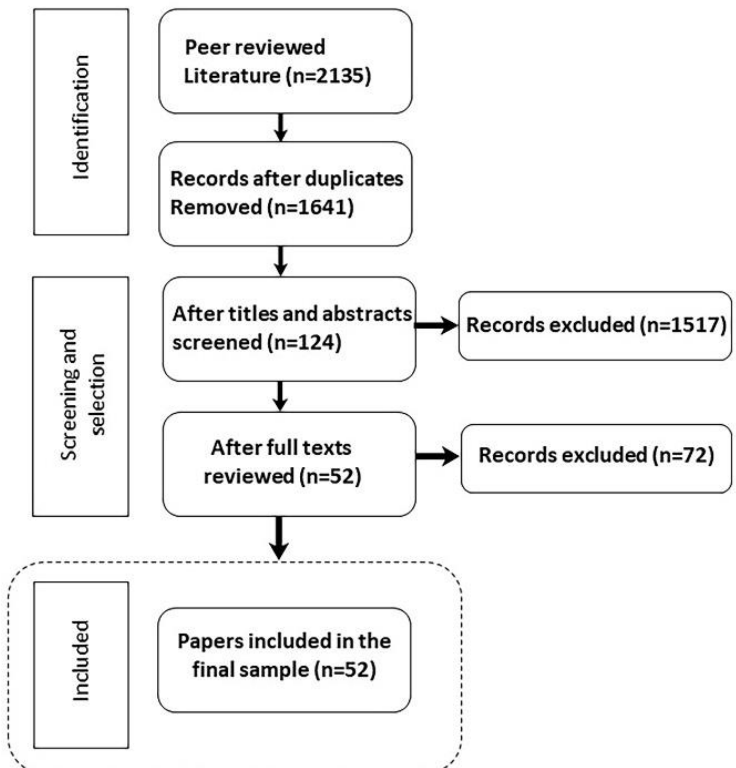


Figure 2. Overview of the article’s selection process (Adapted from Zhong et al., 2018)

Dates and Source Titles

All articles were published in a wide variety of domains and across 31 academic journals from January 2012 to July 2022.

The earliest article was published in 2012 in the journal of *Environmental Management*. As shown in Figure 2, 2020 and 2021 had the highest number of articles published (12 per year). Our review of publications in 2022 includes only 6 months (January-July) and thus does not reflect the total number of publications for the year. Overall, figure 3 indicates a rising trend in the number of published articles on this topic.

According to the analysis, 52 articles were published in 30 different peer-reviewed journals. Five journals published three or more articles during this period. These were *Urban Forestry and Urban Greening*, with the most articles (n=5), *Sustainability* (n=4), *Landscape and Urban Planning* (n=3), *Urban Water Journal* (n=3), and *Water* (n=2).

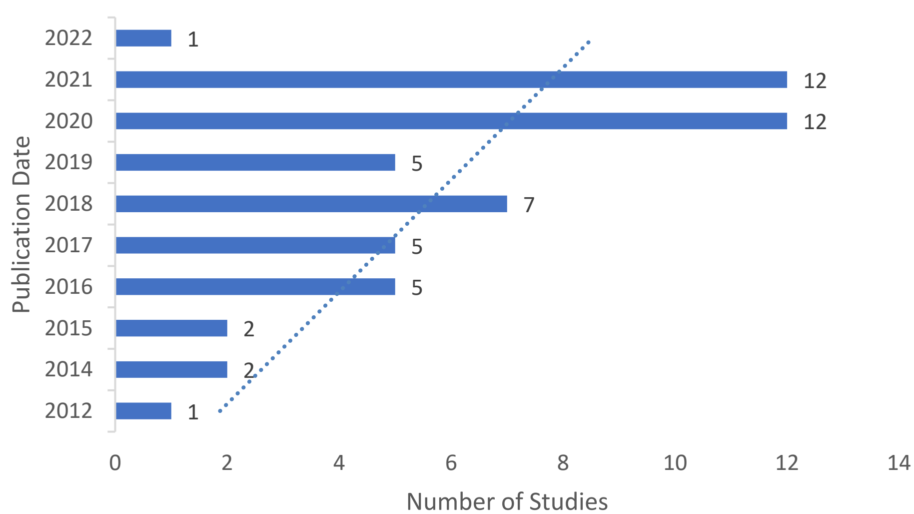


Figure 3. Publication dates for all articles (total n=52)

Types of UGS

Nineteen classes of UGS were identified in the mapped literature. The different types of UGS included in sampled articles and their frequencies among studies are illustrated in Figure 4. Urban forest was the most common UGS type that was found to be effective in flood regulation in the literature (Berland et al., 2017), followed by urban agricultural land (e.g., urban food-producing gardens and farms). Some UGS such as rain gardens and green roofs were categorized both as low impact development (LID) and green stormwater infrastructure (GSI) in some articles (e.g., see Fahy & Chang, 2019; Fiori & Volpi, 2020). According to the Environmental Protection Agency's (EPA) definition, the term low impact development (LID) refers to "systems and practices that use or mimic natural processes that result in the infiltration, evapotranspiration or use of stormwater to protect water quality and associated aquatic habitat" and green stormwater infrastructure (GSI) defined as "an approach to managing stormwater runoff in ways that mimics the natural environment as much as possible, using plants, soil, and stone to filter and manage stormwater more effectively, reducing how much enters our sewer systems, and protecting our rivers and streams" (EPA, 2022). Following these definitions, green roofs that are beneficial for flood stormwater reduction in cities (Twohig et al., 2022) were the most studied GSI/LID type, followed by rain gardens.

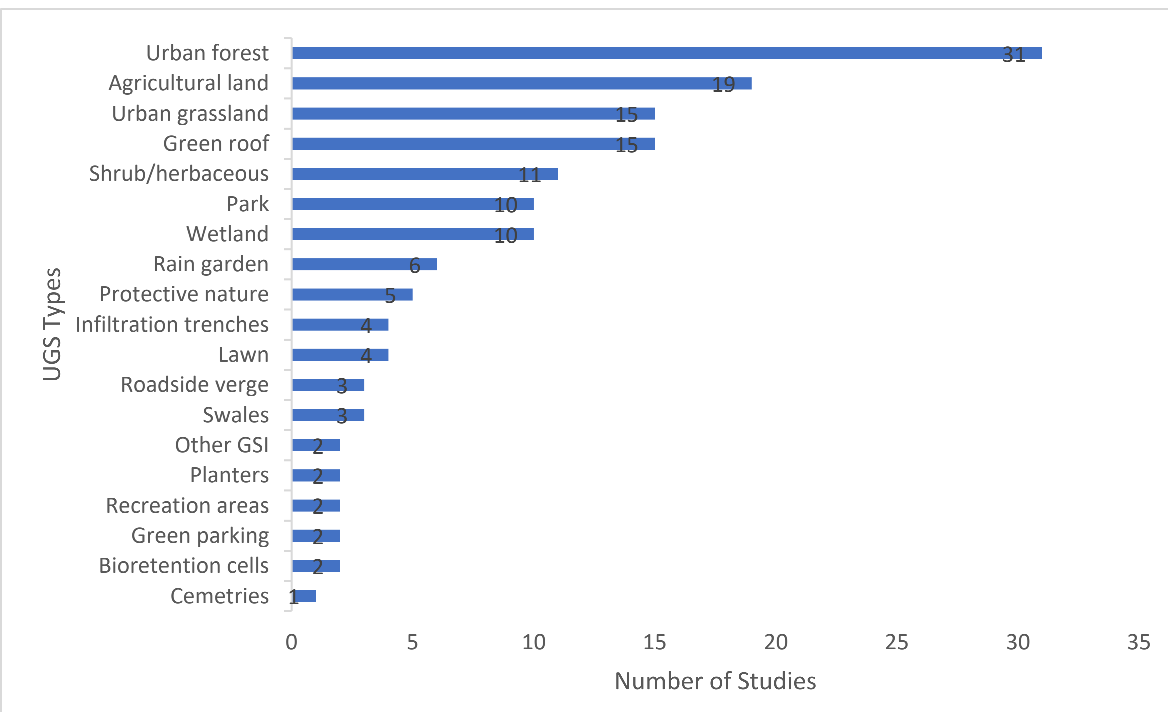


Figure 4. UGS types in all studies

Types of Modeling Methods

Based on the research methodologies, four groups of models and tools were utilized in the selected literature: process-based models (51), empirical models (30), statistical models (23), and programming tools (3). Out of 52 articles, 14 articles used only one methodological approach, while the remaining 38 articles included multiple methods.

The most common study methods were process-based or numerical models, which all articles used except one (Kim et al., 2017). ArcGIS (27), followed by EPA SWMM (10) provided by US Environmental Protection Agency's hydrological model, were the most commonly used models in the literature. Other models included QGIS (2), multi-criteria decision analysis (1), software Infoworks ICM (1), J2000 hydrological model (1), i-Tree Hydro (1), surface-subsurface hydrological model (ParFlow) (1), Integrated urban flood modeling system (IFMS Urban) (1), ENVI (1), MIKE SHE model(1), Landscape Green Infrastructure Design(L-GrID) (1), USGS Thornthwaite Water Balance (TWB) model (1), ERDAS Imagine (1), and community-scale simulation model (1).

Empirical models were considered the second most common type of modeling approach and included regression analysis (13), FRAGSTATS (12), Soil Conservation Service Curve Number (SCS-CN) (9), correlation analysis (4), Intensity-Duration-Frequency (IDF) curve (3), hydrological equations (3), the use value economic model (value of runoff regulation) (1), radial basis function neural network (1), and Minimum Cumulative Resistance (MCR) Model (1). Statistical studies included: ANOVA analysis (1), chi-square test (1), and panel data model (3). Lastly, the programming approach involved two: Python (1) and MATLAB (2).

Topics

Six topics were identified during the full review. All topics reported as dependent variables in these studies were coded based on how the spatial components of the green spaces impact flooding. Figure 5 indicates the count of studies for each of the six topics. The most common topic that occurred was flood hydrology with 41 articles (79% of all topics), followed by flood costs, flood vulnerability, flood risk management, flood intensity, and flood estimation (n=2, 4% of all topics). Most articles emphasized the hydrological responses of UGS in comparison with other dimensions, such as vulnerability. Flood hydrology studies examined discharge, total surface runoff, streamflow, and water-logging reduction in urban areas. Studies that categorized flood costs included three articles with flood damage assessment and valuing the runoff reduction resulting from UGS (Zhang et al., 2012; Brody et al., 2017; Sohn et al., 2021). Estimating flood probability was the main topic of flood estimation studies (Kim et al., 2016; Miller & Brewer, 2018). Moreover, the authors of only two articles on flood vulnerability used the Intergovernmental Panel on Climate Change (ICPP)'s framework to analyze vulnerability based on three factors: sensitivity, capacity, and exposure (Kim, Song & Chon, 2021; Sakieh, 2017).

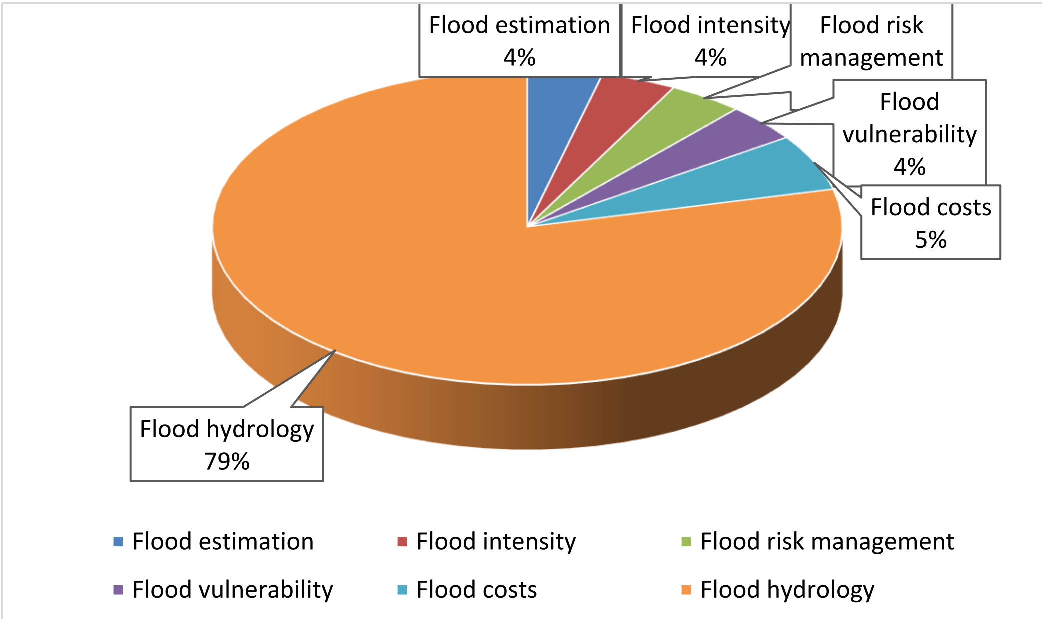


Figure 5. Topics appearing in the literature

Spatial Metrics of UGS Per Study Topic

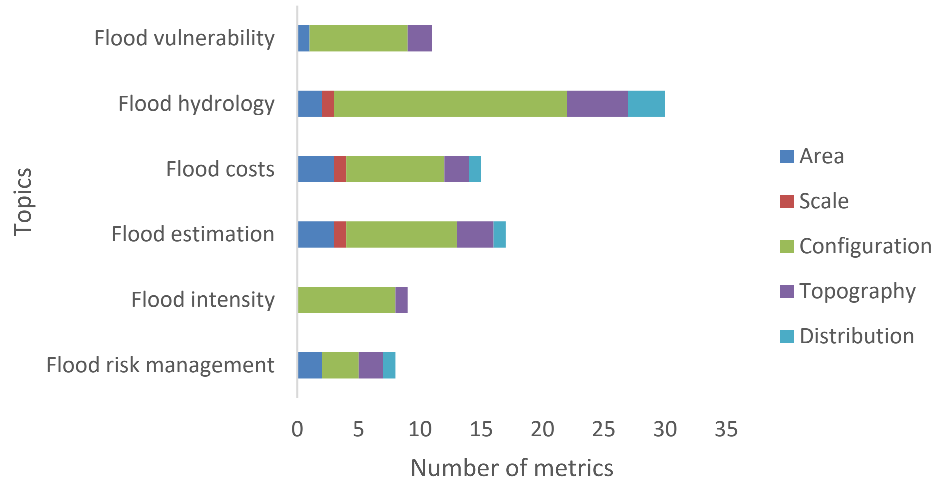
Thirty-four spatial metrics of UGS with flood-regulated services as independent variables were identified. The variables were categorized based on five major components: distribution, scale, configuration, typography, and area. Spatial configuration had the most spatial dimensions (n=83), followed by topography (n=46), distribution (n=18), scale (n=5), and area (n=25). The most common spatial factors are known as landscape metrics, which were frequently calculated through the FRAGSTATS software, a spatial pattern analysis program for quantifying landscape structure (McGarigal and Marks 1995). Landscape pattern indices, also known as landscape metrics, quantify changes in landscape spatial patterns caused by both anthropogenic and natural disturbances such as urban flooding (Gillanders et al., 2008).

Distribution in these studies refers to at least three concepts: (1) the distribution of UGS and its influence on flood regulation, and/or (2) the spatial arrangements of UGS in terms of dispersed or centralized UGS and its effect on flood reduction, and/or (3) how the geographic location of UGS across an urban area impacts flood regulation. In this review, scale is a component of distribution unless the study (1) addressed the impact of UGS at different scales (e.g., plot, sub-catchments, and catchment) and/or (2) compared UGS in various sized cities, and/or (3) examined different scale/size of UGS (e.g., small scale GSI such as rain gardens or large scale GSI such as bioretention basin). Topography refers to the UGS's surface elevation and slope, which were mostly measured through the digital elevation model (DEM) and digital terrain model (DTM). The frequency and meaning of 34 spatial metrics are illustrated in Table 3.

As shown in Table 3, the most common spatial metrics in the literature were topographic metrics: digital elevation model (DEM) (n=18) and slope (n=18). The second most examined metric was UGS ratio/coverage (n=16), followed by geographical location (n=15), and landscape shape index (LSI) (n=14). The five most frequent metrics used to assess flood regulation were UGS area, topography, and shape. The distribution of spatial metrics for each flood regulation topic showed that scale metrics were not reported in flood intensity, vulnerability, and risk management studies (Fig. 6). This distribution also showed that the greatest number of configuration metrics were applied in flood hydrology studies (n=19). No distribution metrics of UGS were examined for flood intensity and vulnerability analysis. Moreover, the number of studies that addressed scale was similar for three topics: flood hydrology, costs, and estimation.

Table 3. Spatial metrics examining the functionality of UGS for flood regulation

Dimension	Spatial metrics	Meaning	No.
Distribution		Refers to both geographical location and dispersion of UGS in an urban area	
	Spatial arrangement	Dispersed or centralized UGS and its effect	1
	Equitable distribution	Spatially homogenous placement of UGS	2
	Location	UGS's position in different parts of the city	15
Configuration		Refers to the spatial aspect of UGS types such as arrangement, location, size, and connectivity	
	Correlation length (GYRATE_AM)	Mean distance between each cell in a patch and the patch's centroid cells	1
	Shannon's evenness index (SHEI)	Describes the even degree of distribution of different kinds of landscape	1
	Area Weighted Mean Shape Index (AWMSI)	The average shape index (SHAPE) of patches of the corresponding patch type, weighted by patch area so that larger patches weigh more than smaller patches	2
	Effective Mesh Size (MESH)	Quantifies the degree of landscape fragmentation	2
	Landscape division index (DIVISION)	The landscape's division degree by patches	2
	Total Edge (TE)	An absolute measure of the total edge length of a particular patch type	2
	Clumpiness index (CLUMPY)	The proportional deviation of the proportion of like adjacencies involving the corresponding class from that expected under a spatially random distribution	3
	Edge Density (ED)	The ratio of the total length of all patches' edges to the total landscape area	3
	Fractal dimension index (FDI)	Shape complexity across a range of spatial scales	3
	Patch Density (PD)	The ratio of the number of patches to the total landscape area	3
	Aggregation index (AI)	The total edge shared by each class	4
	Contagion (CON)	Describes the contagion degree of the same kind of patch	4
	Connectivity (CONNECT)	Measures each pair of patches that are either connected or not within a certain search radius	5
	Contiguity (CONTIG)	Assesses the spatial connectedness, or contiguity, of cells within a grid-cell patch to provide an index of patch boundary configuration and thus patch shape	6
	Largest patch index (LPI)	Quantifies the percentage of total landscape area comprised by the largest patch	6
	Euclidian Nearest Neighbor (ENN)	The straight-line distance between nearest-neighbor patches of the same type	7
	Proximity (PROX)	Each patch size is divided by the square of its distance from the focal patch	7
	Cohesion (COHESION)	Measures the physical connectedness of the corresponding patch type	8
	Landscape Shape Index (LSI)	Provides a simple measure of class aggregation or clumpiness and, as such, is very similar to the aggregation index	14
Topography		Refers to the arrangement of the natural and artificial physical features of an urban area.	
	Digital surface model (DSM)	A three-dimensional representation of the heights of the Earth's surface, including natural or man-made objects located on it	2
	Digital terrain model (DTM)	A three-dimensional, bare-earth representation of a terrain or surface topography, consisting of an array of points with a defined height	2
	Digital elevation model (DEM)	A gridded raster data and a three-dimensional representation of a terrain, which filters out and excludes terrain vector features	18
	Slope	A rising or falling surface	18
	Concavity (depression)	A lower elevation of UGS than its surroundings and can temporarily retain storm waters	3
	Topographic wetness index (TWI)	Quantify topographic controls on hydrological processes	3
Area		Refers to the size and ration of UGS in an urban area	
	Perimeter-Area Ratio (PARA)	A simple measure of shape complexity, but without standardization to a simple Euclidean shape	1
	Class Area (CA)	Percentage of UGS comprised of a patch type	1
	UGS ratio (coverage)	The ratio of the area occluded by vegetation to the entire space	16
	Percentage of landscape (PLAND)	Percentage of a particular patch type	5
	Mean Patch Size (Area)	Average patch size	2
Scale		Refers to different levels of UGS which have been focused in studies	
	scale	Refers to UGS in different scales of the city (e.g., plot, sub-catchments, and catchment) OR studied UGS in various sized cities OR studies different scale/size of UGS (e.g., small scale GSI such as rain gardens or large scale GSI such as bioretention basin)	5



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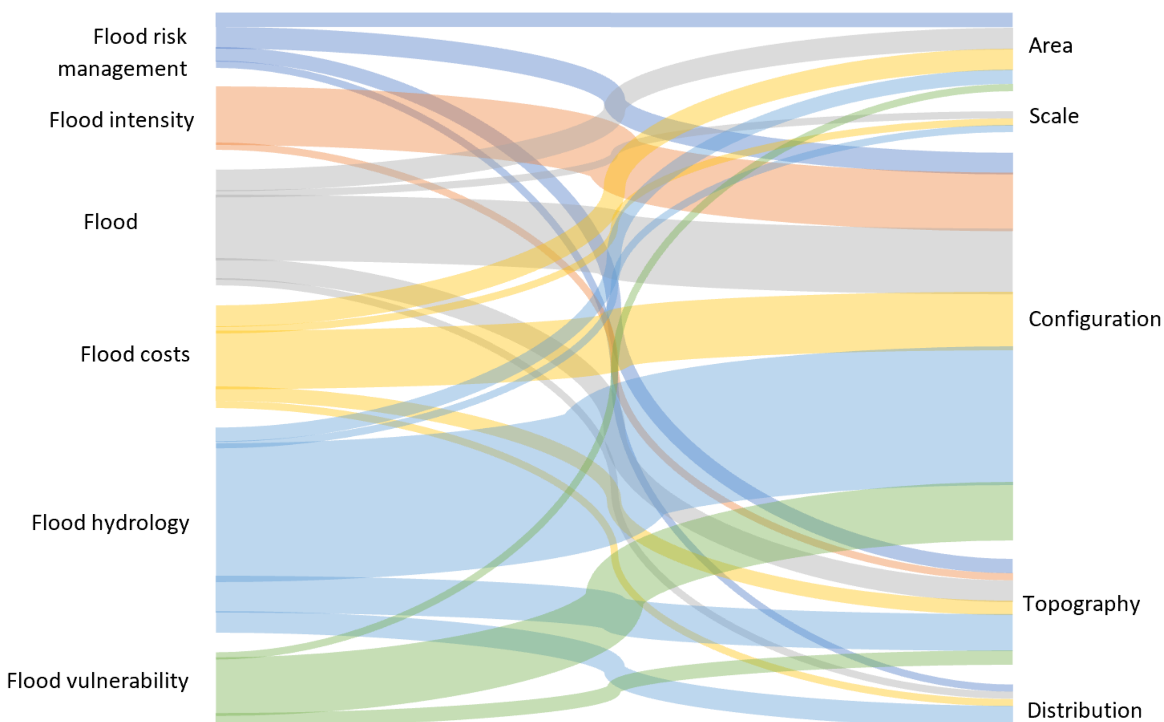

Figure 6. Systematic map of the five most reported spatial metrics addressed by each of the five flood regulation topics illustrated (a) as a bar chart showing the distribution and frequency of metrics, and (b) as a Sankey diagram, where the thickness of each band corresponds to the number of metrics involving the linked flood topics and spatial dimensions

The Effectiveness of Spatial Metrics in Flood Studies

To synthesize the influence of reported spatial metrics reported in Table 3, we selected the most common metrics for each spatial dimension including slope, DEM, LSI, UGS coverage, and location. The COHESION index was also included due to its importance in analyzing the spatial configuration of UGS. The "scale" metric was not considered because it was infrequently used. The results of the studies indicated that the performance of UGS varied by geographic context due to different climatic and environmental conditions. Thus, UGS impacts on flood regulation might vary by city and region, and the results of one study may not be generalizable to other geographic areas.

Topography is a well-established spatial variable and is typically measured by using slope for small-scale UGS such as rain gardens and Digital Elevation Model (DEM), digital surface model (DSM), and digital terrain model (DTM) for larger UGS such as wetlands or grasslands. Slope was one of the most basic topographical factors for hydrologic analysis of different types of UGS, especially in steep zones. Studies showed that a higher estimated slope of the UGS surface could intercept more runoff (Lim & Welty, 2017; Zhou et al., 2019); however, since its effectiveness is related to other factors such as soil type, it is not a determining factor (Kim & Park, 2016). Also, as one-third of all articles reported (n=18), DEM is a useful dataset to determine surface-water catchment boundaries and flow pathways/accumulation of UGS to examine its impact on flood regulation, especially on hydrological topics (Miller & Brewer, 2018).

The shape of UGS is also an important variable. Calculations of shape-based spatial configuration metrics based on the Landscape Shape Index (LSI) was one of the most frequently used spatial attributes. According to the findings of these studies, larger UGS with variable and patch shapes were found to help reduce stormwater runoff (Bai et al., 2018; Zhang et al., 2015; Kim & Park, 2016; Brody et al., 2017). Yet, the results of studies in Inner Mongolia (China) and the city of Ghent (Belgium) suggested that the shape of UGS alone may not have a significant impact on flood intensity or runoff reduction (Peng et al., 2019; Li et al., 2020). These studies found that the degree of influence depends on other factors, such as distribution and distance.

Another essential spatial factor affecting the overall functionality of UGS in flooded areas is the area and percentage of vegetated lands. The studies showed that increasing UGS coverage could significantly decrease the total runoff or economic cost of flooding in, for example, Chinese cities (Kim, 2021; Yao et al., 2020; Li et al., 2016), although the degree of this reduction depends on some factors such as the precipitation duration/frequency and seasonal characteristics in Swedish cases (Sjöman & Gill, 2014). Almost one-third of articles (16) reported that UGS coverage was an influential factor to reduce the amount of runoff, flood damage, flood probability, and risk management in different case studies. However, as the results of a study in Shenzhen, China indicated, different urban areas might respond differently to scenarios of changing UGS ratio depending on topography and land use. Also, in some cases, increasing UGS coverage may not help certain water-related issues, such as waterlogging (Qian et al., 2021).

Additionally, the results of studies using COHESION as a strong measurement to examine the physical connectedness of the corresponding green patches were inconsistent across different flood topics, especially flood costs and hydrology. The findings of some articles in both virtual and real cases (e.g., Indonesia) showed that the more dispersed the green patches, the more reduction in surface runoff (Maheng et al., 2021; Yang & Lee, 2021b). Some studies found that layout features were more crucial for flood mitigation than connectivity between green spaces in China (Bai et al., 2018), meaning that the dispersion of UGS throughout the landscape was a better strategy than increasing clustering and connectivity. In addition, some studies related this type of effect to the scale of UGS, which means that the connectivity of UGS on a small-scale increases runoff and had the opposite effect over a large scale in South Korea (Kim & Park, 2016). One study examined the impact of dispersed or disconnected UGS on flood damage loss reduction in the Gulf of Mexico, US (Brody et al., 2017) and found that large green patches lost their capacity to mitigate flood damage when they were fragmented. Another study in the city of Ghent, Belgium recommended increasing the connectivity of UGS to reduce urban runoff (Li et al., 2020). Given this inconsistency between case studies, it is still unclear whether the connectivity of UGS influences the total urban runoff.

Finally, the spatial location of UGS and its impact on flood regulation was one of the important factors that the authors reported in less than one-third of the articles (15) which is consistent with the outcome of a comprehensive review by Zhang and Chui (2018), who analyzed the spatial allocation strategies of GI. Furthermore, since diverse parts of the cities usually experience unequal impacts of climate change and urbanization due to unbalanced distribution of resources and UGS, well-sited UGS in different parts of the city can mitigate such negative impacts (Hsu et al., 2021). For example, in a study by Kim (2021), the locations of UGS and their relative positions to the current drainage system may have different flood mitigation effects across South Korea. As the findings of these studies demonstrated, the closer to urban sewerage and drainage networks, the more positive hydrological impacts in terms of runoff and streamflow reduction (Yao et al., 2020; Ercolani et al., 2018). As a result, the optimization of UGS to better conduct urban runoff to deal with the negative impacts of urban flooding has been growing, especially among green stormwater infrastructure (GSI) facilities because GSI's effectiveness varies depending on the geographic region (Qian et al., 2021). The location of UGS concerning the downstream or upstream site is also a significant factor. The findings of a virtual case study indicated that some types of UGS (e.g., rain gardens and green roofs) may potentially make flooding more likely when retrofitting is done in downstream areas, nearer the outlet (Fiori & Volpi, 2020).

Discussion

This study provides the first systematic map on the most common spatial metrics of UGS that mitigate urban flooding in countries around the world. These findings identify important research areas for urban geographers, policymakers, planners, and civil engineers. This systematic mapping of 52 scientific articles is relevant to researchers and decision-makers considering common factors and metrics that affect the functionality of spatial factors of UGS for flood regulation. A summary of the key conclusions of the evidence maps as well as its limitations, including significant evidence gaps and associated directions for more synthesis and research follows.

Summary of Key Findings

Our mapping exercise revealed that a total of 52 articles reported the influence of different spatial metrics on UGS performance for flood regulation. Studies often used process-based modeling to examine the impact of different configurations and spatial characteristics of UGS on flood regulation. Most studies were conducted in countries in the industrialized Global North and Asia rather than low-income and developing countries.

Flood hydrology was the most common topic addressed, and the spatial configuration of UGS was consistently identified as an important factor in flood regulation. Although the topography of UGS was not found to be a determining factor to control urban flooding, it was an important factor in stormwater management and runoff in densely built and relatively low-sloped cities where the capacity to attenuate and evacuate rainwater is limited. Runoff gathered in drainage swales or piped underground eventually finds its way into slowly draining creeks and bayous.

Our review indicated that the effectiveness of UGS varies spatially based on land use/land cover, climatic, and other contextual factors. The results of most studies indicated that the location, distribution, and arrangement of UGS depending on sewer systems or upstream/downstream positions of the site may have different impacts on runoff mitigation and flood loss. These results suggest that UGS planning must site GSI and other types of UGS according to their locational functionality against flooding.

Evidence Gaps and Priorities for Future Research

The mapping exercise revealed several research gaps. First, studying the spatial dimension of UGS is limited to developed countries, and there is a critical need to analyze spatial factors in other countries, especially the Global South, as well as Australia, where regular flooding occurs in urban areas. Empirical research and theoretical modeling in these contexts can clarify the associations between spatial factors of UGS and flood regulation in different land uses, urban contexts, and climate conditions.

Second, some studies have investigated the impact of UGS coverage and shape on flood regulation, but there is no consensus among studies about the optimized efficiency of these criteria. Thus, we strongly recommend quantifying the potential effects of ratio, area, shape, and geometry of UGS across different scales and different flood characteristics and processes. Although some studies suggest that larger UGS patches have more potential to reduce runoff in urban areas and may reduce flood damage (Brody et al., 2017; Kim & Park, 2016), it is not yet clear exactly how much green space is needed to regulate flooding for individual cities, nor its actual impact on flood vulnerability, intensity, estimation, and risk management. Also, our systematic mapping showed that fewer studies (n=5) examined the impact of the UGS scale on flood regulation. There is a need to investigate the tradeoffs and synergies of scale matches and mismatches.

Third, our findings indicate that there is still limited research on the impacts of siting UGS at different spatial scales in cities, including within or around cities. Further, there has been little consideration of how UGS siting can improve flood regulation in disadvantaged/marginalized communities (Zellner et al., 2016; Qian et al., 2021; Fahy & Chang, 2019). Future research should investigate the associations between various UGS locations in urban areas and their potential flood regulation consequences. Although research on the benefits of equitable distribution of UGS has increased in recent years in different contexts (see Hunter et al., 2019; Cartier, 2021; Pallathadka et al., 2022), more research to further investigate the impact of equitable distribution of UGS on reducing flood risks is needed.

Fourth, most articles focused on process-based modeling approaches. Other numerical modelings, empirical modeling, machine learning, and advanced remote sensing methods can be applied to help researchers analyze and predict flood regulation scenarios based on differential spatial factors of green spaces. Comparing the results of these models results may help identify the most optimized solutions for different urban contexts.

Fifth, there are opportunities for more spatial configuration metrics to be calculated and examined both individually and cumulatively regarding their potential to address flood regulation in various contexts (McGarigal et al., 2012). These new spatial configuration metrics can help researchers find correlations between a wide variety of metrics and better realize their functionalities in various contexts. There is a need to quantify the possible associations between these variables and all flood regulations topics to explore optimized UGS planning in cities. In addition, due to inconsistent results among studies, it is crucial to further assess the impacts of the spatial configuration of UGS, such as connectivity, on flood regulation across different climatic and soil conditions. Finally, since most of the studies have focused on the runoff reduction impact of UGS, there is a need to investigate the effect of spatial factors of UGS on other topics of flood regulation, especially vulnerability and intensity, through more empirical studies.

Conclusion

This study analyzed the relationship between spatial factors of UGS and flood regulation through a systematic mapping of 52 peer-reviewed articles. The results of systematic mapping indicated that the general topic is gaining popularity among multiple environmental disciplines due to the growing climate and urbanization threats in urban areas.

Results from this review show that five spatial dimensions of UGS, including distribution, scale, area, configuration, and topography with different degrees can be manipulated to be effective for flood regulation services in urban settings. Previous research has identified several variables and criteria for each category that require further analysis for UGS planning and decision-making in various contexts, climate conditions, and scales. Understanding the interactions among different combinations of these variables is important to evaluate the efficacy of UGS for flood regulation in different scenarios and individual cities. The results of this review can serve geographers, environmental engineers, landscape planners, and environmental scientists who examine the impact of spatial factors of UGS on different aspects of flood regulation in different contexts and support practitioners and policymakers who develop and implement urban resiliency planning in face of increasing climate change and urban population growth. This study has some limitations. Given the variety of UGS definitions, it is possible some relevant studies were not included. Additionally, only articles published in English language journals were considered. Future studies should address these limitations.

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CHAPTER 3

ARTICLE 2: TO WHAT EXTENT HAVE NBS MITIGATED FLOOD LOSS AT A REGIONAL SCALE IN THE PHILADELPHIA METROPOLITAN AREA?

Introduction

Urban and regional environments have experienced significant transformations due to rapid urbanization, leading to a myriad of challenges. This is especially pronounced in densely populated urban areas where the proliferation of grey infrastructure, such as highways, parking lots, and towering buildings, has increased the risk of flooding. Various studies, including those by O'Donnell and Thorne (2020), Pattison and Lane (2011), Venter et al. (2020), and Zuniga-Teran et al. (2020), indicate that climate change and alterations in land use/land cover (LULC), which involve the substitution of vegetated regions with impervious surfaces like roads, rooftops, and parking lots, exacerbate the damaging effects of floods.

Additionally, floods are becoming more severe, lasting longer, and occurring more frequently because of changes in climate, rapid urbanization, and changing human demographics globally and throughout the United States (US) (Tellman et al., 2021; IPCC, 2021). Direct flood damages in the United States have cost a total of $99 billion and more than 1,000 deaths over the last 10 years, with an upward trend in flood losses over time (NWS, 2022). The findings of a recent study show a 26.4% increase in US floods by 2050 under intermediate climate change scenarios of RCP4.5 (Wing et al., 2022). In 2021, Hurricane Ida caused an estimated $16 to 24 billion in flooding damage in the Northeastern United States, making it the most expensive storm to impact the region since Hurricane Sandy in 2012, with an estimated $44 billion in insured loss (CoreLogic, 2021). In addition, about 83% of the population lives in urban areas in the United States today, with 89 percent (400 million) of the national population projected to live in cities by 2050 (UN Habitat, 2018). A once-in-100-year flood threatens 41 million people in the United States alone (Wing et al., 2018). According to projections, urban land cover will nearly double over croplands and forests by 2050 in the U.S. (Seto et al. 2012; Chen et al., 2020), causing the degradation of the local and national ecosystem, exacerbating climate change, human health, and global warming (Venter et al. 2020; Zuniga-Teran et al. 2020).

Over the two last decades, several adaptation and mitigation policies (e.g., channels, pipelines, and storage tanks) have been suggested to reduce the risk associated with urban flooding in urban and regional areas (Ferreira et al., 2021). However, the use and upkeep of these traditional approaches have proven to be expensive and insufficient to address the problems posed by increasingly frequent extreme precipitation events associate with climate change and the ensuing floods in metropolitan areas (Hoyer et al., 2011). NbS (e.g., urban parks, green roofs, floodplains, etc.) are examples of effective adaptation to increased flood risk that can mitigate the negative impacts of climate change and population growth in the river or coastal cities. Due to beneficial outcomes that enable a more effective reduction of flood impact in urban areas, NbS has become an emerging subject as a flood risk management technique (Samuels, 2022).

However, the success of these adaptation strategies depends on their quantity and quality to reduce flood risk in different regions (Woodruff et al., 2022). Understanding to what extent NbS size within the study area and its spatial characteristics such as shape, connectivity or contiguity could mitigate the risk of flooding would help to facilitate the availability and to increase efficiency of NbS in flooding hazards and its impact (Razzaghi

Asl & Pearsall, 2023). Despite continuous attempts to emphasize the positive influence of NbS in mitigating flood damage, there is a lack of county-scale assessments of the impact of NbS quantity and quality for reducing cumulative damages (population, agriculture, and property) from riverine flooding. In the practical realm of NbS planning, it becomes essential to account for the size and shape of the area being considered (Kim et al., 2021). This is especially significant in rapidly urbanizing regions where a significant portion of the urban landscape is already occupied by built environments and grey infrastructure (Sakieh, 2017). Consequently, the expansion of NbS within the county encounter limitations due to the constraints posed by the pre-existing built environment. Hence, it becomes crucial to carefully evaluate and optimize the shape and configuration of NbS to fully leverage its potential benefits and enhance its effectiveness in addressing riverine flooding.

To support the above concerns regarding the growing risk of flooding and the effectiveness of NbS to mitigate this risk, this paper examines the potential of NbS as a flood loss mitigation tool in one of the fastest-growing counties of Pennsylvania. This research addresses the following question: To what extent have NbS quantity and quality mitigated flood loss at Montgomery County in the Philadelphia Metropolitan Area? Montgomery County has a long history of flooding over previous decades, including 134 events costing $10 million USD in damages from 1996-2019. This study draws on Expected Annual Loss Score (EALS) data associated with riverine flooding from the National Risk Index (NRI) provided by the Federal Emergency Management Agency (FEMA), which has data on total annual loss of buildings, agriculture, and population from flooding from 1996-2019. The land cover 2019 map from National Land Cover Database

(NLCD) of U.S. Geological Survey was used to realize vegetated nature-based solutions (e.g., mangroves, green spaces). This study employs three different spatial statistics methods, including spatial autocorrelation (Global Moran's I), Generalized Linear Model (GLR), a county regression, and a local regression technique, Geographically Weighted Regression (GWR), to assess non-stationarity in relationship between NbS composition and configuration and EALS across Montgomery County.

Nature-based Solutions and Flood Loss

Although conventional structural flood mitigation infrastructure systems (e.g., dams, drainage systems) are efficient in urban areas, they are increasingly failing in the face of extreme rainfall events and increased development. Additionally, gray infrastructure is expensive, energy-intensive, and does not offer the range of additional benefits that come with natural infrastructure-based solutions (Lallemant et al., 2021). For this reason, complementary solutions like natural infrastructure and NbS as more environmentally and economically sustainable are gaining popularity among stakeholders, policy makers, and planners (Dottori et al., 2021; Razzaghi Asl & Pearsall, 2023).

In the last decade, there have been numerous efforts to precisely define and elucidate the concept of 'NbS.' In 2015, the European Commission (EC), for the first time, established an official definition for NbS, as indicated by "actions address environmental, social and economic challenges simultaneously by maximizing the benefits provided by nature (…) inspired by, supported by, or copied from nature". Another definition was made by the International Union for Conservation of Nature (IUCN) as: "actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits." (IUCN, 2009). Although the search to find a satisfactory definition of NbS continues (Sowińska-Świerkosz & García, 2022; Hanson et al., 2020), by using these broad definitions, we can avoid seeing NbS as merely engaged in novel ecosystems (e.g., constructed wetland) or vegetated land covers (e.g., agricultural lands) in areas. Rather than being confined in different green and blue interventions and minutiae of these elements, it is better to see NbS, similarly to the above definitions from IUCN and EC, as a "promising umbreall concept to address a number of societal and envionrmental challenges arising from climate change, urbanisation, and population growth, through the delivery of ecosystem services". Given to this definition, NbS typically encompass a wide range of approaches and practices that leverage nature and natural ecosystems to address various environmental, social, and economic challenges. While NbS often focus on natural areas and ecosystems, they can also include other vegetated land covers such as agricultural lands as a critical component. These features allow water to infiltrate the ground, reducing the volume and velocity of surface runoff during rainfall events. NbS also provides additional benefits like improved air quality, temperature regulation, and enhanced urban aesthetics. (Brody et al., 2017; Castellar et al. 2021; Zolch et al., 2017).

There is a growing body of research on the flood mitigation potential of NbS (Razzaghi Asl & Pearsall, 2023). Multiple research efforts have analyzed the extent to which vegetated green infrastructure reduces flood damage and improves resilience (Kousky and Walls, 2014). A common approach among these studies for considering flood damage has entailed the property (buildings and content) loss from flooding based on insured claims (Brody et al., 2017; Brody et al., 2012). For example, Sörensen & Emilsson (2019) found that urban blue-green infrastructure (e.g., stormwater control measures) scenarios have significant effect on recusing the property damage from previous flood events that resulted in insurance claims in Malmö, Sweden. In another study, Bagstad et al. (2013) indicated that NbS approaches, such as riverine and coastal wetland restoration, can provide cost-effective benefits by reducing flood damage to buildings and infrastructure. Yet, a few studies have investigated the impact of green spaces coverage on property and population loss from flooding in Indian states (Bhattacharjee & Behera, 2018).

Furthermore, there have been studies examining the location of NbS, specifically within floodplains, and their impact on flood-related losses. In Ulsan, South Korea, Kim (2021) discovered that a higher proportion of green space within a city and within floodplains, compared to its presence outside floodplains, may have a mitigating effect on flooding risks when considering financial insurance payments as a response variable. Similarly, Brody and Highfield (2013) found that preserving open space within floodplains helps maintain the natural functions of wetlands and riparian areas, which have been proven to mitigate flooding and significantly decrease property damage over time. However, these studies primarily focused on preserving the quantity of nature-based infrastructure, without addressing the influence of its quality on flooding. Moreover, these studies mainly assessed the economic damage to properties caused by flooding and the role of NbS quantity in minimizing such damages. However, they did not fully investigate the overall extent of damage from flooding, nor did they examine the influence of NbS configuration on flood events.

Landscape ecology provides a useful conceptual and analytical framework for comprehending the causes and effects of spatial patterning at the NbS-flood interface across boundaries of heterogeneous landscapes (Forman, 1995; Gill et al. 2007). Some studies have examined the impacts of NbS structure including composition (the quantity and variety of NbS kinds, regardless of their spatial structure or organization) and configuration (the quality and spatial aspect of NbS types, as well as their arrangement, location, and direction) on flood risk with a more focus on runoff mitigation (Zhang et al., 2015; Yao et al., 2015; Kim et al., 2021; Lee, 2020). Yet, the results of previous studies at different scales, specifically regarding the NbS quality (e.g., shape) indicators are inconsistent, limiting a comprehensive understanding of the role of these factors in flood reduction. For example, Bai et al. (2018) and Kim & Park (2016) found that larger urban green spaces with diverse and irregular shapes can effectively mitigate stormwater runoff, while studies conducted in Inner Mongolia (China) and the city of Ghent (Belgium) indicated that the shape of UGS alone may not have a significant influence on flood intensity or the reduction of runoff (Li et al., 2020b; Peng et al., 2019).

Additionally, only a handful of studies have directly investigated the role of NbS structure on flood damage (Razzaghi Asl & Perasall, 2023). Sohn et al. (2021) investigated the flood damage costs (property damage in US dollars) in coastal Texas and found that maintaining larger, more disordered, dispersed, less fragmented, and less linked patterns of green infrastructure through time will aid in lowering the per-capita costs of flood damage at the county level. Similarly, Brody et al. (2017) put forth the claim that large and continuous natural open areas play a significant role in mitigating flood-related damages along the Gulf of Mexico in the United States. There is need for more evidence on the impact of NbS configuration (complexity and connectivity) and composition (size) on riverine flooding in the study area, to inform planning and practice for flood damage mitigation at the regional scale.

Despite persistent efforts to highlight that NbS reduces flood damage, there is need for additional research on the role of NbS in reducing overall property, agriculture, and population losses resulting from riverine flooding. Previous studies have primarily focused

on the impact of green spaces on insurance claims, specifically in coastal areas (Sohn et al., 2021; Kim et al., 2020), neglecting the broader implications such as agricultural and population damages and there is also needed to consider how the characteristics of NbS, such as configurational shape and connectivity factors, impact flood and damage outcomes.

This research aims to fill these gaps by examining the potential impact of NbS and two metrics of shape and connectivity on total property, agriculture, and population loss. To accomplish this, a novel approach utilizing the National Risk Index dataset, which incorporates complex modeling techniques, was employed. The study was conducted in Montgomery County, chosen for its unique urban-rural interconnections, enabling a more holistic understanding of the impacts of NbS on flood-related losses. The findings of this research will be valuable to flood practitioners, policy makers, and urban planners seeking to enhance their understanding of NbS and its potential contributions to mitigating flood damages.

Methods

Study Area

This study focuses on Montgomery County, which is situated in the Philadelphia Metropolitan Area in southeast Pennsylvania (Figure 1). Geographically, Montgomery

County exhibits a diverse landscape, ranging from farmland and open countryside in the northern region to densely populated suburban subdivisions in the south and central areas. With a land area of approximately 1,250 km^2, the county comprises 211 Census Tracts and is susceptible to flooding from the Schuylkill and Delaware Rivers. Montgomery County is home to over 850,000 residents, and its population continues to grow (U.S. Census Bureau, 2020). The study area experiences a humid subtropical climate, with temperatures ranging from −10.6°C to 42.2°C. On average, there are 88 days per year when the minimum daily temperature drops below freezing (0°C), while there are only 10 days per year when the maximum daily temperature falls below freezing (Rossi et al., 2023).

The area has a long history of pluvial flooding (Montgomery County Hazard Mitigation Plan, 2022). Notably, in September 2021, severe flooding resulting from Hurricane Ida affected a significant portion of Montgomery County along the Schuylkill River. Additionally, Norristown, a city within the county, experienced substantial rainfall, and flooding during Hurricane Irene in August 2011, making it one of the most flood-prone cities in the area (The Reporter, 2021). Recent years have witnessed an increase in precipitation intensity attributed to climate change (Kunkel et al., 2020). Moreover, the substantial growth in public and commercial services as well as population rate, which form the primary economic activities in the area, has led to a rapid rise in impervious surfaces, amplifying the risk of flash flooding (Rossi et al., 2022). The selection of this study area was driven by four main factors: 1) a moderate-to-high risk of flooding over the next 30 years, as projected by Flood Factor and the National Flood Hazard Layer (NFHL) published by FEMA, 2) a high population growth rate based on the US Census Bureau 2020, 3) diverse types of NbS (Fig. 7).

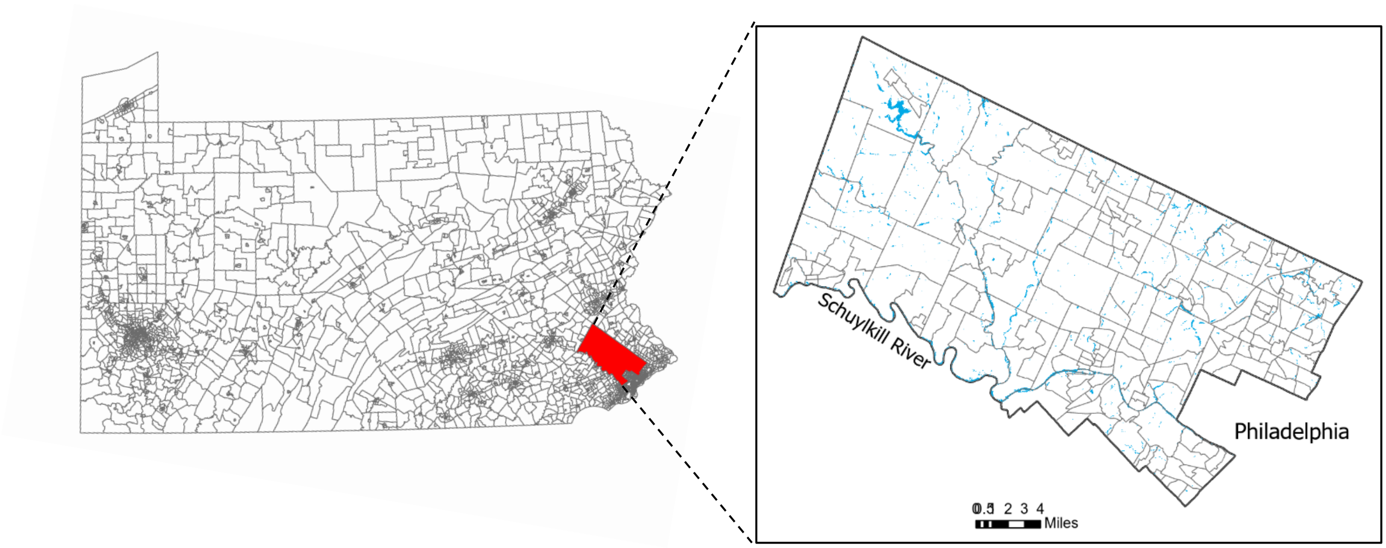

Figure 7. Study area of Montgomery County, Pennsylvania, USA with delineated Schuylkill River, local creeks, and subregions

Data

The Expected Annual Loss (EAL) data for riverine flooding in the study area was obtained from the National Risk Index (NRI) dataset, which is provided by the Federal Emergency Management Agency (FEMA) in collaboration with various stakeholders and partners, including academia, local, state, and federal government agencies (FEMA, 2023). The NRI dataset is an online tool designed to identify and illustrate the communities in the United States that are most vulnerable to 18 different natural hazards (Zuzak et al., 2022). In the context of this study, the EAL represents the average economic loss in dollars resulting from riverine flooding each year per Census Tract. To calculate the Expected Annual Loss Score (EALS) for each consequence type (buildings, population, and agriculture) within each Census Tract, the NRI dataset quantifies the values of buildings and agriculture in dollars. However, the measurement of population focuses on fatalities and injuries. To establish a standardized unit of measurement, the EAL associated with the population was converted into a population equivalence using a value of statistical life

(VSL) methodology (FEMA, 2023). According to this approach, each fatality or every ten injuries is considered equivalent to an economic loss of $11.6 million. To calculate the EALS for river flooding type, the EAL values for the three consequence types (building, population equivalence, and agriculture) are combined. This summation represents the total Expected Annual Loss for riverine flooding within the Census Tracts of Montgomery County. These values are then compared and ranked across the flooded communities. The Expected Annual Loss score for each Census Tract is determined based on its national ranking.

Figure 8 shows the modeling workflow followed in this study to examine the spatial association of NbS and its configuration metrics in floodplains with EALS.

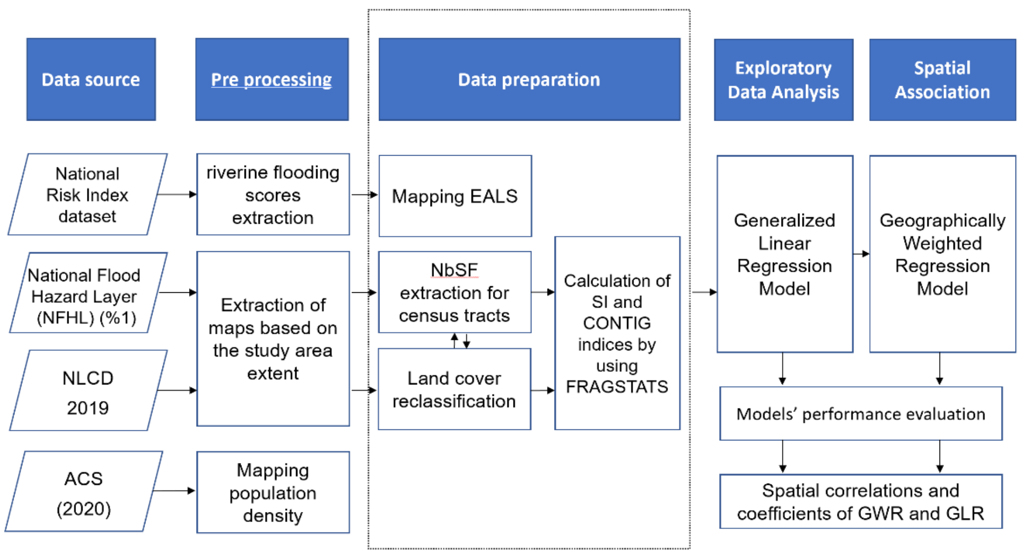

Figure 8. The workflow of an spacially explicit modeling approach in this research

The first two steps were the data collection and pre-processing. The primary data sources for the explanatory variables are the US Census tract-level data for 2019, the land cover 2019 map which was obtained from U.S. Geological Survey's National Land Cover Database (NLCD), Impervious surface (%) which was taken from NLCD 2019 Percent Developed Imperviousness (CONUS), and American Community Survey (ACS) estimates.

NLCD provides 30 m spatial resolution land cover maps for the whole United States and is used to identify vegetated NbS. Based on previous studies and the definition of NbS interventions in this research, the NLCD classes that may be associated with or contribute to NbS include:

- Forest and woodland: These areas can provide habitat for wildlife, improve water quality, and contribute to carbon sequestration.
- Wetlands: wetlands play a vital role in flood regulation, water purification, and providing habitat for various species.
- Grassland and herbaceous: These areas can contribute to natural flood management and are important for biodiversity and pollinator habitat.
- Shrubland: Similar to grasslands, shrublands can have ecological benefits and play a role in flood management.
- Open water: Natural or restored water bodies can serve as wetland habitats and contribute to flood control (Sohn et al., 2021; Park & Guldmann, 2020; Woodruff et al., 2022).

It's important to note that the effectiveness of these land cover categories as NbS can vary depending on their location, condition, and how they are managed. Given that the objective of this research is to encompass all the natural features within floodplains that have the potential to be effective in managing flood risk, a total of ten classifications were identified for NbS: open space (21), deciduous forest (41), evergreen forest (42), mixed forest (43), shrub/scrub (52), grassland/herbaceous (71), pasture/hay (81), cultivated crops (82), woody wetlands (90), and emergent herbaceous wetlands (95) (Figure 9b).

An additional factor contributing to flooding in the study area is the presence of development within designated flood zones. The Federal Emergency Management Agency

(FEMA) has defined a specific geographic area as the flood zone based on the probability of flooding during certain storm return periods. The National Flood Hazard Layer (NFHL) provided by FEMA includes a 100-year flood zone layer, which is also referred to as the base flood or the 1-percent annual chance flood. To examine the relationship between NbS and EALS, population density was considered as a control variable since it directly affects housing and economic activity in the area. The population density data for 2019 was obtained from the US Census Bureau. Population density was measured as the number of residents per acre of the county area. The analysis in this study was conducted using data from 177 populated Census Tracts within Montgomery County. It's important to note that out of the total 211 Census Tracts in the county, 23 were excluded from the study as they did not have any flood zones.

Drawing upon the findings of previous studies (Sohn et al., 2021; Brody et al., 2017; Bai et al., 2018; Kim & Park, 2016; Razzaghi Asl & Pearsall, 2023), we computed two potential indicators of NbS configuration, namely the shape index (SI) and contiguity index (CONTIG), specifically tailored to assess riverine flooding at the census tract level. This analysis was conducted using FRAGSTATS version 4.2. SI provides a simple measure of the perimeter and area of a patch and represents the complexity of landscape patch shapes. CONTIG measures the mean number and position of contiguous NbS cells and indicates the spatial connectedness (McGarigal, 2015). Higher values of SI and CONTIG represent more complex and contiguous patterns of NbS. It should be emphasized that the high value of isolation alone denotes a NbS condition that is impaired.

Table 4 provides the definition and basic statistics of each index used in the analysis.

Table 4. Datasets and main variables

Variable	*Source*	*Range*	*Mean*
Dependent variable			
Expected Annual Loss Score (EALS)	National Risk Index dataset* for flooding	0 ~ 38	13.4
Independent variables			
NbS in floodplains (NbSF) area (km^2)	National Flood Hazard Layer (NFHL)	0 ~ 3.2	0.31
Impervious area (IA) percentage	NLCD 2019	1.83 ~ 74.1	27.7
Shape index (SI)	NLCD 2019	13.2 ~ 100.98	74
Contiguity index (CONTIG)	NLCD 2019	0.7 ~ 0.8	0.75
Control variable			
Population density (per acre) (PD)	U.S. Census tract data	0.31 ~ 30.32	5.55

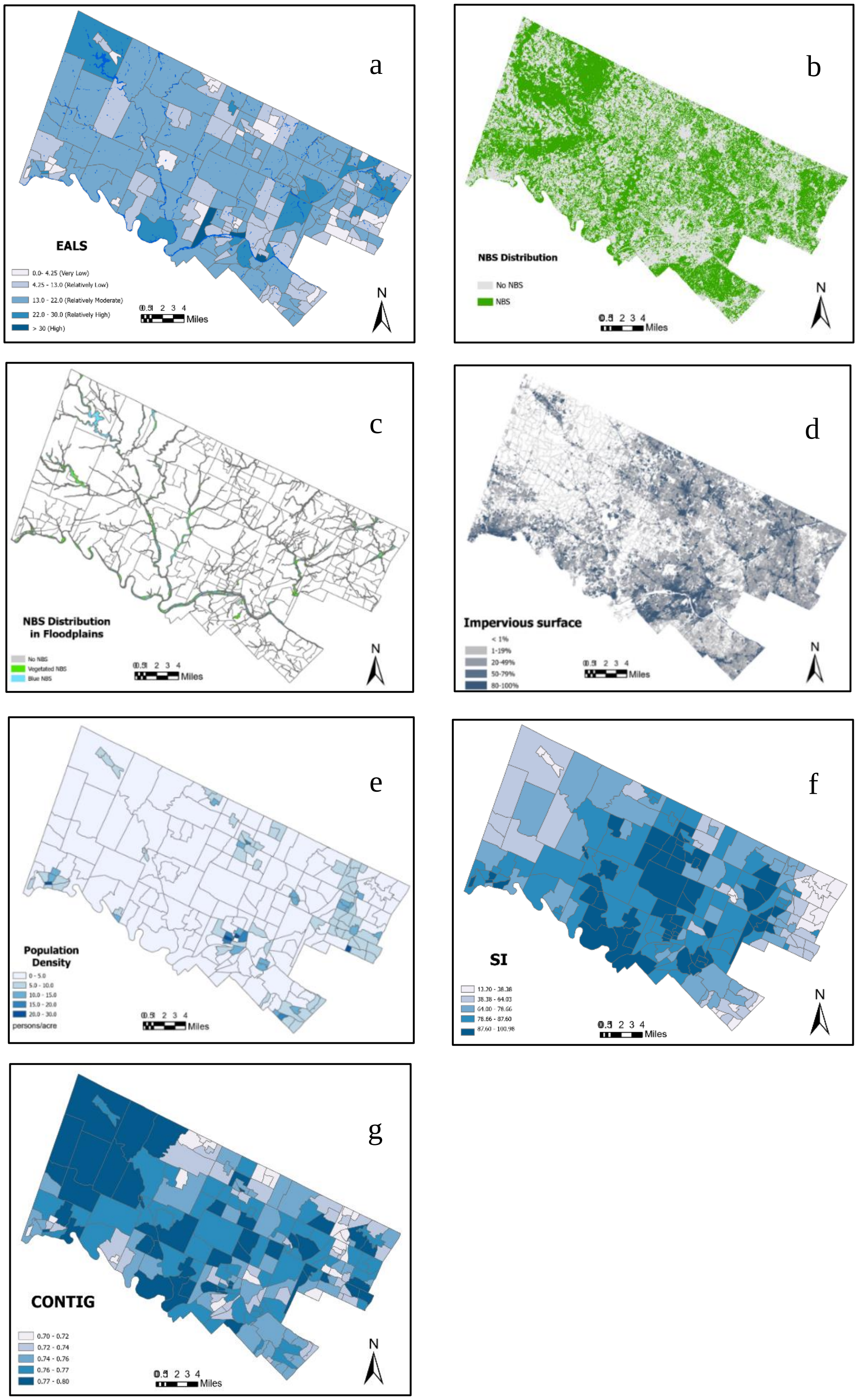

Figure 9. The distribution of different variables in study area, including a) Expected Annual Loss Score b) NbS distribution in the whole study area c) NbS distribution in 100-year flood zone area distribution d) Impervious surface percentage in study area e) Population density f) Shape index and g) Contiguity index.

Data Analysis

This study utilized both global and local regression techniques to investigate the spatially varying relationship between NbS area and flood building loss conditions across at two scales: county-wide and local. On the county-wide scale, Generalized Linear Regression (GLR) was employed as a benchmark model, allowing for a comparison with the local models. On the local scale, Geographically Weighted Regression (GWR) was employed to identify unique and spatially explicit relationships within each census tract.

In this study, GLR model was chosen as an appropriate approach for modeling the response variable (EALS), taking into consideration the low spatial dependency. The GLR model allows for the establishment of a linear relationship between predictors and the response, even when the relationship is not inherently linear. The utilization of a link function facilitates this connection between the response variable and the linear model (McCullagh & Nelder, 1989). Collinearity was detected by the variance inflation factor (VIF). To test normal distribution, heteroscedasticity, and spatial autocorrelation, three tests of Jarque-Bera statistics, Breusch-Pagan, and Global Moran's I were used, respectively based on previous research (Yang et al., 2022; Pearsall & Christman, 2012; Bae et al., 2021).

Unlike traditional linear regression models such as OLS, the GLR does not assume a normal distribution of the response variable's error terms. This divergence from normality is particularly relevant in the context of spatial analysis, where spatial non-stationarity can occur. Linear regression models with constant coefficients, such as OLS, do not account for spatial non-stationarity and may result in deviations from the expected outcomes (Anselin, 1988). GLR is represented as follows:

$$f[\mathrm{E}(Y_i|x_i)] = \sum_{j=0}^{p} \beta_j x_{jp} + \epsilon_i$$

where f is a function of the mean response "link function"; Y_i is the dependent variable EALS at Census tract i, β_j is regression coefficient, x_{jp} stand for independent variables (IA, PD, NbSF, SI, and CONTIG); and ε_i is the error.

To address the issue of spatial non-stationarity and capture the spatially varying relationship between the predictors (e.g., NbS variables) and the response variable (EALS), the study employed Geographically Weighted Regression (GWR). GWR offers an alternative to traditional regression analysis by allowing coefficients to vary with geographic position. By decomposing the global relationship into specific geographical units, GWR provides insights into the local dynamics of the relationship and captures spatially explicit patterns (Fotheringham et al., 2002). The application of GWR in this study aims to consider the variable relationship between NbSF, IA, PD, SI, CONTIG and the EALS variable from a local perspective. This localized analysis enhances our understanding of the specific interactions and impacts of these variables within different geographic locations (Brundson et al., 1996). It is calculated as follows:

$$y_i = \beta_0(u_i, v_i) + \sum_k \beta_k(u_i, v_i) X_{ik} + \varepsilon_i$$

where y_i is EALS at census tract i, β_0 (u_i, v_i) represents the intercept at position i; β_k (u_i, v_i) is the coefficient of the kth independent variable estimated for each census tract i at location (u_i, v_i); ε_i is a random error. The integrated GLR and GWR capabilities in the ArcGIS Pro program were used to develop models for social and greenness conditions. For GLR and

GWR models, EALS per Census Tract was regressed against the four variables: vegetated NbS size in floodplains, impervious surface percentage, shape and contiguity indicies.

The models in this study were compared using two evaluation metrics: the corrected Akaike Information Criterion (AICc) and the adjusted R^2. AICc serves as an indicator to assess model performance and to compare the adequacy of GLR and GWR models, as discussed by Joseph et al. in 2012. In the context of these models, when the AICc difference exceeds 3, a lower AICc value and a higher R^2 value suggest a superior goodness of fit (Fotheringham et al., 2002: 95-97). The adjusted R^2 measures the proportion of variance in the response variable explained by the predictors, accounting for the number of predictors and sample size.

Results

Spatial Pattern of NbS

There is higher coverage of NbS in rural and suburban areas, while urban areas exhibit lower NbS presence. The eastern part of the county has higher population density and a greater amount of impervious surface compared to the western part of the county. There are also more Census tracts with relatively high and high EALS in East Montgomery, likely due to rapid urbanization and their proximity to the Schuylkill River and Wissahickon Greek. The presence of extensive impervious surfaces in the East County signifies significant development and urban expansion. However, there is a balanced distribution of NbS coverage between the two parts, with denser vegetated NbS in the western region. West Montgomery features a substantial area occupied by golf courses, the Green Lane Reservoir, preserves, Green Lane Park, and primarily low-to-medium-density development. This area boasts a larger quantity of vegetated NbS situated in floodplains, characterized by green corridors and linear parks. Furthermore, the shape index map exhibits a predominant circular pattern, where the central county displays higher values of the shape index (SI). This indicates that the central area encompasses more complex shapes for NbS, while the surrounding counties exhibit relatively simpler shapes. Lastly, the distribution map of CONTIG reveals that nearly all Census Tracts in the study area exhibit high values close to 1. This indicates a contiguous pattern for NbS, where the NbS components within each Census Tract are closely connected or adjacent to one another (Fig. 9).

Global Analysis of EALS Based on GLR Model

The results of the Generalized Linear Regression (GLR) reveal a significant positive correlation between each of the three independent variables, including Nature-Based Solutions in Floodplains (NbSF) ($b = 6.428$, $p < 0.01$), Impervious Area (IA) ($b = 0.175$, $p < 0.01$), and Contiguity index (CONTIG) ($b = 72.58$, $p < 0.01$) with the Expected Annual Loss Score (EALS) of flooding (Table 5). By contrast, a significant positive correlation is observed between control variable of population density (PD) and EALS ($b = 0.45$, $p < 0.01$). Also, shape index (SI) exhibits a very low negative correlation with EALS ($b = - 0.018$), indicating that the complexity of patches in each Census tract is not a predictor of EALS. Among the five beta coefficients of explanatory variables, the highest absolute beta coefficient is 72.587 for CONTIG, underscoring the significance of NbS connectivity as the most influential factor contributing to the Expected Annual Loss Score of flooding. The results of the VIF demonstrated no collinearity between independent variables (VIF < 3). Furthermore, tests such as Jarque-Bera statistics, Breusch-Pagan (heteroscedasticity), and Global Moran's I (0.2 < Moran’s I < 0.6; z score > 6.23) indicate a relatively high level of spatial autocorrelation, emphasizing the necessity of conducting a local Geographically Weighted Regression (GWR) analysis.

Table 5. Results of Generalized Linear Regression (GLR) model for Expected Annual Loss Score.

Variable	Coefficient	Robust SE	Robust t	Robust P	VIF	Moran's I
Intercept	-44.44	19.07	-2.32	0.020	---	----
NbSF	6.428	1.264	5.083	0.000*	1.504	0.21*
IA	0.175	0.059	2.961	0.0034*	2.823	0.402*
SI	-0.018	0.0242	0.780	0.435	1.071	0.598*
CONTIG	72.587	24.892	2.915	0.0039*	1.244	0.297*
PD	0.451	0.148	3.046	0.0026*	1.996	0.299*
Model Diagnostics	Multiple R^2: 0.240, adjusted R^2: 0.222, AICc: 1399.10, Koenker (BP): 30.952*, Jarque-Bera: 5.590*					

Note: SE = standard error; VIF = variance inflation factor. *Significant at the 0.01 level.

Spatial Heterogeneity of EALS Based on the GWR Model

Table 6 presents the relationship between EALS and NbS and population density as per the GWR model. The overall R-square coefficient of determination nearly doubles in comparison to the GLR model, reaching a R^2 of 0.44. The local R^2 values in the GWR map range from 0.34 to 0.53. The higher local R^2 values occurred in West Montgomery (Fig. 10a). The lower AICc value and higher R^2 suggests that GWR is more effective in identifying the local-scale association between EALS and independent variables. Furthermore, the analysis using Global Moran's I test showed a significant clustering pattern in the standardized residuals (Moran's I = 0.103; z score = 3.059).

Table 6. Local-scale association between Expected Annual Loss Score and NbS status based on the GWR model

Variable	GWR Coefficients				Directions of relationship in the GWR model			
	Min	Max	Mean	SD	+ (%)	+ sig. (%)	- (%)	- sig. (%)
Intercept	0.2085	0.3209	0.1337	0.1672	---	---	---	---
NbSF	0.3087	1.0887	0.6244	0.2090	100.00 %	100.00 %	0.00 %	0.00 %
IA	0.2856	0.4167	0.3624	0.0294	100.00 %	100.00 %	0.00 %	0.00 %
SI	0.1718	- 0.0309	- 0.1015	0.0313	0.00 %	0.00 %	100.00 %	00.00 %
CONTIG	0.3387	1.0227	0.2353	0.2816	80.00 %	21.90 %	20.00 %	0.00%
PD	-0.3912	0.2416	0.312	0.0318	0.00 %	0.00 %	100.00 %	100.00 %
Model Diagnostics	Multiple R^2: 0.442, adjusted R^2: 0.372, AICc: 530.865, Moran's I: 0.103							

Note: + sig. (%) and - sig. (%) refer to the proportion of 5 % significance for positive correlation and negative correlation, respectively.

When comparing the GLR model's result for population density (PD) to GWR model, it becomes evident that the GWR model reveals more nuanced information, as depicted in Figure 3b. A significant positive correlation between the PD and EALS was observed in 100.00% of the neighborhoods. The average GWR coefficient for this relationship was 0.312, with a standard deviation of 0.0318. It shows the smallest mean of GWR coefficients (-0.391). The influence of PD on EALS is particularly pronounced in Northern districts of the County.

Regarding the amount of NbS in floodplains on a global scale, there is great evidence suggesting that a higher amount of NbS located within floodplains can increase the expected annual loss of flooding. Similarly, GWR result demonstrates in all (100.00%) census tracts a positive significant relationship with ELAS. It is worth noting that this factor exhibits the highest mean of GWR beta coefficients (at 0.6244) compared to other variables. This disparity is particularly pronounced in a small part of East Montgomery. As one moves outward from this area to the West, the degree of association gradually decreases (refer to Fig. 10c). In terms of impervious surface, in contrast to the global GLR model, the GWR model reveals a higher level of detail (see Fig. 10d). It uncovers a significant positive correlation between the percentage of impervious surface and EALS in all census tracts (100.00%) with the mean GWR coefficient being 0.362 (SD = 0.029). The most significant association among the census tracts is observed in Southern part of county, specifically in Upper Meridian Township and as one moves to the left or right from this central area, the association diminishes, forming a distinct focal pattern.

In 21.90% of neighborhoods, a significant positive correlation was discovered between the CONTIG (contiguity) and EALS (expected annual loss score) variables. This finding suggests that higher connectivity among NbS patches can lead to an increase in the expected annual loss score from flooding. Specifically, the GWR analysis revealed an average coefficient of 0.235 with a standard deviation of 0.281. This relationship was particularly observed in the densely populated urban areas of Pottstown and Conshohocken cities (Fig. 10e). Lastly, regarding the shape index (SI), there is no evidence that more complex shapes of NbS patches are associated with lower or higher amount of EALS from both global and local perspectives. The highest level of association within the SI is concentrated in the Northern districts of county, gradually diminishing as we move outward from this central area (Fig. 10f).

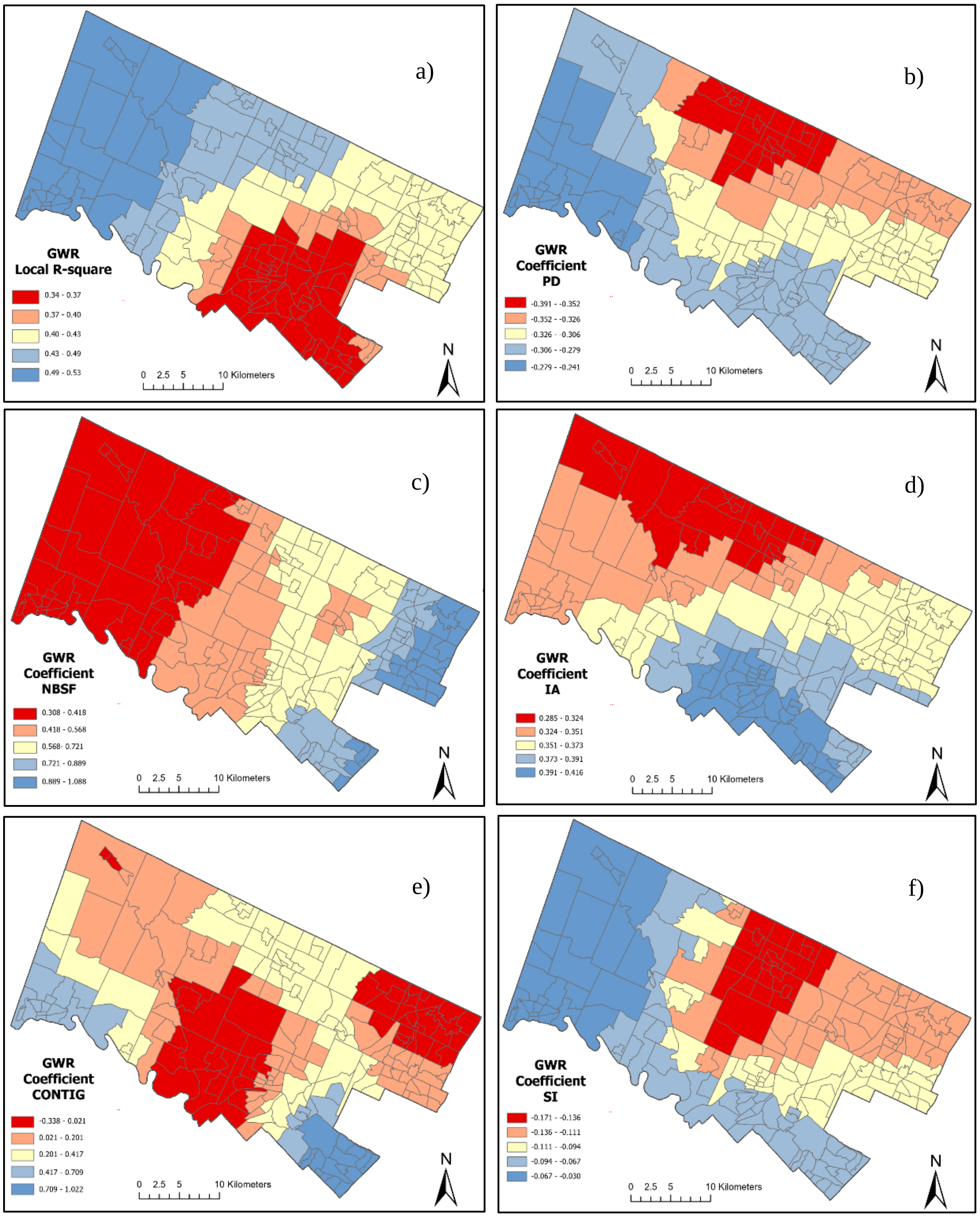

Figure 10. Spatially-explicit GWR results, including a) Local R^2 b) GWR coefficient, population density c) GWR coefficient, NbS in floodplains d) GWR coefficient, impervious surface percent e) GWR coefficient, contiguity index and f) GWR coefficient, shape index.

Discussion

The results of this study show that there is a strong positive association in all census tracts (100.00%) between each of the two variables of impervious surface and NbS size in floodplains with the expected annual loss of flooding in the study area, while population density significantly and positively affects EALS. In contrast, the study findings reveal that irregular NbS patches show limited effectiveness in reducing total loss from flooding. Despite their presence, they do not yield a significant reduction in flood damage. However, the study uncovers a concerning trend with connected NbS patches in nearly one-fifth of the census tracts (21.90%), particularly in densely populated urban areas located in the Southeast and Southwest regions of the County. Surprisingly, the presence of connected NbS patches in these areas significantly amplifies the magnitude of flood loss, exacerbating the damage caused by flooding events.

One notable finding is the positive and statistically significant relationship between the percentage of impervious surface and EALS. The higher flood loss arises from the predominance of impervious surfaces within urban areas, which leads to increased surface runoff and places strain on the drainage system, consequently amplifying the risk of flood hazards. Therefore, it is crucial to consider incorporating "green" elements into gray infrastructure in urban areas across the county. This integration aims to mitigate the impact of impervious surfaces such as roads, buildings, and artificial facilities on flood risk. This finding aligns with previous research that has often observed an increase in flood risk and damage associated with higher levels of imperviousness (Brody and Zahran, 2007). However, it should be noted that other studies, such as Brody and Highfield (2013) on a national scale in the US and Brody et al. (2017), have indicated that the percentage of impervious surface within a community does not have a statistically significant effect on flood property damage. These contrasting findings highlight the complexity of the relationship between impervious surface and flood damage and suggest further analysis to understand the impact of additional factors.

Furthermore, the study results show a significant positive correlation between the size of NbS in floodplains and EALS which is inconsistent with previous findings (Kim, 2021). While scholarly evidence to support the physical basis of this causal relationship is lacking, two plausible explanations are conceivable. First, according to the theory of Gilbert White (1945) which referred to as the "levee effect", the presence of more structural facilities like levees can lead to an increase in human activities and development in flood-prone areas. Similar to this theory, it is probabale that implementing gray infrastructure to protect from flooding in the study area, could lead to create more farms and their associated activities (e.g., constructing new buildings, crop production facilities, etc.), which are considered in more population, property and agriculture loss from flooding. In other words, by having more accessible agricultural NbS in floodplains, with the tidal effects of rivers serving as the main source of irrigation, it is plausible that farmers may produce a greater quantity of crop products, equipments, and facilities which in turn might be at risk of flooding. This leaves many agricultural lands, especially those in floodplains, at risk. As figure 9c shows, farms in this area tend to be concentrated in river valleys because the soils are fertile and easily cultivated. Thus, many farms in this area are vulnerable to floods and the existing NbS has not been able to effectveily mitigate the loss from flooding.

Second, this result could be linked to the inadequate quality of existing and recently implemented NbS and their lack of adaptability to the local ecosystem, leading to a heightened vulnerability of the natural environment to flooding risks (Seddon et al., 2020). Implementing inappropriate NbS in floodplains, which are not suitable for effective natural flood management, could potentially exacerbate the risk of flooding and fail to restore or utilize natural land cover and channel-floodplain features. Therefore, further research is warranted to detect various types of NbS implemented in floodplains as well as constructed infrastructure to understand the intricate human-nature relationships unfolding in these regions, as observed in the case of Chenab River in Pakistan (Tariq et al., 2021).

This study found a significant positive correlation between CONTIG and EALS, suggesting that NbS patterns featuring large contiguous and successive patches contribute to heightened total loss from flooding in some certain geographic locations which is occupied by a denser development. The intensified impact of floods on immediate adjacent buildings loss may be attributed to the presence of larger interconnected NbS patches within dense urban areas, which influence the direction of surface water flow. Alternatively, this finding might be associated with the specific type of hydraulic conductivity between agricultural lands. It is plausible that the interconnected agricultural lands amplify the transfer of floodwater and debris flow to adjacent lands, thereby leading to increased damages (see O'Connell et al., 2007). Lastly, SI is a landscape metric providing information about the complexity and irregularity form of NbS, and a high value of SI indicates a more complex patch shape. Accordingly, there is no evidence showing a significant relationship between shape index and EALS in the study area which is inconsistent with the results of recent studies (Sohn et al., 2021; Kim et al., 2020) which show a relationship between shape complexity of NbS with flood damage and vulnerability.

Conclusions

This study contributes to the existing knowledge by examining the complex spatial relationships between NbS and the expected annual loss score (EALS) of flooding in Montgomery County in Pennsylvania. Firstly, the primary focus is on addressing total property, agriculture, and population loss from riverine flooding rather than simply considering insured claims which includes property damage. In addition, this research aims to explore the spatial heterogeneity of NbS in floodplains, NbS shape, and NbS contiguity through local spatial regression analysis by employing the GWR model offers a more comprehensive analysis compared to GLR model to uncover the spatial variations in NbS configuration and composition. By doing so, the areas with high impact of NbS on flood loss reduction were identified.

The findings emphasize the significance of four key variables: population density, impervious surface, NbS size in floodplains, and CONTIG metric, which collectively account for approximately 45% of the variance in the expected annual loss score resulting from flooding. Although this may appear moderate, it aligns well with similar regression models that explain flood loss at the county jurisdictional level (as observed in Brody et al., 2007). The major results from this study are: 1) smaller amount of NbS in floodplains has the greatest impact on reducing the total damage from flooding; 2) more disconnected NbS patches effectively reduce the annual flood loss in denser areas; 3) lower percentage of impervious surface effectively decrease the annual loss of flooding; and 4) shape complexity of NbS patches does not affect flood loss. Results from the Generalized Linear Regression (GLR) and Geographically Weighted Regression (GWR) models also demonstrate non-stationarity in the relationship among these variables, with the GWR model exhibiting superior model fit when compared to the GLR model.

While this study takes an important first step to consider the potential impact of NbS on total flood loss in one of the fastest growing counties in the U.S., further study is needed on the topic. First, it is important to note that while efforts were made to consider optimal parameters, there is still a possibility that certain parameters were not included in the models. Including additional socioeconomic and environmental variables as well as more landscape metrics and comparing their performances over time could further enhance the study. Second, future research should include variables quantifying specific characteristics of buildings and agricultural lands, such as size, type, building materials, degree of development, etc. Third, I evaluated each metric at the census tract level due to the NRI availability in this level. Additional work should seek to overcome this limitation by examining different metrics at finer scales, particularly at the census block scale by using density-based approaches to downscale the data such as dasymetric mapping. Fourth, future investigations should look within specific urban areas and rural hinterlands to better contextualize the results of this more regional study. Finally, this study has focused on analyzing Montgomery County in the U.S. However, to gain a more comprehensive understanding, further research should consider larger samples of counties or concentrate on more specific geographic areas for in-depth investigation.

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CHAPTER 4

ARTICLE 3: NATURE-BASED SOLUTIONS AND FLOOD VULNERABILITY IN SMALL URBANIZING REGIONS: A CASE STUDY IN THE PHILADELPHIA METROPOLITAN AREA

Introduction

Around the world, floods are becoming more severe, lasting longer, and occurring more frequently because of changes in climate, rapid urbanization, and human demographics (US) (Tellman et al., 2021; IPCC, 2021). Direct flood damages in the United States have cost a total of $99 billion and more than 1,000 deaths over the last 10 years, yet this average hides an upward trend in flood losses over time (NWS, 2022). The findings of a recent study show a 26.4% increase in US floods by 2050 under intermediate climate change scenarios of RCP4.5 (Wing et al., 2022). Recently Hurricane Ida caused an estimated $16 to 24 billion in flooding damage in the Northeastern United States, making it the most expensive storm to impact the region since Hurricane Sandy in 2012, with an estimated $44 billion in insured loss (CoreLogic, 2021). In addition, about 83% of the population lives in urban areas in the United States today, with 89 percent (400 million) of the national population anticipated dwelling in cities by 2050 (UN Habitat, 2018). A once-in-100-year flood threatens 41 million people in the United States alone (Wing et al., 2018). According to projections, urban land cover will nearly double over croplands and forests by 2050 in the U.S. (Seto et al. 2012; Chen et al., 2020), causing the degradation of the local and national ecosystem, exacerbating climate change, human health, and global warming (Venter et al. 2020; Zuniga-Teran et al. 2020).

Given the escalating risk of flooding and projected population change in the U.S., small urbanizing and suburban regions that are growing will need to mitigate the impacts of climate change (Wing et al., 2022; UN Habitat, 2006; US Census Bureau 2021). As some studies indicate, these areas have higher vulnerability to natural hazards due to their lower capacity to cope with extreme weather events, having less priority in regional decision-making, fast growing environmental degradation, and lack of diverse infrastructure systems as well as their tendency to more economic growth. (Cross, 2001; Birkmann et al., 2016; Jamshed et al., 2020; Rumbach, 2016). Yet, there is a lack of understanding about their actual risks and vulnerability to flooding due to few studies undertaking flood risk analysis in smaller regions (O'Donoghue et al., 2021; Lehmann et al., 2021). The flood vulnerability comprised three key dimensions: exposure, sensitivity, and resilience based on the vulnerability framework established by the Intergovernmental Panel on Climate Change (IPCC) (McCarthy et al., 2001), which considers exposure as valued societal elements (e.g., people, buildings) located in floodplains, sensitivity as the likelihood of the entity being adversely affected when exposed to the hazard, due to its inherent characteristics, and adaptive capacity (resilience) as the ability of an entity to make adjustments when confronted with a hazard, thereby diminishing its impact based on definitions in previous research (Tate et al., 2021; Chang et al., 2021; Kim et al., 2021).

Flood-oriented environmental justice (EJ) research has conventionally centered around the unequal distribution of undesirable land uses and socioeconomic status of residents in flood prone areas. Numerous quantitative and spatial investigations have consistently shown that individuals from racial/ethnic minority backgrounds and those with lower socioeconomic status are disproportionately subjected to the risk of flooding (Collins et al., 2018; Wing et al., 2022). Although often low-income and communities of color bear a disproportionate burden of flood hazard due to their living in low-lying and flood-prone areas (Chakraborty et al., 2014), there is not enough evidence to support whether the people in these areas and more especially in smaller regions alongside rivers are always more vulnerable to flooding (Maldonado et al., 2016). Prior EJ and flood vulnerability research often has focused on large and mega coastal cities (Montgomery and Chakraborty, 2013; Mazumder et al., 2022). It is crucial to investigate these areas in more detail because they do not usually suffer from critical burdens experienced in megacities such as land shortage, high-density areas, air pollution, food insecurity, and lack of nature. Moreover, these areas might be better equipped to deal with flooding because they could develop flexible institutions and management practices more easily than large cities (Burkett, 2013). In a nutshell, the varying and scale-dependency of vulnerability assessment raises question of how vulnerable small urbanizing regions are to severe flooding.

The International Union for Conservation of Nature (IUCN) defined NbS as: "actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits." (IUCN, 2009). Given to the capability of NbS to include a brad spectrum of green and blue interventions, it is better to see NbS, similarly to the above definition, as a "promising umbreall concept to address a number of societal and envionrmental challenges arising from climate change, urbanisation, and population growth, through the delivery of ecosystem services". Given to this definition, NbS typically encompass a wide range of approaches and practices such as grasslands, trees, wetlands, and green roofs that leverage nature and natural ecosystems to address various environmental, social, and economic challenges. NbS contributes to flood vulnerability by providing water-related ecosystem services such as stormwater management and flood regulation (McPhearson et al., 2023; Castellar et al. 2021). These features allow water to infiltrate the ground, reducing the volume and velocity of surface runoff during rainfall events. NbS also provides additional benefits like improved air quality, temperature regulation, and enhanced urban aesthetics (Brody et al., 2017; Castellar et al. 2021; Zolch et al., 2017). Yet, the specific application and success of NbS will depend on the local context and the goals of a particular project. While there are different types of implemented NbS depending on the context (McPhearson et al., 2023), for the scope of this study, I will classify two types of NbS, namely trees and shrubs/grasses due to their distinictiveness and predominance in the study area. By delving into these particular NbS categories, we aim to shed light on their specific contributions and practical implications in the context of this study.

However, uneven distribution of urban and regional nature place EJ communities at more risk of climate change (Tozer et al., 2023; Langemeyer & Connolly, 2020). As such, it is necessary to understand how and where this green distributive imbalance is likely to occur and worsen flood vulnerability in fast growing regions (Pallathadka et al., 2021). Yet it is not yet clear exactly its relationship with flood vulnerability including both social and biophysical indicators. In fact, adding limited NbS (e.g., trees and shrubs) in small regions may have significant effects on reducing vulnerability of people and places to flooding, especially in more vulnerable regions (Liu et al., 2021). Therefore, despite the acknowledgment that the NbS has an impact on biophysical flood vulnerability (Kim et al., 2021; Pallathadka et al., 2022), there is little research that examines the linkage between NbS and social and biophysical vulnerability indicators in urbanizing regions (Razzaghi Asl & Pearsall, 2023). To be more precise, empirical knowledge regarding the spatial distribution of NbS and factors influencing social and biophysical vulnerability to floods at the local level and especially in small urbanizing regions is still lacking. This understanding is crucial for guiding adjustments in natural flood mitigation policies to promote social resilience and EJ.

To support the above concerns regarding the growing risk of flooding and the effectiveness of NbS to mitigate this risk in small urbanizing regions, this paper examines the relationship between NbS density and flood vulnerability in eight adjacent small townships/boroughs of Montgomery County in the Philadelphia Metropolitan Area. The primary goals are to pinpoint the areas with the highest vulnerability and lowest NbS density to establish a range of indicators to assess social and biophysical vulnerability related to riverine flooding. To achieve this, I utilize 100-year (1% annual chance of flooding) and 500-year flood (0.2% annual chance of inundation) zones as of 2021 flood hazard maps provided by Federal Emergency Management Agency (FEMA). By integrating socioeconomic data, land cover information, biophysical indicators, and bivariate spatial cluster analysis, I aim to answer two key research questions: firstly, where do high flood vulnerability and NbS density coincide in the study area; and secondly, which social and physical characteristics distinguish these places? Utilizing this analysis can enhance our comprehension of flood vulnerability and facilitate a more equitable integration of NbS, thereby ensuring EJ for all residents.

Study Area

The study area consists of eight regions in Greater Philadelphia in southeastern Pennsylvania, including Upper Merion township, Lower Merion township, Norristown, Conshohocken, Norriton, Plymouth township, Whitpain township, and Whitemarsh township– Montgomery County with a total land area of about 243 km^2 that is prone to Schuylkill River and its sub-branches flooding (Figure 11). The area is located approximately 20 miles north-west of Philadelphia city. The study area experiences a humid subtropical climate, with temperatures ranging from −5°C to 31°C. On average, there are 88 days per year when the minimum daily temperature drops below freezing (0°C), while there are only 10 days per year when the maximum daily temperature falls below freezing (Rossi et al., 2023).

All eight regions are rising in population (U.S. Census Bureau, 2020) with range 0.3-1.89 % between 2010-2020 and have a lengthy history of pluvial flooding (Montgomery County Hazard Mitigation Plan, 2022). Notably, in September 2021, severe flooding resulting from Hurricane Ida affected a significant portion of Montgomery County along the Schuylkill River. Additionally, Norristown, a city within the study area, experienced substantial rainfall, and flooding during Hurricane Irene in August 2011, making it one of the most flood-prone cities in the area (The Reporter, 2021). The study area has experienced increasing precipitation intensity in more recent years driven by climate change (Kunkel et al., 2020). Moreover, the substantial growth in public and commercial services as well as population rate, which form the primary economic activities in the area, has led to a rapid rise in impervious surfaces, amplifying the risk of flash flooding (Rossi et al., 2022). The selection of this study area was driven by three main factors: 1) a moderate-to-high risk of flooding over the next 30 years, as projected by Flood Factor and the National Flood Hazard Layer (NFHL) published by FEMA, 2) a high population growth rate based on the US Census Bureau 2020, 3) diverse types of NbS.

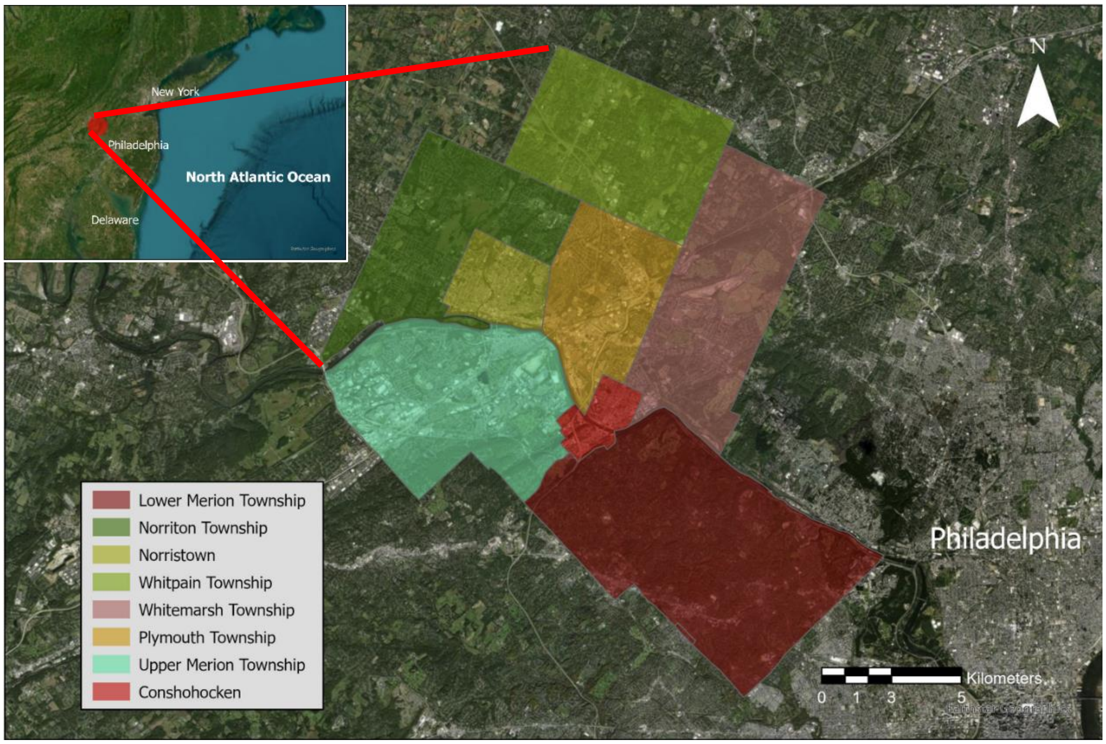

Figure 11. Study site

These regions have a wide range of social and landscape characteristics, while have almost similar climatic attributes allowing for comparative examination (Table 7). For example, while Norristown has the biggest proportion of African Americans (33.9%) and Hispanic residents (26.1%), Conshohocken has the highest proportion of White (93.4%). Upper Merion is majority white (70.2%), but the Asian population (19.1%) is proportionately highest among the eight regions. To my knowledge, we do not have prior research expertise investigating flood vulnerability, NbS, and sociodemographic and environmental variables in this area.

Table 7. Key social and physical characteristics in the study areas.

Characteristics	Study township/borough							
	Whitpain	Plymouth	Whitemarsh	LMT	UMT	Norristown	Conshohocken	Norriton
Mean annual precipitation					1194 mm			
Mean Annual high and low temperature					(-5) - (31) ºC			
Population (2020)	20333	18256	19707	63633	33613	35748	9261	30402
Annual Population Growth Rate (2020)	0.3%	0.8%	1.0%	0.8%	1.89%	0.30%	1.52%	0.20%
Population Density (2020)	871 km^2	1231 km^2	762 km^2	1526 km^2	1122 km^2	5762 km^2	5226 km^2	1434 km^2
Demography (2020)	White:77.3% Black:8.2% Hispanic:10.9% Asian:8.4%	White:77.0% Black:9.2% Hispanic:5.6% Asian:7.5%	White:85.3% Black:2.7% Hispanic:4.2% Asian:7.8%	White:79.7% Black:7.1% Hispanic:3.7% Asian:7.7%	White:70.2% Black:7.3% Hispanic:3.3% Asian:19.1%	White:39.7% Black:33.9% Hispanic:26.1% Asian:3.0%	White:93.4% Black:2% Hispanic:1.8% Asian:2.1%	White:78.2% Black:12.0% Hispanic:6.9% Asian:4.5%
Impervious Surface Areas % (2016)	33%	48%	36%	25%	43%	62%	67%	37%

LMT: Lower Merion Township; UMT: Upper Merion Township

Methodology

This study uses a GIS-based approach to examine the relationship between NbS and flood vulnerability. Given to the above definitions, NbS is an holistic and flexible concept that includes all green and blue land cover which could provide different types of ecosystem services. Different studies have considered NbS with diverse lenses for their objectives. In each case and depending on societal or environmental challenges that are supposed to be mitigated, one or more types of NbS should be considered. NbS is case based. Since most of the area has been covered by grass and trees, this study concentrates on two widely recognized types of vegetative NbS: tree canopy and shrub/grass cover. These two NbS types have been extensively documented in prior research for their effectiveness in pluvial flood regulation, as they offer substantial green coverage and sufficient water storage capacity (Kuehler et al., 2017; Hobbie & Grimm, 2020). I explore these patterns in eight urbanizing regions within the Philadelphia Metropolitan Area.

In this study, flood vulnerability score for each CBG, was conducted using the Intergovernmental Pannel on Climate Change (IPCC) formula including three components of exposure, sensitivity, and resilience (adaptability). Six steps were carried out to analyze the spatial coincidence between flood vulnerability scores and NbS density: (1) data collection and extraction of thematic layers, (2) construction of flood sensitivity, exposure, and resilience maps using ArcGIS Pro and different overlay approaches, and (3) explaratory spatial analysis to calculate the spatial coincidence of NbS density and flood vulnerability using Local Indicators of Spatial Association (LISA). The methodology of this research is shown as a flowchart in Fig. 12.

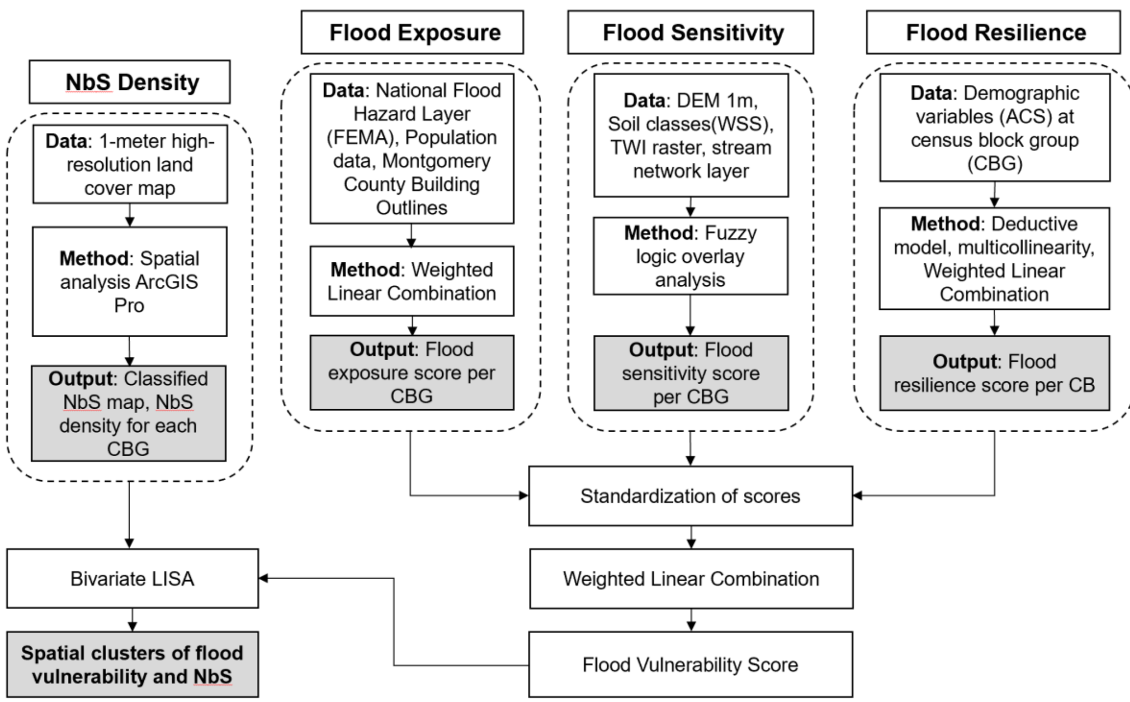

Figure 12. The workflow of an spacially explicit modeling approach in this research

I chose the census block groups (CBG) as the unit of analysis because it provided the most detailed geographic data available for the desired demographic and environmental sample.

Data and Methods Used

Flood Zone Map

I acquired the flood hazard area delineation from the Federal Emergency Management Agency (FEMA), which included the 100-year (1% annual chance of flooding) and 500-year flood (0.2% annual chance of inundation) zones as of 2021. These zones are categorized as high risk and moderate risk, respectively. I combined these two layers because they collectively offer broader spatial coverage, which is important in the context of potential future uncertainties. The merged zone provided complete coverage across all eight regions. The analysis in this study was conducted using data from 193 CBGs within the study area. Eighteen indicators selected based on a comprehensive review of previous flood vulnerability research were combined into a flood vulnerability score (Cutter et al., 2003; Tate et al., 2021; Rehman et al., 2019; Moreira et al., 2021; Ouma and Tateishi, 2014) (Table 2).

NbS Density

For calculating NbS density, I employ high-quality land cover datasets with a spatial resolution of 1 meter, sourced from the University of Vermont Spatial Analysis Laboratory via the Pennsylvania Spatial Data Access (PASDA). These dataset uses leaf-off Light Detection and Ranging (LiDAR) data from 2006-2008, leaf-off orthoimagery from 2005-2008, and leaf-on orthoimagery from 2013. Assigning land cover classes considers a rule-based expert system integrated into an object-based image analysis technique (OBIA). The land cover map was reclassified to show two types of vegetated NbS including trees and shrub/grass (Fig. 13). To calculate the NbS density at the Census Block Group (CBG) scale, I divided the area covered by NbS features that intersected a

CBG by the total area of that CBG. This method allows us to quantify the presence of NbS in relation to the geographic extent of each CBG accurately.

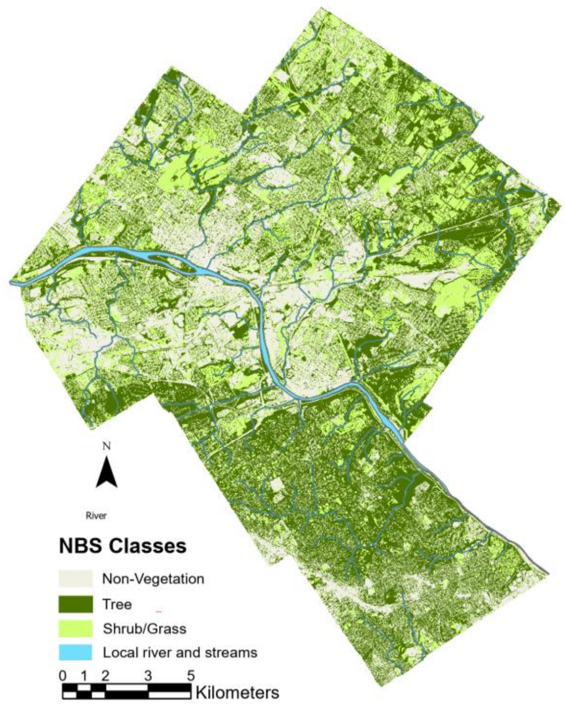

Figure 13. Nature-based solutions classification in the study area

Flood Vulnerability Indicators

Table 8 shows all indicators of vulnerability and their datasets used in this work. The selection of vulnerability variables was cariied out based on prior research and flood vulnerability assessments, as they are recognized as key indicators of vulnerability to flooding (Pallathadka, et al., 2022; Tate et al. 2021; Chakraborty et al. 2014; Raduszynski et al. 2023; Sauer et al., 2023; Fenglin et al., 2023). Previous flood vulnerability assessments tended to largely focus on either social or biophysical indicators, with few using a combination of both. Since the goal of this study is not creating a comprehensive robust vulnerability index, nor advancing the current assessment models, rather focusing on the coinciding NbS density and vulnerability as sum of the impacts of three different components (exposure, resilience, and sensitivity) in the study area, I used a deductive model to include resilience indicators. Deductive models follow a top-down approach, employing a more direct index (Tate, 2012). Usually, these models select ten or fewer variables, standardize them, and aggregate them into a single index (Cutter et al., 2000; Meijer et al., 2023). An illustration of this approach was firstly demonstrated by Cutter et al., 2000 in Georgtown County, South Carolina, in which they created an index, the Social Vulnerability Index (SVI), through a combination of literature review and expert interpretation. The following sections explain the selected indicators and the used methods.

Table 8**.** Indicators of flood vulnerability

Components	Indicators	Data source	Direction	Range
Exposure	Population	ACS 2020	+	325 ~ 4221
	Property	Pennsylvania Spatial Data Access (PASDA) (2023)	+	6 ~ 1494
Sensitivity	Elevation (DEM)	USGS 2015 (1-meter DEM)	-	0 ~ 152
	Slope	USGS 2015 (1-meter DEM)	+	0-87
	Soil class	Web Soil Survey (WSS)	+	
	Topographic wetness index (TWI)	Pennsylvania Spatial Data Access (PASDA) (2020)	+	-1.2 ~ 27.9
	Tpographic position index (TPI)	USGS 2015 (1-meter DEM)	-	-24.9 ~ 26
	Drainage density	Pennsylvania Spatial Data Access (PASDA) (2000)	+	0 ~ 0.003
Resilience	Median household income ($)	ACS 2020	+	27600~ 250000
	Population with bachelor's degree (%)	ACS 2020	+	0 ~ 0.67
	Population aged 65 and above (%)	ACS 2020	-	0.03 ~ 0.71
	Population aged 5 and below (%)	ACS 2020	-	0.02 ~ 0.21
	Poverty (%)	ACS 2020	-	0 ~ 0.26
	Renter (%)	ACS 2020	-	0.08 ~ 0.85
	Black population (%)	ACS 2020	-	0 ~ 0.94
	Asian population (%)	ACS 2020	-	0 ~ 0.82
	Median housing value ($)	ACS 2020	+	0 ~ 1594000
	Employment in transportation and public utilities (%)	ACS 2020	-	0 ~ 0.16

Flood Resilience Score

The initial stage of the deductive approach involves the selection of input variables. In accordance with Meijer et al., (2023), I commenced by excluding variables deemed 'obviously redundant' based on the multicollinearity threshold ($\rho > 0.9$) of the input variables. Variables with stronger backing in the literature (e.g., median housing value, poverty) were retained, while other variables were held under consideration for subsequent stages. Among the remaining 10 variables (Table 8), the correlations between variables were re-evaluated using Pearson's ρ, employing a threshold value of 0.7. Although the two variables of "Median household income" and "Median housing value" were highly correlated ($\rho=0.8$), I kept these variables in the analysis due to some justifications: (1) "Median household income" and "Median housing value" may capture distinct facets of socioeconomic status. While they might be correlated, they could have different implications for social resilience and adaptability to flooding. For instance, income may affect access to resources for immediate recovery, while housing value might influence long-term adaptive capacities, (2) including both variables provides a more comprehensive understanding of the socioeconomic factors influencing resilience and adaptability. This approach allows for a nuanced analysis that considers the joint impact of income and housing value on the dependent variable, providing a more holistic picture, (3) there is also a few theoretical basis for keeping these variables in the study. First, both income and housing value can be viewed as components of the social system affecting adaptive capacities in socio-ecological systems (SES). SES theory supports examining multiple dimensions of socioeconomic status to understand how they collectively influence resilience to flooding. Second, both income and housing value contribute to the community's capital assets, influencing its ability to cope with and recover from flooding events. The Capital Assets framework supports the inclusion of multiple forms of capital in the analysis (Moser, 1998). Finally, based on social capital theory, both income and housing value may influence social capital. For instance, higher income may enable participation in community networks, while housing value might impact the stability of social ties. Including both variables aligns with a social capital perspective on resilience.

To calculate flood resilience, I utilized 5-year estimates of sociodemographic variables from 2020, which were generated by the U.S. Census Bureau as part of the American Community Survey (ACS). The subsequent phase entailed the standardization of each parameter into a linear scale ranging from 0 to 1, with associated equal weights determined using minimum-maximum rescaling formula below.

$$V_i = \frac{X_i - X_{imin}}{X_{imax} - X_{imin}}$$

Where V_i = normalized value of indicator X_i, X_{imin}, and X_{imax} represent the minimum and maximum values of a specific indicator i, respectively. To standardize indicators that exhibit an inverse relationship with flood resilience, the following formula was employed:

$$V_i = \frac{X_{imax} - X_i}{X_{imax} - X_{imin}}$$

These distinct factors were then aggregated through a weighted linear combination (WLC), following a straightforward additive weighting method as expressed by the following equation:

$$F(x) = \sum Wi.Xi$$

where Wi is equal to normalised criteria scores, and Xi is criteria weights. The aggregation method of WLC was used to map the flood resilience vulnerability.

Flood Exposure Scores

The population data was taken from the ACS 2020 for each CBGs. To calculate property in each CBGs, I used the Montgomery County Building Outlines 2023 dataset obtained from the Pennsylvania Spatial Data Access (PASDA). Similar standardization method was used to normalize all values into a linear scale ranging from 0 to 1. A WLC model was utilized in ArcGIS Pro to overlay two property and population layers to extract flood exposure score per CBG.

Flood Sensitivity Scores

The environmental data for mapping flood sensitivity is derived from different sources. The one-meter resolution digital elevation model (DEM) data was taken from the U.S. Geological Survey (USGS) and then used for creating slope map through Slope function in Arc GIS Pro. Different soil groups dataset was taken from the Web Soil Survey (WSS) including four major classes of A (high infiltration rate), B (moderate infiltration rate), C (slow infiltration rate), and D (very slow infiltration rate). To consider hydrological parameters in the flood sensitivity analysis, I used three specific indicators including Topographic Wetness Index (TWI), Topographic Position Index (TPI), and drainage density. TWI is a wetness index that can be used as an indicator of an area that has the potential for flooding (Pourali et al., 2016). The Topographic Wetness Index (TWI), the most commonly used hydrologically based topographic index, describes the tendency of a cell to accumulate water; it is defined as follows,

$$TWI = \ln\left(\frac{SCA}{\tan\varphi}\right)$$

where SCA is the Specific Catchment Area and φ is the slope angle, assuming the properties of the soil as uniform. Well-drained dry areas (steep slopes) are associated to low TWI values (Mattivi et al., 2019). I used the TWI dataset provided by the Pennsylvania State University in 2020 taken from the Pennsylvania Spatial Data Access (PASDA). TWI raster datasets uses 2006-2008 LiDAR (Light Detection and Ranging) elevation points produced by the PAMAP Program. TPI is a straightforward and highly efficient technique for categorizing landforms into slope positions and surface segments (Bashir, 2023). TPI factor values are instrumental in identifying and characterizing different relief landforms, including valleys, slopes, and relief ridges (Lin and Billa, 2021). The TPI map depicts areas with a significant likelihood of experiencing waterlogging. It is calculated by comparing the elevation of each pixel to its surrounding neighbors.

Additionally, higher drainage density values are indicative of reduced infiltration rates and increased surface flow velocity (Dragičević et al., 2019). High drainage density is frequently associated with elevated sediment transport within the river network, increased flood peak levels, steep terrain, and reduced suitability for agriculture. The drainage density values were calculated by using stream network layer obtained from PASDA and the total drainage area based on this formula:

$$D_d = \frac{\sum_1^n L}{F}$$

where, L is the length of the waterway [km], N is the number of waterways, and F is the contributing drainage area [km^2].

To measure flood sensitivity for each CBG based on six different indicators, I used Fuzzy logic overlay analysis. Fuzzy theory is an approach for assessing previously neglected information within the traditional set concept, represented as a real value ranging from 0 to 1, which corresponds to the degree of membership (Zadeh, 1965). Recently, many studies have adopted this theory into spatial analysis, such as disaster vulnerability analysis, susceptibility analysis, and site selection analysis (Kim et al., 2021; Yang et al., 2018). Hence, drawing from a thorough review of existing literature, I employed fuzzy logic overlay analysis to quantitatively assess the spatial dimensions of flood sensitivity. This study followed a standard workflow, encompassing the four key steps including: 1) problem definition and site selection criteria, 2) criteria layer collection, 3) assignment of fuzzy membership values, and 4) execution of fuzzy overlay analysis. The first two steps, involving the evaluation of flood sensitivity, had already been completed. I proceeded with the second step by conducting a multicollinearity test among six input variables using Pearson's ρ, with a threshold set at 0.7. The results revealed no significant collinearity between the variables, suggesting the absence of redundancy. Consequently, this third step was executed based on fuzzy logic membership functions. I employed two specific fuzzy logic membership functions: MS Small and MS Large. These functions derive their names from their sigmoid-shaped graphs and are characterized by their relationship to the mean and standard deviation. MS Small assigns a high fuzzy membership to values below the mean, while MS Large assigns a high fuzzy membership to values above the mean. The selection of these functions was made following an analysis of the data distribution of the indicators. In this study, the MS Small membership function was applied to elevation, slope, and drainage density, with high fuzzy membership assigned to values less than the mean. Conversely, the MS Large membership function was used for soil type, TWI and TPI, with high fuzzy membership assigned to values greater than the mean. By appropriately assigning these fuzzy membership values, we generated several reclassified surfaces, each displaying values between 0 and 1. The fourth step involved the overlaying of these reclassified surface layers (Fig 14). The choice of the appropriate type of fuzzy overlay was a critical consideration in deriving the final spatial representation of flood sensitivity. There exist five types of fuzzy overlays: AND, OR, Product, Sum, and Gamma. In this study, I opted for the Gamma (0.9) type due to its complexity, which demands expert knowledge and a combination of various submodels (Kim et al., 2021; Parsian et al., 2021).

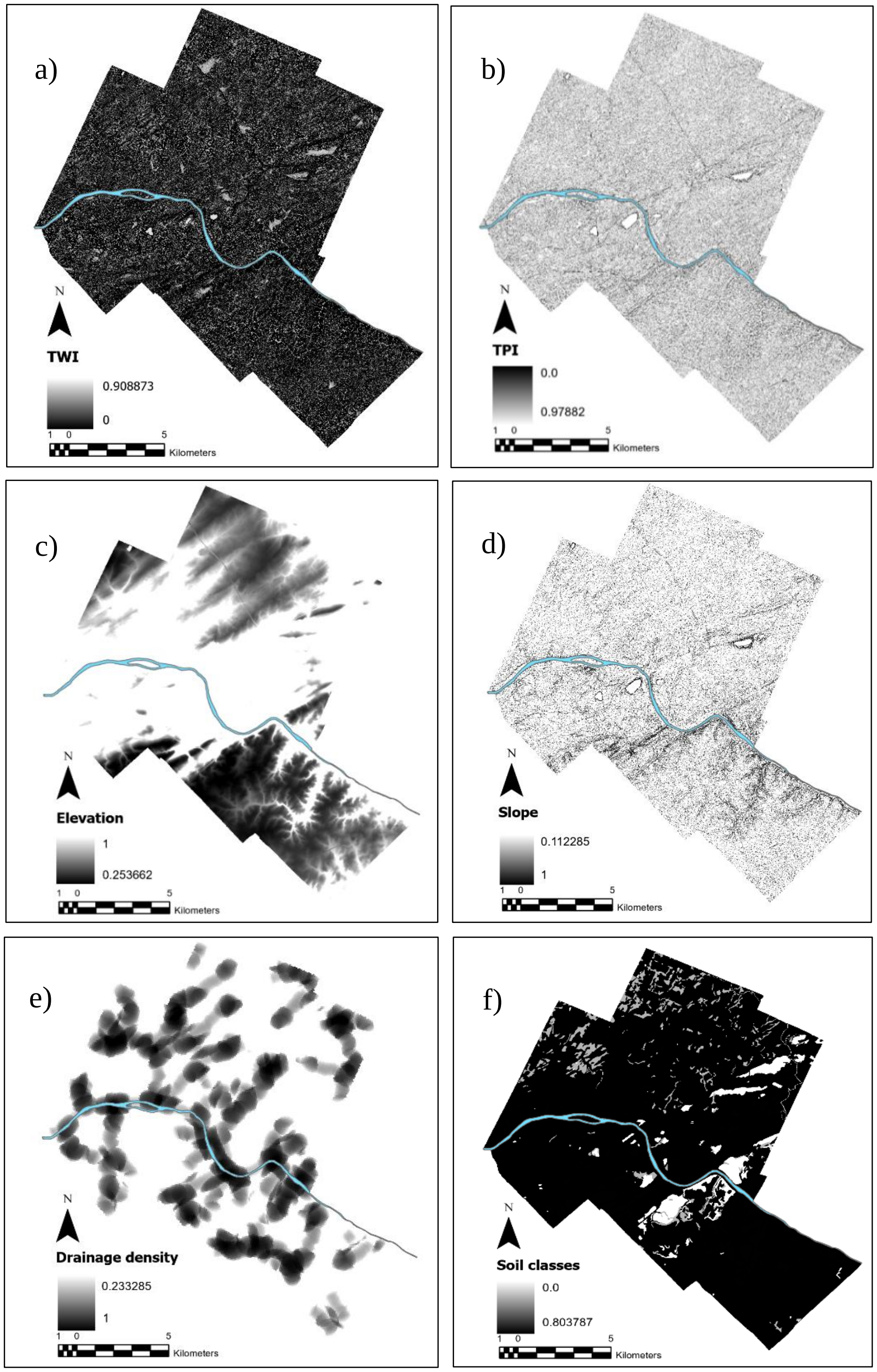

Figure 14. The results of fuzzification of flood sensitivity indicators: (a) TWI, (b) TPI, (c) elevation, (d) slope, (e) drainage density, and (f) soil classes.

During the execution of the fuzzy overlay analysis, the river area was excluded where the possibility of flooding within the study site was determined to be non-existent.

Flood Vulnerability Scores

The normalized values of flood exposure, flood sensitivity, and flood resilience were used to quantify flood vulnerability score for each CBG spatially. To create a flood vulnerability map for each CBG, a weighted linear combination formula using the IPCC's framework is applied below.

Flood vulnerability= Flood exposure + Flood sensitivity – Flood resilience

Based on previous studies, I equally weighed the components (Cutter et al., 2003; Chang et al., 2021). The final composite flood vulnerability score is then normalized again to have a range between 0 and 1 (0 = the least vulnerable, 1 = most vulnerable). (Fig. 15)

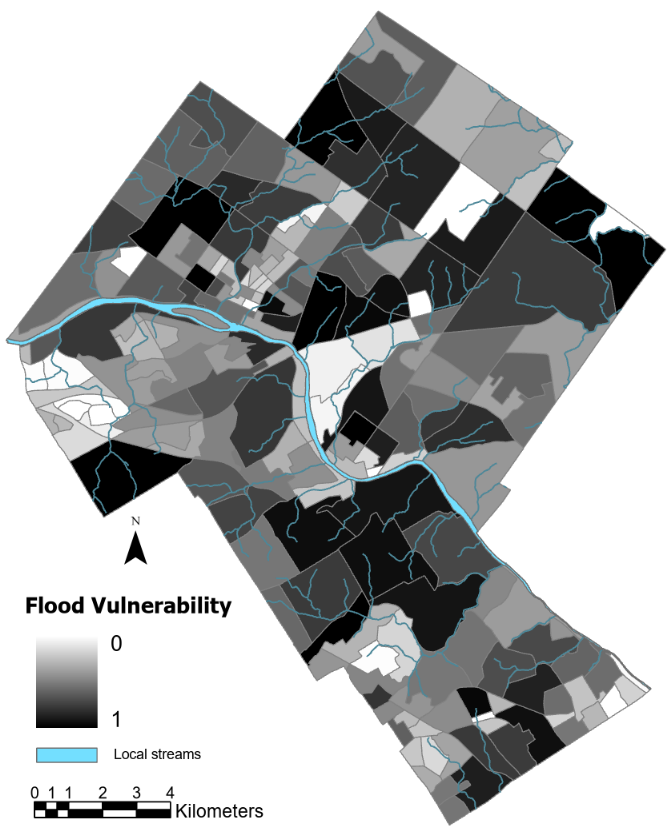

Figure 15. The results of the flood vulnerability assessment

The most vulnerable regions are situated in Lower Merion, Plymouth, and Norriton. These areas exhibit several key characteristics, including a significantly higher population density, greater property exposure, a higher percentage of Black and Asian populations, a higher proportion of renters, elevated poverty rates, and a notable concentration of employment in transportation and public utilities. Surprisingly, these regions also display a comparatively higher income level and housing value near the Schuylkill River. Moreover, there are some CBGs with lower vulnerability score that are located far away from the main river which might be related to their proximity to local streams as well as lower population and exposure properties to flooding. In contrast, certain CBGs with lower vulnerability scores are situated in proximity to the river, particularly within the Plymouth and Conshohocken regions. These areas are primarily characterized by public commercial buildings, which are comparatively at a lower risk of flooding compared to the aforementioned residential regions. In terms of their biophysical attributes, the vulnerable areas demonstrate a lower soil filtration rate, steeper slopes, a reduced topographic position index (TPI), encompassing valleys, a higher drainage density, and an elevated topographic wetness index (TWI), indicating the presence of more water-related features near the Schuylkill River and its tributary streams.

Exploratory Spatial Analysis

Bivariate spatial distribution maps are becoming a more common result of integrated geospatial analysis. However, cluster mapping using Local Indicators of Spatial Association (LISA) can be used to discover coincident extremes that are also spatially nonrandom. LISA assesses spatial autocorrelation, or the degree to which values in one location are comparable to those in other areas (Anselin, 2005). To map statistically significant clusters of phenomena of interest, LISA statistics can be performed in both univariate and bivariate modes using GeoDa version 1.20. Previous studies used both univariate and bivariate LISA statistics to investigate geographical autocorrelation in social vulnerability (Tate et al., 2021; Frigerio et al. 2018; Cutter and Finch 2008), however, there is no study to quantify social and biophysical vulnerability and specifically in association with NbS distribution. The global Moran's *I* can detect the spatial dependency of flood vulnerability and NbS density.

$$\text{Moran's } I = \frac{N}{\sum_{i=1}^{N}\sum_{j=1}^{N} W_{ij}} \times \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} W_{ij}(X_i - \overline{X})(X_j - \overline{X})}{\sum_{i=1}^{N}(X_i - \overline{X})^2}$$

where W_{ij} is a spatial weight matrix which define the spatial interaction between X_i and its neighboring pixels X_j, and $\overline{X}$ is the mean pixel intensity level within the neighborhood.

I used bivariate LISA to quantify spatial clusters of NbS distribution and surrounding flood vulnerability using the flood vulnerability scores and NbS density as below.

$$\text{LISA } \frac{(X_i - \overline{X})}{\sum_{i=1}^{N}(X_i - \overline{X})^2} \sum_{j=1}^{N} W_{ij}(X_j - \overline{X})$$

LISA distinguishes between two types of spatial dependence: positive spatial autocorrelation (clusters) and negative spatial autocorrelation (heterogeneity). Positive autocorrelation arises when high values of flood vulnerability are found in proximity to high values of NbS density (High-High hotspots), while negative autocorrelation manifests when low values of flood vulnerability are surrounded by low values of NbS density (Low-Low cold spots). In this context, clusters with high flood vulnerability and low NbS density can be considered as priority areas and hold significance in tailoring mitigation policies. Conversely, regions with limited NbS features, coupled with low flood vulnerability, fall under the category of low concern. Areas characterized by abundant NbS features and vulnerability may require customized NbS infrastructure. Pearson’s correlation coefficients were used to examine the direction and strength of the relationship between NbS density and flood vulnerability score for each CBG. The results will shed light on how effectively current and past NbS, and flood policies have addressed socio-ecological vulnerability to flooding in these locations.

Results

The global bivariate Moran's I statistic registers at 0.231, suggesting a relatively low level of positive spatial autocorrelation. This implies that, on average, the connection between flood vulnerability and NbS density within the study area exhibits only a minor degree of spatial grouping. Nevertheless, it's essential to note that global statistics may obscure significant localized variations in spatial autocorrelation. As a result, I conducted bivariate LISA analyses to depict spatial autocorrelation patterns within each CBG. The findings reveal distinct geographic arrangements of spatial clustering. In Figure 16, you can find maps displaying bivariate LISA clusters (Figure 15a) and corresponding statistical significance (Figure 16b). Even as the significance threshold increases from $p < 0.05$ to $p < 0.01$, the locations of these clusters remain relatively consistent with emerging some new CBG, especially in West Norriton and Plymouth according to the significance map. The most of High-High clusters occur in Lower Merion and Norriton.

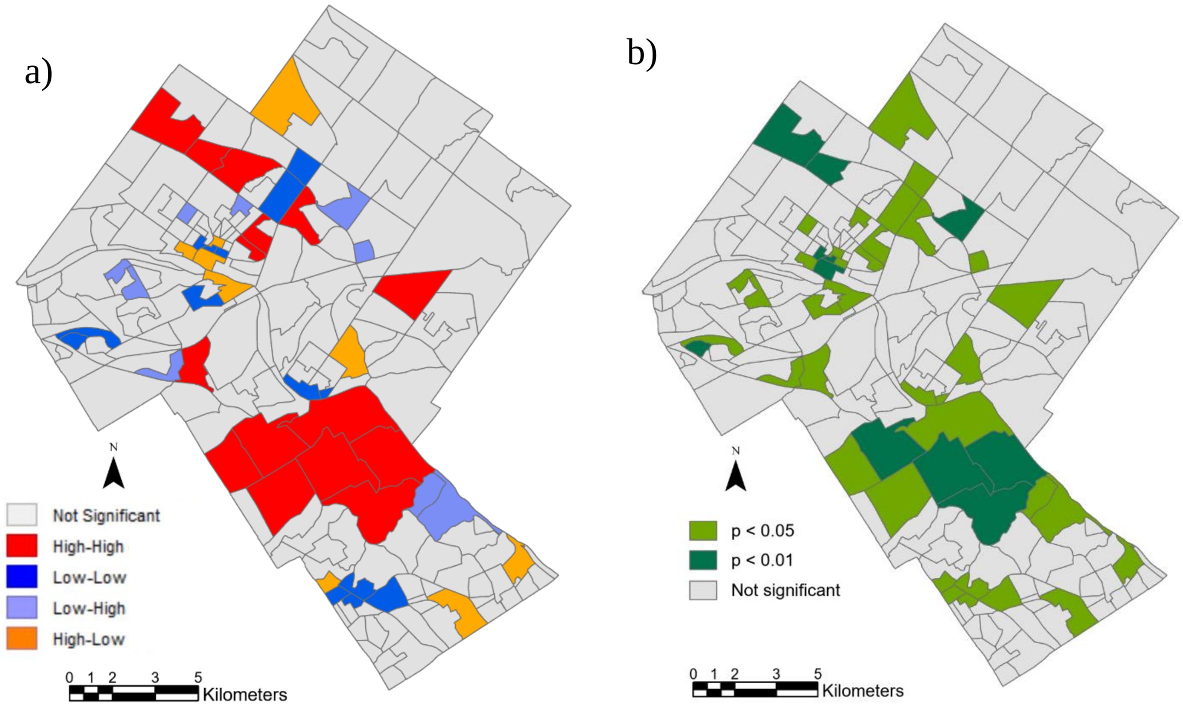

Figure 16. LISA of flood vulnerability and surrounding NbS density. **a)** Cluster map and **b)** Cluster significance

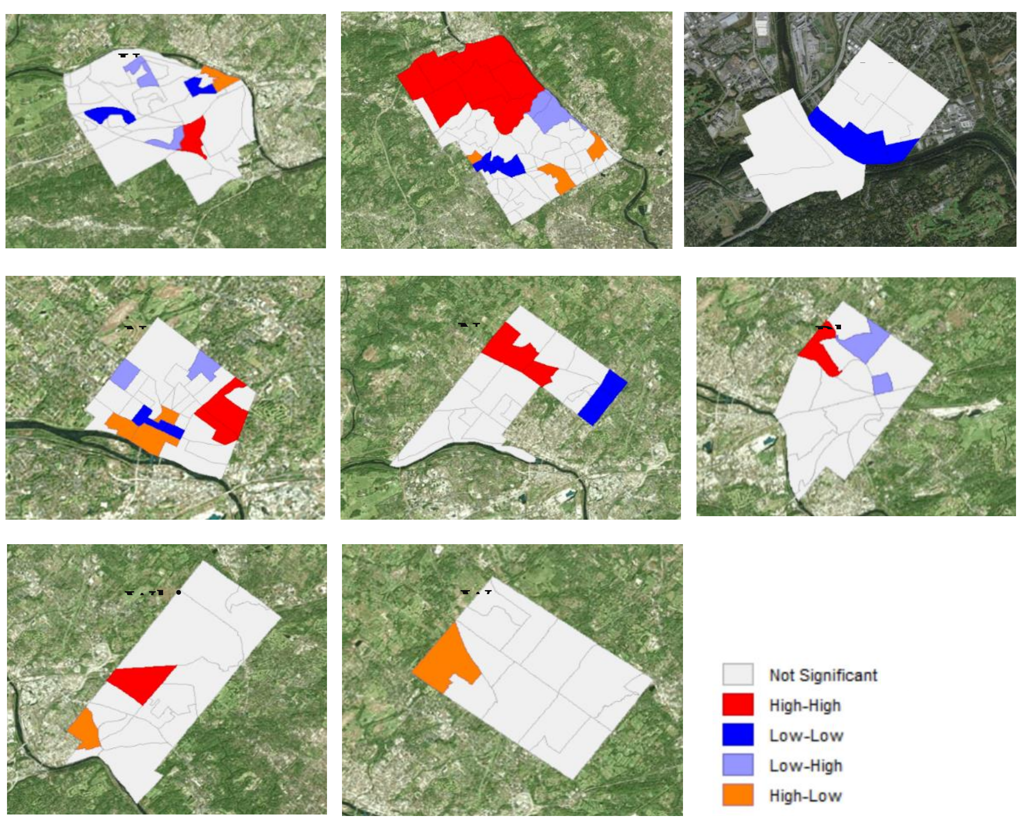

Figure 17. Bivariate LISA for eight different townships/boroughs

The high-low (HL) clusters, depicted in orange, represent areas where CBG with elevated flood vulnerability are adjacent to CBG characterized by low NbS density. Considering the elevated flood vulnerability in HL clusters, it is undoubtedly advisable to prioritize these areas for NbS investment. These clusters are most notably found in five regions with the highest (by total area) in Whitpain, with smaller clusters in Upper Merion, Lower Merion, Norristown, and Whitemarsh (Fig. 17). CBG within these HL clusters boasts a population density of 6 individuals per acre in habitable areas, signifying a significantly higher level of urbanization compared to the national average. In total, these HL clusters are inhabited by approximately 13854 people. Demographically, HL clusters are occupied by African Americans (21%) and Asian (3%). The $89000 median household income is above the national average which is $70000.

Additionally, the High-Low (HL) clusters encompass a total of nine Census Block Groups (CBGs) distributed across five regions, accounting for 6% of the total population, with a higher concentration in the city of Norristown. HL clusters exhibit a relatively higher density of tree canopy (>0.3) in suburban CBGs compared to grass (<0.25), while they have low densities of both types of NbS in urbanized CBGs (<0.1) (Fig. 13). The results reveal a relatively strong correlation (r^2=0.62) between NbS density and flood vulnerability in Plymouth Township, which has an average lower density of NbS compared to other regions.

The high-high (HH) hotspots, represented in red, correspond to regions where CBG exhibit above-average flood vulnerability and are surrounded by CBG demonstrating higher-than-average NbS density. These hotspots are primarily concentrated in Lowe Merion Township, with a higher degree of drainage density. These spatial patterns are evident in the regions' maps for flood vulnerability (Fig. 14), but they become even more pronounced in the bivariate analysis. Overall, CBGs within these hotspots are predominantly suburban and agricultural featuring a population density of 2 individuals per acre in habitable areas. Collectively, these HH clusters are inhabited by approximately 20587 people.

The low-high (LH) and low-low (LL) clusters also identify locations with bivariate extremes. The low-high clusters depict areas characterized by low flood vulnerability alongside neighboring high NbS density and are inhabited by around 8400 people. In these areas, extreme floods or substantial changes in flood probability are unlikely to have a significant impact due to the substantial presence of NbS. The LH clusters are located in Plymouth, Upper Merion, Lower Merion, and Norristown. LH clusters demonstrate a comparatively greater density of grasslands (>0.45) in contrast to trees (<0.25), suggesting that grasslands may have a more substantial impact than trees in mitigating overall vulnerability to flooding. The low-low clusters are located specifically on the riverside of Conshohocken city and densely populated area in Norristown. These regions showcase the most minimal levels of both flood vulnerability and NbS density, making them low concern candidates for future considerations in the development of nature-based flood mitigation policies.

Because of the exploratory nature of Local Indicators of Spatial Association (LISA), the resulting spatial clusters do not possess significant statistical explanatory power. However, they do serve as valuable pointers for further investigation (Tate et al. 2021). I utilized these clusters to address the second research question: What indicators distinguish High-Low (HL) hotspots from other areas? Table 9 highlights indicators displaying significant differences in average values between tracts within High-Low (HL) clusters and all other tracts. These results are related to the LISA cluster significance level of 0.05. Notably, italicized rows in Table 9 signify indicators that exhibit a decrease in mean value as one transitions into an HL cluster. It's important to note that all indicators demonstrated statistically significant distinctions between HL clusters and other areas ($p < 0.01$) other than flood exposure component in Norristown with almost no change. By dissecting the HL clusters, our attention is directed towards the lower end of the vulnerability spectrum. The HL clusters focus on the socioeconomic and environmental traits of highly vulnerable regions that encompass comparatively less amount of two types of NbS. The top distinguishing components for HL clusters are flood exposure in Upper Merion (151%) and flood sensitivity in Lower Merion (133%).

Table 9**.** Distinguishing characteristics of high–low clusters

Site	Indicator	High-low	All others	% Change
Upper Merion	Flood exposure	0.83	0.33	151.1
	Flood sensitivity	*0.05*	*0.13*	*-61.5*
	Flood resilience	*0.55*	*0.68*	*-19.1*
	NbS Density	*0.34*	*0.74*	*-54.0*
Lower Merion	*Flood exposure*	*0.43*	*0.45*	*-4.4*
	Flood sensitivity	0.28	0.12	133.3
	Flood resilience	*0.62*	*0.71*	*-12.6*
	NbS Density	0.83	0.73	13.6
Norristown	Flood exposure	0.35	0.35	0.0
	Flood sensitivity	*0.015*	*0.018*	*-16.6*
	Flood resilience	*0.49*	*0.59*	*-16.9*
	NbS Density	*0.32*	*0.47*	*-31.9*
Whitpain	Flood exposure	0.78	0.45	73.3
	Flood sensitivity	0.38	0.24	58.3
	Flood resilience	*0.56*	*0.60*	*-6.6*
	NbS Density	*1.07*	*1.08*	*-0.9*
Whitemarsh	Flood exposure	0.63	0.47	34.0
	Flood sensitivity	*0.21*	*0.34*	*-38.2*
	Flood resilience	*0.55*	*0.64*	*-14.0*
	NbS Density	*0.93*	*0.95*	*-2.1*

Rows in italics indicate indicators that exhibit a decrease in their mean values when transitioning into a high-low (HL) cluster.

NbS density and flood vulnerability are significantly correlated to each other in six of eight regions other than Conshohocken and Whitemarsh (Table 4); however, correlations are relatively modest ($0.13< r^2 <0.62$, $p<0.05$). In all six regions, NbS density and flood vulnerability are significantly and negatively correlated, meaning the more NbS, the less flood vulnerability. In Plymouth, NbS density and flood vulnerability are moderately correlated to each other ($r^2=0.62$), whereas in Whitpain, two variables are weakly correlated. This outcome can be attributed to a notable characteristic of Plymouth township's landscape. Specifically, nearly half of the township's land cover is dominated by impervious surfaces, characterized by the presence of shopping malls and extensive parking lots. In stark contrast, the remaining portion of the township boasts lush, densely vegetated areas. This stark dichotomy in land use patterns, with one side characterized by extensive impervious surfaces and the other adorned with thriving greenery, contributes significantly to the observed result. The highest negative significant Pearson coefficient is seen in Norriton, a highly urbanized region.

In terms of correlation between flood sensitivity and NbS density, there is a negative significant association in all regions with relatively high correlation ($0.45< r2 <0.85$, $p<0.05$). The highest R^2 among these regions is for Norriton ($r^2=0.85$) followed by Conshohocken ($r^2=0.80$). Furthermore, in three out of the eight regions, including Norristown, Upper Merion, and Lowe Merion there exists a notable and statistically significant positive correlation between NbS density and flood resilience (as shown in Table 4), meaning a denser NbS, more resilience to flooding. However, it's worth noting that these correlations are relatively moderate ($0.39< r2 <0.58$, $p<0.05$), with coefficients ranging from 0.103 to 0.276. Lastly, since higher flood exposure is usually associated with lower NbS density, a significant negative correlation with relatively high correlation is seen between these two variables in Whitpain ($r2= 0.72$, $p<0.05$). Yet, flood exposure and NbS density are positively and significantly correlated in three regions including Plymouth, Lowe Merion, and Norristown with moderate correlation ($0.30 < r^2 < 0.56$, $p<0.05$) which might be related to the building layouts (e.g., multilevel) and other impervious surfaces (e.g., roads).

Table 10**.** Correlation coefficient between NbS density and flood vulnerability components in each region.

Components	**Regions**							
	Whitpain	Plymouth	Whitemarsh	LMT	UMT	Norristown	Conshohocken	Norriton
Flood vulnerability	-0.184**	- 0.552*	0.406	- 0.313*	- 0.323**	- 0.312**	0.984	- 0.592*
Flood sensitivity	-0.688	-0.480*	-0.611**	- 0.589	-0.316*	-0.133*	-0.403**	-0.940*
Flood resilience	0.669	- 0.143	0.202	0.276*	0.103**	0.133*	-0.251	-0.153
Flood exposure	-2.722**	0.635**	-0.055	0.357**	0.290	0.586*	-0.212	-0.057

LMT: Lower Merion Township; UMT: Upper Merion Township
* Correlation is statistically significant at the 0.01 level.
** Significant at the 0.05 level.

Discussion

Being among the limited number of studies investigating flood vulnerability across various small urbanizing regions and considering multiple factors, the present research sheds light on the intricate aspects of flood vulnerability at a more detailed spatial level within the combined 100-year and 500-year floodplains. While it lacks explanatory detail, the LISA findings assist in pinpointing areas and aspects of flood vulnerability that warrant further investigation. The LISA analysis highlights priority areas with higher scores of flood vulnerability coupled with lower densities of two types of vegetated NbS including tree canopy and shrubs/grasses. Among the studied eight small urbanizing regions situated within the Philadelphia Metro Area, Norristown stands out with the highest concentration of HL clusters, with Lower Merion and Whitpain townships following closely behind in second and third place, respectively. Remarkably strong correlations emerge when examining the relationship between various factors and the density of NbS in CBGs. Specifically, there is a statistically significant correlation between flood sensitivity and NbS density across all CBGs. Additionally, flood resilience exhibits a robust 63% correlation with NbS density, underlining the importance of vegetated areas in bolstering community resilience to floods. Moreover, flood vulnerability shows a substantial 88% correlation with NbS density, underscoring the pivotal role of NbS in reducing vulnerability to flood events. Finally, flood exposure, though still showing a significant 7% correlation with NbS density, seems to be relatively less affected by the density of NbS in CBGs compared to other factors. This could be attributed to the interplay of buildings and activities within green spaces. This suggests that the rise in green space does not necessarily lead to a reduction in the resident population and the number of buildings in the area.

Surprisingly, the High-Low (HL) clusters comprise lowe percentage of black residents (compared to other CBGs) with an average household income higher than the mean value of all other CBGs. This discovery partially contradicts previous studies that often observed a strong correlation between non-white and low-income populations with increased social vulnerability to flooding (Chakraborty et al., 2014), as well as declined ecosystem services benefits of tress in underserved communities (Gourevitch et al., 2021). This unexpected finding could be justified by some following considerations: (1) HL clusters may have a distinct demographic composition influenced by factors such as migration patterns, historical development, or local policies. The area might attract a diverse population mix that doesn't align with broader trends observed in other CBGs, (2) The higher average household income in HL clusters may be indicative of localized economic disparities or specific economic activities that contribute to increased income levels. This could be due to the presence of industries, businesses, or employment opportunities not found in other CBGs, (3) The area could be undergoing gentrification, resulting in changes to the socio-economic and demographic landscape. Gentrification might attract higher-income individuals while displacing existing populations, leading to the observed disparities (Anguelovski et al., 2018), (4) Changes over time in the demographics and socio-economic characteristics of HL clusters, compared to the period covered by previous studies, could explain the divergence from expected patterns, and (5) Local policies or interventions aimed at addressing social vulnerabilities may have had a positive impact on HL clusters, contributing to improved economic conditions and demographic diversity.

Additionally, The heightened flood vulnerability in these areas is not solely due to greater exposure to flooding, nor the socioeconomic status, but is also influenced by various overlapping geophysical factors such as slope and Topographic Wetness Index (TWI). This finding validates the assertion made by Cutter et al. (2000) that areas with the greatest biophysical vulnerability may not consistently align with regions harboring the most vulnerable populations. The proximity of two third of HL CBGs to Schuylkill River (Fig. 15) and the elevated risk of riverine flooding are additional significant factors characterizing the HL clusters.

Furthermore, it becomes evident that surface vegetation, such as shrubs and grass, may have a more substantial impact than tree canopies in reducing flood vulnerability in LH clusters. This finding could be rationalized by some considerations, especially from flood sensitivity perspective: (1) There are some scholarly evidence that grass and shrubs, with their lower canopy height, may facilitate better water absorption and infiltration, aiding in the reduction of flood vulnerability, especially in areas prone to lower-intensity flooding (Armson et al., 2013), (2) The root systems of grasses and shrubs may be more effective in stabilizing soil and preventing erosion, contributing to enhanced flood resilience in regions with NbS, (3) Local land use planning initiatives may have prioritized the establishment of grasslands over trees in flood-prone areas, aligning with the observed higher density of grasslands in LH clusters, (4) Community preferences and cultural factors may influence the choice of vegetation. If local communities prioritize grasslands for various reasons, including aesthetics or recreational purposes, it could contribute to the observed pattern. However, these justifications primarily focus on assumptions, and there is no evidence of a comprehensive interplay between different types of NbS and flood vulnerability. In summary, these findings indicate that expanding grassland in urban and regional areas in the studied regions could be a highly effective strategy for reducing vulnerability to flooding. This aligns with previous research, emphasizing the positive impact of incorporating more green spaces in urban areas, resulting in lower imperviousness and subsequently reducing annual flood-related losses (Kousky and Walls, 2014; Brody and Highfield, 2013). These findings collectively underscore the importance of strategically incorporating and enhancing NbS, particularly in regions with specific flood-related challenges, and highlight the potential for substantial improvements in flood resilience and mitigation efforts through further analysis to understand the impact of different types of NbS as well as influential additional factors.

Furthermore, the research findings illuminate the crucial role played by both flood exposure indicators, namely population density and property distribution, and flood sensitivity factors encompassing environmental and geophysical attributes. These factors emerge as powerful differentiators, effectively distinguishing High-Low (HL) clusters from their High-High, Low-High, and Low-Low counterparts within the study's geographic scope. This differentiation is particularly pronounced in the Upper and Lower Merion townships, where urban development is more prevalent and NbS density is significantly higher. This finding carries significant implications, notably advocating for the strategic augmentation of green elements in specific geographical zones characterized by distinctive topographical characteristics. In particular, focusing on areas characterized by steep slopes and specific terrain attributes such as lower Topographic Wetness Index (TWI) in conjunction with reduced Topographic Position Index (TPI), such as valleys in Lower Merion, emerges as a promising approach to mitigate the vulnerability of both individuals and the local landscape to riverine flooding. This course of action is substantiated by scholarly research, exemplified by the work of Marapara et al. (2020), which underscores the critical importance of considering topographical elements like slope and elevation when evaluating the effectiveness of tree-based flood risk reduction strategies. These findings not only bolster the argument for planting greenery in regions prone to riverine flooding but also accentuate the necessity of tailoring these interventions to the specific topographical attributes of the area.

Conclusions

This study contributes to the existing body of knowledge by investigating the spatial relationship between NbS and vulnerability to flooding within one of the most rapidly expanding regions in the Philadelphia Metropolitan Area. What sets this research apart is its comprehensive approach, which integrates social and biophysical indicators of flood vulnerability. This perspective extends previous studies that often examined either social or biophysical vulnerability separately in the context of green solutions. Furthermore, this research goes beyond the surface-level examination of NbS and delves into the spatial intersection of two specific types of NbS: trees and grass. This analysis is carried out at a finer resolution, focusing on eight distinct small urbanizing regions within the study area. To achieve this, the study employs the bivariate Local Indicators of Spatial Association (LISA) model, which offers a localized assessment of variations in comparison to the more conventional global Moran's model. By adopting this approach, the research can pinpoint areas characterized by a high degree of vulnerability to flooding and a simultaneously low density of NbS, characterized as High-Low clusters. It not only provides valuable insights into the spatial distribution of flood vulnerability but also identifies priority areas for flood mitigation policies. By highlighting regions where vulnerability remains high and NbS density is insufficient, this study offers actionable information that can guide the development and implementation of targeted strategies to enhance resilience against flooding in rapidly urbanizing areas.

The primary findings emerging from this study can be summarized as follows:

Spatial distribution of flood vulnerability: although the most CBGs with higher degree of vulnerability are located close to the main river and local streams, there are some larger CBGs far away from this general pattern, indicating the impact of other social and environmental indicators on flood vulnerability.

Disproportionate representation of flood exposure and sensitivity factors: notably, the research reveals that flood exposure indicators in Upper Merion and flood sensitivity factors in Lower Merion exhibit a pronounced overrepresentation within the High-Low

(HL) clusters. These findings underscore the critical need for heightened attention when planning and implementing new NbS in these specific regions.

Proximity to main river and NbS impact: another significant discovery is the proximity of a greater number of HL clusters to the main river. This suggests the substantial potential impact of introducing green elements, such as grass and trees, in these riverside areas, which could play a pivotal role in flood mitigation efforts; and

Greener areas and flood vulnerability: a noteworthy finding is the observed negative correlation between NbS density and flood vulnerability, particularly in areas with a substantial presence of greenery, including grass and shrubs (e.g., Plymouth). This suggests that introducing additional green spaces in other urbanized zones has the potential to significantly reduce the vulnerability of both people and the built environment to flooding.

Well-planned NbS and flood vulnerability: a significant concentration of High-High (HH) clusters is observed in a specific section of Lower Merion characterized by dense tree coverage and elevated flood vulnerability scores. This finding underscores the limited impact of NbS on reducing vulnerability. It underscores the imperative for the thoughtful implementation of NbS, emphasizing factors such as location, distribution, and the incorporation of robust technical and infrastructural foundations in mitigation planning.

While this study takes an important first step to consider the potential impact of NbS on social and biophysical vulnerability in small regions in the U.S., further study is needed on the topic. First, it is important to note that while efforts were made to consider optimal parameters, there is still a possibility that certain parameters were not included in the vulnerability model. Including additional socioeconomic and environmental variables and comparing their effectiveness through inductive as well as hydrodynamic modeling approaches could further enhance the results of study. Second, future research should include variables quantifying specific characteristics of NbS, such as type and configuration, etc. Third, future investigations should look within specific urban areas and rural hinterlands to better contextualize the results of this more regional study. Fourth, more research is needed on the spatial indicators and socioeconomic characteristics of HH clusters to understand the rationale behind shaping these areas. Finally, this study has focused on analyzing eight small regions in the Philadelphia Metro Area in the U.S. However, to gain a more comprehensive understanding, further research should consider larger samples of small regions or concentrate on more specific geographic areas for in-depth investigation.

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CHAPTER 5
CONCLUSIONS TO THE DISSERTATION

Summary of Key Results

It is highly likely that urban and suburban areas will face growing vulnerability to the occurrence and impacts of pluvial flooding. This is primarily attributed to the combined influences of ongoing urban development, leading to heightened levels of soil-sealing, and climate change, which is anticipated to amplify the intensity and frequency of extreme precipitation. Therefore, in contemporary academic and political discourse, considerable emphasis has been placed on the application of urban greening and its associated ecosystem services within the framework of NbS on both the global and national fronts. Yet, much of the research around the flood responsiveness of NbS approaches is focused on the impacts of routine green elements such as grasslands and wetlands of coastal and mega cities on biophysical and economic vulnerability. This thesis offers valuable insights into how NbS influences an integrated social and biophysical vulnerability and mitigates losses related to riverine flooding in one of the rapidly urbanizing regions the Philadelphia Metropolitan Area. The objective is to enhance comprehension regarding the current role of NbS in the planning for flood adaptation. The findings suggest that these solutions can 1) significantly impact vulnerability to flooding, as well as enhance the adaptability of these areas to a changing climate and 2) might be effective to reduce the loss from flooding under certain circumestances.

The major contributions of this study include 1) exploring the role of spatial configuration and composition of NbS on total poputalion, property, and agriculture loss of flooding as well as vulnerability to river flooding in some of the small flood-prone urbanizing regions and 2) opening the black box of small urbanizing regions to understand the interplay between NbS and flood regulation. This study marks the inaugural attempt to use GIS, spatial statistics and a systematic mapping approaches to understand the capabilities of various NbS types and quantities on mitigating both loss and vulnerability to flooding.

The systematic mapping literature review in paper one demonstrates that the effectiveness of flood regulation services in urban settings can be influenced by manipulating five spatial dimensions of NbS: distribution, scale, area, configuration, and topography, each with varying degrees of impact. The results reveal that previous research on spatial configuration have examined how variables such as slope, DEM, green space coverage, and landscape shape index impact runoff reduction and less documents have addressed the association between NbS composition and configuration and flood vulnerability and loss, especially in rapidly urbanizing regions. This study also shows that urban forest including tree canopy is the most common used type of NbS in literature to mitigate the negative impact of flooding.

In paper two, I sought to examine the potential of NbS for flood loss mitigation by using Generalized Linear Model (GLR) and Geographically Weighted Regression (GWR) techniques. This study's findings partially contradict previous research by revealing an unexpected relationship between NbS quantity in floodplains and expected annual loss. This outcome highlights the occurrence of the "NbS effect", which is potentially unfolding in flood-prone areas. Findings also suggest that small size and disconnected patches of NbS in floodplains in some dense urban areas effectively reduce total losses from flood events.

In paper three, I investigated the spatial coincidence between the density of NbS and flood vulnerability within eight small neighboring regions situated in Montgomery County within the Philadelphia Metropolitan Area using the Local Indicator of Spatial Association (LISA) analysis. The results identified regions of concern (High-Low clusters) characterized by elevated flood vulnerability scores and reduced concentrations of tree canopy and shrubs/grasses in almost 6% of the overall population, with a notably greater concentration observed within the city of Norristown. Also, it shows that grass potentially can reduce flood vulnerability more than trees, especially in Low-High clusters. Grass can play a crucial role in reducing flood vulnerability through absorption of water, stabilization of soil, reduction of surface water velocity, infiltration, and creation of natural buffers.

An intriguing revelation emerging from this study delves into the socioeconomic nuances characterizing the High-Low clusters. The data unearthed a discernible pattern where the percentage of black residents is notably lower and the median housing income is comparatively higher in these regions. This notable disparity in demographic and economic factors prompts further examination. One potential explanatory factor for this trend lies in the overarching demographic composition of the study area. Notably, the study reveals that the overall percentage of white residents in all CBGs within the examined region surpasses the average of the Philadelphia Metro Area. However, despite this correlation, the precise nature of the relationship between the demographic makeup, economic characteristics, and the resultant vulnerability of these locations remains elusive within the confines of this study.

Collectively, these findings underscore the pivotal importance of strategically integrating and enhancing NbS, particularly in regions contending with specific challenges related to flooding. This emphasizes the prospect for substantial improvements in flood resilience and mitigation strategies through deliberate urban planning and the widespread adoption of NbS. Despite being small, the studied regions exhibit growth and already possess a considerable amount of NbS, contributing significantly to their reduced vulnerability to floods. Preserving and sustaining these existing NbS will be crucial as these regions continue to expand and develop. The proactive conservation of such nature-centric interventions becomes integral for fostering long-term resilience against the evolving threat of floods.

Policy Implications

The findings of the study indicated that NbS is a flexible and holistic approach that seeks to incorporate a variety of natural and semi-natural elements to provide solutions to diverse environmental and societal challenges. NbS implementation could therefore benefit from a more performance-based planning approach; a flexible approach to urban planning which accommodates the integration of multiple land uses and considers urban complexity. In addition, its specific focus on real-world solutions to intertwined social, economic and environmental sustainability challenges makes it an approach that can be particularly effective in drawing attention to the potential of nature in devising pathways to urban sustainability transformations. Given that the primary inquiry of the study pertains to the sustainable growth of urbanizing regions without intensifying the risk of flood inequality, the outcomes derived from the examination of the influence of NbS on flood loss in chapter 3 and the correlation between NbS and flood vulnerability in chapter 4 have uncovered various planning implications for flood mitigation policies.

Promotion of Urban Greening Policies

The study indicates that NbS, such as the integration of urban forests and grasslands, plays a pivotal role in diminishing vulnerability to flooding. To actively foster urban greening, it is imperative to implement a multifaceted approach encompassing regulatory measures, incentivization strategies, and community engagement initiatives. Regulatory frameworks such as vulnerability-equity-structure (VES) proposed in this study can be established to mandate the incorporation of green spaces within flood mitigation and urban planning, ensuring that NbS elements are integral components of development projects. Furthermore, the study indicates that manipulating spatial dimensions of NbS can influence their effectiveness in flood regulation. Incorporating spatial configuration and composition of NbS , including factors such as connectivity, size, and location, and topography considerations into urban planning can optimize the benefits of NbS in mitigating flood losses.

Diverse NbS Strategies for Flood Mitigation

The study underscores the efficacy of diverse types and quantities of NbS in alleviating both the impact and susceptibility to flooding. When formulating policy interventions, it is imperative to account for local conditions, including factors such as elevation, slope, socioeconomic status, among others, and preferences. Consequently, the acknowledgment and endorsement of a varied array of NbS strategies, tailored to the unique characteristics of specific urban contexts, assume paramount importance, particularly in rapidly urbanizing regions.

Equity Considerations in Flood Vulnerability

This investigation revealed socioeconomic intricacies in regions with diverse levels of flood vulnerability. Policymakers need to be attentive to potential disparities in vulnerability linked to demographics and income levels, striving to prevent disproportionate impacts on vulnerable communities. It is imperative to incorporate considerations of social equity into strategies aimed at reducing flood vulnerability, acknowledging the influence of demographic and economic factors. Furthermore, the importance of intersectionality research and analysis is paramount in light of the aforementioned findings, as it allows for a nuanced understanding of how various social, economic, and demographic factors intersect with climate-induced vulnerabilities. Such an approach ensures that policies and strategies not only address flooding risks but also account for the diverse and interconnected aspects of vulnerability, promoting more inclusive and effective urban resilience measures.

Research and Data-Informed Decision-Making

The research underscores the significance of employing sophisticated techniques for analyzing the spatial dimensions and effects of NbS. Policymakers are encouraged to allocate resources for robust research and comprehensive data collection, laying the foundation for informed, evidence-based decision-making. This necessitates strategic investments in research, Geographic Information System (GIS) technology, spatial statistics, and systematic mapping approaches. By doing so, policymakers can enhance their understanding of the diverse capabilities of various NbS types and quantities in the realm of flood mitigation.

Climate-Resilient Urban Planning

The study underscores the pivotal influence of climate change in intensifying the risks associated with flooding. It is imperative that policies actively advocate for urban planning frameworks that take into account future climate scenarios, aiming to bolster the long-term resilience of urban areas. To achieve this, there is a pressing need to seamlessly integrate climate change adaptation strategies into urban planning processes, specifically addressing the expected rise in extreme precipitation events. By incorporating forward-looking climate considerations, urban planning can proactively anticipate and respond to the evolving challenges posed by climate change, thus fostering more sustainable and resilient urban environments.

Outlook and Future Research

This thesis presents a novel analytical framework that integrates landscape ecology, climate vulnerability (social and biophysical vulnerability), and environmental justice perspectives to analyze the potential of NbS for flood vulnerability and loss in the context of small urbanizing regions. The spatially explicit and novel methodology developed in this study provides a normative tool for rapidly growing regions undertaking spatial planning for flood mitigation and equitable development. The following paragraphs provide detailed explanations of potential expansions and enhancements to the methodological approach and evaluation, aiming to strengthen the recommendations for urban and landscape planning.

First, various studies have delved into the influence of NbS type, size, connectivity, and shape on flood regulation. However, a consensus on the optimized efficiency of these criteria, particularly concerning flood vulnerability and loss, remains elusive. While certain investigations propose that larger and connected NbS patches exhibit greater potential for mitigating flood runoff and vulnerability in urban settings, potentially reducing flood damage (Brody et al., 2017; Kim & Park, 2016; Kim et al., 2021), the present study diverges from this perspective. It contends that smaller-sized and disconnected patches of NbS, strategically situated in floodplains within densely populated urban areas, can effectively curtail total losses arising from flood events. Therefore, a crucial recommendation arises: a comprehensive quantification of the potential effects of NbS size, connectivity, and shape across diverse scales and in the context of varying flood characteristics and processes. This nuanced exploration is imperative to decipher the multifaceted dynamics at play and to inform more contextually tailored and effective strategies for flood mitigation in urban areas. Furthermore, it is essential to integrate additional types of NbS, including mangroves and wetlands, into the analysis, with a specific emphasis on small coastal growing regions. By scrutinizing these factors across different scales and diverse contexts, the research community and policymakers can gain a more holistic understanding, fostering evidence-based decisions that align with the diverse urban landscapes and hydrological conditions.

Second, in the course of this research, a spatially explicit modeling approach has been employed to delve into the intricate spatial relationships between NbS and the vulnerabilities and losses associated with floods. Going beyond this, the integration of other process-based methodologies, such as hydrodynamic modeling, can further enrich the analysis. By combining hydrodynamic modeling with spatial analysis, researchers gain a more comprehensive understanding of flood sensitivity scores, drawing insights from the nuanced spatial factors that influence NbS outcomes. The juxtaposition of these various models' results becomes instrumental in the quest for optimized solutions tailored to specific regional contexts. Through a comparative analysis of the outcomes derived from spatially explicit models and hydrodynamic models, researchers can discern patterns, correlations, and divergences. This comparative lens facilitates the identification of approaches that prove most effective and efficient in diverse geographical settings, contributing to the development of adaptable and region-specific strategies for mitigating flood vulnerabilities and losses. This multifaceted approach not only enhances the robustness of the research findings but also provides valuable insights for policymakers and practitioners engaged in the implementation of Nature-based Solutions for resilient flood management.

Third, the findings of this study offer valuable insights into the intricate relationship between the size of NbS and the mitigation of flooding losses in floodplains. The introduced concept of “NbS effect” sheds light on the observation that an increased presence of NbS in floodplains correlates with a higher total reduction in flooding losses. This phenomenon may be tied to the complex dynamics associated with vegetated areas, potentially leading to negative and disproportionate impacts on property values—an aspect recognized in the literature as “green gentrification” (Anguelovski et al., 2018). Furthermore, the greater prevalence of NbS could act as a catalyst for expanding agricultural lands in flood-prone areas. This theoretical proposition aligns with similar concepts like “living with risk” by Cutter (1993) and the "Levee effect" articulated by Wight (1945). The intricate interplay of these factors underscores the need for more extensive spatial and empirical research to delve into the impact of NbS size in floodplains on both green gentrification and agricultural loss. This inquiry prompts consideration of what specific NbS size in floodplains can concurrently diminish flooding losses while also influencing housing values. Exploring this question opens avenues for nuanced investigations into the optimal size of NbS interventions in flood-prone regions, balancing the objectives of flood risk reduction and housing value preservation. This research not only contributes to a deeper understanding of the dynamics involved but also informs practical considerations for policymakers and urban planners seeking to strike a balance between sustainable flood management and maintaining the economic and environmental integrity of floodplain areas.

Fourth, there is an increasing demand for research on the impact of NbS for multiple hazards. For example, strategies for water harvesting can be designed to serve dual or multiple purposes, encompassing both flood and landslide prevention alongside the management of drought hazards. Implementing these versatile NbS holds substantial promise for reducing risks associated with multiple hazards, particularly in the face of anticipated climate change conditions in the future (Debele et al., 2023). There are opportunities to investigate the association between NbS composition and configuration and multiple hazards, especially in areas with a history of compound natural hazards.

Fifth, one notable finding was the socioeconomic characteristics of High-Low (prioritized) areas with a higher percentage of white and higher medican housholed income. This demographic skew raises pertinent questions about the intersectionality of race and socioeconomic status, warranting a closer investigation into how these factors may interplay to shape the observed disparities. Further exploration is imperative to unravel the nuanced interconnections between race, income, and vulnerability, shedding light on the multifaceted factors influencing the social fabric of these communities.

Finally, scientific or quantitative findings regarding the flood vulnerability and loss mitigation potential of NbS lack efficacy if this knowledge fails to reach practitioners and contribute to floodplain management and urban planning. There is a clear imperative for enhanced collaboration and communication with practitioners and decision-makers within flood-prone areas to discern the specific types of knowledge required and determine when in the hazard mitigation planning processes it is most valuable. Alterations to institutional frameworks are essential to facilitate greater inter- and transdisciplinary research, fostering improved pathways for mainstreaming NbS into urban and landscape planning practices.

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