DOCTOR DISSERTATION

Study on Blue-Green Infrastructure Network to reduce local flooding in the central Hanoi, Vietnam

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ABSTRACT

Urban flooding is a pressing issue in many rapidly developing cities around the world. Moreover, urban flooding is a significant challenge facing rapidly growing cities, particularly in developing countries like Vietnam. The city's rapid urbanization, characterized by extensive land cover change and increased impermeable surfaces, has significantly contributed to its vulnerability to flooding. The traditional drainage systems, often overwhelmed by heavy rainfall and inadequate maintenance, exacerbate the problem, leading to frequent and severe flood events that disrupt daily life, damage infrastructure, and pose risks to public health and safety. Hanoi, the capital city of Vietnam, is no exception, experiencing recurrent inundation events exacerbated by rapid urbanization and climate change. The study also highlights the current flood risk situation in Hanoi, revealing that areas of central Hanoi such as Hoan Kiem, Ba Dinh, and Dong Da are particularly vulnerable to flooding due to their low-lying topography, insufficient drainage infrastructure, and high population density. This research aims to assess urban flooding susceptibility and flooding risk in Hanoi and explore the potential of blue-green infrastructure (BGI) as a sustainable solution. Through the integration of Geographic Information Systems (GIS), and statistical analysis, this study evaluates various factors contributing to urban flooding susceptibility, including land use, topography, hydrological characteristics, and infrastructure, population. In addition, the study also considers building a network of BGI intervention corridors at optimal costs in reducing flood risks and enhancing urban resilience. Furthermore, the analysis shows that the potential of BGI in the study area is quite large. These findings highlight the importance of integrating BGI into urban planning and development strategies to mitigate the impacts of urban flooding in Hanoi and similar cities. This study contributes to improving knowledge of urban flood management. It provides valuable insights for policymakers, urban planners, and stakeholders in implementing sustainable and resilient urban development activities in Hanoi and beyond.

Chapter 1 (Introduction) provides a comprehensive overview of the research topic, including the background, the significance of studying urban flood risk in Hanoi, and the role of BGI. It outlines the research problem, objectives, and questions, setting the stage for the subsequent chapters.

Chapter 2 (Literature Review) reviews the existing literature on urban flood risk and BGI. It begins by discussing the development and direction of research on urban flooding. Then, discuss the natural

and man-made factors that contribute to flood risk in Hanoi. Next, this chapter explores the environmental and socioeconomic impacts of urban flooding. Finally, evaluate the current landscape status and current BGI projects in Hanoi and identify challenges and opportunities for implementing this project. Finally, it looks at case studies and best practices from other cities to draw lessons for Hanoi.

Chapter 3 (Methodology) details the research design and methods used in this study. It describes data collection methods, including surveys, document collection, and secondary data analysis. This chapter outlines the study area in Hanoi and explains the data analysis techniques used.

Chapter 4 (Urban flooding susceptibility in Hanoi) focuses on modeling flood susceptibility in Hanoi. Using geographic information systems (GIS) and other spatial analysis tools, the chapter identifies areas most prone to flooding based on various factors such as this. This result provides a foundation for understanding flood susceptibility in the city.

Chapter 5 (Spatial Flood Risk Assessment for Hanoi City) builds a detailed flood risk map based on three factors: flood hazard, flood vulnerability and flood exposure. These maps incorporate additional data, including population density and socioeconomic data, to assess the potential impact of flooding on different areas of Hanoi. This chapter aims to highlight the areas of highest risk and provide information about the risks so that mitigation strategies can be put in place.

Chapter 6 (Blue-Green Infrastructure in the central of Hanoi) evaluates the development potential of BGI in Hanoi. It includes building a suitability assessment map for BGI, identifying existing BGI locations and developing a BGI network at the best cost based on BGI suitability analysis. This chapter contributes to a BGI construction methodology that can be integrated into urban planning and contribute to overall resilience.

Chapter 7 (Conclusion) summarizes the key findings and offers policy recommendations based on the study. Then, identify limitations in the study and directions for future research.

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Nomenclature

BGI - Blue – green infrastructure

GIS - Geographic Information Systems

AHP - Analytical Hierarchy Process

SUDs - Sustainable urban drainage systems

IPCC - Intergovernmental Panel on Climate Change

SRTM - Shuttle Radar Topography Mission

DEM - Digital elevation model

NDVI - Normalized Difference Vegetation Index

LULC - Land Use/Land Cover

TWI - Terrain Wetness Index

USGS - United States Geological Survey

CRU - Climatic Research Unit

MCDA - Multi-criteria decision analysis

CR - Consistency Ratio

CI - Consistency Index

RI - Consistency Index

AUC - Area Under the Curve

Chapter 1

INTRODUCTION

1.1 Research background.

One of the primary challenges posed by global and local environmental changes is that despite enhanced efforts to mitigate flood risks, the frequency and intensity of floods have more than doubled in recent years. This alarming phenomenon is recurring on a large scale worldwide, particularly in developing countries, where urban flooding has emerged as a major issue in disaster management. A survey of the causal factors leading to the failure of flood control structures in mitigating urban floods, illustrated by examples from cities around the globe, identified four critical categories. These are (a) rapid and unplanned urban growth with little regard for land use regulations and infrastructure development, (b) inadequate observation networks to record and analyze hydrometeorological data, (c) suboptimal design and implementation of structural mitigation measures, and (d) poor enforcement and governance systems. Several policy issues have arisen concerning (a) early flood warning, (b) flood modeling scenarios, (c) the validity of design concepts and criteria, and (d) flood regulation and management.

One of the main challenges posed by global and local environmental changes is the need to integrate research and evaluation into the decision-making process. When addressing highly uncertain and high-risk issues such as natural disasters and climate change, this integration is particularly difficult but essential. Drainage management is a key issue in reducing urban flood risk, involving multidisciplinary aspects such as irrigation, flood prevention, wetlands, rainwater harvesting, waste management, transportation, slums, housing, and more. Drainage and sewer systems require significant investment, but the costs of investment and maintenance can be reduced through more efficient planning and operation as well as incorporating innovative solutions. Master planning with direct and indirect provisions offers opportunities for risk-based land use planning and aligning the entire urban management system in a risk-sensitive manner.

Most cities and towns in Vietnam are facing the challenge of seasonal flooding, causing significant issues for research and planning. With the efforts of the government and local authorities, the number of scientific research projects on natural disasters and flooding has increased and received greater attention in recent years. Hanoi is among these cities. However, the research conducted here has been limited to small areas or has served only specific objectives of particular sectors and purposes, lacking coherence and consistency. Therefore, comprehensive research on flooding from multiple perspectives, with practical applications in urban planning and flood management, is essential and urgent for a rapidly developing city like Hanoi. To determine the real problem of flooding that Hanoi currently has in order to make choices for surface water management that are sustainable and appropriate to Hanoi's urban situation. Blue - green infrastructure is one of the methods being chosen to permanently address the problem of stormwater management. Although there are many difficulties in converting from gray infrastructure and implementation, this method has proven long-term benefits for the city in many aspects, including the problem of urban flooding. However, in Hanoi, stormwater management is still focused on the gray system, and practical research and applications on blue - green infrastructure are scarce.

For these reasons, the researcher has chosen the topic: “The Study on Urban Flooding Risk and Blue-Green Infrastructure in Hanoi, Vietnam” as the focus of the dissertation.

1.1.1. Overview of the urban flooding problem

Flooding is the most common form of natural disaster and has serious consequences globally [1,2]. The frequency and duration of floods are increasing, with floods having quadrupled in tropical regions from 1985 to 2015 [3]. Moreover, the estimated risk of floods escalated by 20 to 24% during the period from 2000 to 2018 [4]. In addition, between 1970 and 2019, floods accounted for 44% of all documented natural disasters and were the cause of 31% of the total economic losses [5], with 1298 major flood incidents recorded worldwide between the years 2010 and 2019 alone [6]. All cities face risks from a range of natural and human-made disasters, including those arising from extreme weather events, fires, and industrial accidents. There can also be significant variations in the capacity of city authorities, households, and organizations to implement measures to limit the escalation of risks and to ensure a rapid and effective response when flooding or other disasters occur. Coastal hazards can be particularly disruptive to settlements in coastal and estuarine areas, which are home to a significant portion of the world's population. An estimate suggests that 60% of the global population lives within 60 kilometers of the coast [7]. Ports and other settlements located on coasts or estuaries are at the highest risk due to the increased severity and frequency of floods and storms caused by global warming. Several factors have compounded the difficulty of designing an effective and sustainable flood mitigation policy for urban areas. Many previous studies have shown that heavy rainfall is not the only significant factor that influences flooding; other factors such as unplanned urban growth [8], the ecological environment [9], changes in land use/ land cover [10], inadequate drainage infrastructure [11], and green infrastructure management [12] also play crucial roles. Harsh weather conditions resulting from the impact of local climate change and various uncontrolled anthropogenic activities such as urbanization and population growth have become additional primary causes of flood disasters [2,13].

Historically, Southeast Asia's close relationship with water attracted traders from other parts of Asia seeking goods and new markets. Ancient settlements expanded, and new ones emerged around lowland rice fields near rivers. In the 20th century, pressures on local ecosystems became evident. Traditional practices of sustainable resource use were replaced by overexploitation to meet the demands of a growing population. Many of the ancient forests, especially in lowland areas, were cleared for timber, agriculture, tea, and rubber plantations. Rapid population growth and urbanization in the late 20th century led to increased city dwelling, as people moved away from rural farms. By the early 21st century, most Southeast Asians lived in urban areas, unlike their parents and grandparents who lived in rural settlements (figure 1-1).

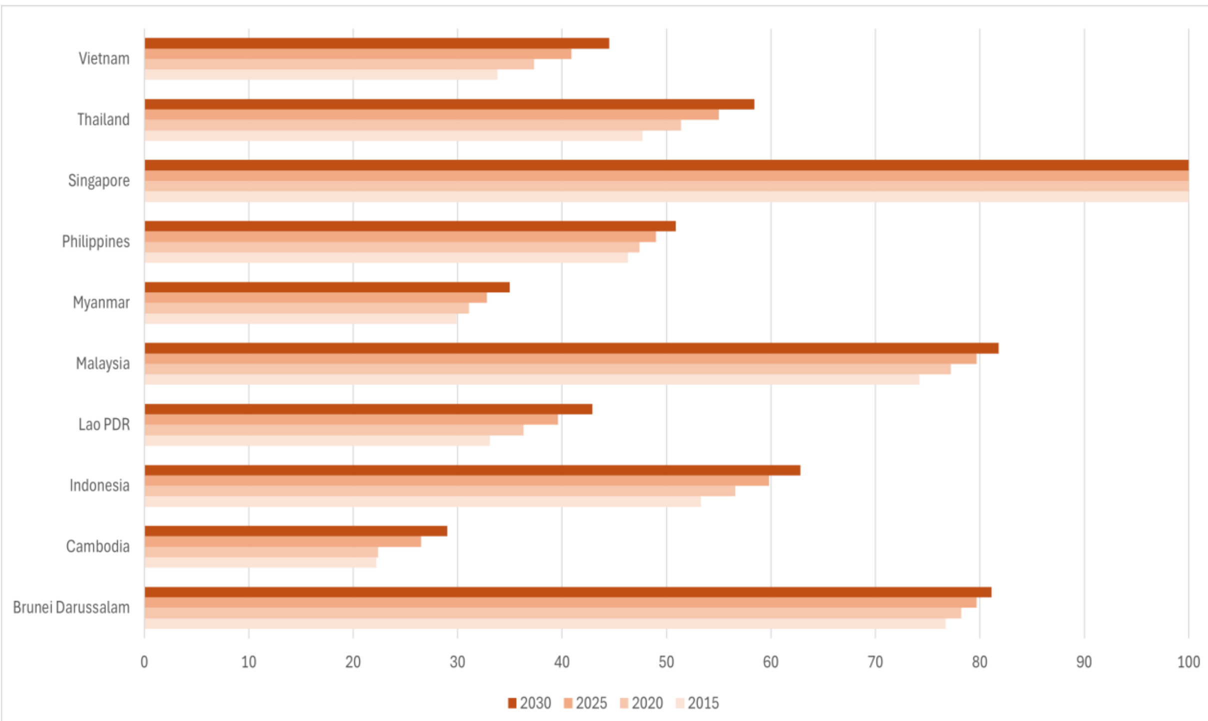

Figure 1-1: Urbanization in Southeast Asia

Compared to the rest of the region, Southeast Asia has a very large area with large cities located on low-altitude coasts. This has largely contributed to making it susceptible to frequent damage and loss of life due to flooding. As Southeast Asia's economy has grown, so has the interaction of its people with water. Wealthier cities like Singapore and Kuala Lumpur have reached a 'post-industrialization' stage, where they are proactively and sustainably managing the impacts of rising tides and heavy rainfall, seeking to re-establish a harmonious relationship with water. Meanwhile, less developed countries and smaller cities are still grappling with early industrialization and must focus on flood management as they contend with the effects of climate change. However, the region still lacks a comprehensive system to address the forthcoming water challenges.

Different parts of the world are facing different impacts of climate change. The people of Southeast Asia are particularly susceptible to the effects of flooding due to the geography of the region and the rapid growth of their economies and populations in recent decades (Table 1-1).

Table 1-1. Most observed climate and natural disasters in Southeast Asia.

	Floods	**Heat**	**Droughts**	**Storms**	**Earthquakes**	**Wildfires**	**Landslides**
Brunei Darussalam	x	x				x	x
Cambodia	x	x	x			x	
Indonesia	x	x	x		x	x	x
Lao PDR	x		x	x		x	
Malaysia	x	x	x	x	x	x	
Myanmar	x	x		x		x	
Philippines	x	x		x	x		
Singapore	x	x	x				
Thailand	x	x	x			x	
Vietnam	x	x					

While certain areas in the Indochina region are already identified as hotspots for flooding and related diseases, new hotspots are anticipated to emerge in the Philippines, Indonesia, and Thailand. Existing high-risk areas are also expected to become more severe. Here, the likelihood of populations experiencing floods and associated diseases is projected to increase significantly in many countries under the worst-case climate change scenarios. In Indonesia, 185 million people (68.2% of the population), in Vietnam, 68 million people (70% of the population), and in the Philippines, 68 million people (69.7% of the population) are expected to be continuously affected by floods and related diseases [14]. (Figure 1-2)

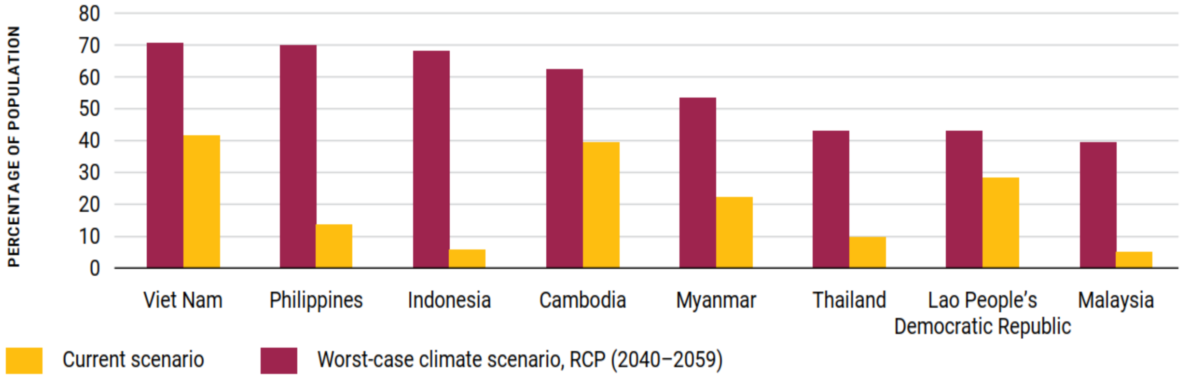

Figure 1-2. Percentage of the population exposed to the risk of floods and related diseases under current and worst – case (RCP 8) scenarios in Southeast Asian countries.

Sources: ESCAP calculations, based on World Bank, Climate Change Knowledge Portal, 2018; UN WPP-Adjusted Population Density 2020 and Disability Adjusted Life Years (DALYs) estimates 2000–2019

Serious floods occur in many Vietnamese cities during the monsoon season every year. Global climate change is currently leading to changing weather patterns and affecting the monsoon. Increasingly heavy rainfall is causing greater flooding in urban areas, leading to severe disruption to urban infrastructure. In addition, urban sewers are increasingly used to treat wastewater and overflows lead to epidemics. Given the concentration of population and economic assets in vulnerable areas, Vietnam ranks among the top five countries most severely affected by climate change [15,16], with one-third of its population currently exposed to flood risks [17]. Rapid urbanization in Vietnam is exacerbating environmental issues in urban settings, which is compounded by the growing unpredictability of extreme weather events [18]. Hanoi, one of the largest and most densely populated cities in Vietnam, has witnessed increasingly intricate and challenging urban flooding in recent years [19,20]. The main causes of deep flooding are shown in Figure 1-3.

Urban flooding can occur when heavy rainfall causes: (a) streams or channels to overflow, (b) drainage systems to become blocked due to their inability to handle large volumes of water or being obstructed by debris, and (c) sewer overflows caused by illegal connections and the drainage system's inability to manage the increased water volume. The most severe flooding tends to happen after prolonged rainfall, when the ground is saturated, and water levels in streams are high. If an intense burst of rain occurs, causing a large amount of rainfall in a short period, flash flooding can happen with little or no warning. Flooding is exacerbated by developments encroaching on floodplains, obstructing floodways, and reducing natural flood storage. Continued development and redevelopment to higher density land uses in major cities, along with increased impervious surfaces such as roads, roofs, and paving, due to rising development densities, result in more runoff.

Takahashi (1964, 1971) studied flooding events in Japan, revealing that floods are influenced not only by natural factors but also by varying social conditions across different regions and times [21, 22]. Flood occurrences are linked to the increase of impermeable surfaces and man-made drainage systems like conduits and channels. In small urban basins, land use typically includes rooftops, streets, and other impervious surfaces, which direct runoff into storm sewers, altering the hydrologic cycle by increasing surface runoff and reducing groundwater flow. These changes lead to higher peak discharges and more frequent flooding. Additionally, on-road vehicle parking, particularly in commercial zones and residential areas at night, exacerbates the obstruction of rainfall runoff during heavy rains. As the social structure evolves in post-industrial society, urban areas become denser and more complex. Newly developed urban facilities, information systems, and networks are especially vulnerable to flood damage. Recent urban floods illustrate a new type of disaster, causing unique damage to urban environments.

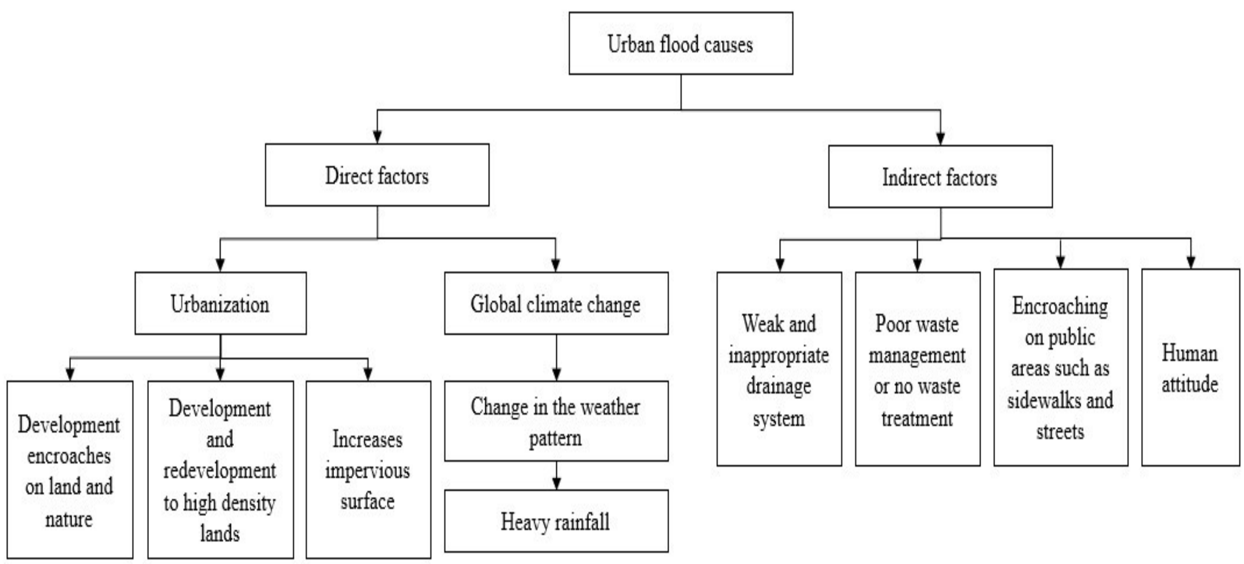

Figure 1-3. Urban flood causes

1.1.2. The importance of blue green infrastructure in urban areas.

BGI, or Blue-Green Infrastructure, is an integrated approach that merges natural elements (green components) with water management strategies (blue components) within urban environments. This approach aims to develop sustainable, resilient, and eco-friendly urban areas by emulating the effectiveness of natural systems.

Urban water systems, particularly underground stormwater drainage systems, are subject to various environmental and social pressures and have become significant points of criticism [23- 26] Common causes of stress on urban water systems include deteriorating water quality, changes in the water cycle, depletion of water resources, reduced water availability, ecosystem degradation, and the impacts of climate change such as heavy rainfall, flooding, and drought, as well as their socio-economic consequences. These factors necessitate a transformative change in how stormwater is managed in cities [25, 26].

We typically envision a city as consisting of buildings, roads, concrete, asphalt, and other hard, grey elements. But what if we considered a city with multiple layers, including water and vegetation? These elements significantly enhance and shape human life. This concept is known as Blue-Green Infrastructure (BGI), an essential layer in creating a livable city.

For too long, we have relegated water to underground systems, keeping it out of sight and out of mind, and neglected the importance of green spaces. Despite their crucial role in our lives, these elements have not had strong advocates. However, as times change, we have come to realize that grey infrastructure alone cannot address the challenges posed by climate change.

A variety of terms have emerged to describe alternative solutions that challenge the dominant perspectives on water engineering infrastructure and natural control. These terms are closely tied to their geographic context, with their core ideas differing only slightly [24, 27- 30].

Among these alternatives are concepts such as sustainable urban drainage systems (SUDS), green infrastructure, and blue-green infrastructure, which emphasize the integration of natural processes into urban water management. These approaches aim to mitigate the adverse effects of urbanization on the water cycle and improve resilience to climate change by promoting infiltration, evapotranspiration, and the reuse of rainwater. By enhancing the ecological functions of urban landscapes, these systems seek to restore natural hydrological cycles disrupted by conventional engineering practices.

Moreover, these innovative water management strategies not only address environmental challenges but also offer social and economic benefits. They can improve urban aesthetics, enhance biodiversity, and provide recreational spaces, contributing to the overall quality of life for urban residents. The shift towards such holistic and sustainable water management practices represents a paradigm change in urban planning and infrastructure development, advocating for a more integrated and adaptive approach to handling urban water issues.

Therefore, the evolution of urban water systems management is crucial in the face of growing environmental challenges and the need for sustainable development. By adopting these alternative solutions, cities can better cope with the complexities of water-related issues and ensure a more resilient and sustainable future for their inhabitants.

Generally, the advocated solutions for sustainable stormwater management propose a more cyclical approach, one that mimics the natural water cycle, manages both water quality and quantity, and promises socioeconomic, environmental, and ecological benefits [23, 28, 30- 32]. BGI, or Blue-Green Infrastructure, is an integrated approach that merges natural elements (green components) with water management strategies (blue components) within urban environments. This approach aims to develop sustainable, resilient, and eco-friendly urban areas by emulating the effectiveness of natural systems. Blue-Green Infrastructure (BGI) solutions operate on the principle of utilizing stormwater, allowing it to infiltrate and manage runoff by directing it into waterways and corridors. These systems collect stormwater through technologically enhanced, nature-based facilities such as ponds, wetlands, porous pavements, swales for detention and conveyance, trenches, open channels, dams, green roofs and walls, and bioretention systems [27] (Figure 1-4).

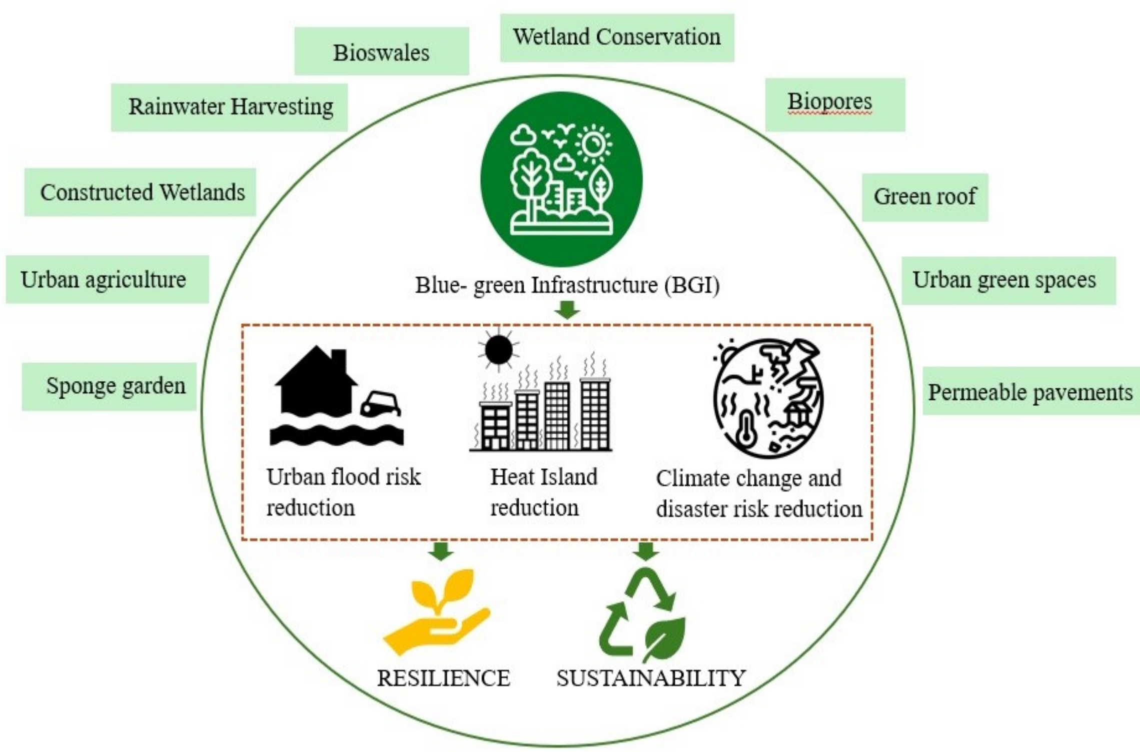

Figure 1-4. Blue- green infrastructure for addressing Urban resilience and sustainability

Such systems can enhance water resources, improve water quality, support aquifers, waterways, and vegetation, and contribute to the overall environmental quality [33]. By imitating the natural processes of water infiltration, evaporation, and reuse, these solutions offer a holistic approach to urban water management. This approach not only addresses the challenges posed by conventional infrastructure but also brings additional social, economic, and ecological value.

Blue-Green Infrastructure (BGI) provides a practical and beneficial solution for urban areas grappling with the challenges of climate change. By integrating blue infrastructure (urban hydrological functions) with green infrastructure (vegetation systems) in urban landscape design, BGI can complement and sometimes even replace traditional grey infrastructure. This approach not only addresses environmental concerns but also delivers socio-economic benefits that surpass those of its individual components combined.

When integrated into a comprehensive system, the components of Blue-Green Infrastructure (BGI) projects enhance urban ecosystems by utilizing natural processes within man-made environments. BGI merges the need for sustainable water and stormwater management with the demands of adaptive urban life and planning, creating resilient and eco-friendly urban spaces.

1.2. Research purpose and structure.

1.2.1. Research problem

Urban flooding is a persistent and escalating issue in Hanoi, Vietnam, driven by a combination of rapid urbanization, climate change, and inadequate infrastructure. The city's low-lying topography, heavy monsoon rainfall, and extensive impervious surfaces exacerbate its vulnerability to flooding. This situation is further compounded by insufficient drainage systems and the encroachment on natural water bodies, which disrupts the natural water flow and retention.

Despite the recognition of these challenges, current flood management strategies in Hanoi often rely on conventional engineering solutions that may not sufficiently address the root causes of flooding or enhance the city's long-term resilience. These traditional approaches also tend to overlook the multifaceted benefits of integrating natural systems into urban environments.

Blue-green infrastructure (BGI) presents a promising alternative, combining water management with the creation of green spaces to provide ecological, social, and economic benefits. BGI strategies, such as green roofs, permeable pavements, urban wetlands, and restored waterways, can enhance the city's capacity to manage stormwater, reduce flood risks, and improve overall urban sustainability.

However, the implementation and effectiveness of BGI in Hanoi remain underexplored. There is a need to systematically assess the city's flood susceptibility and risk areas, evaluate the sustainability and network of existing and potential BGI sites, and integrate these findings into urban planning and policymaking.

Thus, the central research problem of this study is to understand the extent and spatial distribution of urban flood risk in Hanoi and to evaluate the potential of BGI as a sustainable solution to mitigate these risks.

1.2.2. Research objectives.

The objective of this study is to assess the urban flooding risks in Hanoi, Vietnam, and to evaluate the potential of Blue-Green Infrastructure (BGI) as a sustainable solution for flood management. This study aims to identify the main factors contributing to urban flooding, analyze the effectiveness of current infrastructure and propose a suitable BGI network for the natural water cycle, improving flow quality and surface water management and environmental benefits. The goal is to develop comprehensive recommendations for urban planning and flood risk management that can improve the resilience and sustainability of Hanoi's urban environment.

To achieve the above goal, the thesis has performed the following tasks:

• Establish a theoretical basis and approach for urban flooding and blue-green infrastructure in Hanoi.

• Identify and map flood-prone areas in Hanoi. Analyze historical flood data to understand the frequency, intensity, and impact of past floods.

• Identify and map areas vulnerable to urban flooding.

• Assess the effectiveness of existing flood management infrastructure in Hanoi and identify gaps where current infrastructure cannot effectively mitigate flood risks.

• Explore suitable areas for blue-green infrastructure construction in surface water management.

• Launch a low-cost blue-green infrastructure network based on the current state of the landscape.

Geographical Scope:

The research primarily focuses on the city of Hanoi, Vietnam. Analyses, assessments, and proposals will be conducted within the specific context of Hanoi.

Content Scope:

The study focuses on urban flood risks and the potential of Blue-Green Infrastructure (BGI) as a sustainable flood management solution. It includes only factors related to urban flooding, such as topographical factors, urban planning, social infrastructure. It does not extend to other natural disasters such as droughts, earthquakes, or tsunamis. Evaluation of BGI solutions includes components such as BGI suitability, and BGI networks but does not delve into the detailed technical solutions of each component.

Technical Scope:

The study employs standard tools and models in urban and environmental research, such as GIS (Geographic Information Systems), AHP method. It does not develop or test new modeling tools or techniques but primarily applies and customizes existing tools to the context of Hanoi.

1.2.3. Research Questions

(1) What are the main factors causing urban flooding in Hanoi?

This question seeks to identify and analyze the main causes of urban flooding in the city, including natural, infrastructural, and human-induced factors.

(2) What are the spatial patterns and distribution of urban flooding risks in Hanoi?

This question aims to identify and analyze the geographic areas within Hanoi that are most prone to flooding.

(3) What are the key environmental, infrastructural, and socio-economic factors contributing to urban flooding risk in Hanoi?

This question seeks to understand the primary factors that influence the likelihood and severity of flooding in different parts of the city.

(4) How can we analyze and establish an accurate map of urban flood risk in Hanoi?

This question explores the methods and technologies most suitable for mapping and analyzing flood risk areas.

(5) How can Blue-Green Infrastructure be integrated into Hanoi's urban planning and development to enhance flood resilience?

This question seeks to develop recommendations and strategies for incorporating BGI into the urban planning framework to improve the city's resilience to flooding.

1.2.4. Significance of the study

Scientific Significance

The research outcomes of the dissertation on urban flooding risk and Blue-Green Infrastructure in Hanoi contribute to the characterization and differentiation of flood risk areas on maps. Additionally, the results enrich the research methods, and flood risk assessment for urban planning and management in alignment with sustainable blue-green infrastructure and environmental protection at the municipal level.

Practical Significance

The research findings, along with the thematic maps produced, provide reliable scientific grounds for urban managers and planners to spatially allocate development areas. This aids in enhancing the urban infrastructure, improving flood resilience, and ultimately elevating the quality of life for the residents of Hanoi.

1.2.5. Structure of the thesis

The thesis comprises seven chapters, one appendix, and a list of references as following:

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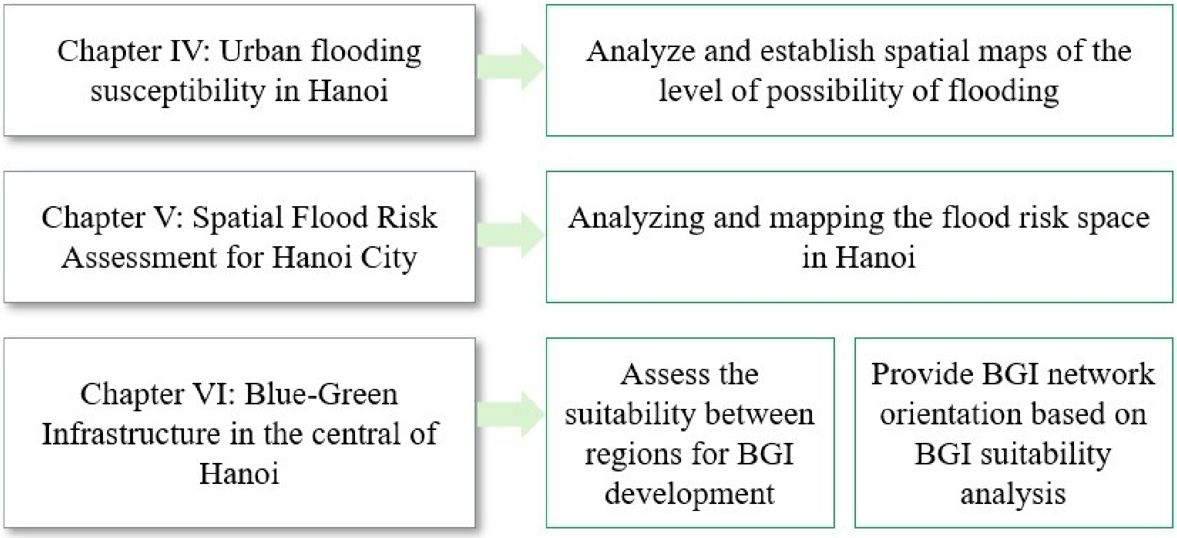

Figure 1-5. Research purpose

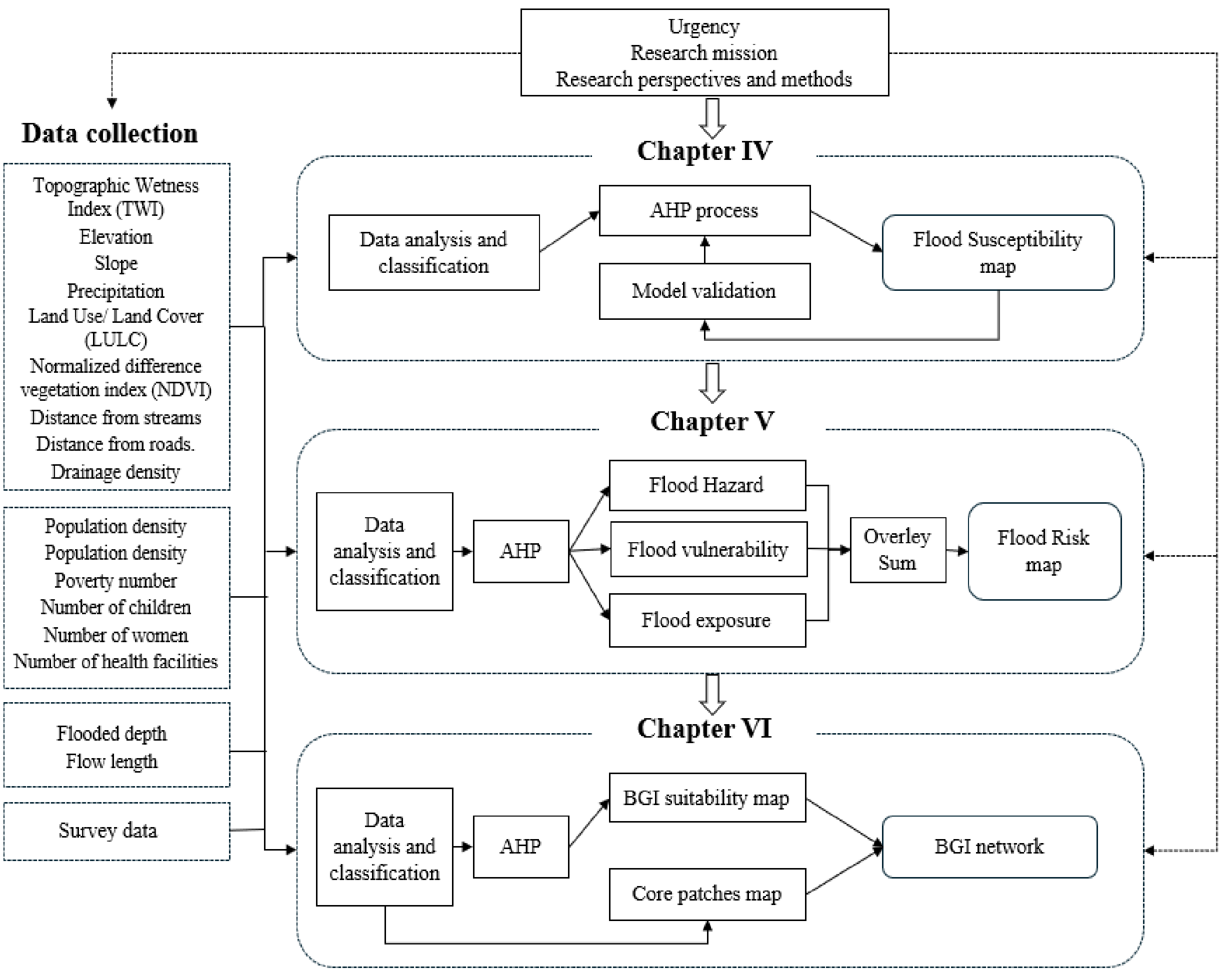

Figure 1-6. Research diagram.

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Chapter 2

LITERATURE REVIEW

This chapter begins by describing the context of urban flooding research and some sustainable solutions to flooding. It outlines research directions and the importance of the ongoing problem of urban flooding in the world. The second part reviews an overview of studies on urban flooding and green infrastructure planning in Vietnam. Identify Vietnam's efforts and limitations in research on urban flooding and sustainable solutions for urban areas. The final section of this chapter explores the concepts of risk, vulnerability, adaptive capacity, and resilience as well as indicators to explore these concepts in urban areas.

2.1. Overview of related research issues

2.1.1. Overview of urban flood research in the world

Flooding is one of the most serious natural disasters, significantly impacting human lives. Throughout history, humans have learned to live with natural disasters, which are often considered inevitable. However, with the development of urban areas, people began to pay attention to researching disaster-related issues, including floods, to find solutions to mitigate their impacts. Urban flood research has evolved through distinct stages over time.

Pre-research stage (before the 1970s): Urban flooding was not highly regarded, and detailed studies were lacking. Research and data on flooding primarily focused on rural areas and river basins. Seminal works such as White's (1945) examination of human adjustment to floods [1] and Horton's (1945) hydro physical approach to stream morphology [2] laid the groundwork for subsequent investigations. During this period, a study by Robert E. Horton became known for his theory of soil infiltration, which is the basis for many modern hydrological models. His work on water infiltration has led to a better understanding of surface runoff processes and how water moves through soil environments [3].

Primary research stage (1970s - 1990s): With increasing urbanization and city development, attention to urban flooding grew. Initial studies often focused on measuring and modeling floods, identifying causes and consequences, but specific solutions were lacking. Efforts during this stage concentrated on practical floodplain management measures, as demonstrated by studies like Burby's (2001) analysis of flood insurance [4] and Molle et al.'s (2009) exploration of hydraulic bureaucracies [5].

Advanced research stage (1990s - present): Advancements in science and technology have opened up new opportunities for researching and addressing urban flooding. Research has become increasingly diverse and complex, including fields such as climate change, project management, and green infrastructure development. Moreover, research methods have been improved and advanced. In this stage, themes like the influence of global phenomena such as the El Niño Southern Oscillation on flood risk [6] and the conceptualization of urban resilience [7] have emerged, reflecting a deeper integration of interdisciplinary perspectives and a heightened emphasis on adaptability and sustainability in urban flood management strategies.

In particular, several seminal studies have significantly altered the traditional research direction on flooding. Douglas, I. et al. (2008) explored the relationship between urbanization and flood risk, particularly in impoverished areas of African cities, by conducting participatory vulnerability analyses in five African cities. [8].

Wong, T. H. F., & Brown, R. R. (2009) emphasized the role of blue-green infrastructure (BGI) in creating water-sensitive cities, mitigating flood risk, and improving the urban environment. [9].

Zevenbergen, C. et al. synthesized flood risk management strategies and lessons from major flood events, proposing more sustainable approaches to flood management. [10].

The IPCC report of 2014 provides evidence of the increasing frequency and intensity of flood events due to climate change, prompting the development of response strategies and risk management [11].

Sampson, C. C. et al. described the development of a global flood hazard model, providing detailed maps to aid in disaster risk management [12].

These studies are landmark contributions in the field of flood research, providing both theoretical and practical foundations for modern and sustainable flood management strategies. In recent years, urban flooding has become one of the greatest challenges facing cities worldwide. The combination of factors such as climate change, urban environment, and unsustainable development has led to increasingly severe and complex flooding situations. In the context of urban flood research, recent studies have focused on various approaches, from analyzing the causes and impacts of flooding to proposing mitigation and adaptation solutions. Many research directions focus on analyzing flood risks and mitigation solutions. The following research directions highlight the necessity of applying advanced technologies, integrated management, and sustainable solutions to address the challenges of urban flooding in the context of ongoing climate change and urbanization.

(a) The research direction focuses on Flood Modeling and Forecasting: this includes studies on inundation models, encompassing hydrological and hydraulic modeling, real-time forecasting models, and climate change modeling. Hydrological and hydraulic modeling involves the use of computer models to predict and simulate flood events, assessing the impact of flood management measures [12]. Bates, P. D., & De Roo, A. P. J. (2000) described a simple raster-based model for flood simulation, providing efficient methods for flood forecasting [13].

Real-time forecasting involves the development of real-time forecasting systems to provide early warnings and quick responses in the event of floods. Werner, M. G. F. et al. presented methods for real-time forecasting, focusing on determining consistent roughness values for flood extent estimation [14].

Climate change modeling integrates climate change scenarios into flood models to predict changes in the frequency and intensity of floods. Arnell, N. W., & Gosling, S. N. (2014) evaluated the impact of climate change on river flood risk on a global scale, using future climate models for analysis. [15].

(b) Research utilizing Information and Communication Technology (ICT) is a prevalent method nowadays as it can support data collection in data-scarce areas. Additionally, machine learning models greatly aid researchers in the computational stage of flood research modeling. Kumar, A. et al. described a water quality monitoring system using IoT and machine learning, enhancing flood forecasting capabilities and risk management [16]. Mosavi, A. et al. provided an overview of machine learning models used for flood prediction, emphasizing the potential of big data and AI in flood risk management [17].

(c) Flood research integrating Blue-Green Infrastructure (BGI)

The design and evaluation of BGI is one of the effective research directions for green infrastructure solutions such as rain gardens, green roofs, and artificial ponds in flood mitigation. Furthermore, integrating BGI into urban planning helps enhance urban resilience to flooding. Ahiablame, L. M. et al. evaluated the effectiveness of low-impact development (LID) methods such as BGI in urban water management and flood risk reduction [18]. Fletcher, T. D. et al. discussed the development and application of terms related to sustainable urban water management, including Blue-Green Infrastructure (BGI) [19].

(d) Research Direction on Risk Management and Vulnerability Assessment

This research direction will focus on assessing vulnerability, analyzing factors that increase community vulnerability to floods. Additionally, this research direction will develop and evaluate flood risk reduction strategies, including policy development and spatial planning. Balica, S. F. et al. introduced an index for assessing the vulnerability of coastal cities to floods, aiding in identifying high-risk areas [20]. Jha, A. K. and colleagues provided comprehensive guidance on integrated urban flood risk management, including effective risk reduction strategies [21].

(e) Research Focus on Climate Change Adaptation

This research direction emphasizes the development of strategies to adapt to climate change, including adjustments to urban planning and infrastructure. It involves analyzing future climate scenarios and their impact on flood risk to formulate long-term adaptation plans. Mees, H. L. and colleagues explored the responsibilities of both public and private sectors in climate change adaptation, including urban adaptation strategies [22]. Arnell, N. W. and colleagues evaluated the impact of global climate policies on flood risk, utilizing future climate scenarios for analysis [23]. Additionally, there are numerous studies focusing on comprehensive management [24,25], post-flood recovery and reconstruction [26,27], and policy development [28].

The number of studies on urban flooding and solutions is increasingly growing across various countries and territories, including areas with limited data availability. This indicates that urban flooding research remains a crucial task in the era of significant climate change and rapid urbanization. This serves as an essential repository for authors to shape their approach and select appropriate research methodologies for their thesis. Many studies have indicated that research on urban flooding is a crucial step in the process of sustainable urban management and planning. To ensure the reliability of these flood studies, it is necessary to delve into the specific characteristics of each city and consider multiple factors such as natural conditions, economic, social, and infrastructure aspects. This perspective is applied in the thesis when the research model incorporates various factors assessed with the participation of experts from different fields.

2.1.2. Natural Factors

Floods are a natural phenomenon and are considered natural disasters when they impact humans. Therefore, many different natural factors are assessed to affect floods. Climate change has increased both the intensity and duration of floods.

(a) Rainfall

Intensity and duration of rainfall: Heavy rainfall over a short period (thunderstorms) can cause rapid flooding. Prolonged rainfall (steady rain) can lead to gradual flooding. Heavy rainfall during the rainy season often causes flooding in tropical and subtropical regions. Trenberth (2011) and colleagues have pointed out that climate change is altering global rainfall patterns, increasing the intensity and frequency of heavy rainfall events. This increases the risk of flooding in many areas [29]. Meanwhile, Allan & Soden (2008) analyzed the amplification of extreme rainfall due to global warming. This phenomenon leads to more frequent and severe heavy rainfall events, resulting in increased flood risk [30].

(b) Terrain and Geology

Regions with steep slopes often have strong currents, which can lead to erosion and flash floods. Depressions, flat areas, those near rivers, or coastal areas are prone to flooding due to inadequate drainage. Soil type also influences flooding due to its permeability. Sandy soil has better water permeability than clay soil, making clay soil more prone to flooding. O'Connor & Costa (2004) compiled the largest floods in history, analyzing their causes and scale, emphasizing the role of terrain and geological structure [31]. Montgomery & Dietrich (2002) studied the formation of high-slope flows, demonstrating the role of terrain in increasing flow velocity and power [32]. Li, Z., et al. (2017) identified that steep terrain and soil slope significantly influence the development of floods and landslides [33].

(c) Hydrology

The size and shape of river basins affect the speed and volume of water flowing downstream. Dense river networks can distribute water more quickly but also increase the risk of flooding if prolonged heavy rain occurs. Moreover, stream flows also influence water drainage density and can cause flooding. Knighton, D. observed that the structure and shape of river basins strongly influence flow dynamics and flood potential [34]. Ward, P. J., et al. argue that river basins and their response to heavy rainfall events play a crucial role in determining flood risk [35]. Meanwhile, Wohl, E. noted that small river basins can also significantly contribute to flood risk through sudden streamflows [36].

According to Horton, R. E., terrain characteristics and river networks have a significant impact on flow dynamics and flood risk [37]. Strahler, A. N. conducted quantitative analysis of river networks to better understand flood risk [38]. Additionally, Hergarten, S., & Neugebauer, H. J. pointed out that river networks can self-organize in response to environmental conditions, influencing flood risk [39].

(d) Climate and Weather

Climate change is increasing the frequency and intensity of extreme weather events such as heavy rainfall, storms, and sea level rise. Global climate phenomena such as El Niño and La Niña can cause unusual weather patterns, increasing the risk of flooding in certain areas. According to the IPCC (2012), climate change is intensifying the intensity and frequency of extreme weather events, including floods [40,41]. Field, C. B., et al. argue that extreme weather events, such as heavy rainfall and storms, may become more frequent and severe due to climate change [42].

(e) Vegetation and Forest Cover

Trees and vegetation help reduce the velocity of water flow and increase the soil's water infiltration capacity, thereby reducing the risk of flooding. Therefore, deforestation removes the protective vegetation cover, leading to erosion and floods. Deforestation increases the risk and severity of floods, especially in developing countries [42]. Forest ecosystems play a crucial role in water regulation [43], cooling [44], and reducing flood risk. Additionally, Laurance, W. F., et al. (2018) identified that deforestation in the Amazon can lead to climate change and increase flood risk [45].

(f) Sea Level Rise

Sea level rise increases the risk of coastal flooding, especially during storms and high tides. Additionally, saltwater intrusion reduces the soil's water infiltration capacity and affects coastal ecosystems. Some studies have predicted sea level rise, indicating that coastal areas will face higher flood risks [46, 47]. The impact of sea level rise due to climate change [48] leads to saltwater intrusion into coastal aquifers, increasing the risk of flooding [49].

These studies and citations all emphasize the importance of natural factors such as rainfall, terrain, hydrology, climate, vegetation, and sea level rise in influencing flood risk. A deep understanding of these factors helps improve the prediction and management of flood risk globally.

2.1.3. Anthropogenic Factors

As society develops, urbanization increases in low-lying areas, leading to profound natural changes that significantly impact flood disasters in unpredictable ways. Human-induced factors have caused considerable effects on urban flooding.

(a) Urbanization and Urban Development

Urban expansion may reduce the area of impermeable land, and increase water accumulation and runoff, contributing to increased urban flood risk [50]. Rapid urban growth can also lead to inappropriate land use, increasing flood risk [51].

(b) Inefficient Drainage Systems

Ineffective or overloaded drainage systems can increase urban flood risk, especially in areas with outdated or malfunctioning drainage systems [52]. Rapid urban change and development can cause drainage system failures, increasing flood risk [53].

(c) Land Use Change

Land use changes through construction, filling, or land use changes can reduce the soil's water permeability and increase urban flood risk [54]. Land use changes can alter water flow and cause flooding, especially in areas with weak soil [55].

(d) River Basin and Water Flow Alteration

River basin development, canalization, and natural flow alteration can increase urban flood risk by altering water flow and flow stability [56]. Construction of structures such as dams, and culverts can increase urban flood risk by altering the natural flow of water [57].

These factors are often the result of economic and social development but can also be adjusted and managed through sustainable urban development and effective flood risk management.

2.2. Blue-Green Infrastructure (BGI)

Instead of viewing a city as a single, discrete entity, it can be more insightful to think of it as layers of various activities and physical features interacting with one another. Among these elements, water stands out as the most influential in shaping a city and supporting urban activity and human life. Water is essential for human survival and numerous economic activities.

Despite its importance, we have long relegated water, one of the most crucial resources for a functional city, to underground systems, rendering it out of sight and mind. There is an increasing recognition that ensuring clean and sufficient freshwater will be a critical challenge for cities in the 21st century.

Traditionally, urban water infrastructure has been managed by using simple quantitative models to predict future water demand, followed by constructing additional infrastructure to meet this demand. This method prioritizes technology and large physical interventions aimed at manipulating natural processes to meet human needs. However, this reliance on "grey" infrastructure—characterized by extensive use of concrete and metal—is becoming inadequate in addressing the additional pressures on urban water supply caused by rapid urbanization, increased impervious land cover, and climate change.

In fact, relying solely on grey infrastructure can exacerbate these issues. For example, the conventional method of managing urban stormwater runoff involves collecting precipitation in a connected sewer system and quickly transporting it out of the city. As cities expand, the increase in impervious surfaces generates a larger volume of stormwater runoff in a shorter time, overwhelming existing sewer systems and leading to more frequent flooding.

Blue-Green Infrastructure offers a feasible, economical, and valuable option for urban regions facing the challenges of climate change. It complements and, in some cases, mitigates the need for grey infrastructure. Blue-Green Infrastructure (BGI) represents a paradigm shift that recognizes the importance of and value in including the role of urban hydrology within urban water management. The “Blue” recognizes the importance of the physicality of water itself, while the “Green” connects urban hydrological functions with vegetation systems in urban landscape design. The resulting BGI has overall socio-economic benefits that are greater than the sum of the individual components.

2.2.1. Definition and Components

BGI is an integrated system of green and blue elements in urban landscapes and water management, aimed at reducing the impacts of flooding, alleviating waterlogging, improving water quality, and generating other social and environmental benefits in urban areas. The main components of the BGI system include Green Infrastructure, Blue Infrastructure, and Integration.

Green Infrastructure comprises green areas such as parks, gardens, and open spaces arranged within urban areas. Trees and vegetation have the ability to absorb rainwater, reducing pressure on drainage systems, and providing ecological living spaces for species.

"Green infrastructure can help reduce the risk of flooding by increasing the permeability of urban surfaces, allowing rainwater to infiltrate into the soil rather than running off into storm drains." [58]

"Urban green spaces such as parks and gardens play a vital role in flood risk management by absorbing and storing rainfall, reducing the volume of runoff reaching drainage systems." [59]

Blue Infrastructure includes elements related to water management, such as reservoirs, canal systems, and water storage areas. Reservoirs and canals can store and regulate water flow, reducing the risk of flooding, and providing water for irrigation and domestic use.

"Blue infrastructure, including constructed wetlands and retention ponds, provides effective flood control by storing excess water during heavy rainfall events and releasing it slowly over time." [60]

"The implementation of blue infrastructure such as permeable pavements and green roofs helps to manage stormwater runoff, reducing the risk of urban flooding and improving water quality." [61]

Integration in BGI typically combines both green and blue elements into a cohesive system, leveraging the strengths of both to minimize the impacts of flooding and improve the urban environment.

Integration of green and blue infrastructure in urban planning allows for a holistic approach to flood risk management, combining the benefits of both natural and engineered systems." [62]

"Integrated green and blue infrastructure strategies not only reduce flood risk but also enhance biodiversity, improve air quality, and create recreational opportunities for urban residents." [63]

BGI not only improves water management and reduces flood risk but also brings many other benefits to the community, such as improving air quality, creating green open spaces, and enhancing urban vitality.

2.2.2. Benefits of BGI

Effective flood management:

BGI helps absorb, retain, and regulate stormwater flow, minimizing the risk of flooding in urban areas [64]. The BGI system, including reservoirs, natural drainage basins, and green infrastructure, can reduce flood alerts and flood damages [65].

Improving water quality:

BGI helps remove pollutants from stormwater by allowing water to infiltrate into the soil and filter through soil layers. Green areas and reservoirs in BGI provide a habitat for microorganisms capable of purifying water [66, 67].

Enhancing urban living environments:

Green spaces in BGI provide ecological spaces, helping to reduce urban heat and improve air quality. BGI creates comfortable and interesting areas for urban residents, promoting social interaction and creating cultural value for the community [68, 69].

Enhancing livelihoods and economic development:

BGI can create job opportunities in the management and conservation of green and water systems. BGI projects add value to urban areas, increasing tourism potential and property values [70, 71].

Enhancing resilience to climate change:

BGI provides a flexible means to cope with the impacts of climate change, such as heavy rainfall and water source changes. BGI systems can be adjusted and improved to respond to changing weather conditions [72, 73].

BGI systems are gaining recognition in many cities and countries worldwide, with numerous programs and organizations dedicated to raising awareness and supporting the implementation of BGI projects. Although the number of successfully built and operational BGI projects is still relatively small, it is steadily increasing.

However, several challenges remain in increasing awareness, adoption, and implementation of BGI. One challenge is that many BGI projects are implemented on a small scale, such as at the level of a single building or block. Another challenge is the relatively small number of BGI projects, especially when compared to the growing interest in and demand for them. Additionally, despite the diverse societal, ecological, and economic benefits that BGI projects provide, many of these benefits are difficult to quantify. Even when they are quantifiable, BGI projects often lack the resources to conduct thorough data collection. This is particularly challenging for before-and-after studies, which require data collection before project implementation.

2.2.3. Experience in building and developing BGI

Experience from Singapore

As an island nation in the Asian region, Singapore also faces severe flooding situations. In December 1978, Singapore endured a major flood when 512mm of rain fell in just one day. Thousands of people had to evacuate, and there were significant losses in terms of lives and property. At that time, the young government of Singapore faced challenges in flood control while still needing to preserve fresh water sources for the millions of residents. However, today, only about 40 hectares of land in Singapore are at risk of being submerged, compared to 3,178 hectares in 1970. Singapore has become one of the exemplary countries in successfully addressing urban flooding and drainage issues. What solutions has Singapore implemented to solve its drainage problems?

Singapore's experience in building and developing BGI on an urban scale

Without resorting to complicated measures, Singapore implemented the construction of water reservoirs across the country to increase water storage capacity for both flood control and freshwater storage. Through a system of rivers, drains, and canals, rainwater from two-thirds of Singapore's land area is directed into 17 reservoirs. These reservoirs play a crucial role in reducing flooding in some of the island's low-lying areas (Figure 2-1).

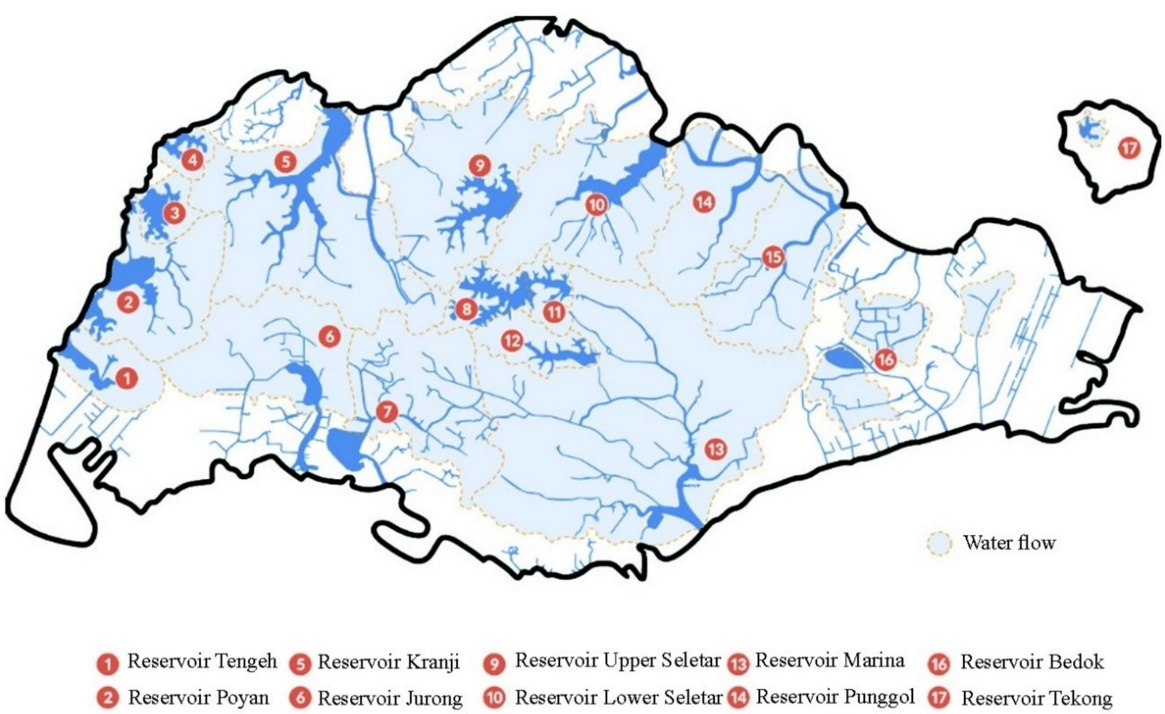

Figure 2-1. Map of 17 reservoirs in Singapore [74]

Table 2-1. Summary table of area and proportion of each type of vegetation in Singapore [75]

Types of plants	Area (ha)	Ratio (%)	Number of arrays
No vegetation	28270.43	38.85	22275
Vegetation is managed	19972.96	27.45	29075
Shrubs	4307.54	5.92	8340
Young secondary forest	14288.48	19.64	2920
Old secondary forest	994.68	1.37	42
Primary forest	118.34	0.16	15
Mangroves	662.43	0.91	491
Freshwater swamp	76.6	0.11	227
Freshwater swamp forest	283.12	0.39	125

Along with the 17 freshwater reservoirs, a vegetation cover system occupies 56% of the total area of the entire island nation. Managed vegetation accounts for 27% of the total area, while 29% is covered by spontaneous vegetation such as forests, shrublands, freshwater swamp forests, and mangrove forests (Table 2-1). This is considered a sustainable solution to reduce the runoff of rainwater, thereby mitigating the flooding situation in Singapore.

Singapore's experience in building and developing BGI on a regional scale

In each urban area, there are green parks, gardens, and wooded areas (Figure 2-2). Roads and green corridors form continuous "green patches." Between buildings, there are connected green spaces. The connection and expansion of green areas in each region have helped reduce runoff at the local level and decrease the pressure on the urban drainage system.

Singapore's experience in building and developing BGI on a point scale

Bishan-Ang Mo Kio Park in Singapore is a significant regional park that connects the Bishan and Ang Mo Kio residential areas, which were developed in the 1970s. In the early 1980s, a concrete canal was constructed to mitigate flooding by channeling water from the surrounding neighborhoods into the Kallang River basin. This catchment area is now part of Singapore's water reuse system. In 2006, Bishan Park was selected as one of the first 20 pilot projects under Singapore’s national ABC Waters Program. At that time, both the park and the canal required restoration. The Public Utility Board (PUB), responsible for Singapore's municipal water management, decided to use Bishan Park as a demonstration project. The goal was to retain the canal's functionality while improving water quality and managing stormwater runoff through additional green design elements. This project also aimed to enhance community activities and recreation. PUB collaborated with Singapore's Parks Board, merging their budgets to support the project. The resulting award-winning design removed the concrete canal, showcasing innovative water management and recreational improvements.

Figure 2-2. Singapore blue – green plan [76]

Figure 2-3. Bishan-Ang Mo Kio Park location

The former concrete canal has been transformed into a natural, winding stream that helps clean runoff through bioretention and filtration. During heavy rain, the stream swells and floods the surrounding green areas, illustrating the resilience of blue-green infrastructure (BGI) in handling extreme weather.

Today, the park provides both a recreational area for residents and a space to enjoy nature, wildlife, and water in Singapore, bridging the gap between a public park and a semi-natural canal.

Blue-Green Infrastructure at Bishan-Ang Mo Kio Park

The Bishan-Ang Mo Kio Park project covers a total area of 62,000 square meters and was initiated under municipal ownership with investment from both Parks and the Public Utilities Board (PUB). Construction of the park began in 2009 and was completed in 2012. The project was motivated by the need to address several pressing urban challenges, including climate change adaptation, reducing the urban heat island effect, and restoring natural ecosystems. A key goal of the park was to manage rainwater effectively to prevent flooding, stabilize groundwater levels, and improve overall water quality, while simultaneously addressing water pollution and promoting water recycling.

Additionally, the park was designed to provide much-needed recreational spaces in a densely populated urban area, enhance biodiversity, and increase surface permeability to allow for better water absorption.

Functionally, the park features a comprehensive rainwater management system that integrates flood prevention and groundwater stabilization. The design incorporates a variety of retention systems, drainage solutions, open water features, and closed water loops, all aimed at promoting climate resilience. The park also offers extensive recreational areas and open spaces, including opportunities for urban gardening and farming.

Key facilities within the park include playgrounds and water play areas, community spaces, pet-friendly areas, wetland biotopes for natural water purification, cycle paths, sunbathing lawns, and cafes. These amenities enhance the park’s functionality as both a green space and a community hub.

The total cost of the project was 68 million SGD, reflecting the scale and ambition of this blue-green infrastructure initiative.

Figure 2-4. BGI value gained from Bishan-Ang Mo Kio Park

Source: https://beta.nparks.gov.sg/visit/parks/park-detail/bishan-ang-mo-kio-park

Experience from Chicago – USA

Chicago's experience in building and developing BGI on an urban scale

Chicago focuses on the conservation and expansion of green spaces within the city. Since 2004, the Chicago Wilderness Green Infrastructure Vision has been implemented with the goal of protecting natural forests, rivers, wetlands, and vegetation, while also expanding and connecting these areas through green corridors and pathways. The dark green areas represent the existing natural regions (parks, forests, and preserves). Alongside these are landscape features, green corridors, and green pathways designed to connect the ecological systems into a unified whole (Figure 2-5).

Figure 2-5. BGI System Vision Map of Chicago's Wildlands [77]

Chicago's experience in building and developing BGI on a regional scale

At the regional and neighborhood level, to address flooding and climate change adaptation, Chicago has implemented a stormwater management system that includes the construction of over 100 "green streets" with permeable pavements. The most effective project is the two-mile "sustainable street" in Chicago's Lower West Side, currently recognized as the "greenest street in America." On this street, rainwater flows through the sidewalks to a layer of porous rock where it is purified by bacteria (Figure 2-6). The water is then used for irrigation or percolates through deep sand layers to return to Lake Michigan. This is an effective blue-green infrastructure (BGI) solution for conserving water resources, reducing runoff, and efficiently controlling urban flooding.

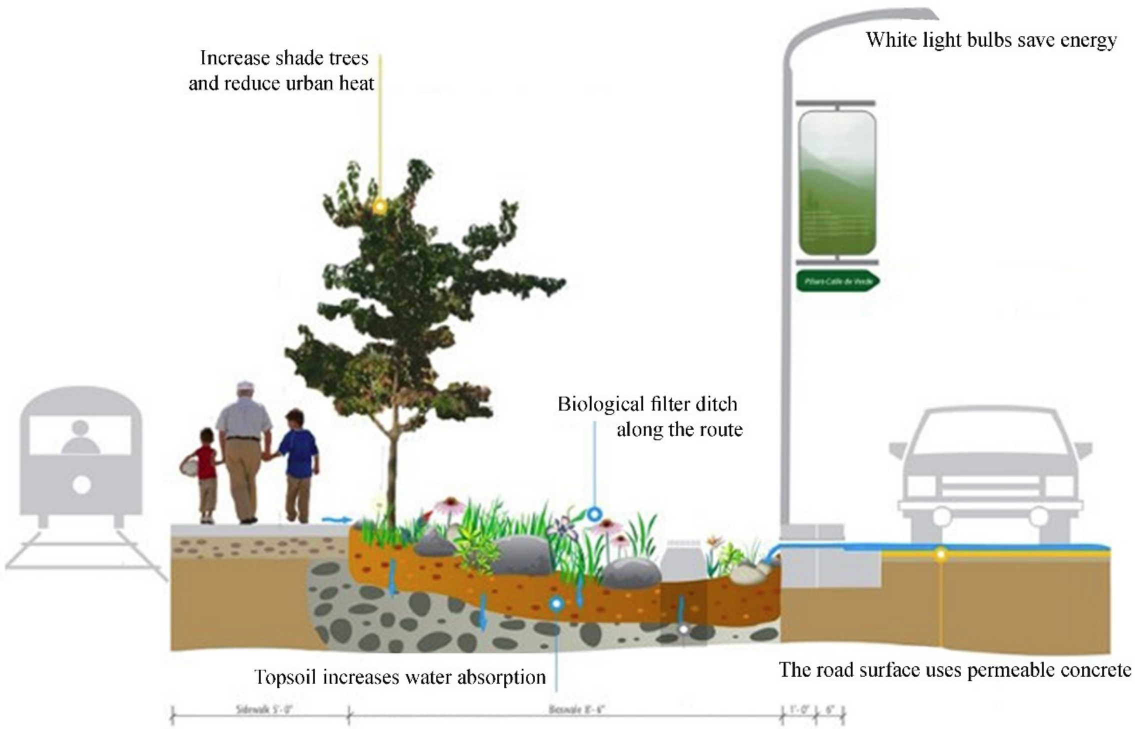

Figure 2-6. The section of "Sustainable Road" in the Lower West Side, Chicago [78]

2.3. Status of flooding research and BGI project in Hanoi

2.3.1. Status of flooding research in Hanoi

With global climate warming [79], urbanization [80], and greenhouse gas emissions [81, 82], both the intensity and frequency of floods are expected to increase. Climate change is forecasted to elevate sea levels along with the frequency and severity of floods in Southeast Asia and around the world [83, 84]. Given the concentration of population and economic assets in vulnerable areas, Vietnam ranks among the top five countries most severely affected by climate change [85,86], with one-third of its population currently exposed to flood risks [87]. Rapid urbanization in Vietnam is exacerbating environmental issues in urban settings, which is compounded by the growing unpredictability of extreme weather events [88]. Hanoi, one of the largest and most densely populated cities in Vietnam, has witnessed increasingly intricate and challenging urban flooding in recent years [89,90]. There have been several studies utilizing various methods and approaches on urban flooding in Hanoi. Among them, Luo and colleagues presented a calibrated flood model using reference images to assess the impact of four extreme rainfall events on water depth and flooded areas in downtown Hanoi [91]. An assessment of future tangible flood damage in the urban basin of the To Lich River, Hanoi, was conducted by Kefi and colleagues using spatial analysis methods and the integration of multiple datasets related to flooding [92]. Additionally, Nguyen Hieu and colleagues assessed the status of historical flooding events that occurred at the end of 2008 through satellite image analysis, GIS, and terrain characteristics [93]. Recently Loi assessed vulnerability to flooding using the AHP based on pre-event characteristics in the Hoan Kiem district, Hanoi [94]. Each study has its strengths and limitations, but collectively, they enhance our awareness and understanding of the damage caused by urban flooding in Hanoi. However, current studies are focusing on specific aspects and do not provide a comprehensive overview (Appendix 2-1). To support the development of suitable surface water management and flood mitigation solutions, this study investigates the entire study area and categorizes the susceptibility to flooding and flood risk levels for different regions. The calculations and analyses will be conducted using survey data and GIS data obtained on the urban surface elements, with the aim of fairly treating both the central areas of Hanoi and the suburban areas. Subsequently, we will compare the differences and issues between these two parts of the study area to determine the priority levels and appropriate solutions for each area.

The flooding situation in Hanoi has improved significantly since 2008, especially along the main routes, thanks to the efforts of the city government. The government has increased the number of water pumping stations, such as the Yen So and Yen Nghia stations. The next plan is to add more pumping stations at Lien Mac, Dong My, Yen Thai, and Dao Nguyen. These key stations pump water out to external rivers (the Red River, the Day River) with a total design capacity of 503 m^3/s according to the plan. This should fundamentally address widespread flooding, ensuring protection against rainfall of 240 mm in one day or 340 mm over three days, corresponding to a 10% frequency or a 10-year recurrence cycle. However, localized flooding in some streets and roads still persists. This localized flooding is not expected to be resolved in the coming years.

In addition to increasing the number of pumping stations, policies to address flooding in Hanoi mainly focus on renovating the drainage system. These projects have been ongoing for a long time but still show inefficiency in dealing with flooding during the rainy season.

2.3.2. Status of BGI project in Hanoi

Currently, the situation of BGI in Hanoi is receiving special attention due to increasingly serious issues related to flooding and water management. Like many other major cities around the world, Hanoi is facing challenges of climate change, rapid urbanization, and inadequate infrastructure.

BGI projects are being implemented in Hanoi to minimize the risk of flooding and improve the urban living environment. The city of Hanoi consists of two main parts: 12 central districts with dense population and 17 suburban districts mainly focused on agriculture and urban green corridors. However, according to surveys, the central urban areas have limited blue-green infrastructure, with mostly scattered lakes and parks that are heavily cemented. Meanwhile, in the suburban areas with large green land reserves serving as the lungs of the city, green spaces are being converted for agricultural development, leading to issues such as water pollution in rivers and lakes, ecosystem degradation, biodiversity loss, and poor landscape quality. This raises the need to evaluate the development of districts from the perspective of BGI development.

BGI measures being implemented in Hanoi include the construction of smart drainage systems, renovation and expansion of green spaces, construction of rainwater reservoirs, and the use of information technology for water monitoring and management, as well as the implementation of green roofs and green alleys in central districts. However, most of these are small-scale projects lacking comprehensive integration. Meanwhile, suburban districts are also orienting towards new rural development, integrating BGI into regional planning and development strategies. Despite the recognized benefits of Blue-Green Infrastructure (BGI) in urban flood management, its implementation in rapidly growing cities like Hanoi faces significant challenges. These challenges include limited public awareness and understanding of BGI concepts and benefits, financial constraints, and complex regulatory procedures. Without effective community engagement and stakeholder collaboration, the full potential of BGI to mitigate flood risks and enhance urban resilience may not be realized.

Introduction of the current situation of landscape in Hanoi - green areas and water bodies
According to the City Development Master Plan towards 2030, with visions extending to 2050, Hanoi is projected to be the political-administrative center of a country with a population of one hundred million. It is also envisioned as a major hub for culture, science and technology, education and training, economy, tourism, and trade within the Asia-Pacific region.

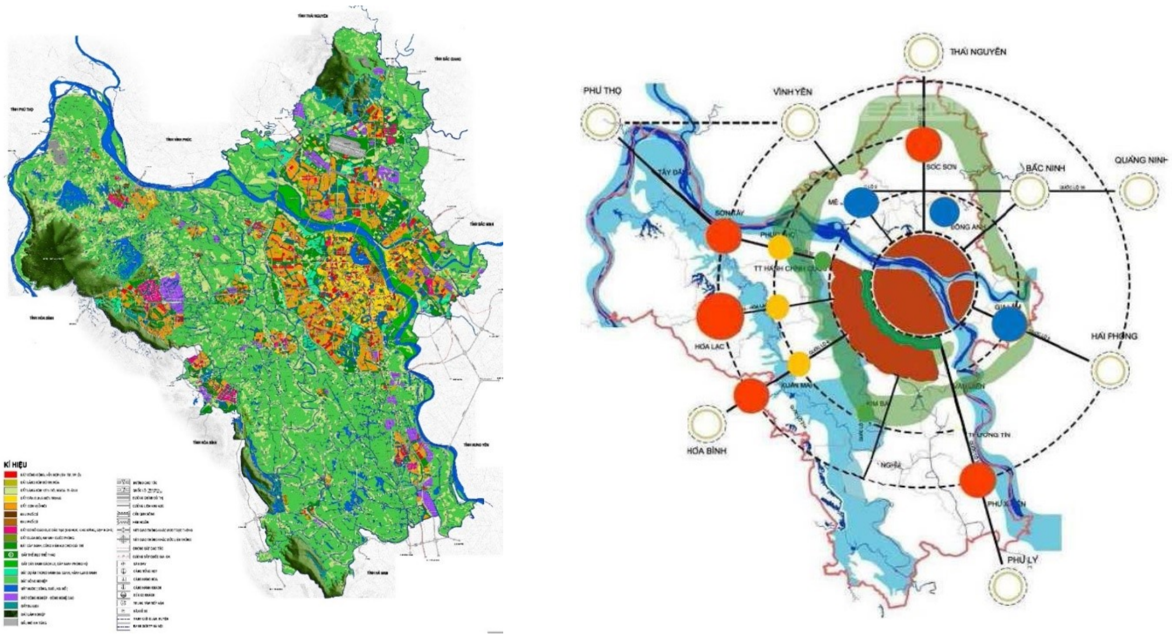

Figure 2-7. The Master plan of Hanoi Capital until 2030 and visions to 2050 [95]

In the future, Hanoi aims to evolve into a "City of Green, Culture, Civilization, and Modernity." The capital city's development will be rooted in conserved natural landscapes, such as the mountains in Ba Vi, Tam Dao, and Huong Son, as well as its extensive green spaces due to fertile agricultural land. Additionally, it will be culturally rich, drawing from traditional villages and a vast system of historical monuments, such as the Temple of Literature and thousands of other heritage sites. With over 1,000 years of history, Hanoi boasts a unique character unparalleled elsewhere in the country.

Hanoi is also working towards a robust and dynamic economy with modern and comprehensive urban infrastructure. Nonetheless, it is crucial to preserve both tangible and intangible heritage assets, as they represent a deeply established culture in one of the earliest cradles of civilization in the country. The concept of a multi-central city is seen as fitting for Hanoi's future development, as illustrated in Figure 2-7. The central districts and peripheral satellite towns will be interconnected, forming a comprehensive road network with an efficient transit transport system. This model has proven effective for many megacities in developing countries and is suitable for Hanoi as well.

The concepts of "green corridor" and "green belt" are highly applicable to the Hanoi Region and can be further developed. In the future city development structure, green corridors will make up about 70% of the natural land area, encompassing the entire rural area of Hanoi. These green corridors extend along the Day River, Tich River, Nhue River, Ba Vi Mountain, and Huong Tich site, as well as along city ring road no. 4, crossing the Red River and connecting to the area around Soc Temple. These green corridors help delineate urban areas and limit spontaneous urbanization. They comprise various elements, such as natural conservation areas, agricultural development zones, villages, and cultural heritage sites. The key visions and strategies from the Ministry of Construction's Master Plan, approved by the Prime Minister in 2011, concerning green areas and water bodies, are summarized as follows:

- To develop and conserve rural areas and natural forests.
- To manage green belts and green buffer zones to prevent urban expansion from the inner city
- To optimize the natural resources of parkland and water surfaces.
- To integrate landscape design with environmental solutions to create more links among existing parks and lakes.

Overall, Hanoi boasts diverse charming landscape typologies, with various hydro-geological conditions and fertile delta soil favorable for the development of flora and fauna. The region offers a wide range of rainforest ecosystems, agricultural areas, rivers, lakes, ponds, and canals. These features are essential for creating genuinely green city and ecological landscape rich in greenery and water attractions.

Overview of the green area development process

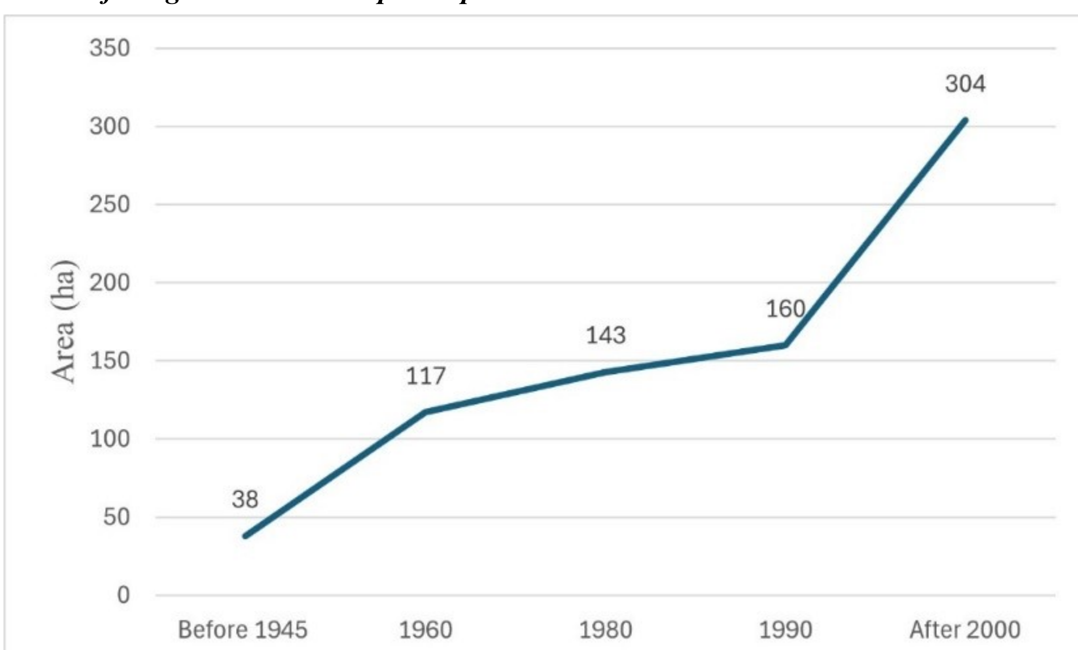

Figure 2-8. Chronological increase in the number of urban parks and mini parks in Hanoi [96]

During the subsequent period, from the early 1960s until 1986, many socialist neighborhoods were constructed in the city with proper consideration given to green issues in planning standards. The spaces between apartment blocks were designated for green areas with various types of plants. This period saw a chronological increase in the number of urban parks and mini parks in Hanoi (Figure 2-8). In the late 20th century, the economic boom, coupled with inadequate control policies and rapid population growth, exerted significant pressure on urban development. This resulted in the widespread occupation of public places and open spaces, leading to a rapid decline in the green-and-blue network in terms of quantity. Recently, there has been a significant shift in public awareness and the attitude of authorities regarding the importance of green spaces in urban development. Increasing green areas in the city has become a pressing concern. Efforts are evident in the planning of numerous new parks and gardens after the year 2000, such as Hoa Binh Park, Flower Garden, and various mini parks and walkways in peripheral urban areas like My Dinh 1, My Dinh 2, and Van Quan Town.

The green area per capita in Hanoi is relatively low, averaging 5 square meters per person across the entire city, while in the central district, this figure is estimated to be only about 2 to 3 square meters per person. According to the City Development Master Plan for Hanoi, issued in 1998 by the Ministry of Construction, the goal was to increase the green area per capita to 15 square meters per person by the year 2020. The total green area and the greening indicator are given in Figure 2-9 and Figure 2-10

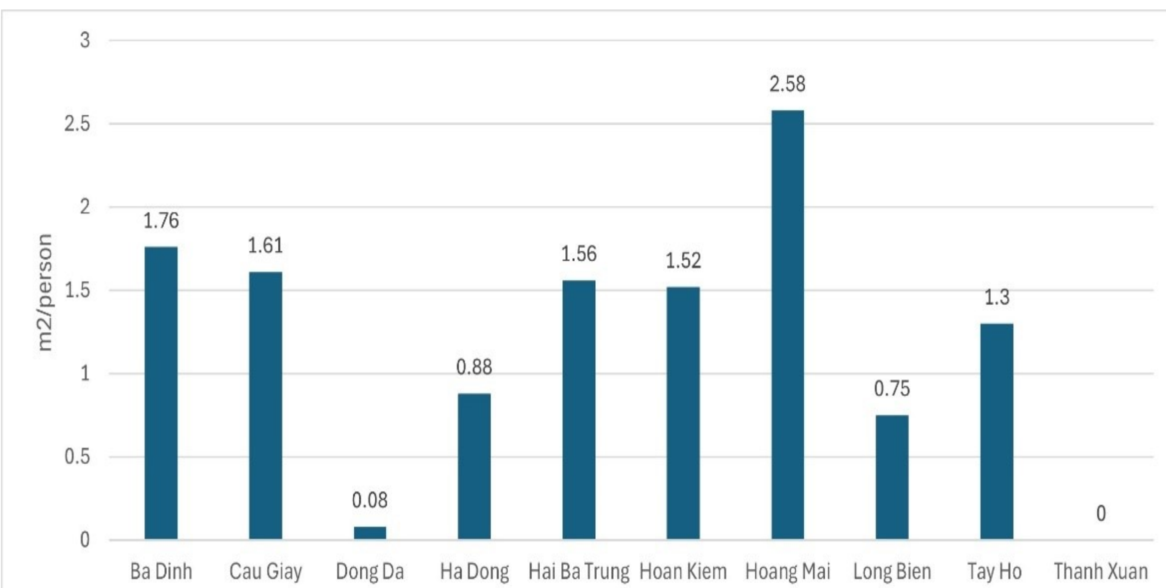

Figure 2-9. Area of the parks and gardens by ten inner city administrative division [97]

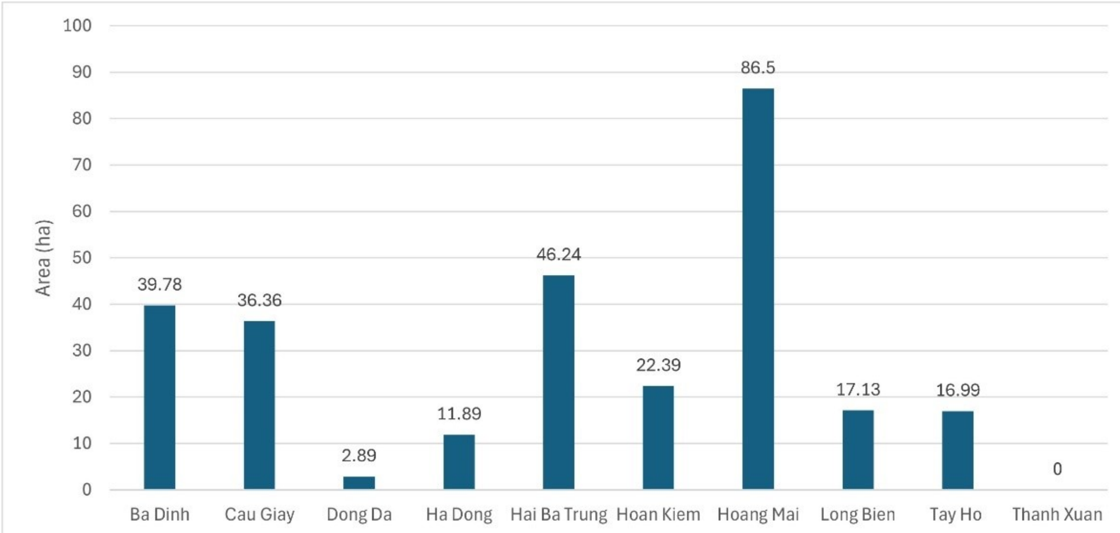

Figure 2-10. Statistics of street tree area per capita in the inner city [97]

2.4. Related definitions

Risk

According to the IPCC (Intergovernmental Panel on Climate Change), risk is the combination of the likelihood of an event and its consequences. Specifically, in the context of climate change, risk is determined by the interaction of hazards, vulnerability, and exposure [97]. Natural disaster risk is the possibility of potential harm to life, property, livelihoods, and economic, social, and environmental assets due to the impact of natural events. [98].

Hazard

Hazardous nature is a phenomenon, substance, activity, or condition capable of causing harm to life, property, livelihoods, and economic, social, and environmental assets. Hazards can be natural (such as earthquakes, floods), man-made (such as industrial accidents, chemical spills), or a combination thereof [98]. The hazardous nature is the occurrence of events or phenomena, whether natural or man-made, that have the potential to cause harm, damage, or other adverse consequences [97].

Exposure

Exposure refers to the presence of humans, livelihoods, species, ecosystems, assets, or services in areas that may be affected by climate hazards [97]. Exposure addresses the presence of humans, livelihoods, assets, and services in areas that may be impacted by hazards [98].

Susceptibility

Vulnerability refers to the degree to which a system may be affected by the adverse impacts of climate change. It depends on the sensitivity and adaptive capacity of the system to cope with and adapt to these impacts [99]. Vulnerability is part of susceptibility, referring to the ability of systems, humans, or assets to be affected by hazards [98].

2.5. Summary

The literature review for the study of urban flood risk and blue-green infrastructure (BGI) in Hanoi, Vietnam, delves into key concepts and current research trends in urban flood management, risk assessment, and the implementation of BGI as a sustainable solution. Urban flood risk is a critical issue faced by many rapidly growing cities worldwide, including Hanoi. The risk is influenced by a combination of natural factors such as rainfall intensity, topography, and drainage capacity, as well as anthropogenic factors like urbanization, land use changes, and inadequate infrastructure. Key studies highlight the importance of comprehensive flood risk mapping to identify vulnerable areas and inform mitigation strategies.

BGI refers to the integration of natural and engineered systems that manage water, create sustainable urban environments, and provide ecological, economic, and social benefits. BGI includes green roofs, rain gardens, permeable pavements, and urban wetlands. BGI integrates water management with green spaces to enhance urban resilience and ecological health. BGI offers multiple benefits, including effective flood management, improved water quality, enhanced urban aesthetics, increased biodiversity, and better climate resilience. Moreover, Hanoi is particularly vulnerable to urban flooding due to its rapid urbanization and significant population growth. The city's drainage system is often overwhelmed during heavy rains, leading to frequent and severe flooding events. In Hanoi, the implementation of BGI faces several challenges, including limited public awareness, financial constraints, and regulatory hurdles. Despite these challenges, there are ongoing efforts to integrate BGI into urban planning to mitigate flood risks and improve environmental quality.

After reviewing all the relevant literature and examining the current situation, the author has formulated specific objectives for the study of flood risk and blue-green infrastructure in Hanoi. These objectives are developed through a systematic process.

Appendix

Table 2-1. Flood studies have been carried out in Hanoi

No	Journal	Year	Authors	Title	Connect on the influence factors	Main findings
1	ISPRS International Journal of Geo-Information	2023	Loi, D. T.	Assessment of Urban Flood Vulnerability Using Integrated Multi-parametric AHP and GIS	Flood Vulnerability	The flood vulnerability level based on the pre-event characteristic in Hoan Kiem district
2	VNU Journal of Earth and Environmental Sciences	2013	N. Hieu et al.	Assessment of Flood Hazard in Hanoi City Assessment of Flood Hazard in Hanoi City	Flood Hazard	Assessed the actual state of historical flood happening at the end of 2008.
3	Proceedings of Hydraulic Engineering	2004	Thang, N.T. et al.	Flood Inundation Analysis Based on Unstructured Meshes for the Hanoi Central Area	Flood Inundation	The model application includes three cases: a real heavy rainfall analysis, an assumed exceptionally heavy rainfall analysis and an assumed dike break analysis.
4	Japan Agricultural Research Quarterly	2021	Anh, S.H. et al.	Flood Hazard Assessment of Residential Areas Outside the Protected Area of the Red River Dike System in Hanoi, Vietnam	Flood Hazard	Modeled floods and mapped them using a two-dimensional depth-averaged hydrodynamic model to show the inundation depth levels for the entire area in high resolution.
5	Vietnam Journal of Hydrometeorology	2019	Tran, K. C. et al.	Assessment of urban flooding in Yen Hoa - Hoa Bang area, Cau Giay, Hanoi	Urban Flooding	The numerical model MIKE URBAN is used to simulate the rainfall-runoff, routing, and surcharge processes in Yen Hoa - Hoa Bang areas.
6	Japan Agricultural Research Quarterly	2019	Anh, S. H. et al.	Assessment of Floodwater Behavior in Van Coc Lake, Hanoi in Event of Emergency Situation	Floodwater Behavior	Performed numerical simulations to assess the movement of floodwater in this lake and evaluated the impact of floodwater on its residential areas.
7	Journal of the British Academy	2019	Scaparra, M.P. et al.	Community perceptions of social, economic and environmental impacts of flooding in central districts of Hanoi, Vietnam	Impacts of flooding	The GCRF–OSIRIS Project aims to optimize investment strategies to minimize the impacts of flood disasters, making disaster risk reduction more effective, by introducing operational research methods

8	Vietnam Journal of surveying and mapping science	2013	Hoang, T.T.H et al.	Zoning the risk of flooding due to the influence of prolonged rain in the capital hanoi using remote sensing and gis data	Flooding risk	Analyze flood situation due to heavy rain in Ha Noi (in 2008 and 2013) in order to localize the risk of flooding in Ha Noi by using remote sensing and GIS data
9	Computers and Geotechnics	2014	Duong, T. T. et al.	Riverbank stability assessment under flooding conditions in the Red River of Hanoi, Vietnam	Riverbank stability	A case study on the portion of the Red River flowing through Hanoi using the finite element method and extending the mechanics of saturated and unsaturated soils to understand how the riverbank's FOS varies with RWL fluctuations.
10	Scientific Reports	2018	Luo, P.P. et al.	Flood inundation assessment for the Hanoi Central Area, Vietnam under historical and extreme rainfall conditions	Flood inundation	Presents a calibrated flood inundation model using referenced photos, an assessment of the influence of four extreme rainfall events on water depth and inundation area in the Hanoi central area
11	ISPRS International Journal of Geo-Information	2018	Kefi, M et al.	Assessment of Tangible Direct Flood Damage Using a Spatial Analysis Approach under the Effects of Climate Change: Case Study in an Urban Watershed in Hanoi, Vietnam	Flood Damage	Assess tangible future flood damage in the urban watershed of the To Lich River in Hanoi, Vietnam.
12	Water (Switzerland)	2020	Tran, D.T. et al.	Predicting Urban Waterlogging Risks by Regression Models and Internet Open-Data Sources	Urban Waterlogging Risks	Applied a regression model in ArcGIS with internet open-data sources to predict the probabilities of urban waterlogging risks in Hanoi, Vietnam, during the period 2012–2018 by considering six spatial factors of urban surfaces

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Chapter 3

METHODOLOGY

The previous chapter outlined the characteristics of urban Hanoi, with urban development poorly responding to the natural environment and flooding. This chapter aims to establish a framework of research methods and demonstrate how these methods were applied to the process of selecting, collecting and analyzing data after five months of fieldwork. It includes:

- Research design and practical data collection as applied in the three phases of the study.

- The process of collecting and selecting factors to participate in the calculation model.

- Means of sourcing and selecting data for detailed interpretation.

- Data analysis process.

3.1. Overview of the research design.

The research process will be carried out in three main stages from the beginning (Figure 3-1). Stage one involves data collection, Stage two focuses on preparing the factors involved in the analysis, calculations, and modeling process, and Stage three is the stage of running the model and verifying the results.

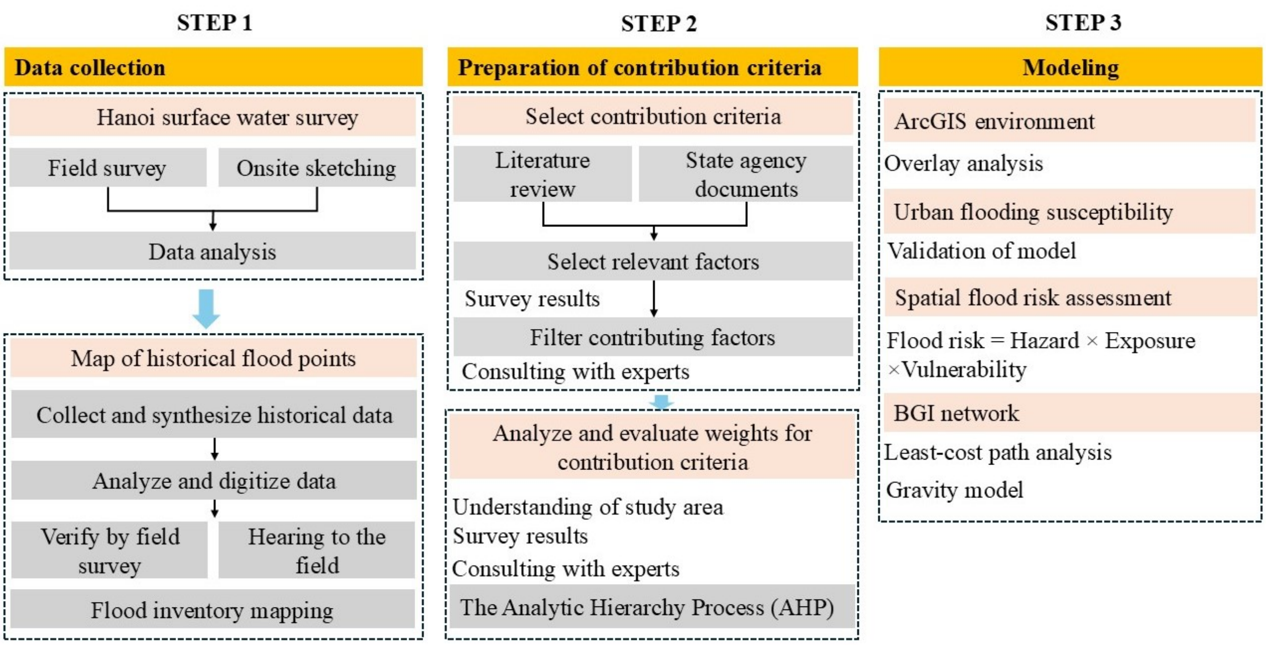


Figure 3-1. An outlined diagram of research

Stage one will be conducted through various methods such as field surveys, onsite sketching, interviews, or data collection from government and local agencies, as well as open-access reports, information, and studies. The collected data will then be classified and preliminarily processed.

Stage two involves analyzing, evaluating, and selecting suitable factors for calculation. This process will be based on scientific foundations from existing studies and expert opinions to enhance the accuracy of the results. After that, maps will be developed for these factors within the GIS environment.

Stage three is the modeling phase, where the models will be executed using tools in ArcGIS. The results will then be verified, and adjustments to the model will be made accordingly.

The data collection process in Stage one is divided into three implementation steps. First of all, data collection explores the current state of water surface space, green space and synthesizes the locations of flooding points in Hanoi city to better understand the characteristics of flooding in this city. From there, the research focuses on reviewing and analyzing the possibility of flooding risk, and the city's level of flooding risk by calculating based on selected appropriate contributing factors. To investigate selected influencing factors, various data collection methods are used including field observations, documentary evidence, and open geospatial data and data collection through conversations with residents. In addition, to make the model more accurate, a survey of experts' opinions was conducted. The three main steps of the data collection process are illustrated in the following order (Figure 3-2).

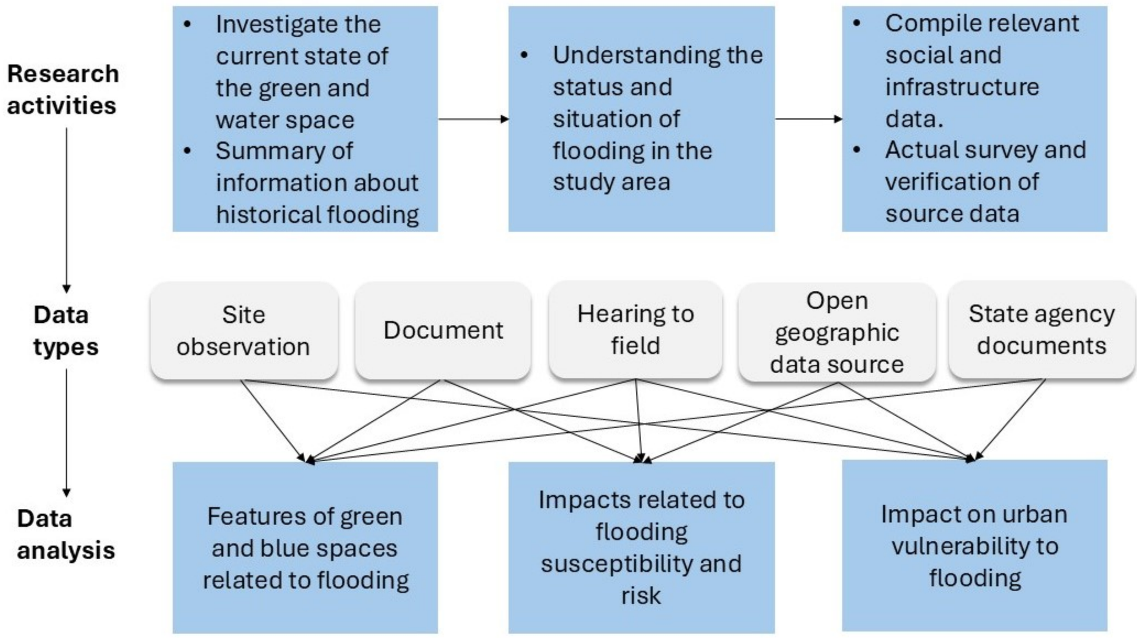


Figure 3-2. An outlined diagram of data collection steps

Step one: Surveying the status of green space and water surfaces in Hanoi

Mapping the distribution of urban water surfaces and their quality status was developed from photographs (Appendix 3-1), satellite data, statistical documents, and memories of local people. The data were collected through on-site surveys, examining each location. The on-site surveys were conducted over a period of one month from March to April 2022, with five or six locations surveyed each day using tools such as cameras, smartphones, and notebooks. This phase mainly surveys the current status of trees and water in the central area of Hanoi—detailed assessment of the problems that this area is facing.

Step two: Collect and consult documents

First, the theoretical foundation for the research was established by collecting and analyzing relevant published research articles through Google Scholar, ScienceDirect, and ResearchGate (Appendix 3-2), along with policy documents from government and local agencies. These preliminary data were classified and analyzed to select appropriate theoretical bases for the study (Appendix 3-3).

The survey element characteristics data was primarily collected from open geographic information systems from reputable sources. After systematically reviewing various sources, including field observations, group discussions, literature reviews, and data from government agencies and expert opinions, regulatory factors relevant to the study were selected.

Step three: Field survey of historical flood sites

This phase compiles infrastructure and social data including population density, poverty rates, number of health facilities, and distribution of female and child populations to explore the level of risk that exists. can happen to urban areas when flooded. This data collection is mainly from statistics from government and local agencies. Interviewing households in the surrounding area to determine a more accurate location for each flooded location. Naturally occurring conversations with local people were used to help the researcher gain a basic understanding of the site and the long-term inundation situation (with voluntary consent from the people local). Data collection was conducted two times, before the rainy season from April to May and after the rainy season. This information is then used to support the construction of input data for the research model. In particular, the flood location map is also used to check the probability of the flood risk model.

Table 3-1 shows the timing of the on-site surveys. The main survey was conducted from March to May 2022, however, due to the corona pandemic situation, a second survey was added in April 2023. Visits to households around flooded areas were conducted for 55 households, however, information was only collected from 42 households, of which 17 households were able to conduct conversations. The data collected from the survey was categorized and analyzed (Table 3-2).

Table 3-1. Fieldwork schedule

Research activities	Participants	Number of participants	Date
Site approach	5-7 Mar 2022		
Site selection	non-residential	73	8 Mar – 5 April 2022
Site observation	non-residential	73	8 Mar – 5 April 2022
Participant approach	Local resident	As many as possible	8 April – 27 May 2022
Hearing to the field	Local resident	42	8 April – 27 May 2022
Unstructured review	11 points are frequently flooded	17	8 April – 27 May 2022
Site observation	residential point		8 April – 27 May 2022

Table 3-2. Fieldwork data.

Data Source	Data Type	Data collection	Data analysis
Site visit	Site observation	Collected in the field by researcher	Spatial/Image analysis
Local residents	Naturally occurring talk	Conducted at the beginning of the fieldwork and lasted until the end of on-site activities.	Content analysis
Local residents	Unstructured interview	Interviewed after choosing appropriate participants from naturally occurring talks	Conversation analysis

The data collected from open geographic data from reliable sources are listed in Table 3-3. The data will be processed and cleaned in preparation for evaluation and selection.

Table 3-3. Data sources

No.	Dataset	Source	Classification methods
1	SRTM DEM	https://earthexplorer.usgs.gov/	
2	Elevation	https://earthexplorer.usgs.gov/	Natural break
3	Distance from streams	SRTM DEM	Supervised classification
4	Slope	SRTM DEM	Supervised classification
5	NDVI	Landsat 8 The United States Geological Survey (http://www.usgs.gov/)	Natural break
6	LULC	https://earthexplorer.usgs.gov/	Supervised classification
7	Distance from roads	Open street map / Field survey	Manual
8	Precipitation	High- resolution gridded datasets climatic research unit (CRU)	Natural break
9	Drainage density	SRTM DEM	Natural break
10	TWI	SRTM DEM	Natural break
11	Hydrologic Soil Group	FAO/UNESCO Soil Map of the World	Manual
12	Water surface	SRTM DEM	Natural break

3.2. Study area.

Hanoi, located between latitude 20°34' to 21°18' N and longitude 105°17' to 106°02' E, is Vietnam's largest centrally administered city, spanning an area of 3,359.82 square kilometers and hosting a population of 8.4 million people (Figure 3-3a). It ranks as the nation's second most populous urban center and has the second highest population density, albeit with an uneven demographic distribution. The majority of residents live in the 12 central districts, while those in the 17 suburban districts are predominantly engaged in agricultural pursuits. Geographically, Hanoi's terrain gradually descends from north to south and from west to east, mirroring the natural flow patterns of its principal rivers (Figure 3-3b). The city can be divided into two regions: low and fairly flat plains, accounting for most of the city area, and mountainous areas concentrated in the northern and western suburbs of Hanoi. The city is located in a typical hot and humid monsoon climate zone, where temperatures increase from April to June, while substantial rainfall occurs from June to September (Figure 3-4), leading to frequent flooding [1]. The average annual precipitation is 1760 mm, with an average of around 114 rainy days per year [2].

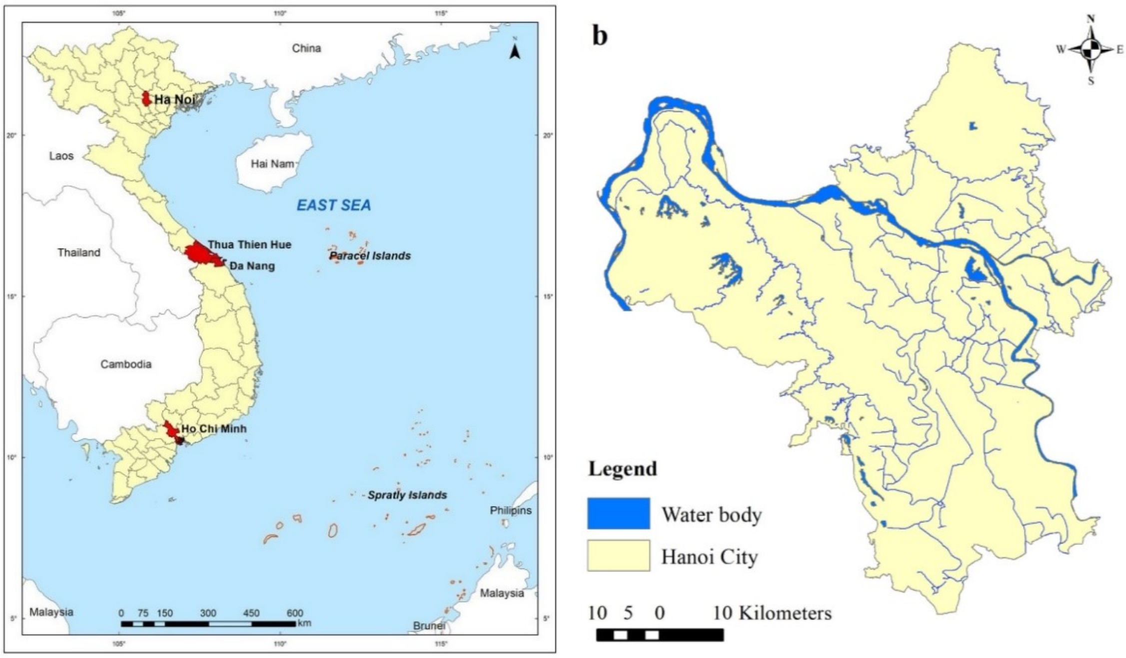


Figure 3-3. a. Location of Hanoi. b. Surface water system of the study area

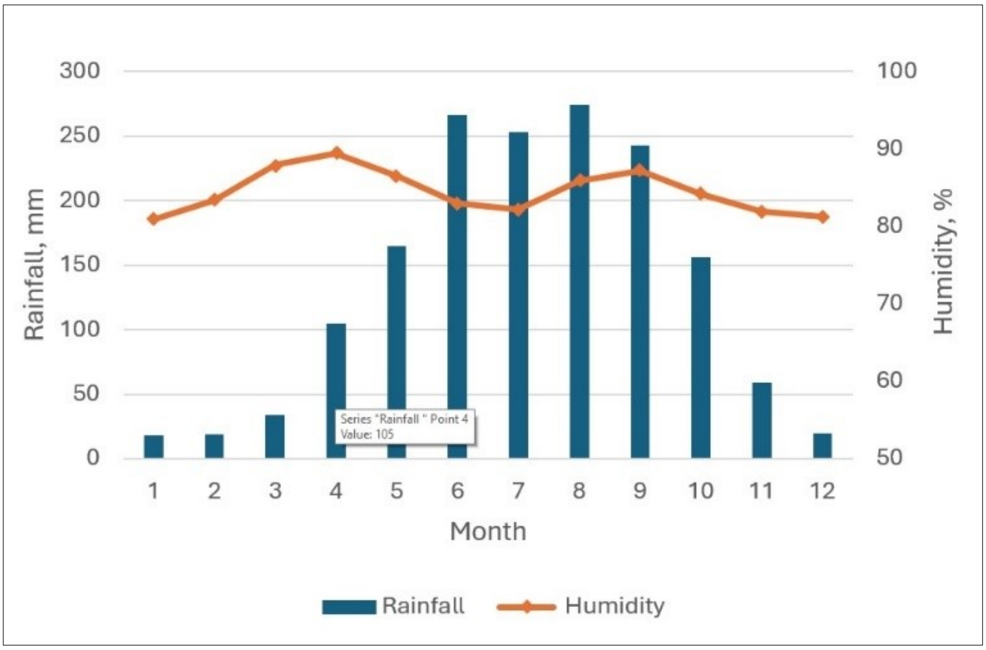


Figure 3-4. Average monthly rainfall and humidity in Hanoi in 2018

3.2.1. Hanoi at risk

Since the Doi Moi period in mid-1986, Hanoi has promoted economic development with rapid urbanization. After the process of focusing on economic development, Hanoi faces many urban problems such as pollution and urban flooding due to uneven urbanization with infrastructure development and urban landscape. As rapid urbanization puts pressure on resources and the environment, the Vietnamese Government officially presented the Hanoi Master Plan (HMP) in

July 2011. The plan's objectives are to develop Hanoi into a sustainable and resilient city by 2030 with a vision of becoming a livable capital by 2050.

With efforts at sustainable changes in planning, floods still become a normal thing when the rainy season comes. Flooding is considered a difficult problem in Hanoi during the rainy season. Natural characteristics such as being located in the low-lying Red River Delta, hydrology, and a rainy climate, combined with outdated urban infrastructure and encroachment on natural space, are all considered factors in evaluation risk and risk of flooding. Flood hazard is defined “as the exceedance probability of potentially damaging flood situation in a given area and within a specific period of time”, with the prevailing indicators for flood intensity such as inundation depth, flow velocity, duration of the flood, and the rate of water rise [3]. Periods of flood and inundation are less immediately destructive but can cause impacts on social life as well as health problems due to affected water sources, stagnant lakes, and lack of water, dirty water drainage, disrupting schools and livelihoods. Urban flooding in Hanoi has become a more serious problem under the impact of climate change and has now become one of the city's important socio-economic and environmental issues.

According to a World Bank report [4], between 1985 and 2010, Vietnam suffered 96 floods. These occur in three geographical regions: the Red River Delta in the North, the Central Coast, and the Mekong Delta in the South. While flash floods appear and cause much destruction in coastal, mountainous, and highland areas, the Red River Delta and Mekong Delta are often affected by river floods and frequent flooding in these areas flood plain. The flood season in the Red River Delta and the four-month period of flooding starting from May to October are believed to be the cause of negative impacts. For instance, in the extensive flooding in Hanoi in 2008, there were at least 92 deaths [5] and over 55,000 houses were damaged, with further significant property damage and 40,000 people being displaced [6]. In recent years, urbanization and city expansion coupled with climate change have led to more frequent flooding in Hanoi, increasing concern among residents during the rainy season.

Statistics of inundated areas according to the boundaries of districts and towns reveal that these areas increase from the northern to the southern districts/towns, and from the eastern to the western districts/towns (Figure 3-5). This pattern aligns with the gradient of Hanoi's delta terrain, which slopes gradually lower from north to south and from east to west.

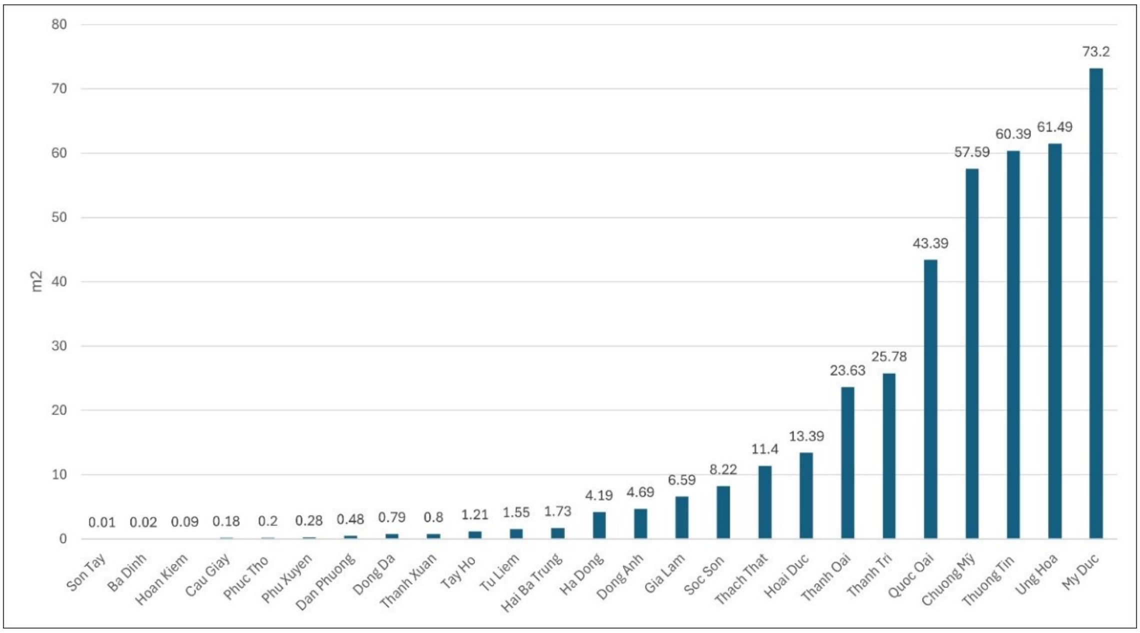


Figure 3-5. Flooded area by district in Hanoi (2008)

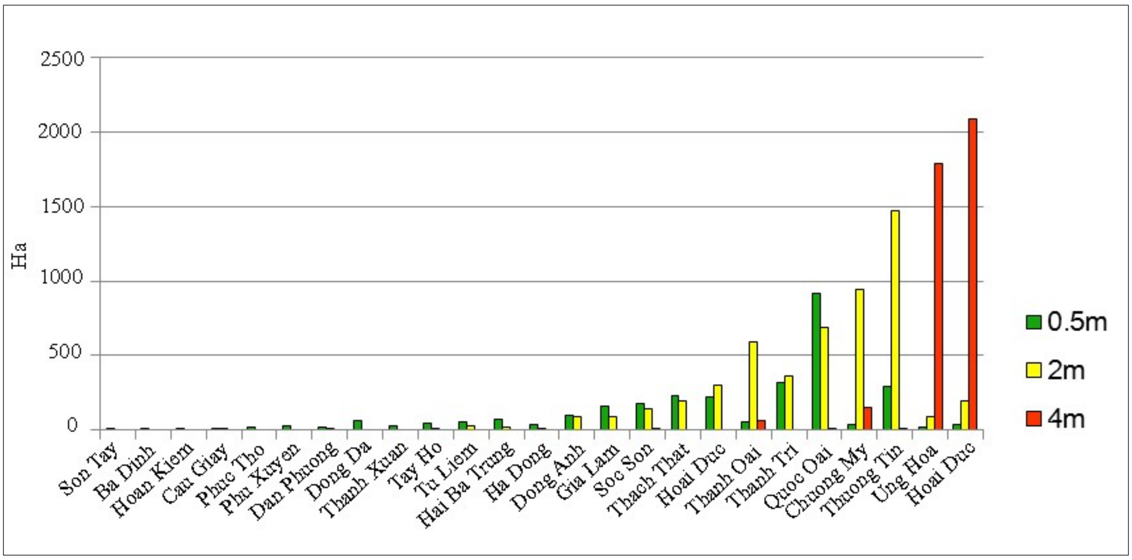


Figure 3-6. Inundated area in Hanoi City (calculated in accordance with inundation levels 0.5m, 2m, and 4m).

Inundated areas also expand in the central part of Hanoi (Figure 3-6), where population density is high. Residents live on elevated ridges along riverbeds, which are 6-7 meters high, and central alluvial plains, which are 4-4.5 meters high. However, due to extensive urbanization for various purposes, such as building houses, condominiums, and roads, many ponds, lakes, canals, and drainage ditches have been significantly narrowed. This reduction in permeable surfaces and drainage capacity makes this area prone to flooding.

Additionally, many infrastructural systems, like roads and residential areas, run perpendicular to the natural flow of water, further reducing drainage efficiency. During heavy rainfall, water cannot drain completely due to the inadequate drainage system in the central area, leading to temporary street flooding with common inundation depths of around 0.5 meters. Flooding is particularly severe in the southwest of Hanoi, in districts like My Duc and Chuong My, where 4300-7300 hectares can be inundated to depths of 2-4 meters. The low-lying terrain is a primary factor contributing to the southern part of Hanoi becoming "a sea" during heavy and prolonged rains.

Survey of 11 perennial and frequent flood points

Eleven studied inundation points are frequent and severe inundations in the rainy season, mainly at major intersections, or on small streets in residential areas with a high density of population (Figure 3-7)

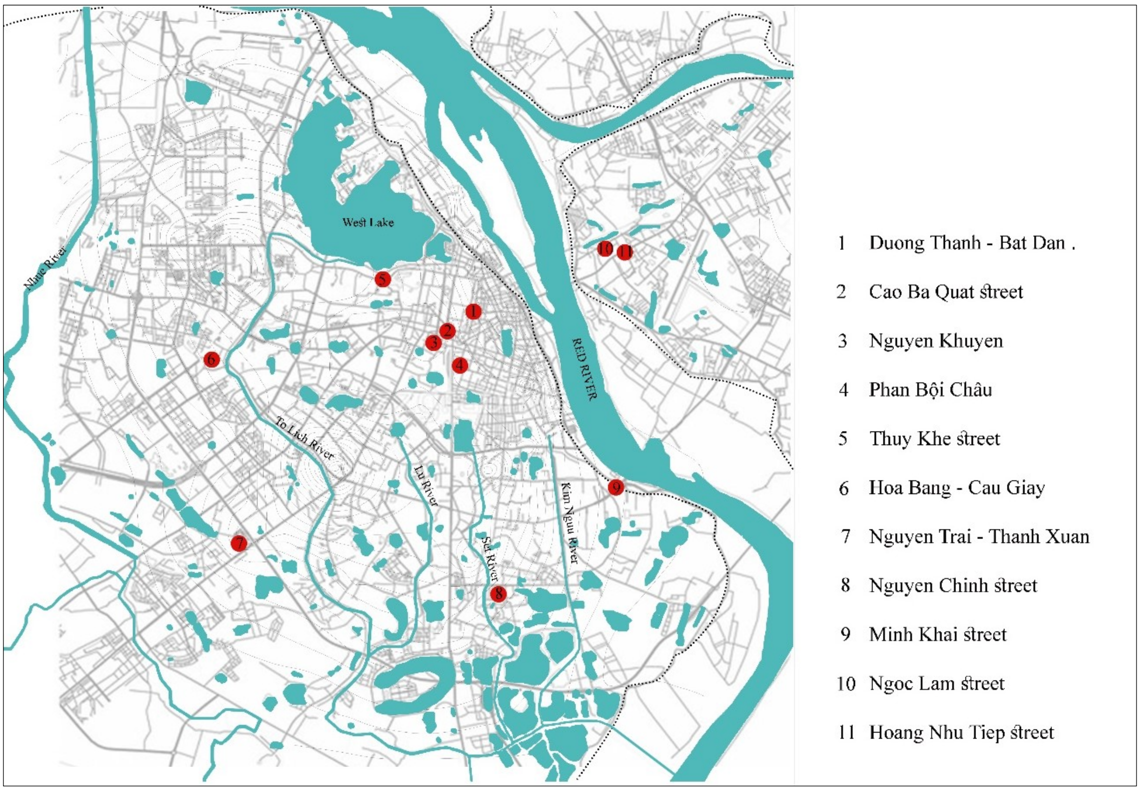


Figure 3-7. Location map of 11 studied flood points

Points located in densely populated urban areas with limited space are difficult to access the water surface and open space: 1, Duong Thanh - Bat Dan, 2. Cao Ba Quat, 3. Nguyen Khuyen, 4. Phan Boi Chau. Points are the intersections with heavy traffic: 7. Nguyen Trai -Thanh Xuan, 9. Minh Khai, 10. Ngoc Lam Street, 11. Hoang Nhu Tiep Street. And points directly affected by urban water surface including 5. Thuy Khe, 6. Hoa Bang-Cau Giay, 8. Nguyen Chinh.

Thanks to the measures to prevent flooding, some points have reduced the level of inundation such as Hoa Bang, Minh Khai, and Nguyen Khuyen. However, climate change and extreme rainfall events have made some areas more severe and potentially dangerous to humans. Figure 3-8 shows the degree of inundation of 11 study sites during the reign of 60mm-100mm in June 2022 in Hanoi. At the 4th and 5th survey sites, the highest flood level is from 30 to 40 cm. And the points with low flood levels below 15cm are the 7,10,11 points. The population density of points 1, 2, 3, 4, 5, and 6 is higher than that of the others. In these areas, the density of housing is dense, mainly small alleys without water surface or green space for temporary rainwater concentration. Floodwater is treated by a drainage system, but those disposal drainpipes are clogged by garbage. However, survey site No. 3 has a lower level of inundation compared to other sites in its group thanks to improvements in the surface water drainage, the treatment systems and the construction and expansion of infrastructure. In the survey, group 6, 7, 8, 9, 10, 11 were surface water areas with easy access to rivers, as a result, floodwaters usually recede faster than in the rest of the survey sites.

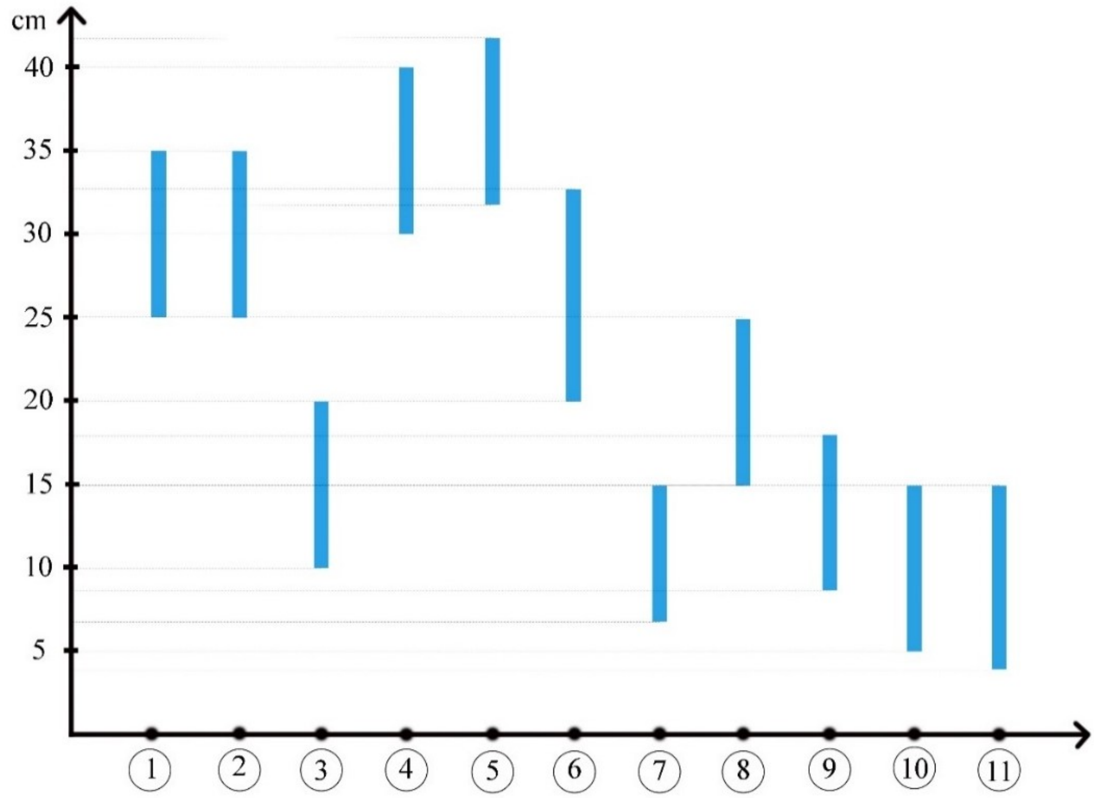


Figure 3-8. Level of inundation of 11 study sites

Through surveys of 55 households, received opinions from 42 households and have a conversation with 17 residents, it is reported that most of them are used to being flooded in the rainy season every year, so they do not have to worry about the flooding risks. Some residents say they feel more insecure due to the increasing frequency and severity of flooding. These people have their main income coming from freelance work (rental housing). While they have no income from trading, they also must pay for the cost of repairing their houses after they are flooded. A very small number of people surveyed have to relocate in the rainy season in June 2022. Besides, 80% of the participants said that the poor and homeless will be the ones who have difficulty when flooded, and 57% of people also affirmed that children and women are also at a disadvantage during floods. 36% of people mean that the alleys are small, so when flooded, rescue vehicles have difficulty accessing and providing relief.

Table 3-4 is the result of assessing the vulnerability of 11 frequently flooded points based on the following criteria: Physical vulnerability of people and infrastructure, Organizational conditions and Unfavorable economic conditions, attitudes and motivations due to flooding.

Table 3-4._Indicators for local flooding vulnerability assessment.

Indicator	Very low vulnerability	Low vulnerability	High vulnerability	Very high vulnerability
Physical vulnerability of people and infrastructure	Good urban spatial areas, and good infrastructure. Rainwater is easily accessible to large bodies of water for drainage. Reasonable population density, ensuring good living space. (9 10 11)	Good urban spatial areas and secure infrastructure Average population density (7 8)	Areas with poor urban space, and flawed infrastructure has deteriorated. High population density (1 2 3 6)	Areas with poor quality space, and infrastructure is too old and degraded. Difficult access to green water surface space. Dense population density (4 5)
Unfavorable organizational and economic conditions	High-income population. The population belongs to a strong group and organization that can support and help regularly	People with good incomes and stable jobs. Join crosses and support organizations 6 7 8 9 10 11	The population has an average income from self-employment join or not join small organizations. Hard to get support from nonprofits. (1 2 3 4 5)	The population has low income and unstable jobs. There are no supportive collective organizations.
Attitudes and motivations	Very low impact perception No stress or worry about damage caused by flooding. Ability to respond to and recover from natural disasters quickly. 7 9 10 11	Low impact perception. There is low concern for damage from inundation. Good ability to cope with and recover from natural disasters. 3 8	High impact perception There is concern about damage from flooding, poor to cope with and recover from natural disasters. 1 5 6	Very high impact perception. High level of anxiety about the impact of inundation. Inability to withstand floods and recover from floods. (2 4 5)

Eleven survey sites are divided into four levels of vulnerability to flooding. Sites 4, 5, and 6 are considered extremely vulnerable to flood risks, while points 9, 10, and 11 are only inconvenient when being interrupted in daily routine for a short period of time.

Most of the frequently flooded areas of Hanoi are major traffic zones or regions with dense road networks and poor drainage systems. Flooding point number 6, Yen Hoa and Hoa Bang are among the most severe and long-standing flood-prone areas. Figure 3-9 presents the flood levels in the Yen Hoa and Hoa Bang neighborhoods in April 2019 due to a storm accompanied by heavy rainfall. The flooding ranged from 0,23 to 0,8 meters over 4 days.

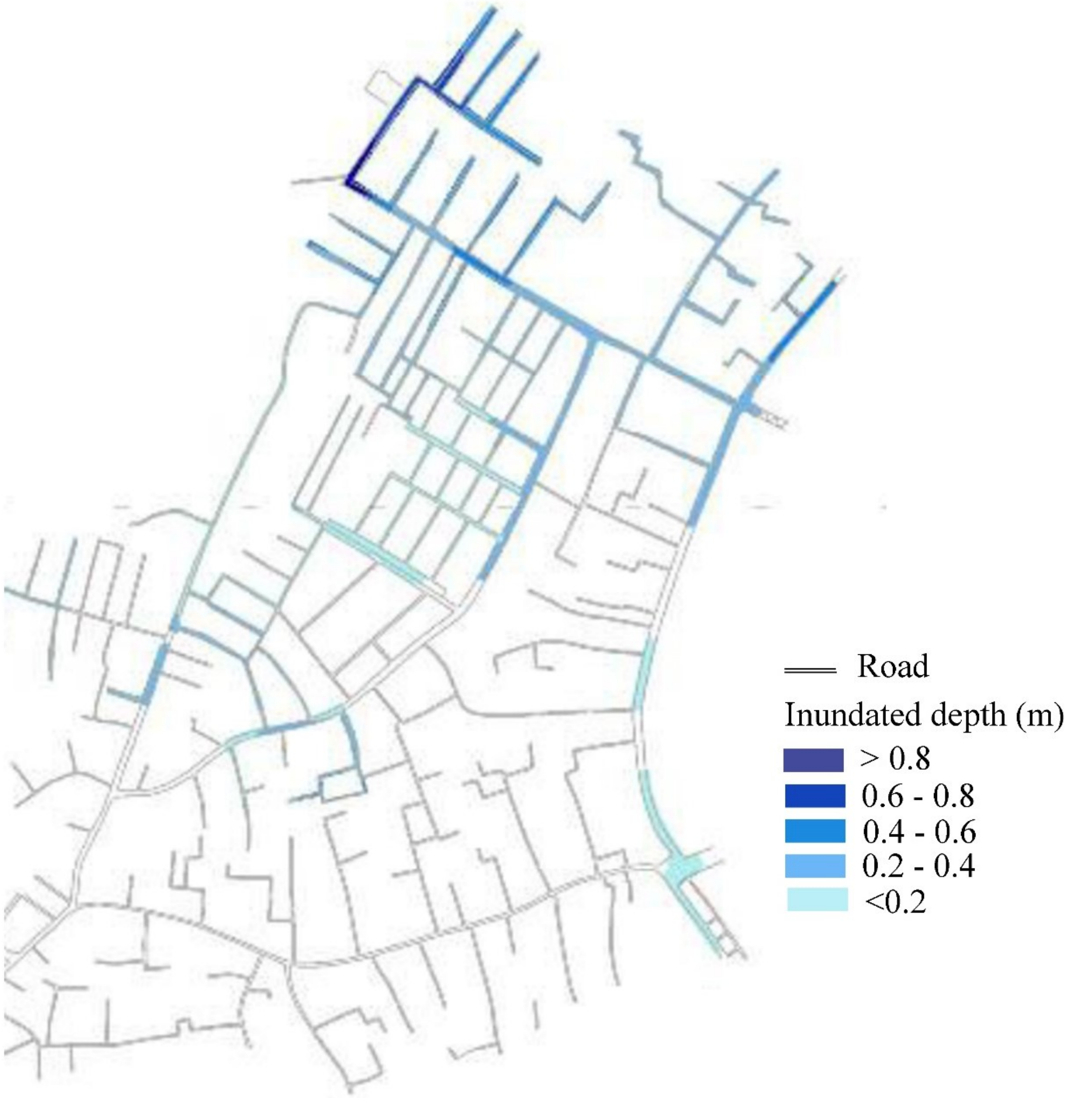


Figure 3-9. Flooding in Yen Hoa area

Hanoi's gray water drainage systems are closely linked to the transportation network. Due to poor drainage systems, frequent flooding occurs at several points on the traffic routes during heavy rains.

3.2.2. Overview of recent flood-control policies

Many years ago, Hanoi was a place with a dense river network because it was located in the low-lying Red River Delta. Like many other cities, the development of flood control measures in Hanoi has changed the city's character. That is the Agricultural dike system for flood protection. The dike system surrounding Hanoi began construction in 1077, aiming for agricultural promotion and water management to maintain the agricultural economy. The first 30km long Red River dike was completed to protect Thang Long citadel, and the dikes were gradually expanded to keep water from overflowing into the fields in time for new crops. After 1438, larger rivers were newly built and renovated on both banks of the Red River, which was too much interference with nature and resulted in the river becoming fierce and dams breaking, flooding continuously. After that, the dike expansion had to be extended to ensure safety from flooding for people and crops. According to statistics, Hanoi's current dyke system is nearly 800km long, of which 626,124km of dykes have been classified (Figure 3-10); 136 barriers with a total length of 167km protect the riverbanks. According to the Hanoi People's Committee in 2024, the total capital for implementing investment planning to build a dike system and prevent floods and storms is about VND 45,342 billion, to repair, renovate and upgrade dikes combined with dike traffic.

These large projects for flood control and agricultural development cause conflicting assessments of the positive and negative impacts of the dyke system on the environmental aspects of the entire city area. High dikes not only reduce soil fertility and fish resources but also increase crop diseases and water pollution, create more alluvial sediment in rivers, and block the natural flow of floodwaters to the sea. The dyke system separates the city from the river flow, causing local flooding when the rainy season comes. Draining rainwater into rivers and the sea faces many difficulties due to the obstruction of natural flow. Hanoi had to install a pumping station system to pump water from the Day River and Nhue River to the Red River. When it rains heavily, they are often overloaded. The role of the dyke system cannot be denied, however, there also needs to be consideration of environmental factors and the circulation of natural flows. The appearance of a giant concrete structure will replace the water landscape and uniquely built environment patterns, which do not fit with the traditional character of the river frontage. There is concern that riverine communities, with their delta identities, local livelihoods, and experience adapting to water, will no longer exist.

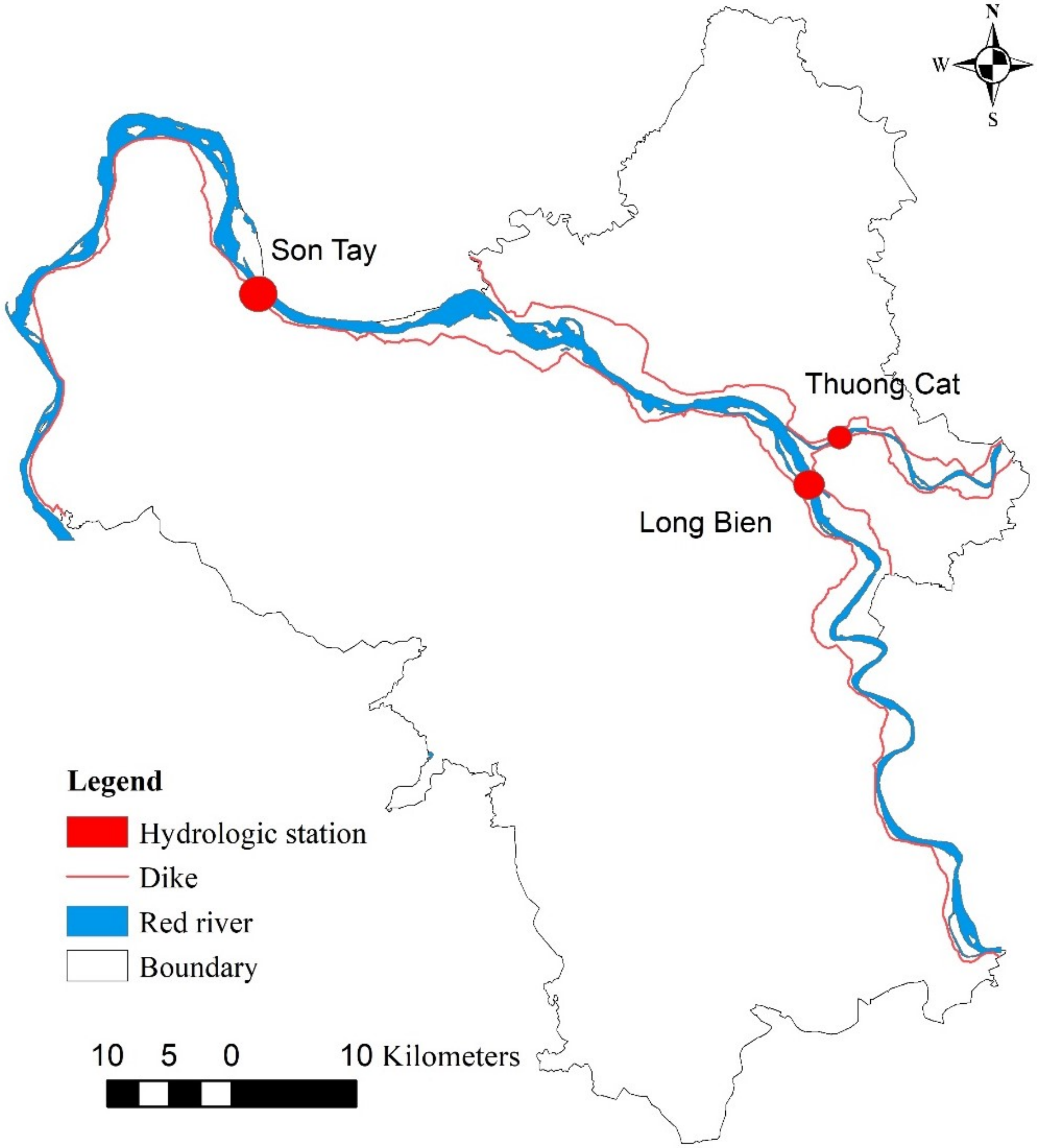


Figure 3-10. Red River dike system

3.2.3. Status of blue-green infrastructure of Hanoi central

Surface water condition of the central area of Hanoi

Based on Figure 3-11 surface waters are divided into four main categories: natural lake, flood control, non-existent, and water treatment.

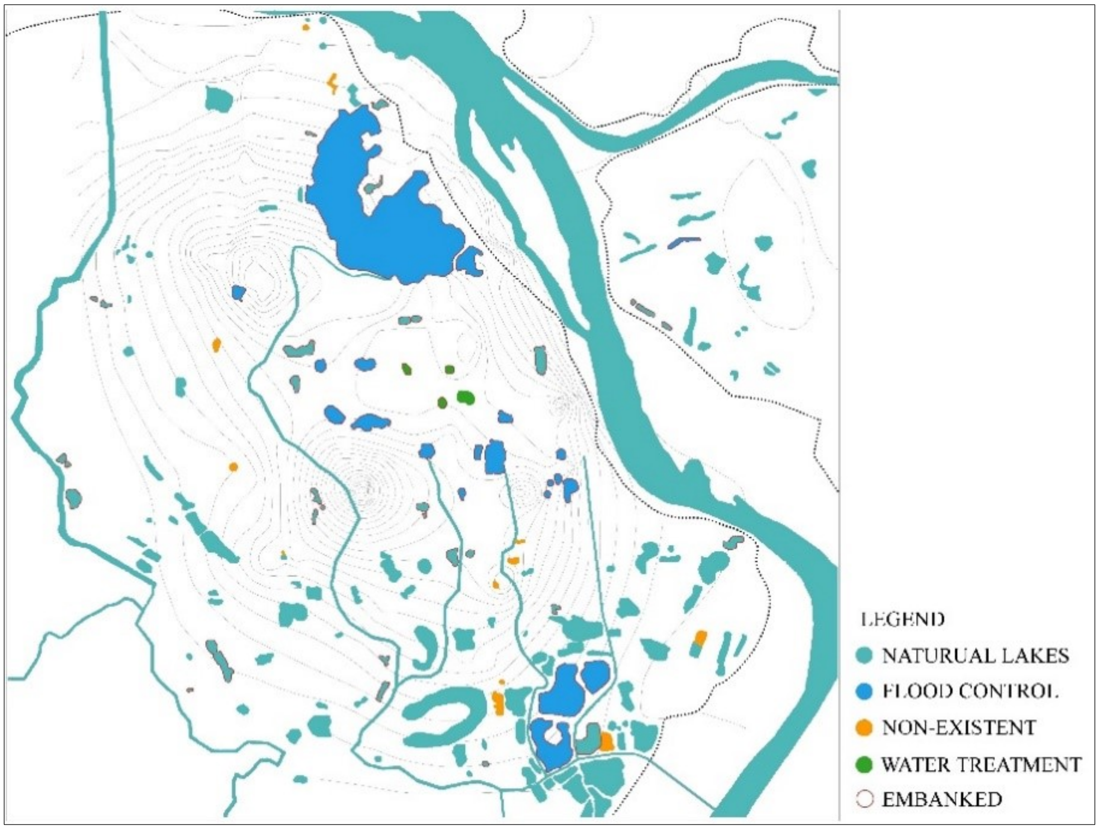


Figure 3-11. Distribution map of water surface types

Group 1: These water surfaces are natural lakes, accounting for about 50% of the surveyed water surface. These lakes are formed naturally from the old ponds and lagoons and from partly filled rivers. In addition, at present, these water surfaces which scatter in residential areas for air-conditioning have not been affected too much by construction.

Group 2: Large water surfaces from natural or artificial lakes (accounting for nearly 40%) have been renovated and built to serve the purpose of temporary water storage and control urban water surges.

- Rapid urbanization and inadequate infrastructure have heightened Hanoi's flood risk, exacerbated by its natural geography and climate change.
- Despite efforts like the Hanoi Master Plan, flooding remains a major socio-economic and environmental challenge.
- Historical flood events highlight the severe impacts, emphasizing the need for effective flood management and sustainable urban planning.

Group 3 and Group 4: They are water surfaces that are difficult to access due to private ownership or specific purposes such as water treatment. However, these surface water areas account for a very small proportion.

Small water surfaces are mainly natural lakes located in residential areas. At the same time, these lakes are scattered with no flow connection with rivers or other large bodies of water. Therefore, the water in these lakes is often unchanged, renewed, or inaccessible to the flow (Figure 3-10). Water surfaces that can be judged well by the naked eye are considered in good condition, not contaminated, still accessible to people, and they can be habitats for organisms. And this percentage accounts for over 80% of the surveyed water surface (Figure 3-12).

Polluted water bodies which are stagnant pools of water in residential areas have been used to store waste due to urban space constraints. Moreover, they are often situated in densely populated areas. The water surfaces are highly contaminated because they are constructed to store water without proper management. As a result, they become a focus of wastewater.

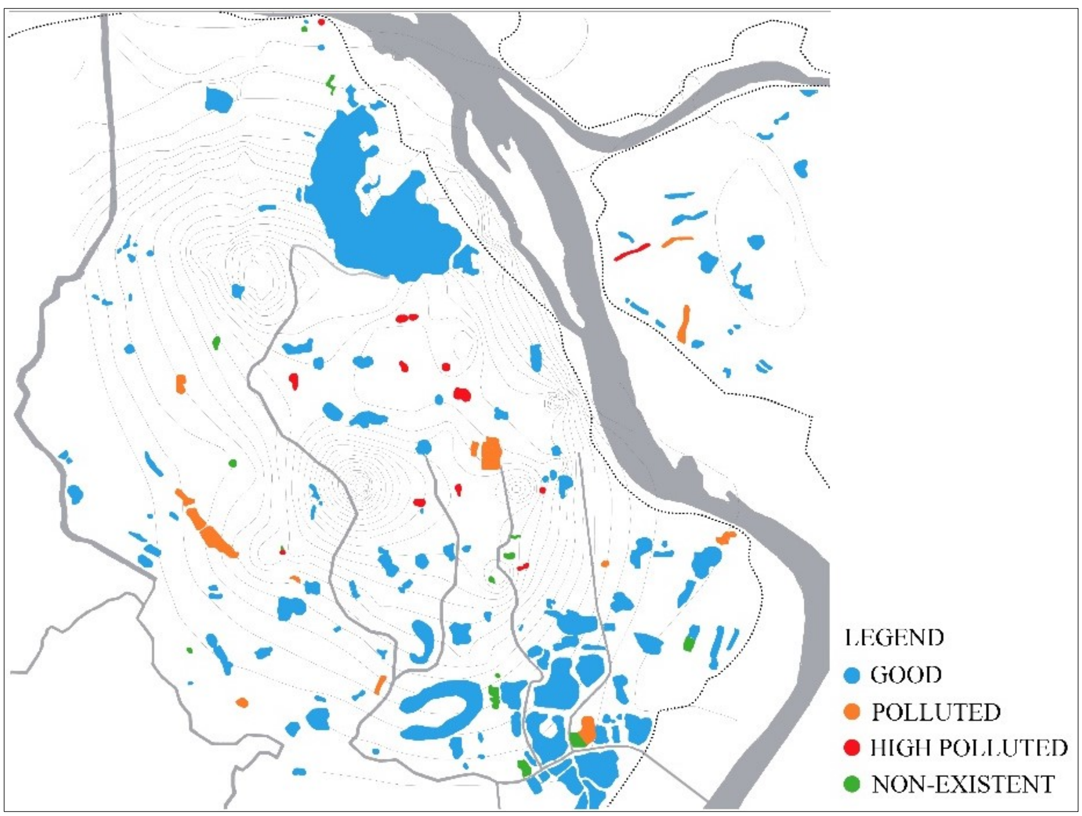


Figure 3-12. Surface water quality map

Through the survey of 24 main lakes in Hanoi, most of the lakes are concreted (Table 3-5), and some of the water surfaces are artificially built in combination with urban green landscapes or parks.

However, there is no setback or little transition for biodiversity and water level rise. Although Hanoi has a large water surface area, most of them are small and discrete lakes and unable to self-regulate.

Table 3-5. Construction status of some surface water areas in the study area

Name	Area (ha)	Under Built	Balance Built	Over Built
West lake	512.4		x	
Hoan Kiem	12		x	
Thien Quang	3.1		x	
Ba Mui	11.6	x		
Linh Quang	3		x	
Giang Vo	7.2		x	
Thu Le	14.4			x
Dong ba	8.2		x	
Lang Thuong	2		x	
Ngoc Khanh	3.7			x
Thanh Cong	5.5		x	
Xa Dan				x
Thanh Nhan	2.5			x
Dam Hong	8.1	x		
Dinh Cong	18.3	x		
Dam Doi	2.5	x		
Linh Dam	78.1		x	
Yen So	172			x
Rue Lake			x	
Than An	2.4			x
Dia Ca	4.5			x
Dong Mo	10	x		
Yen Duyen		x		
Dong Rieng		x		

According to the surface water survey results, the central of Hanoi has a large surface water area but they are mainly small ponds and reservoirs scattered with no flow connection. Along with the process of concreting, most of the ponds and lakes are contaminated, unable to regenerate themselves, or more at risk of severe pollution. This is also part of the reason for the inundation of Hanoi when these lakes cannot temporarily hold water, which increases the risk of flooding due to the inability to drain. Therefore, it is necessary to have reasonable assessments and solutions to promote and take advantage of water surfaces in solving urban flooding.

Based on the results of the risk assessment of 11 localized inundation sites, areas with high population density, limited living space, informal settlements, unstable economic resources, and effects of surrounding planning projects will be more at risk of inundation.

Green spaces condition of the central area of Hanoi

Currently, in central districts like Hoan Kiem and Ba Dinh, the system of parks and flower gardens falls short of meeting the needs of the local population due to limited space and high population density. Despite this, Hoan Kiem Lake and its surrounding green areas remain one of the most notable landscape features and tourist attractions in central Hanoi. Other large parks, such as Thu Le Park and Botanical Park in Ba Dinh District, and Thong Nhat Park in Hai Ba Trung District, range from 10 to 50 hectares in size. These green areas are often associated with relatively large water bodies like West Lake, Truc Bach Lake, Giang Vo Lake, and Ngoc Khanh Lake, contributing significantly to the urban landscape and improving local micro-climate conditions. Thu Le Park, Thong Nhat Park, and Tuoi Tre Park have been modernized and made more attractive to better serve the recreational and relaxation needs of residents. However, in central districts, there are almost no remaining open areas available for additional greening. In new urban development projects, most green spaces are small and dispersed, preventing the formation of an effective network. Additionally, the selection of tree species has not yet been optimal.

The number and scale of parks, gardens, and urban walkways are clearly inadequate in comparison to the rapid urban population growth. Some areas are even occupied and used illegally, while amusement parks for public relaxation and natural parks for scientific research face threats from land fever and new real estate projects. In highly urbanized districts such as Dong Da and Thanh Xuan, the green space per capita is quite low, at just under 0.5 square meters per person. Examples of recent green and/or blue network planning initiatives include Yen So Park, Hoa Binh Park, Linh Dam Park and Lake, and Nhan Chinh Park and Lake.

3.3. Data preparation.

3.3.1. Flood inventory mapping.

Detailed flood inventory mapping, involving a database of historical flood events in an area, is crucial for mapping flood susceptibility [7]. There are various methods to establish flood inventory maps, and the quality of historical flood data determines the accuracy of the predictions regarding flood occurrence in the research area [8]. The flood inventory map in this study was constructed in four steps (Figure 3-13)

Figure 3-13. Diagram of creating a flood inventory map

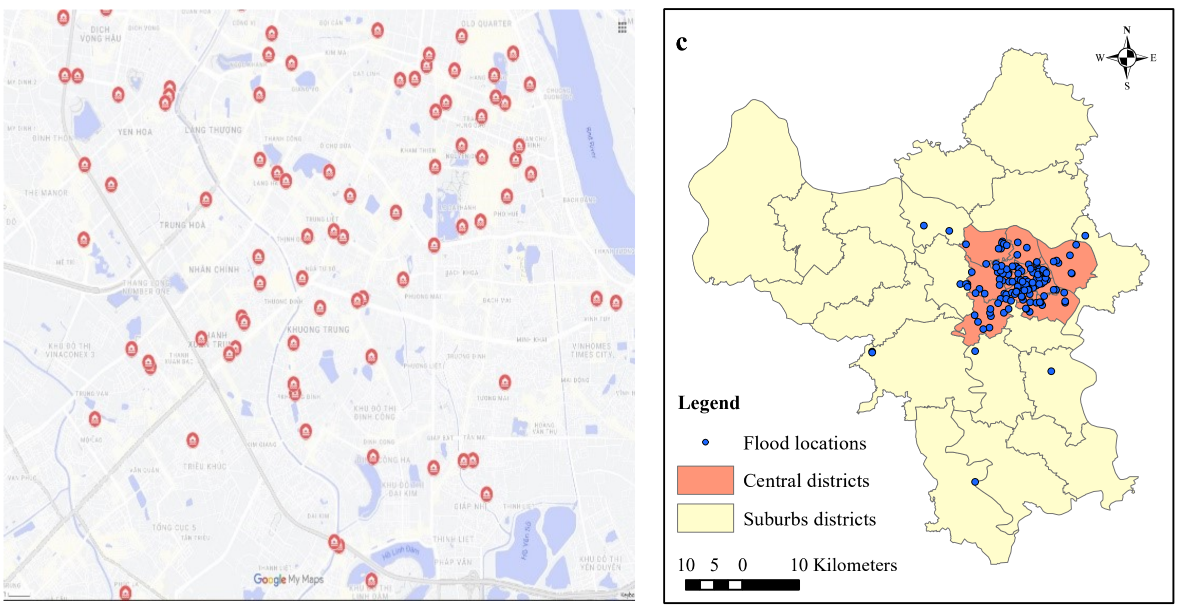


Figure 3-14. (a) Images of the location of flooded points. (b) Historic flood locations (2012 to 2018)

Based on the available data from annual flood reports and studies on flooding in Hanoi and data on past flood events from various sources such as meteorological agencies, flood management agencies, newspapers scientific and press reports, the inventory map was constructed with 148 flood points from the period from 2012 to 2018 (Figure 3-14b) [2]. The locations representing flood-affected areas were adjusted, confirmed, and mapped using GPS points collected during field surveys. The central locations of flooded areas will be updated on Google Maps's My Maps system to facilitate inspection and monitoring (Figure 3-14a). Surveys of existing flood sites were carried out to check and verify the accuracy of the data (Appendix 3-4). In addition, Flood-related data, such as flood depth, duration, and frequency, were verified in the respective areas through natural conversations with local people during the survey.

3.3.2. Flood conditioning factors.

After systematically reviewing a variety of sources, including field observations, group discussions, document reviews and data from government agencies, and expert opinion, moderating factors were identified selected to fit each research model for Hanoi (Table 3-6). Specifically, nine sensitive factors include: Terrain Wetness Index (TWI), elevation, slope, Land Use/Land Cover (LULC), Normalized Difference Vegetation Index (NDVI), rainfall, distance from road, distance from stream and drainage density will be used for flood susceptibility research model. These nine initial flood sensitive data were selected, and the feasibility of data collection was carefully evaluated based on recommendations from previous studies (Appendix 3-5) [9 – 12]. These factors are collected from open geospatial data sources (Table 3-3)

On the other hand, three factors including population density, distance from streams, and land-use category will be used to calculate the flood exposure model. In this study, land use criteria are used to estimate the likelihood of flooding. Land use types were reclassified into four categories: housing and construction land, agricultural land, forest and vegetation, and water bodies. The classification is commonly used for flood risk assessment models [13,14]. Population density is the most important criterion in flood risk analysis because it is determined by human settlements. This data is collected in the 2023 statistical yearbook of 12 districts and districts in Hanoi city.

The five criteria used in this study to analyze flood vulnerability include Poverty number, Distance to roads, number of children, Number of women and Number of health facilities. The poor are more vulnerable to natural hazards [15] and poverty is often considered a structural cause of flood vulnerability. Data on poverty rates are collected in the 2023 statistical yearbook. Transport and health infrastructure play an important role in disaster response and post-disaster recovery activities [16]. Women and children are vulnerable communities to disasters and are prioritized during disaster response.

At the same time, four factors including: Flood susceptibility, Distance to streams, Water surface, and Flow length were selected as source data for the flood hazard model. Areas with a higher susceptibility to flooding will become high flood hazard areas. In addition, factors such as distance from streams, flood-prone areas, or low points of the stream often pose a higher flood hazard due to water and flow accumulation.

Table 3-6. Description of the data categories

Data categories	Subcategories	Unit
Flood susceptibility	Topographic Wetness Index (TWI)	
	Elevation	m
	Slope	degree
	Precipitation	mm/year
	Land Use/ Land Cover (LULC)	m2
	Normalized difference vegetation index (NDVI)	
	Distance from streams	m
	Distance from roads.	m
	Drainage density	km/sq.km
Flood Exposure	Population density	person/km2
	Distance to rivers	m
	Land-use category	m2
Flood vulnerability	Poverty number	number
	Distance to roads	m
	Number of children	number
	Number of women	number
	Number of health facilities	number
Flood hazard	Flood susceptibility	
	Distance to streams	m
	Flooded depth	m
	Flow length	m

Subsequently, these data were cleaned and preprocessed ready for analysis. This involved format conversion, error checking and adjustment, and the creation of usable data layers for the analysis. These factors were subsequently characterized based on field surveys and long-term flood records in Hanoi and processed within a GIS framework. Digital Elevation Model (DEM) and 30-meter resolution Shuttle Radar Topography Mission (SRTM) data were employed for mapping terrain factors. Indices for vegetation, water, and land use were derived from Landsat 8 imagery obtained from the United States Geological Survey (USGS). Annual average precipitation data were obtained from the high-resolution gridded datasets provided by the Climatic Research Unit (CRU).

In the present study, a pixel-based analysis was conducted to assess the attributes of the used models. The sensitivity factors were resampled into a 30m × 30m grid, which was consistent with the size of the available DEM pixels. All vector-format factors were converted into raster format with uniform grid dimensions. All maps of the elements were prepared and converted to the WGS_1984_UTM_Zone 48N coordinate system with a resolution of 30m X 30m, ensuring consistency in spatial resolution. The map of the component elements with units was classified into five layers using native Jenks classification in ArcGIS and manual classification.

3.4. Flood Risk Assessment Framework

The concept of flood risk is often considered to involve the three elements of hazard, exposure, and vulnerability [17–19]. The combination is illustrated as in Equation (1). Flood exposure and flood vulnerability should be combined with flood hazard in assessing flood risk to provide a comprehensive resource reference for decision-makers in flood risk management [20]. Flood hazard can be determined as the potential for harm, loss, or damage of an event occurring at one location [19,21]. Exposure to flood hazard is defined by the potential for personal danger or property damage occurring during flood events [22,23]. Vulnerability is specified by the characteristics of a community that make it vulnerable to the damage of a flood hazard [24,25].

$$\text{Flood risk} = \text{Hazard} \times \text{Exposure} \times \text{Vulnerability} \quad (1)$$

This study aimed to assess the nature and extent of flood risk by analyzing potential flood hazards and evaluating existing conditions of flood exposure and vulnerability that potentially harm people, property, and livelihoods as shown in Equation (1). The case study is the October 2008 flood event of Hanoi city, a hazardous flood event. The indicators or criteria of flood hazard, exposure, and vulnerability are adapted from a variety of studies and based on an analysis of the existing data in Hanoi city. The risk assessment result is integrated into a GIS framework to provide a flood risk map. The incorporation of flood risk assessment into a GIS framework has been applied at global, regional, and local scales in many recent studies [26,27]. Meanwhile, there have been a few applications of geospatial assessment tools, including GIS, to assess the flood risk in Vietnam [28–30]. The proposed flood risk assessment framework of this study is described in Figure 3-15.

The framework presents the relevant relationships between the flood risk components, flood risk assessment, and flood risk management that is proposed for Hanoi city. This is the first time that a holistic flood risk assessment combining hazard, exposure, and vulnerability indicators has been conducted in the study area.

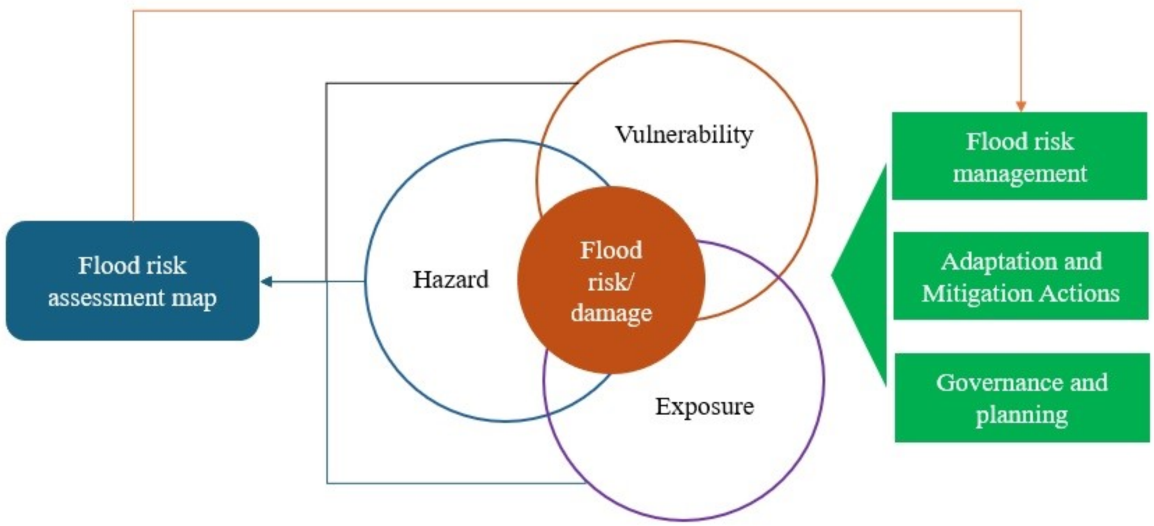


Figure 3-15. Flood risk assessment and management framework for Hanoi city adapted from several studies.

3.5. Multi-Criteria Decision-Making Analysis Model

Multi-criteria decision analysis methods (MCDA) allow working with quantitative variables and are applied to decision-making processes. These methods have potential applications in solving flood risk management issues. Several popular MCDA are Analytical Hierarchy Process (AHP) [31], Analytic Network Process (ANP) [32], Compromise Programming (CP) [33], Multi-Attribute Utility Theory (MAUT) [34], Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) [35]. In this study, AHP is selected to weight criteria and sub criteria for the flood risk assessment model. Several advantages of AHP include direct opinion involvement, simple GIS integration [36], criteria and sub-criteria systematization [37], and consistency in judgment [38]. Besides these advantages, this approach has three main limitations of subjective preference in the evaluation [39], a large number of pairwise comparisons [40], and vague criteria [41]. However, these shortcomings remain in almost all MCDA methods [37,41]. The Analytic Hierarchy Process (AHP) is a decision-making system that involves multiple criteria and determines the weights of each trait grounded on the knowledge and experience of experts proposed by T. Saaty [42]. The AHP allows the evaluation of quantitative, qualitative, and complex criteria and factors on the same scale [43]. Assaying the experts' order of priority helps organize a complex problem into a hierarchical structure of lower problems, making it easier to approach [44, 45]. Within this, the Pairwise Comparison Method is a powerful tool, which helps decision-makers subjectively determine the significance weights of each criterion in a study, thus creating a common system for decision-making processes grounded on multiple attributes [46]. AHP has been used in flood disaster management [47] and ranking projects for disaster recovery [46].

3.5.1. Analytic Hierarchy Process (AHP)

The AHP was used to compare each pair of factors on a 9-point scale (Appendix 3-6). In this, when two factors were of equal importance, a value of 1 was assigned; a value of 9 determined the greatest importance for a factor [48,49]. The compared values were organized as a diagonal matrix. Then, the Square Comparison Matrix and the relative score of each factor were determined by the diagonal matrix and its inverse matrix, in which the diagonal elements had a value of 1 to ensure that each factor was compared with itself. The comparison matrix is represented by Equation 2.

$$A = \left[a_{ij}\right]_{n*n} = \begin{bmatrix} a_{11} & a_{12} & \dots a_{1n} \\ a_{21} & a_{22} & \dots a_{2n} \\ a_{n1} & a_{n2} & \dots a_{nn} \end{bmatrix} \quad a_{ij} = \frac{1}{a_{ij}} \ (a_{ij} \neq 0) \qquad (2)$$

Consistency is an important factor in the AHP as it ensures that choices and rankings are made consistently and logically. Therefore, checking the consistency of the comparison matrix is an important part of the AHP process. Saaty's method is one of the most common ways in which to do this [42]; it produces a Consistency Index and Consistency Ratio (CR, Equation 3).

$$CR = \frac{CI}{RI} \qquad (3)$$

where CI is the consistency index, which can be calculated based on Equation 4, and RI is the random inconsistency index value, which is dependent on the number of factors used in the pairwise matrix (Table 3-7).

$$CI = \frac{\gamma_{max} - n}{n-1} \qquad (4)$$

where γ_{max} is the maximum eigenvalue of the judgment matrix and n is the total number of factors (Equation 5).

$$\gamma_{max} = \sum_{i=1}^{n}\left[\left(\sum_{j=1}^{n} a_{ij}\right) \times w_i\right] \quad (5)$$

The CR value < 0.1 implies an acceptable accuracy for the computed matrix in the AHP analysis [48]. In this study, calculating the weights of factors using the AHP was conducted based on preliminary surveys of local residents and the opinions of six experts in Hanoi city.

Table 3-7. Random consistency indices for randomly generated matrices [19]

n	3	4	5	6	7	8	9	10	11
RI	0,58	0,9	1,12	1,24	1,32	1,41	1,45	1,49	1,51

3.5.2. Survey of experts and AHP calculation

Our expert survey was conducted through online discussions with six experts in Hanoi in the second quarter of 2022. The experts included a researcher in the field of geography (R1) and a researcher in natural geography (R2) at Hanoi University of Natural Sciences; two environmental engineering researchers at the Vietnam Academy of Science and Technology (R3) and Hanoi University of Science and Technology (R4); a lecturer in urban management at Hanoi Architectural University (R5); and an urban planning architect at the Hanoi City Planning Institute (R6).

In this study, the relative importance of flood conditioning factors was determined based on priority levels collected from residents during field surveys. Subsequently, the nine selected calculation component factors were accepted by the six experts. A pairwise comparison matrix was established from each expert, which resulted from the AHP pairwise comparisons after weighting and CR testing. For CR > 0.1, respondents were asked to reconsider and adjust their answers. The survey table is presented as Appendix 3-7.

3.5.3. Validation of model

The accuracy assessment of the models employed is paramount to presenting study outcomes. Various statistical measures have been utilized by different scholars [50]. Among these, the Area Under the Curve (AUC) stands out as the most reliable method for evaluating the proficiency of the Multi-Criteria Decision Analysis (MCDA) model due to its straightforward design, comprehensive nature, and equitable predictive characteristics. In the current study, we utilized AUC as a crucial indicator of the ROC curve. The ROC values demonstrate the model's ability to accurately differentiate between positive and negative observations in the validation sample [51] (Equations 6 and 7).

$$x = 1 - \text{specificity} = 1 - \left[\frac{TN}{(TN+FP)}\right] \quad (6)$$

$$y = \text{sensitivity} = \left[\frac{TN}{(TP+FN)}\right] \quad (7)$$

where TN and FN are true negatives and false negatives, respectively; TP and FP are true positives and false positives, respectively. The quantitative– qualitative relationship between the AUC and model performance accuracy, which ranges from 0 to 1[52], is shown in Figure 3-16.

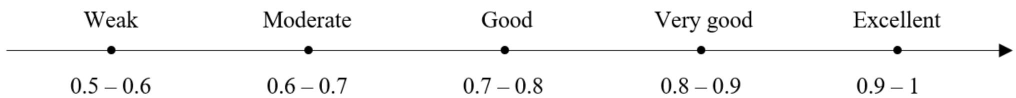


Figure 3-16. Evaluation of the model based on the AUC value

3.5.4. Model creation process.

After calculating the weights, the model results are prepared using the weighted sum and overlay method in a GIS environment, where each coefficient is multiplied by its coefficient weight using Equation 8.

$$M = \sum_{i=1}^{n} w_i \, x_i \quad (8)$$

where M is the model map; w_i is the weight of factor I, and x_i is the classes of flood conditioning factor i. Figures 3-17, 3-18 and 3-19 respectively show the process of building three research models including flood susceptibility map, Spatial flood risk and Developing BGI network for Hanoi city.

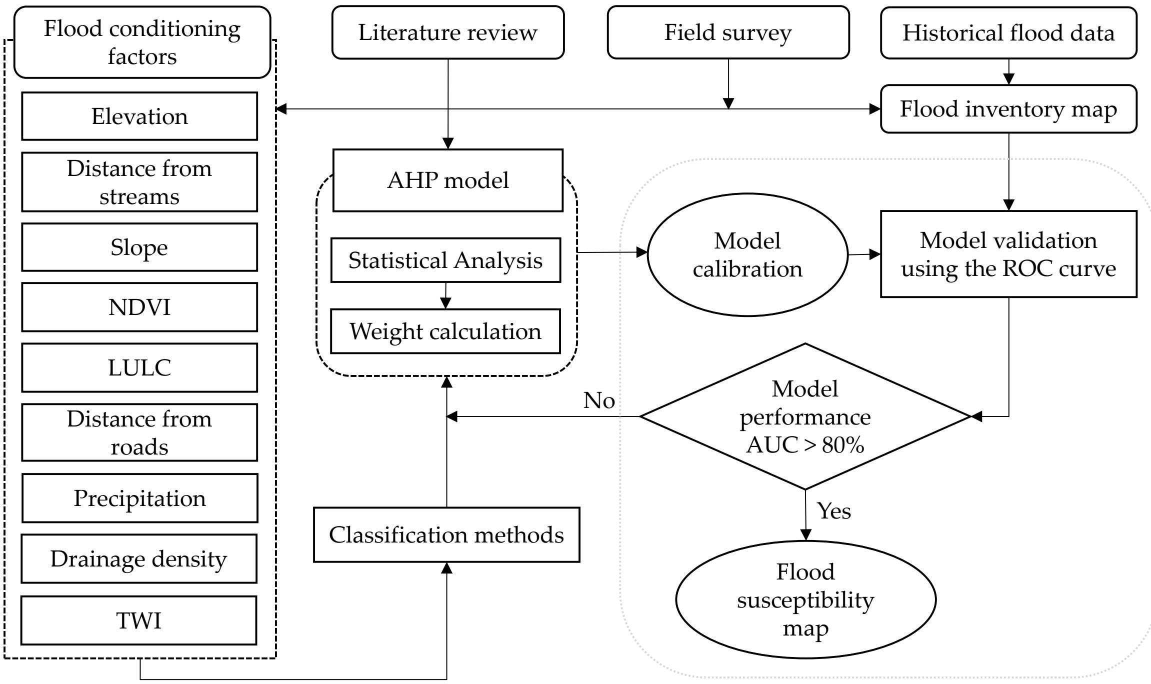


Figure 3-17. Flood susceptibility model process

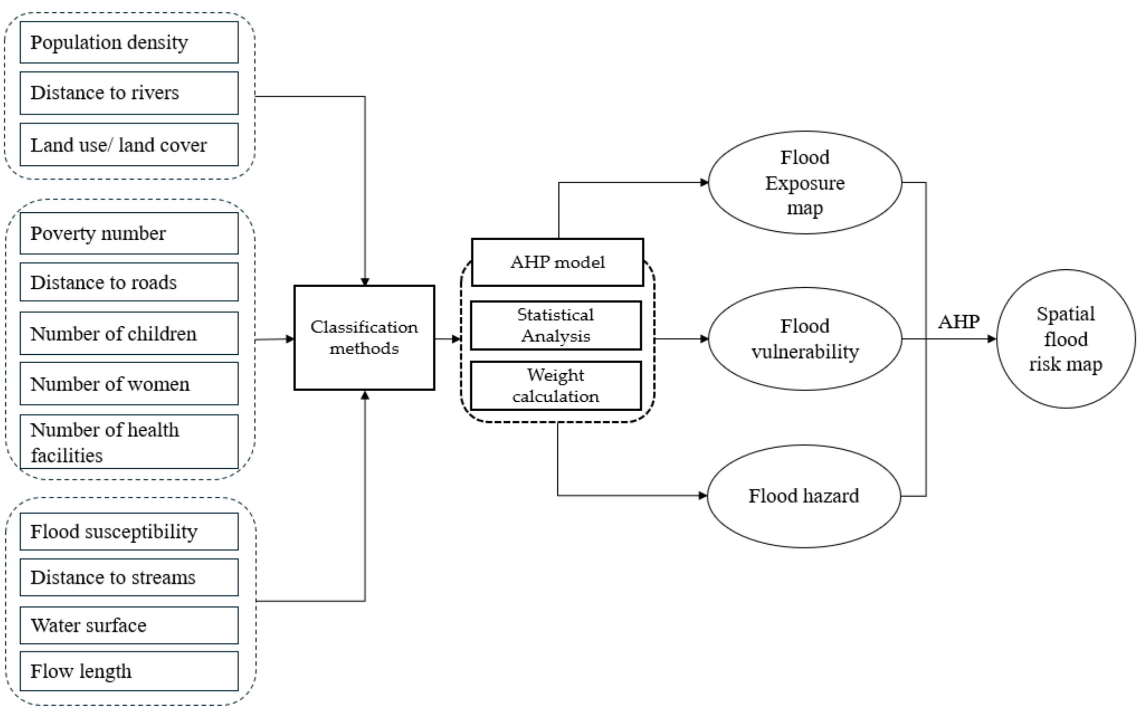


Figure 3-18. Flood spatial flood risk modeling process

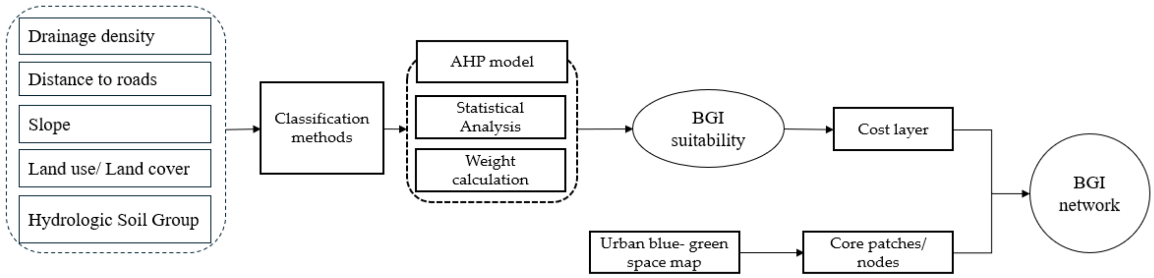


Figure 3-19. BGI network modeling process

3.6. Establishing node-corridor matrix by least-cost path analysis

The Cost Path tool determines the least-cost path from a destination point to a source. Aside from requiring that the destination be specified, the Cost Path tool uses two rasters derived from a cost distance tool: the least-cost distance raster and the back-link raster. These rasters are created from the Cost Distance or Path Distance tools. The backlink raster is used to retrace the least costly route from the destination to the source over the cost distance surface.

The least cost path method is an effective GIS technique for identifying the most efficient route between two nodes by characterizing the landscape as a cost surface [57]. This method is widely used in landscape conservation. For example, Kong et al. utilized the least-cost path function to define green corridors that connect habitat patches in an urban environment to support biodiversity conservation [28]. The least-cost path is determined from the destination to the source. This path, which is one cell wide, guarantees the lowest cost relative to the cost units defined by the original cost raster input into the weighted-distance tool. The Cost Path tool can be used to find the most cost-effective route for constructing a new road or to identify the path from various suburban locations (sources) to the nearest shopping mall (destination). When applied to a road construction scenario, the resulting path represents the least expensive route for building a road from the destination to the source (the existing intersection).

In this study, least cost path analysis is utilized in a GIS environment to define a blue-green network in the central region of Hanoi for stormwater management. The BGI suitability map serves as the cost surface in the GIS environment to execute the least cost path function. Subsequently, the cost distance and cost path tools in the GIS environment are employed to create least cost corridors connecting the identified nodes in the study region.

3.7. Assessment of corridors using gravity model.

Potential corridors that connect blue and green spaces are identified in a GIS environment using the cost path tool. These corridors represent the least-cost paths, meaning they have maximum suitability for connecting one node to another. However, since not all corridors can be established simultaneously, the gravity model is employed to prioritize the most suitable corridors between nodes. For this purpose, the gravity model equations have been adapted from Linehan et al. [32], as shown below

The level of interaction between nodes along the corridors is calculated as follows:

$$Gij = \frac{NiNj}{Dij^2} \qquad (9)$$

where, Gij is the level of interaction between node i and node j and i,j = 1,2, 3,……, n. Ni and Nj represents the corresponding weight values and D2ij represents the cumulative impedance value between node 1 and node 2.

$$Ni = \frac{Si}{Pi} \qquad (10)$$

where, Pi represents the node weight, and Si represents the area of node i.

$$Dij = \frac{Lij}{Lmax} \qquad (11)$$

where, Lij represents the cumulative impedance value of corridor be- tween nodes i and j and Lmax represents the maximum impedance value of all Lij.

3.8. Summary

This chapter explores research methods used in environmental studies, natural disaster risks, and the process of collecting, calculating, and analyzing data. It resolved:

Stages of the data collection process.

- Site selection criteria are based on investigation of urban environmental characteristics.
- The process of surveying, collecting, and selecting factors to participate in the calculation model.
- Sources and selection of data for detailed interpretation and data analysis process.

The next chapter will describe the results of research using these methods to interpret the data examined. It will outline the findings of research on urban flood susceptibility in urban Hanoi and analysis based on historical flood site records.

Appendix

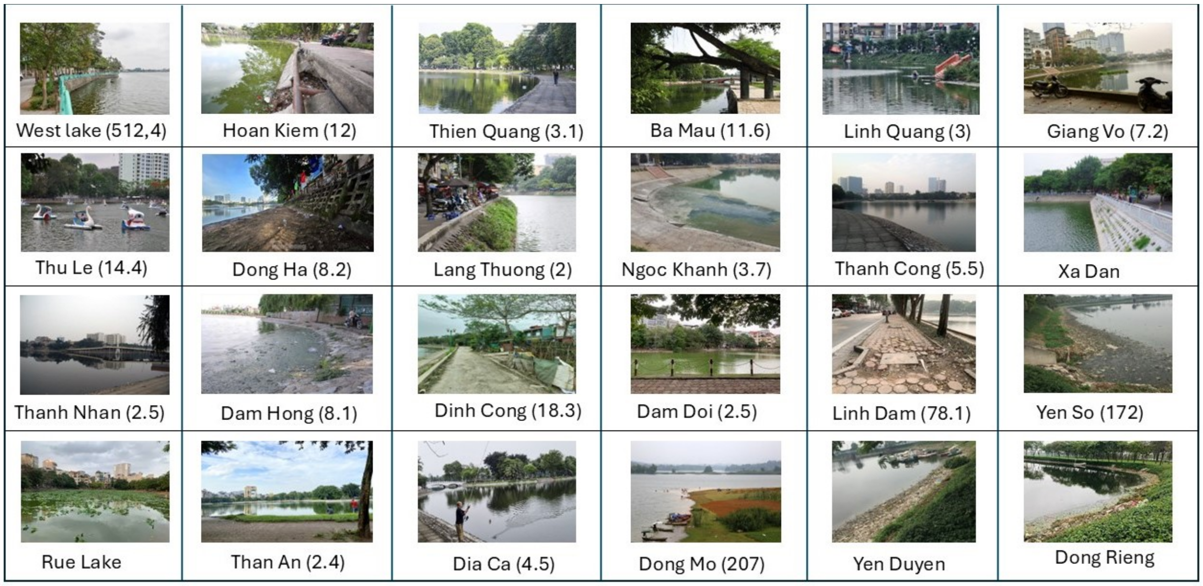


Figure 3-1. Surveying the status of water surfaces in Hanoi

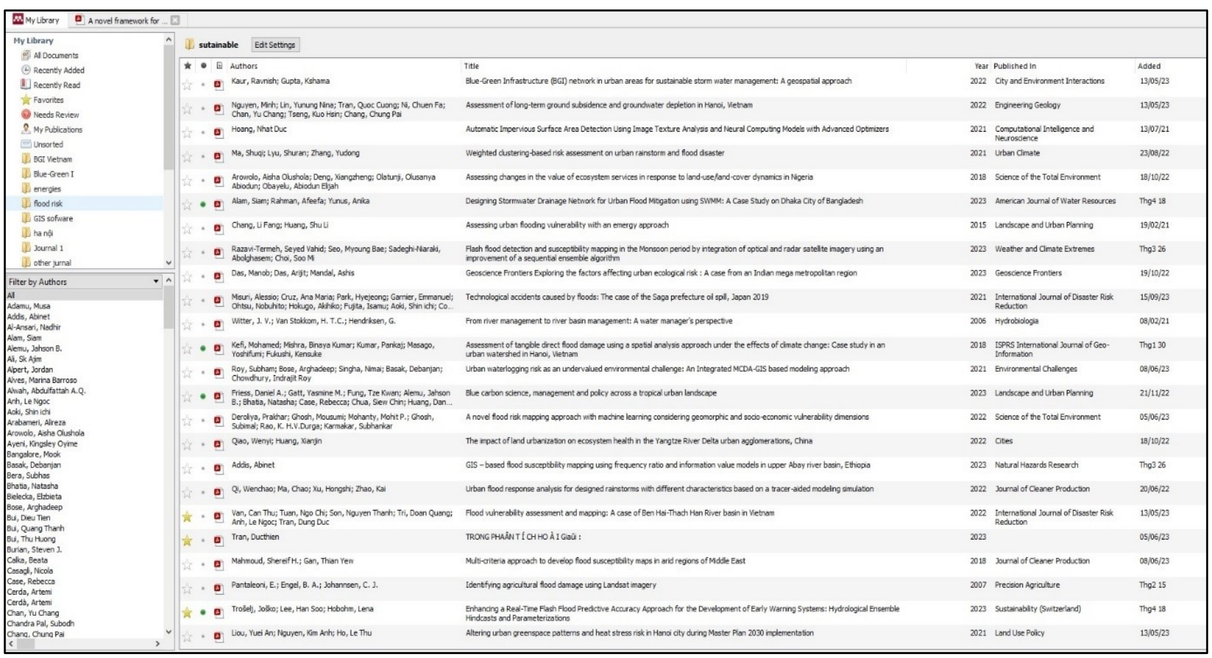


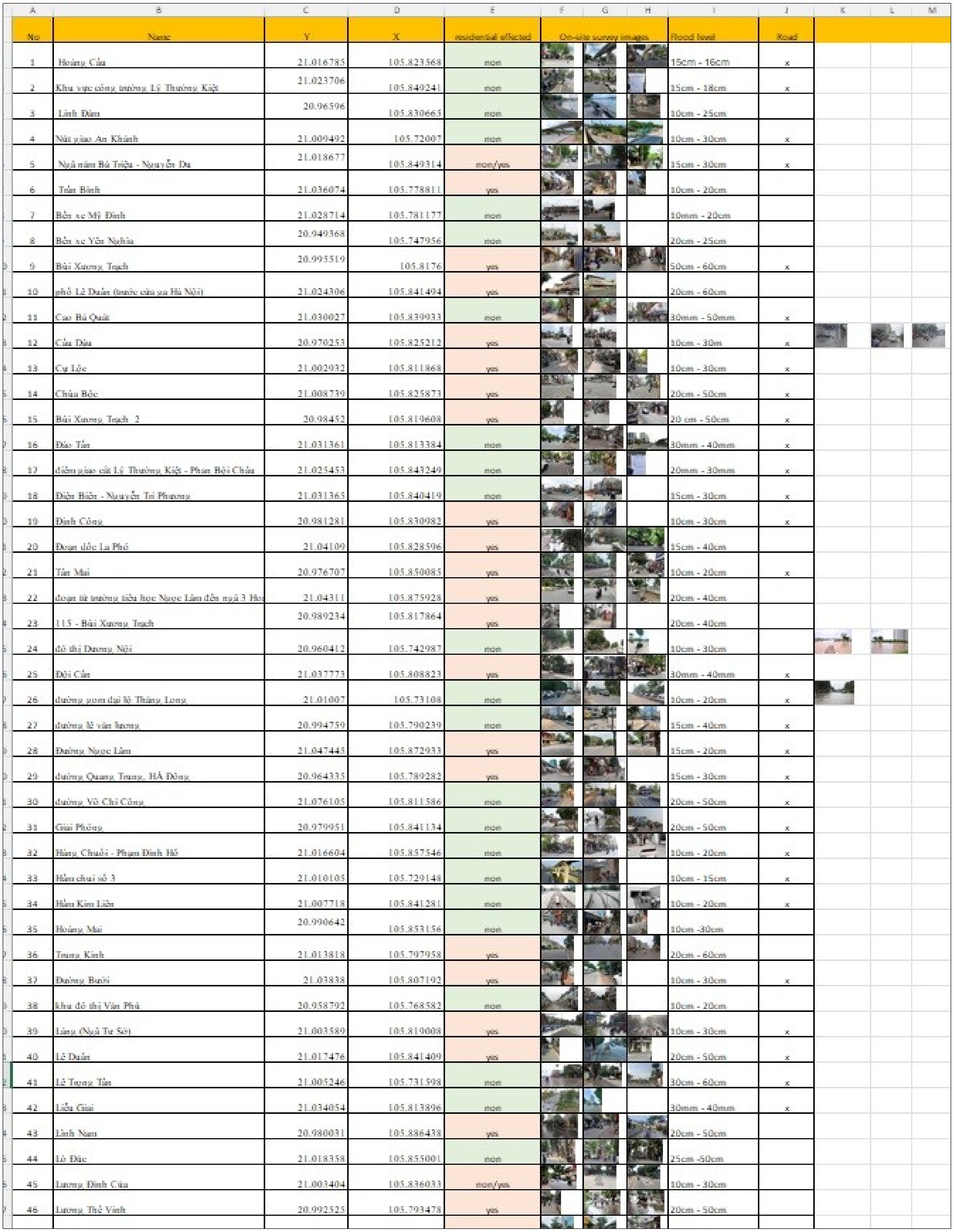
Figure 3-2. File of summarization of full-text articles

Table 3-3. Preliminary selection of contribution criteria

Year	Authors	Title	Connect on the influence factors	Main findings
2023	Loi, D. T.	Assessment of Urban Flood Vulnerability Using Integrated Multi-parametric AHP and GIS	Flood Vulnerability	The flood vulnerability level based on the pre-event characteristic in Hoan Kiem district
2013	N. Hiệu et al.	Assessment of Flood Hazard in Hanoi City Assessment of Flood Hazard in Hanoi City	Flood Hazard	Assessed the actual state of historical flood happening at the end of 2008.
2004	Nguyen Tat Thang et al.	Flood Inundation Analysis Based on Unstructured Meshes for the Hanoi Central Area	Flood Inundation	The model application includes three cases: a real heavy rainfall analysis, an assumed exceptionally heavy rainfall analysis and an assumed dike break analysis.
2021	Anh, Sai Hong et al.	Flood Hazard Assessment of Residential Areas Outside the Protected Area of the Red River Dike System in Hanoi, Vietnam	Flood Hazard	Modeled floods and mapped them using a two-dimensional depth-averaged hydrodynamic model to show the inundation depth levels for the entire area in high resolution.
2019	Tran Kim Chau et al.	Assessment of urban flooding in Yen Hoa - Hoa Bang area, Cau Giay, Hanoi	Urban Flooding	The numerical model MIKE URBAN is used to simulate the rainfall-runoff, routing, and surcharge processes in Yen Hoa - Hoa Bang areas.

2019	Anh, Sai Hong et al.	Assessment of Floodwater Behavior in Van Coc Lake, Hanoi in Event of Emergency Situation	Floodwater Behavior	Performed numerical simulations to assess the movement of floodwater in this lake and evaluated the impact of floodwater on its residential areas.
2019	Maria Paola Scaparra et al.	Community perceptions of social, economic and environmental impacts of flooding in central districts of Hanoi, Vietnam	Impacts of flooding	The GCRF–OSIRIS Project aims to optimize investment strategies to minimize the impacts of flood disasters, making disaster risk reduction more effective, by introducing operational research methods
2013	Hoang, T.T.H et al.	Zoning the risk of flooding due to the influence of prolonged rain in the capital hanoi using remote sensing and gis data	Flooding risk	Analyze flood situation due to heavy rain in Ha Noi (in 2008 and 2013) in order to localize the risk of flooding in Ha Noi by using remote sensing and GIS data
2014	Duong, Thi Toan et al.	Riverbank stability assessment under flooding conditions in the Red River of Hanoi, Vietnam	Riverbank stability	A case study on the portion of the Red River flowing through Hanoi using the finite element method and extending the mechanics of saturated and unsaturated soils to understand how the riverbank's FOS varies with RWL fluctuations.
2018	Pingping Luo et al.	Flood inundation assessment for the Hanoi Central Area, Vietnam under historical and extreme rainfall conditions	Flood inundation	Presents a calibrated flood inundation model using referenced photos, an assessment of the influence of four extreme rainfall events on water depth and inundation area in the Hanoi central area

2018	Mohamed Kefi et al.	Assessment of Tangible Direct Flood Damage Using a Spatial Analysis Approach under the Effects of Climate Change: Case Study in an Urban Watershed in Hanoi, Vietnam	Flood Damage	Assess tangible future flood damage in the urban watershed of the To Lich River in Hanoi, Vietnam.
2020	Ducthien Tran et al.	Predicting Urban Waterlogging Risks by Regression Models and Internet Open-Data Sources	Urban Waterlogging Risks	Applied a regression model in ArcGIS with internet open-data sources to predict the probabilities of urban waterlogging risks in Hanoi, Vietnam, during the period 2012–2018 by considering six spatial factors of urban surfaces



No	Name	Y	X	residential effected	On-site survey images	Flood level	Road
1	Hoàng Cầu	21.016785	105.823568	non		15cm - 16cm	x
2	Khu vực công trường Lý Thường Kiệt	21.023706	105.849241	non		15cm - 18cm	x
3	Linh Đàm	20.96596	105.830665	non		10cm - 25cm	
4	Nút giao An Khánh	21.009492	105.72007	non		10cm - 30cm	x
5	Ngã năm Bà Triệu - Nguyễn Du	21.018677	105.849314	non/yes		15cm - 30cm	x
6	Trần Bình	21.036074	105.778811	yes		10cm - 20cm	
7	Bến xe Mỹ Đình	21.028714	105.781177	non		10mm - 20cm	
8	Bến xe Yên Nghĩa	20.949368	105.747956	non		20cm - 25cm	
9	Bùi Xương Trạch	20.995519	105.8176	yes		50cm - 60cm	x
10	phố Lê Duẩn (trước cửa ga Hà Nội)	21.024306	105.841494	yes		20cm - 60cm	
11	Cao Bá Quát	21.030027	105.839933	non		30mm - 50mm	x
12	Cầu Dậu	20.970253	105.825212	yes		10cm - 30m	x
13	Cự Lộc	21.002932	105.811868	yes		10cm - 30cm	x
14	Chùa Bộc	21.008739	105.825873	yes		20cm - 50cm	x
15	Bùi Xương Trạch 2	20.98452	105.819608	yes		20 cm - 50cm	x
16	Đào Tấn	21.031361	105.813384	non		30mm - 40mm	x
17	điểm giao cắt Lý Thường Kiệt - Phan Bội Châu	21.025453	105.843249	non		20mm - 30mm	x
18	Điện Biên - Nguyễn Tri Phương	21.031365	105.840419	non		15cm - 30cm	x
19	Đình Công	20.981281	105.830982	yes		10cm - 30cm	x
20	Đoạn dốc La Phù	21.04109	105.828596	yes		15cm - 40cm	
21	Tân Mai	20.976707	105.850085	yes		10cm - 20cm	x
22	đoạn từ trường tiểu học Ngọc Lâm đến ngã 3 Ho	21.04311	105.875928	yes		20cm - 40cm	
23	115 - Bùi Xương Trạch	20.989234	105.817864	yes		20cm - 40cm	
24	đô thị Dương Nội	20.960412	105.742987	non		10cm - 30cm	
25	Đội Cấn	21.037773	105.808823	yes		30mm - 40mm	x
26	đường gom đại lộ Thăng Long	21.01007	105.73108	non		10cm - 20cm	x
27	đường lê văn lương	20.994759	105.790239	non		15cm - 40cm	x
28	Đường Ngọc Lâm	21.047445	105.872933	yes		15cm - 20cm	x
29	đường Quang Trung, HÀ Đông	20.964335	105.789282	yes		15cm - 30cm	x
30	đường Võ Chí Công	21.076105	105.811586	non		20cm - 50cm	x
31	Giải Phóng	20.979951	105.841134	non		20cm - 50cm	x
32	Hàng Chuối - Phạm Đình Hổ	21.016604	105.857546	non		10cm - 20cm	x
33	Hầm chui số 3	21.010105	105.729148	non		10cm - 15cm	x
34	Hầm Kim Liên	21.007718	105.841281	non		10cm - 20cm	x
35	Hoàng Mai	20.990642	105.853156	non		10cm -30cm	
36	Trung Kính	21.013818	105.797958	yes		20cm - 60cm	
37	Đường Bưởi	21.03838	105.807192	yes		10cm - 30cm	x
38	khu đô thị Văn Phú	20.958792	105.768582	non		10cm - 20cm	
39	Láng (Ngã Tư Sở)	21.003589	105.819008	yes		10cm - 30cm	x
40	Lê Duẩn	21.017476	105.841409	yes		20cm - 50cm	x
41	Lê Trọng Tấn	21.005246	105.731598	non		30cm - 60cm	x
42	Liễu Giai	21.034054	105.813896	non		30mm - 40mm	x
43	Lĩnh Nam	20.980031	105.886438	yes		20cm - 50cm	
44	Lò Đúc	21.018358	105.855001	non		25cm -50cm	
45	Lương Đình Của	21.003404	105.836033	non/yes		10cm - 30cm	
46	Lương Thế Vinh	20.992525	105.793478	yes		20cm - 50cm	

Figure 3-4. Excel file of summarization of 148 flooding point data

Table 3-5. relevant references illustrate the impact of nine factors on the susceptibility to flooding

	EL	SL	DD	TWI	PR	LULC	NDVI	DS	DR
Mahmoud, S.H.et al [53]	x	x	x		x	x		x	
Tehrany, M.S.et al [54]		x		x	x	x		x	
Bera, S.et al [7]	x	x	x		x	x		x	
Nguyen, D.L.et al [55]		x	x	x	x	x	x	x	x
Costache, R.et al [56]	x	x		x	x	x		x	
Ali, S.A.et al [57]	x	x	x	x	x	x	x	x	
Samanta, S.et al [58]		x		x		x			
Chaulagain, D.et al [59]	x	x	x		x	x		x	
Band, S.S.et al [60]		x		x	x			x	x
Nachappa, T.G.et al [61]	x	x		x	x	x	x	x	x
Zhao, G.et al [62]	x	x	x						
Arabameri, A.et al [63]	x	x	x	x		x	x	x	
Hong, H.et al [64]	x	x		x				x	
Abinet Addis [65]	x	x		x	x	x	x	x	x
Razavi-Termeh, S.V.et al [66]		x		x	x	x	x	x	

TWI— topographic wetness index; EL— elevation; SL— slope; PR— precipitation; LULC— land use/ land cover; NDVI— normalized difference vegetation index; DS— distance from streams; DR— distance from roads; and DD— drainage density

Table 3-6. Saaty comparison scale [42]

Intensity of importance	Definition
1	Equal importance
3	Weak importance of one factor over another
5	Essential importance
7	Demonstrated importance
9	Absolute importance
2,4,6,8	Intermediate values between two adjacent judgments when compromise is required.

Please fill out the survey on the next page if the current page is already filled out

Survey participant information	
Name	
Occupation, major	

AHP ANALYSIS PROCEDURE

MObjective: Application of multi-criteria decision analysis based on GIS and analytical hierarchy process (AHP) in flood susceptibility mapping.

Compare the importance of comparative values in determining flood susceptibility and select a scale by circling in the table below:
The scale from 1-9 is the importance level of the value.
With a value of greater importance, the selection point will be closer to that value.
A scale of 1 means that the two values are of equal importance.
Once completed, you can adjust the comparisons marked 1 to 3 to improve consistency.

Level	Meaning	Explain
1	Equal importance	The two factors contribute equally to the goal
3	Weak importance of one factor over	Experience and judgment slightly favor one factor over another
5	Essential importance	Experience and judgment strongly favor one factor over another
7	Demonstrated importance	One element is so strongly favored over another, its dominance is expressed in practice
9	Absolute importance	Assertion in favor of one factor over another is the highest possible order of assertion.
2,4,6,8	Intermediate values between two adjacent judgments when compromise is required.	

Option	correlated quantitative scores																	Option
	More important							←equal→						More important				
Topographic wetness index (TWI)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Elevation
TWI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Slope
TWI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Precipitation
TWI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	LULC
TWI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	NDVI
TWI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Distance from river
TWI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Distance from road
TWI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage density
Elevation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Slope
Elevation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Precipitation
Elevation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	LULC
Elevation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	NDVI
Elevation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Distance from river
Elevation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Distance from road
Elevation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage density
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Precipitation
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	LULC
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	NDVI
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Distance from river
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Distance from road
Slope	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage density
Precipitation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	LULC
Precipitation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	NDVI
Precipitation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Distance from river
Precipitation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Distance from road
Precipitation	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage density
Land use and Land cover (LULC)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	NDVI
LULC	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Distance from river
LULC	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Distance from road
LULC	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage density
Normalized Difference Vegetation Index (NDVI)	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Distance from river
NDVI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Distance from road
NDVI	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage density
Distance from river	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Distance from road
Distance from river	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage density
Distance from road	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Drainage density

Thank you for taking the time to complete the survey.
Survey results are used for research purposes only, and all of your information is kept confidential.
? Normalized difference vegetation index. (NDVI) is similar to the ecological coating surface index

Figure 3-7. Survey table for Analytic Hierarchy Process

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Chapter 4

URBAN FLOODING SUSCEPTIBILITY IN HANOI

Chapter 3 presents research methods used in selecting, collecting, and analyzing data in the Hanoi urban area. This chapter provides interpretations of data from open geographic data sources and field surveys to establish a flood susceptibility model for Hanoi city. The different characteristics of the factors are analyzed, and the level is classified from very low to very high. Each type of factor is considered and evaluated in pairs based on the opinions of relevant experts. Finally, flood susceptibility modeling is explored in the form of a map to provide a visual view of the likelihood of flooding, the conditions that impact the likelihood of flooding, and the level of flooding at each location. when the area.

4.1. Conditioning factors for Flood susceptibility map.

Through surveys, analyses, literature reviews, and consultation with experts, these five layers were re-ranked into five levels of influence on flood susceptibility: 1– very low; 2– low; 3– moderate; 4– high; and 5– very high. These five levels are also a scale to evaluate the level of likelihood of flooding for each contributing regulatory factor (Table 4-1).

Table 4-1. Classes and rating of the flood conditioning factors

Class Rating	Factor								
	TWI	**Elevation**	**Slope**	**Precipitation**	**LULC**	**NDVI**	**Distance from streams**	**Distance from roads**	**Drainage density**
1	< -16	> 59	> 28	< 16	Vegetation	> 0.3	> 10000	> 5000	< 0.25
2	-16 - (-13)	31 - 59	5 - 28	16 - 16.2	Base soil	0.2 - 0.3	1000 - 10000	1500 - 5000	0.25 - 0.5
3	-13 - (-6)	8 - 31	2- 5	16.2 - 16.4	Agriculture	0.1 - 0.2	500 - 1000	500 - 1500	0.5 - 0.75
4	-6 -2	-6 - 8	1 - 2	16.4 - 16.6	Settlements	0.01 - 0.1	250 - 500	100 - 500	0.75 - 1
5	> 2	< -6	< 1	> 16.6	Water body	< 0.01	< 250	< 100	> 1

4.1.1. Topographic Wetness Index (TWI)

TWI, representing spatial moisture variations within an area, is a crucial factor in constructing flood susceptibility models. It helps to calculate the potential of water permeability in each region [1]. Areas with a high TWI are capable of retaining water and may have a higher susceptibility to flooding [2]. The TWI is typically constructed based on information about the slope and flow accumulation of a region, as shown in Equation 1.

$$TWI = \ln (\alpha/\tan\beta) \quad (1)$$

where α represents the flow accumulation, indicating the ability to channel water from a point on the map to the main drainage point; β is the slope of each grid cell in the model, calculated using elevation data. In this study, the TWI was computed based on the SRTM DEM map of Hanoi, and five layers of TWI values were considered and ranked. Among them, areas with TWI values greater than 2 had have a very high flood susceptibility and values from (-6) to 2 had a high flood susceptibility; TWI values from (-6) to (-13), (-13) to (-16), and less than (-16) ranked as moderate, low, and very low flood susceptibility, respectively. This is depicted in Figure 4-1.

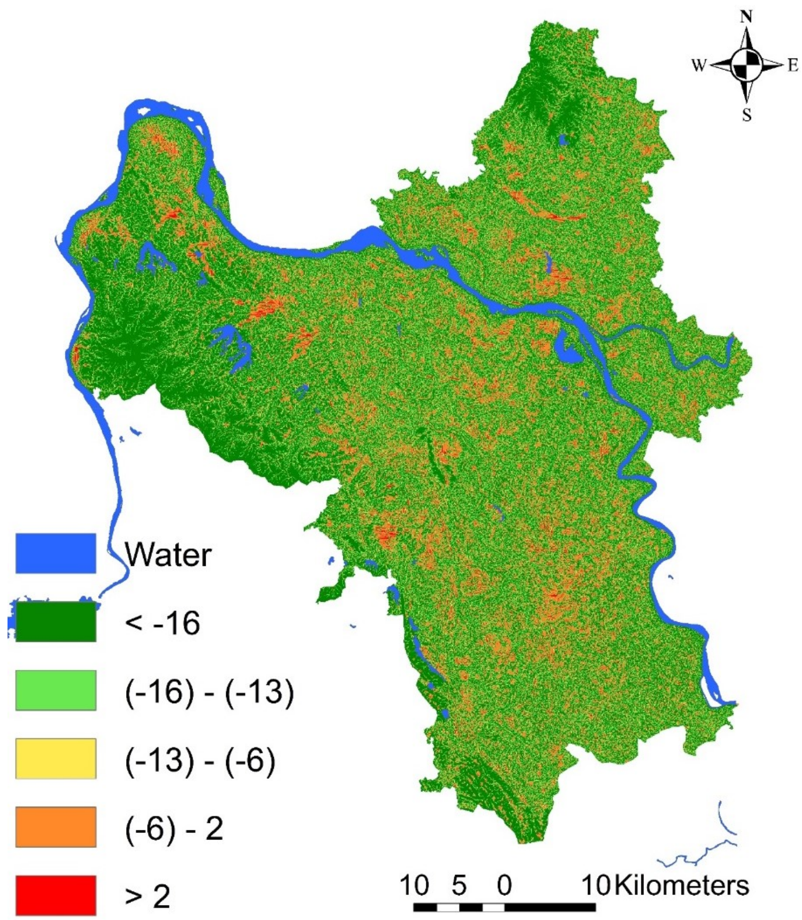

Figure 4-1. Topographic Wetness Index (TWI)

4.1.2. Elevation and Slope

Elevation and slope represent two primary factors that influence flood occurrence within any given region [3]. Typically, areas prone to flooding exhibit low surface slopes and are situated at lower elevations, as evidenced by the elevation classifications commonly used in flood mapping studies [4, 5, 6]. Regions at lower elevations are more susceptible to flooding due to the ease with which rainfall can flow from higher to lower areas under natural conditions [6]. Hanoi is a city in a flat plain area, with most of its territory lacking significant elevation differences. However, due to the gradual decrease in the terrain height and the influence of dense river and lake networks, surface water tends to flow from north to south. According to the research results, five elevation layers were considered for the flood susceptibility assessment and were ranked from very low to very high. The areas with elevations of 8 meters or lower relative to sea level were considered to have a high and very high flooding susceptibility. The northern area with elevations ranging from 8 to 31 meters was assessed as moderate, while areas with elevations above 31 meters were considered to have a low and very low flood susceptibility.

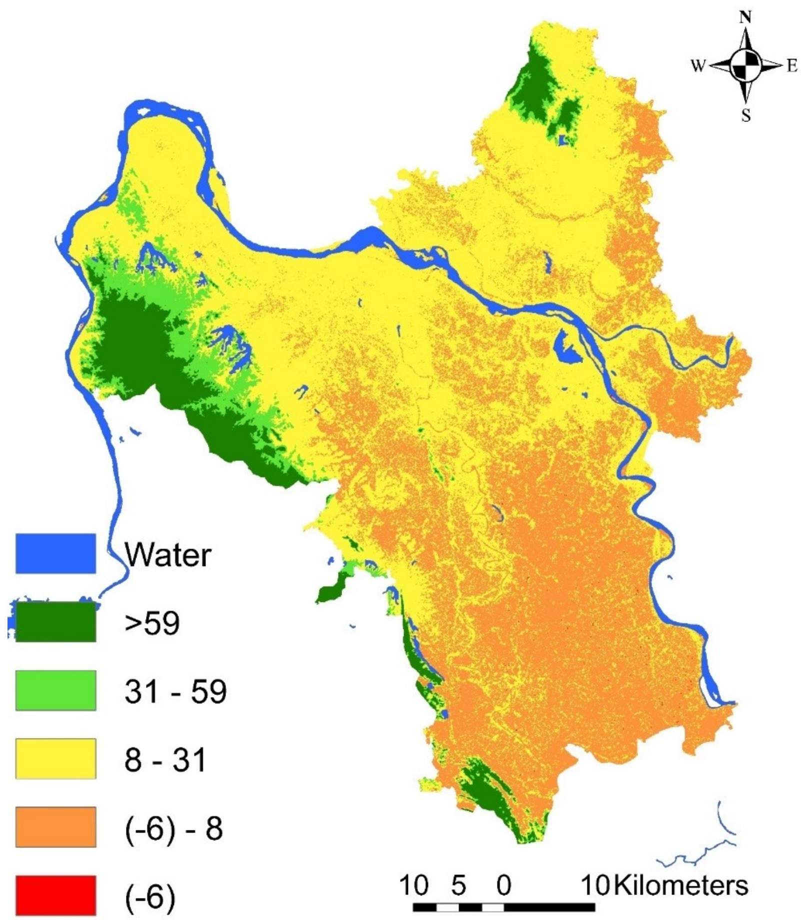

Figure 4-2. Elevation

A specific slope is defined as the percentage ratio of elevation model variance across different regions; similar gradings have been assigned to the percentage slope in various studies, with higher rankings typically attributed to areas with lower slopes and vice versa [5, 7]. Based on the survey results and expert opinions, areas with slopes of 2 degrees or less were classified as having high and very high flood susceptibility. In addition, areas with slopes ranging from 2 to 5 degrees had a moderate flood susceptibility and slopes above 5 degrees a low and very low flood susceptibility. Figures 4-2 and 4-3 illustrate the level of flood susceptibility based on the assessment of elevation and slope distribution.

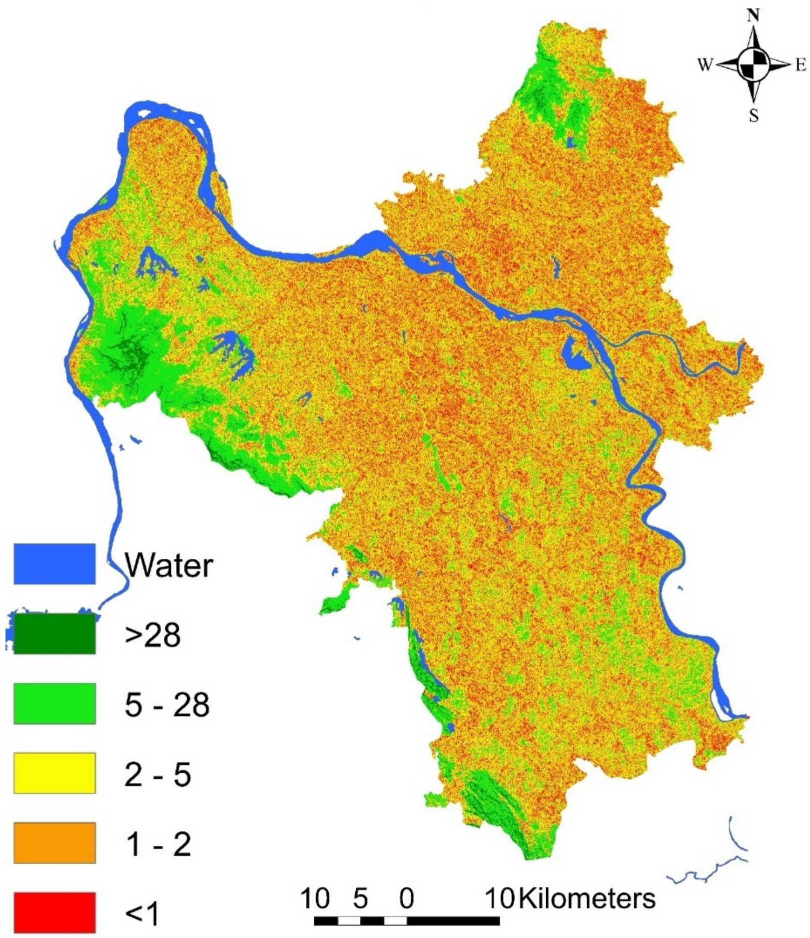

Figure 4-3. Slope

4.1.3. Precipitation

Figure 4-4 presents the corresponding flood susceptibility levels based on the average annual precipitation in the study area. The accumulation of rainfall in an area over a long period can increase the susceptibility to flooding, particularly when groundwater levels cannot drain away quickly enough. The probability of flooding rises with higher levels of rainfall [8]. Being in a tropical monsoon region, Hanoi city receives a significant amount of annual precipitation. This is characterized by heavy downpours and intense rain mainly from June to September during the monsoon season. The total rainfall during the rainy season can account for 80 - 85% of the total annual rainfall, and the maximum daily rainfall can reach 350 to 400 mm (Vietnam Magazine National Hydrometeorology 2016; vnmha.gov.vn), leading to recurrent flooding. In this study, a precipitation map was generated based on Hanoi's 2020 weather data. It was classified from low to high values corresponding to very low to very high flooding susceptibility.

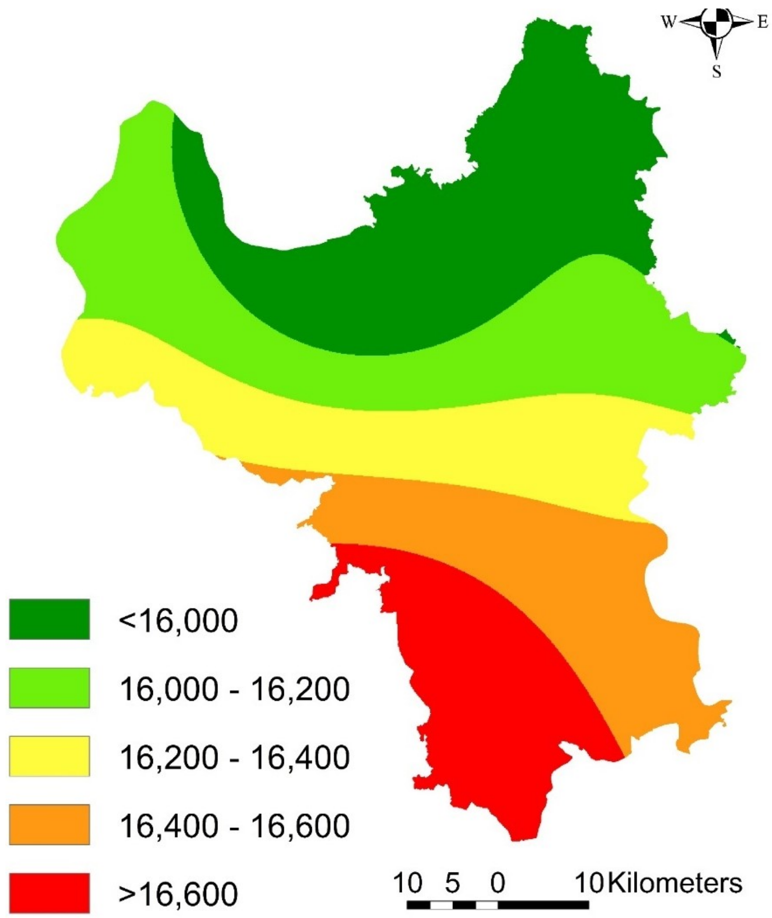

Figure 4-4. Precipitation

4.1.4. Land Use/ Land Cover (LULC)

The land use/ land cover model is closely linked to the frequent incidence of urban flooding, as it pertains to the infiltration rate in which forested areas allow for greater in-filtration than paved surfaces in urbanized regions [9, 10]. Urbanized and developed surfaces produce increased runoff and thus experience a reduced capacity for absorption over time. Consequently, they tend to have a higher susceptibility to flooding compared to abandoned land and land with vegetative cover [11]. Using a supervised classification method with various features on the images collected from Google

Earth and field surveys, Landsat images from 2023 with a spatial resolution of 30m were analyzed to generate the LULC map. The resulting map depicted the distribution of five primary land types: agricultural land, vegetation, settlement land, vacant land, and water bodies. Considering that the urbanization process potentially. Vacant land and vegetation were assessed as being areas with a low and very low susceptibility to flooding, respectively (Figure 4-5).

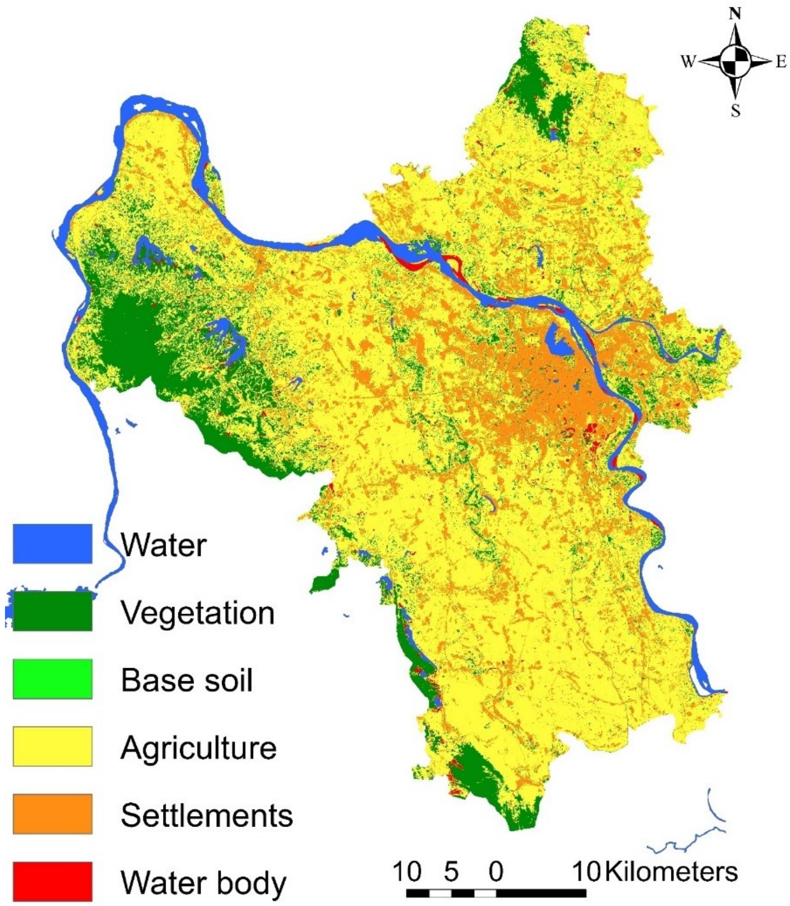

Figure 4-5. Land use/ land cover (LULC)

4.1.5. Normalized difference vegetation index (NDVI)

The NDVI, which is widely used to identify flood events [12,13], is a coefficient for assessing vegetation health and density. Vegetative cover plays a crucial role in mitigating flood susceptibility by interrupting water flow, increasing delay times, and reducing flood hazards, whereas deforested areas can intensify water force and soil erosion, consequently elevating flood susceptibility [14]. Therefore, areas with lower vegetation indices are prone to higher flood susceptibility compared to those with higher vegetation indices. In the current study, the NDVI was computed using the Landsat 8 dataset represented by Equation 2.

$$\text{NDVI} = \frac{\text{Bn}^5 - \text{Bn}^4}{\text{Bn}^5 + \text{Bn}^4} \qquad (2)$$

where Bn^5 and Bn^4 are near-infrared bands and red bands, respectively. According to the research results, areas in Hanoi with an NDVI lower than 0.1 are more prone to flooding. Most urban settlement areas in Hanoi have a low NDVI, with very few areas exhibiting an NDVI below 0.01 which represents a very high flood susceptibility. Moreover, areas with an NDVI ranging from 0.1 to 0.2 were considered to have moderate levels of susceptibility. Areas with a low and very low flood susceptibility have NDVI values ranging from 0.2 to 0.3 and greater than 0.3, respectively. Figure 4-6 shows the calculated NDVI of the study area.

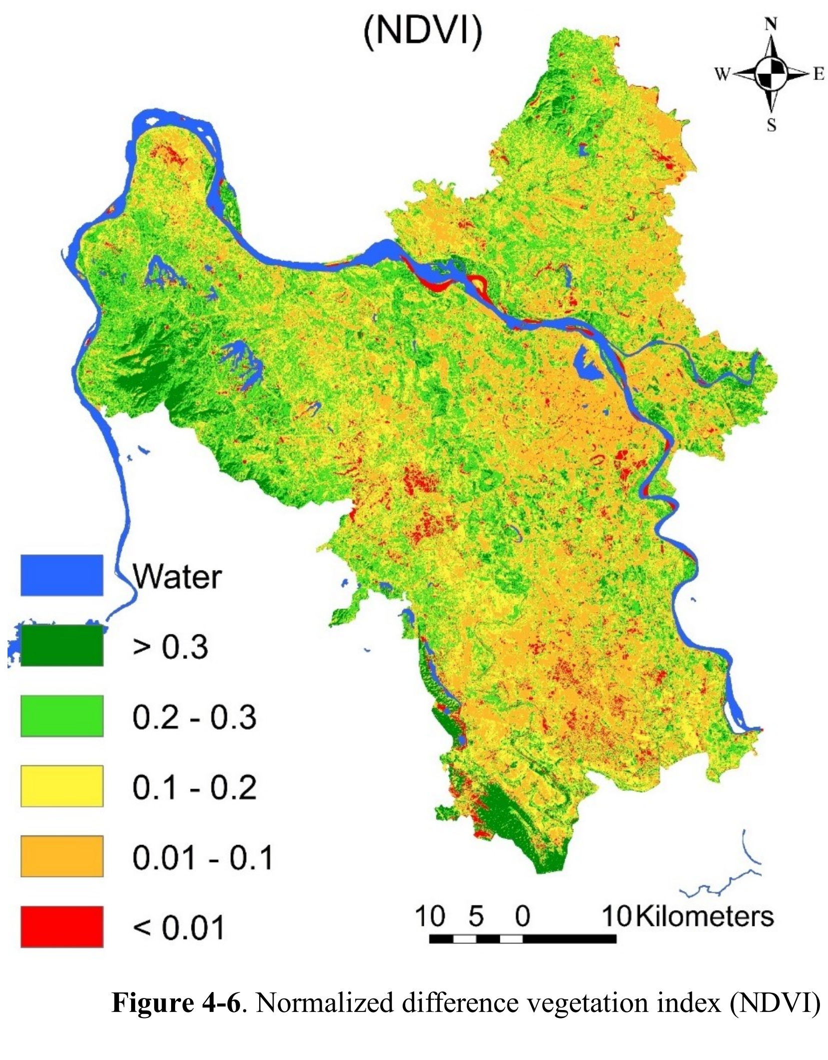

Figure 4-6. Normalized difference vegetation index (NDVI)

4.1.6. Distance from culverts

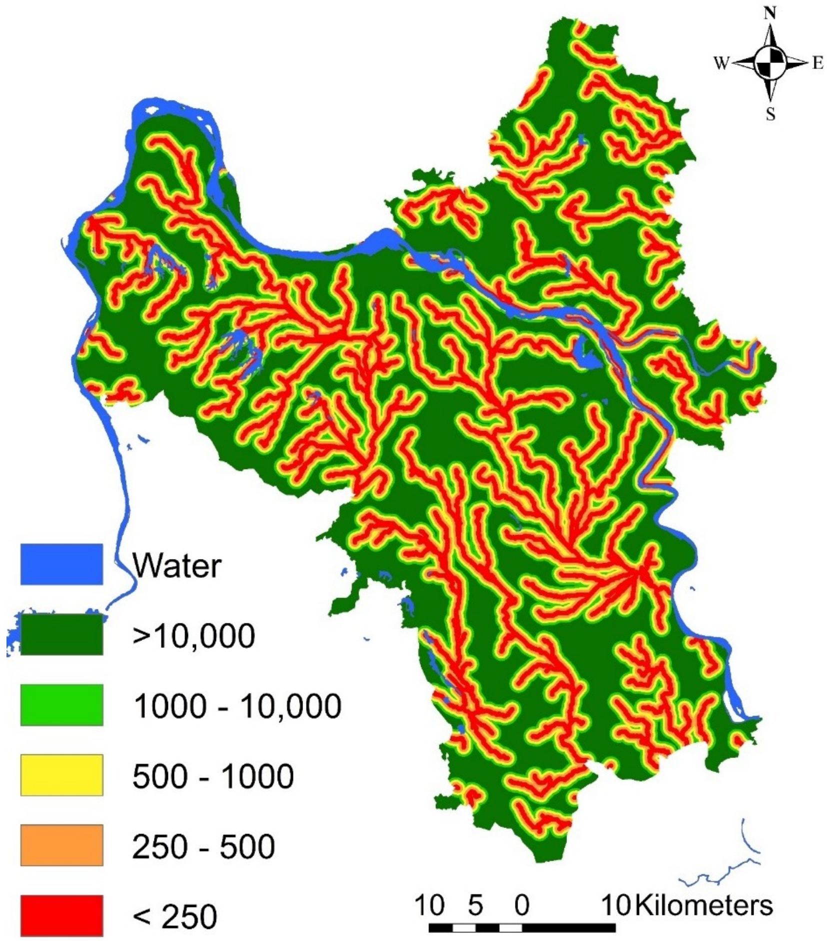

Figure 4-7. Distance from culverts

Areas situated near culvert networks tend to have a higher susceptibility to flooding compared to those located farther away, largely due to their proximity to the flow path of surface runoff [15]. The relationship between flood susceptibility and distance from the culvert network can be somewhat subjective and varies based on the specific conditions of the study area. For instance, Mahmoud and Gan categorized areas within a 200-meter radius of streams as highly susceptible to flooding in arid regions in the Middle East, while areas beyond 2000 meters were considered less susceptible [15]. Conversely, in Markham, Sa-manta and colleagues suggested that areas at distances of less than 1000 meters and 1000-2000 meters from a culvert network exhibited very high and high flood susceptibility, with those beyond 6000 meters showing a low susceptibility [16]. Additionally, in Kathmandu, Chaulagain and colleagues identified areas within a 126-meter range from culvert networks as having a very high flood susceptibility [17]. Numerous studies have shown an inverse relationship between flood susceptibility and distance from culvert networks [18,19]. Drawing from historical flood data in Hanoi, areas within a 250-meter radius of culverts were classified as highly susceptible to flooding, while those at distances of 500, 1000, 10000, and more than 10000 meters from streams were assessed to have a high, moderate, low, and very low flood susceptibility, respectively (Figure 4-7).

4.1.7. Distance from roads

Road construction results in an increase in impermeable surfaces, alters topography, and induces changes in the hydrological patterns in areas near the roads [20]. For flood susceptibility modeling, proximity to roads serves as a significant regulatory factor, impacting surface water flow dynamics or accumulation patterns [21,22]. Drawing from historical flood events in Hanoi, areas prone to frequent and severe annual flooding tend to cluster around major intersections or densely populated regions. In this study, areas within 100 meters of roads were classified as very highly susceptible to flooding, those within 100 – 500 meters were deemed highly susceptible, while areas located between 1500 meters to 5000 meters and beyond 5000 meters from roads were considered to have low and very low flood susceptibility (Figure 4-8).

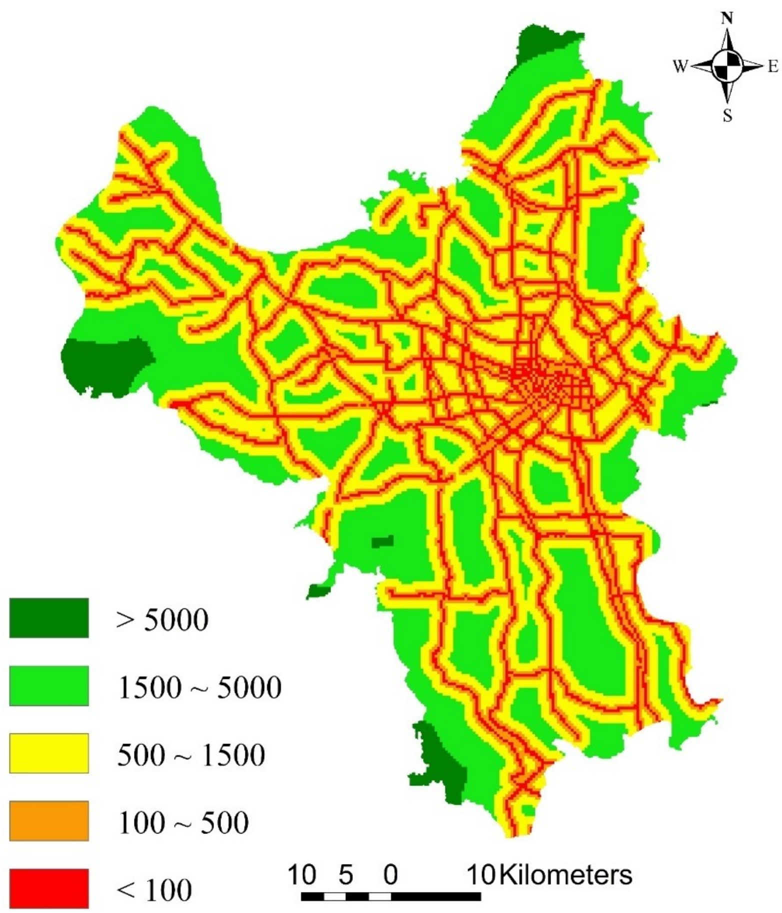

Figure 4-8. Distance from roads

4.1.8. Drainage density

A drainage density map is created by dividing the total length of all streams in a watershed by the total area it covers [23]. In our study, the drainage density map was generated using GIS density analysis tools. A higher drainage density leads to larger surface water flows, increasing flood susceptibility, while a lower density indicates lower flood susceptibility [24]. Thus, the expansion of the drainage network is crucial in creating surface water flows [25], which, in turn, increases the susceptibility to flooding. In this study, the drainage density of Hanoi was divided into five classes. Areas with drainage densities ranging from 0.75 to 1 and greater than 1 were identified as having a high and very high flood susceptibility, respectively. In addition, drainage densities lower than 0.25, ranging from 0.25 to 0.5, and ranging from 0.5 to 0.75 were considered to have a very low, low, and moderate impact on flood susceptibility, respectively. Figure 4-9 illustrates the drainage density map of the study area.

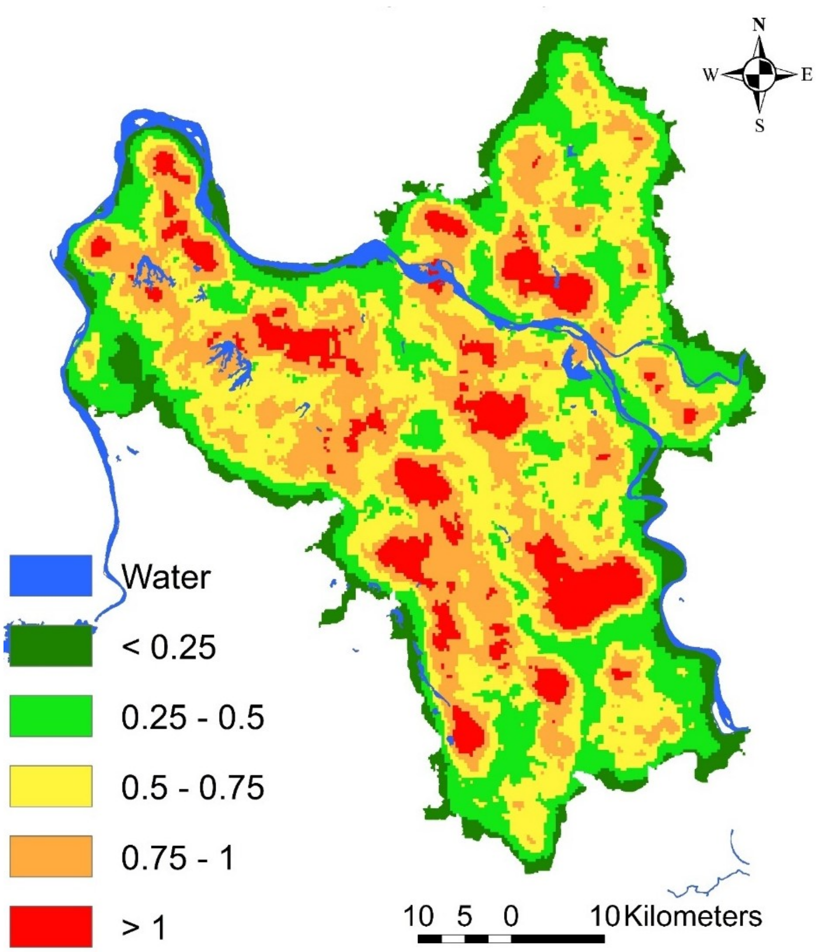

Figure 4-9. Drainage density

4.2. Results of hierarchical analysis for Hanoi flood susceptibility.

Six experts were divided into three groups based on their fields of expertise: natural geography, environmental engineering, and urban management and planning. The survey results from these three groups of experts revealed differences in their evaluations of the contributing factors to flooding. The natural geography group assessed that the regulatory factors were almost equally important in causing flooding (Figure 4-10). Among them, two experts highlighted that water flow and drainage density played a slightly more significant role compared to other factors.

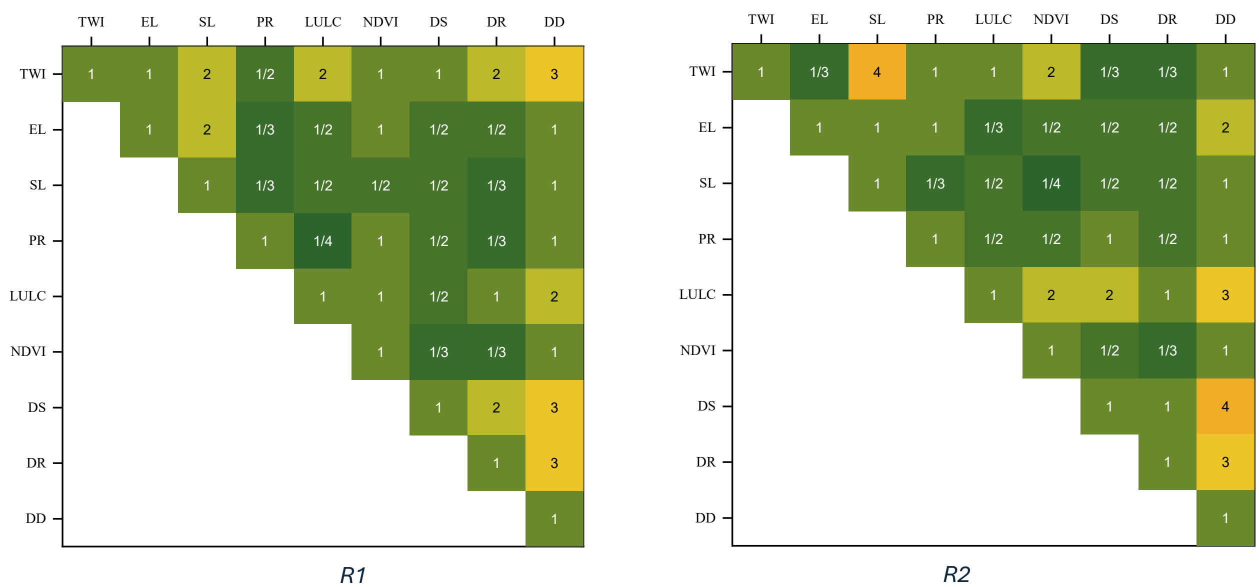

Figure 4-10. Paired comparison results of natural geographic groups

In contrast, the environmental engineering group's analysis indicated that topographical elements such as elevation and slope had a greater contribution to flood causation. However, the overall differences in the impact of these factors were not substantial (Figure 4-11).

Meanwhile, the urban management and planning group prioritized infrastructure-related factors, including proximity to transportation routes and land use (Figure 4-12). They acknowledged that natural factors significantly contribute to flood occurrence. However, for Hanoi, they argued that urban infrastructure planning issues have exacerbated the unpredictability of flooding in the city. They emphasized that while natural elements are important, the planning and development of urban infrastructure have increased the complexity and difficulty in predicting and managing flood risks in Hanoi.

In summary, the natural geography experts consider all regulatory factors to be nearly equally important, with slight emphasis on water flow and drainage density. Environmental engineering experts highlight topographical factors like elevation and slope, albeit with minor overall differences. Urban management and planning experts focus more on infrastructure aspects, particularly transportation and land use, stressing that these significantly heighten the unpredictability and complexity of flooding in Hanoi, even though natural factors remain crucial.

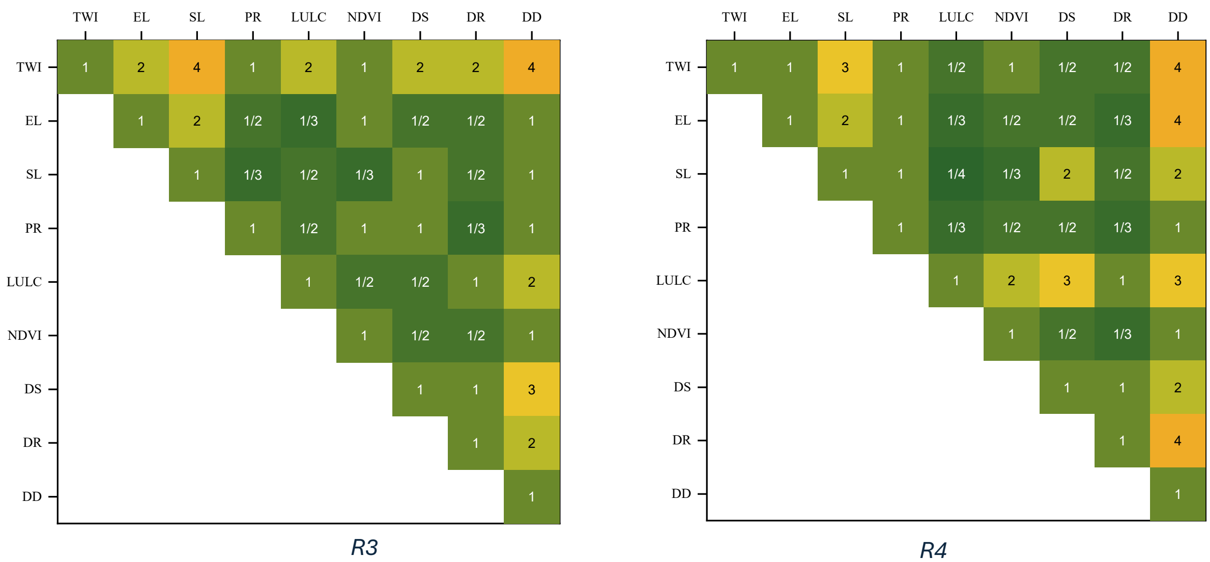

Figure 4-11. Paired comparison results of environmental engineering groups

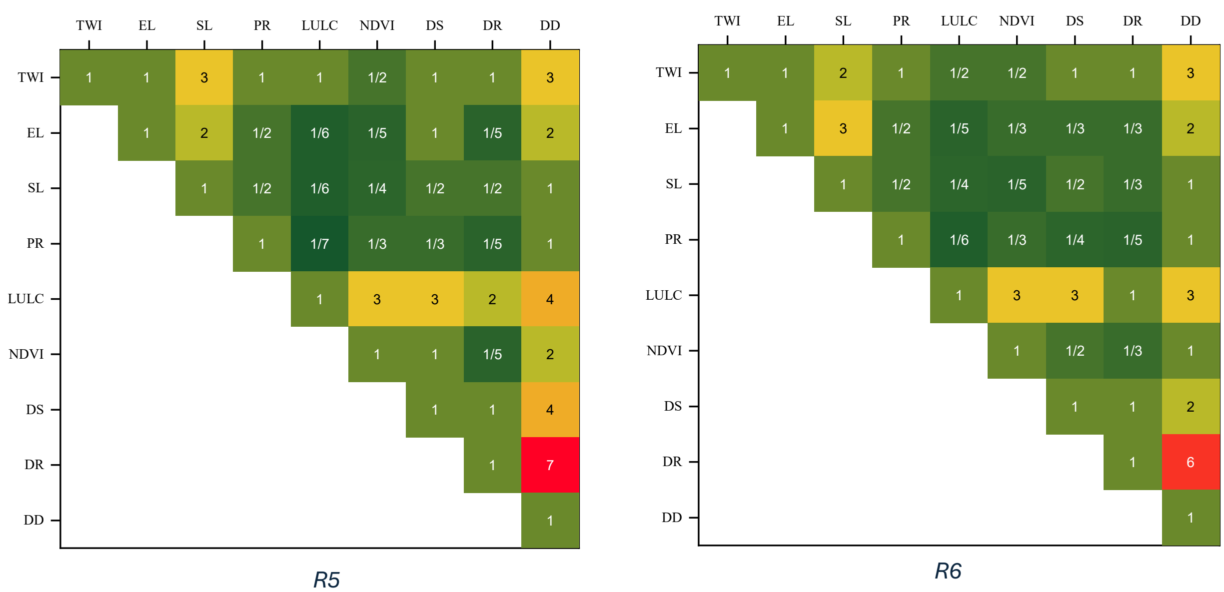

Figure 4-12. Paired comparison results of management and planning groups

After obtaining acceptable CR values in the pairwise comparison matrices from each expert, the average input values of the six experts were calculated to produce a single pairwise comparison matrix (Table 4-2). Table 4-3 presents the normalized values from Table 4-2, which were used to calculate the weights of each conditioning factor and check the CR. The final pairwise comparison matrix was adjusted under the direction of the experts to achieve an acceptable CR and refine the weights of the conditioning factors.

Table 4-2. Class and ratings of the flood conditioning factors

	TWI	**Elevation**	**Slope**	**Precipitation**	**LULC**	**NDVI**	**Distance from streams**	**Distance from roads**	**Drainage density**
TWI	1	1	3	1	1	1	1	1	3
Elevation	1	1	2	1/2	1/3	1/2	1/2	1/3	2
Slope	1/3	1/2	1	1/2	1/3	1/3	1	1/2	1
Precipitation	1	2	2	1	1/3	1/2	1/2	1/3	1
LULC	1	3	3	3	1	2	2	1	3
NDVI	1	2	3	2	1/2	1	1/2	1/3	1
Distance from streams	1	2	1	2	1/2	2	1	1	3
Distance from roads	1	3	2	3	1	3	1	1	4
Drainage density	1/3	1/2	1	1	1/3	1	1/3	1/4	1

Table 4-3. Normalized pairwise comparison matrix

	TWI	Elevation	Slope	Precipitation	LULC	NDVI	Distance from streams	Distance from roads	Drainage density
TWI	0,130	0,067	0,167	0,071	0,188	0,088	0,128	0,174	0,158
Elevation	0,130	0,067	0,111	0,036	0,063	0,044	0,064	0,058	0,105
Slope	0,043	0,033	0,056	0,036	0,063	0,029	0,128	0,087	0,053
Precipitation	0,130	0,133	0,111	0,071	0,063	0,044	0,064	0,058	0,053
LULC	0,130	0,200	0,167	0,214	0,188	0,176	0,255	0,174	0,158
NDVI	0,130	0,133	0,167	0,143	0,094	0,088	0,064	0,058	0,053
Distance from streams	0,130	0,133	0,056	0,143	0,094	0,176	0,128	0,174	0,158
Distance from roads	0,130	0,200	0,111	0,214	0,188	0,265	0,128	0,174	0,211
Drainage density	0,043	0,033	0,056	0,071	0,063	0,088	0,043	0,043	0,053

4.3. Flood susceptibility assessment.

The relative weights of flood conditioning factors derived from the pairwise comparison matrix are presented in Table 4-4, the susceptibility map is shown in Figure 4-5. These reflect the estimated contributions of each factor to flooding susceptibility in Hanoi and include the TWI (13%), elevation (7.5%), slope (5.9%), precipitations (8%), LULC (18.5%), NDVI (10.3%), distance from streams (13.2%), distance from roads (18%), and drainage density (5.5%). Spatial factors with higher weights contribute more significantly to urban flooding susceptibility compared to those with lower weights.

Table 4-4. Weight and rank of flood conditioning factors

Factors	**Weight**	**Rank**
TWI	0,130	4
Elevation	0,075	7
Slope	0,059	8
Precipitation	0,08	6
LULC	0,185	1
NDVI	0,103	5
Distance from streams	0,132	3
Distance from roads	0,18	2
Drainage density	0,055	9

The results in Table 4-4 show that the average LULC, with a weighted score of 0.185, and distance from roads, with a weighted score of 0.18, have the highest priority among all the factors in this study, i.e., these two factors were identified as the primary factors contributing to flooding. Based on historical flooding experience, flood-prone areas are predominantly concentrated in the 12 central districts of Hanoi, where there is a high population density and high impervious surface coefficients. Slope and drainage density play lesser roles in flooding susceptibility in the study area. Figure 4-3 illustrates that, apart from the highlands in the West, the majority of Hanoi's terrain contains slopes ranging from 1-5 degrees. This suggests that the influence of slopes or topographic factors is widespread across the city, resulting in a uniform susceptibility to flooding in most areas. Areas with a drainage density greater than one are mainly concentrated on agricultural land, which is primarily used for rice and flower cultivation.

As depicted in Figure 4-13, the susceptibility map illustrates flooding susceptibility classified into five levels: very high, high, moderate, low, and very low. The area estimated to have a very high susceptibility to flooding constitutes a minute proportion ($0{,}653 km^2$), representing less than 1% of Hanoi's total arthe However, more than 65% ($2412{,}57 km^2$) of the city's territory faces a moderate susceptibility to flooding, while areas with a high susceptibility cover 10.5% ($388{,}314 km^2$) of the city. Areas with a low susceptibility and very low susceptibility account for about 22% ($814{,}986 km^2$)

and 2% ($74{,}717 km^2$) of the city, respectively. As a result of rapid urbanization, the central districts are highly susceptible to flooding during prolonged heavy rainfall.

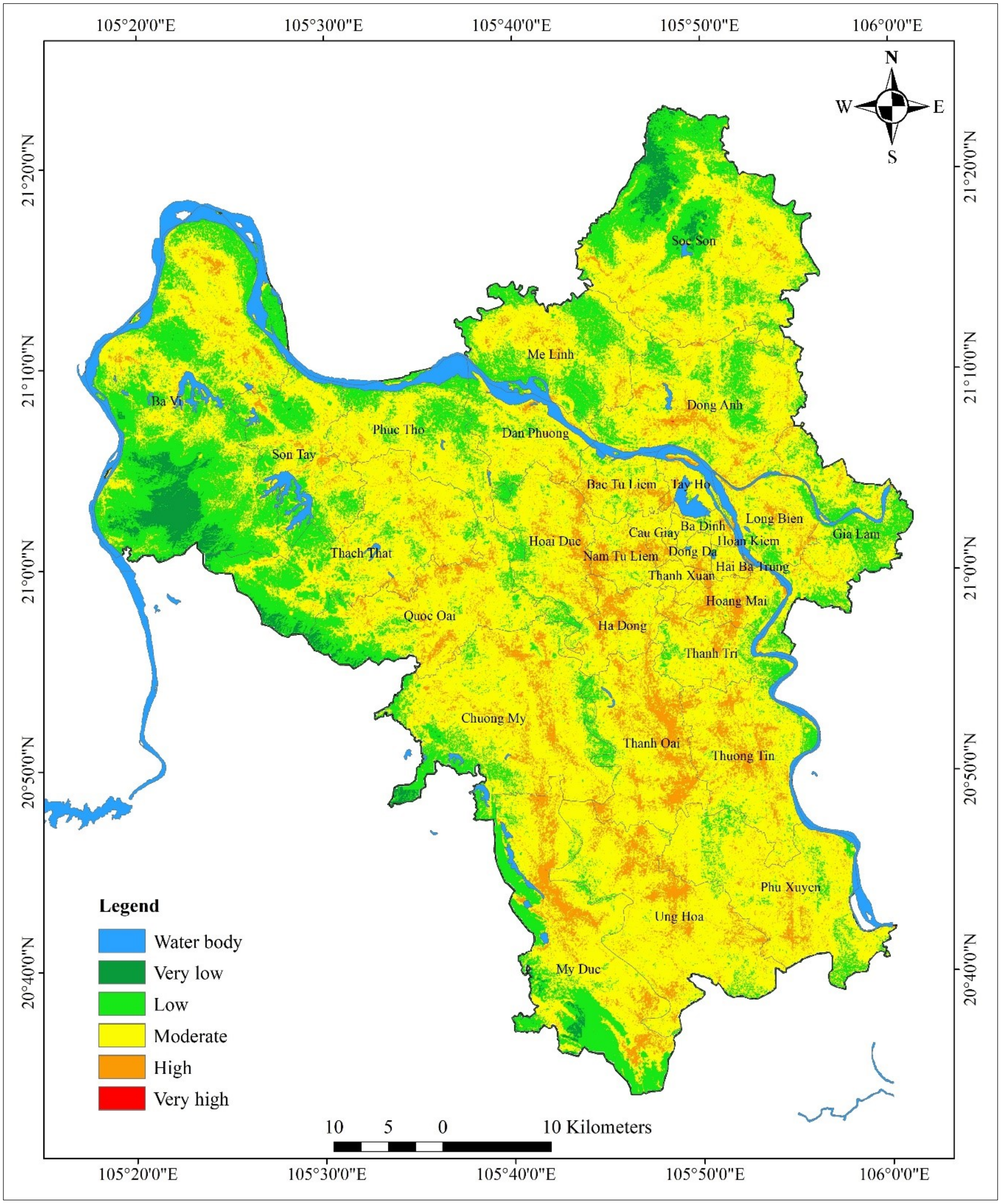

Figure 4-13. Flood susceptibility map of Hanoi

According to on-site surveys in the 12 central districts, flood-prone areas often coincide with major intersections or are densely populated zones. There are characterized by high impervious surface coverage and the flooding is exacerbated by antiquated drainage systems [26]. This impedes water infiltration into the soil, resulting in surface runoff during heavy rainfall events. The ongoing urbanization process in Hanoi is expected to rapidly expand impervious surface areas. Moreover, there is a positive correlation between road density and flooding frequency, with high-susceptibility flood areas typically located within 500 meters of roads. Conversely, flood-safe areas encompass only 24% (889,703 km^2) of the total area and are primarily concentrated in highland regions in the northwest. In recent years, in addition to recurrent flooding hotspots, Hanoi has witnessed the emergence of new flood-prone locations in expanding urban areas.

4.4. Model Validation

A critical steps in ensuring the reliability of any model is accuracy evaluation [27]. In this study, the AUC was computed based on flood occurrence points (148 locations) collected through field surveys in flood-prone areas, city reports, and a literature review. The ROC curve evaluates the success rate and the prediction accuracy of a model by plotting training and validation dataset pairs. The AUC value of the success rate curve (Figure 4-14) indicates that the success rate of our model is 87.3% (AUC = 0.873), i.e., our model has very good accuracy.

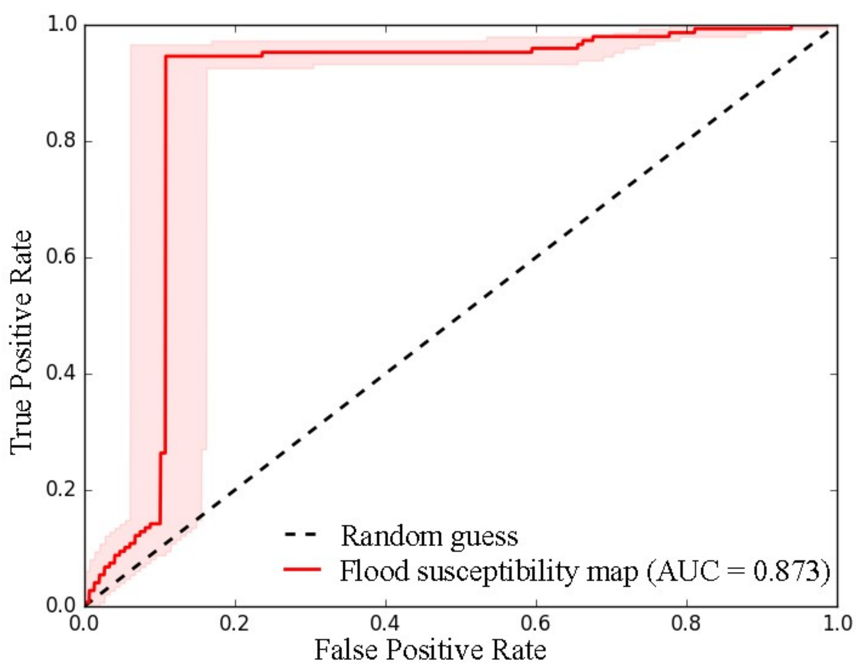

Figure 4-14. AUC value of model

4.5. Analysis of general flood susceptibility planning

Hanoi is bifurcated into two parts, the high-density central districts (Appendix 4-1) and the expansive suburban districts, which encompass nearly 60% of the city's land area dedicated to agriculture (Appendix 4-2). These suburban districts are pivotal to the city's food security, contributing significantly to the sustenance of the urban populace. Notably, a natural event that does not affect human communities is considered a natural event rather than a threat [28]. Therefore, the suburban districts of Hanoi, characterized by their sparse population, receive limited attention and resources. Flood response strategies seem to be focused and catered predominantly to the central districts, despite the higher susceptibility of the suburban areas to flooding.

In urban areas of Southeast Asia that rely heavily on agriculture, the sparsely populated areas often dedicated to agriculture and forestry are particularly vulnerable to flooding. This vulnerability can lead to substantial harm to agricultural productivity, disrupt harvests, and adversely affect the livelihoods of the local populace. The 2018 flood in Hanoi serves as a stark reminder of the devastation that can be wrought upon agricultural-dependent regions in Southeast Asia. According to preliminary statistics from Lao Dong newspaper, Chuong My district alone, the deluge resulted in extensive damage to agricultural assets, including 1,348.2 hectares of rice paddies, 277.9 hectares of vegetable crops, 605.6 hectares of aquaculture, and 187.6 hectares of fruit orchards. The calamity also claimed the lives of 339 livestock, led to the loss of 55,629 poultry, and caused the collapse of 4,855 square meters of livestock shelters, alongside significant property damage. Therefore, underscoring the imperative of identifying and fortifying flood-prone zones, even those sparsely populated, enables effective urban planning and long-term agricultural resilience.

According to the Hanoi City Committee, the city's goal is to achieve an urbanization rate of approximately 60-62% by 2025 and around 65-75% by 2030. Based on the analysis of Hanoi's urban planning map for 2030, the city's development is directed in three basic areas: urban residential areas, agricultural landscape areas, and landscape areas that need protection (Figure 4-15a). Among these, the agricultural landscape area has the highest susceptibility to flooding. According to the Department of Agriculture and Rural Development, Hanoi will focus on developing urban agriculture in parallel with urbanization. Developing agriculture in these areas is considered a suitable direction to ensure food security. These green areas also serve as the lungs of the city. However, as these areas are those with the highest flood susceptibility, they require appropriate irrigation systems, canal networks, and rivers to retain water for agriculture during the dry season and drain surface water during the rainy season.

The central districts of Hanoi are divided into two parts: the Old Quarter and the urban residential center. Among these, the area with a moderate flood susceptibility account for 71.8%, while areas with a high and very high flood susceptibility make up nearly 22%. In contrast, areas with a comprises susceptibility comprise just over 6% (Table 4-13). The Old Quarter, which is the heart of Hanoi, is characterized by outdated and deteriorating urban infrastructure and is difficult to redevelop. According to the Hanoi Statistical Yearbook 2022, the highest concentration of historical flooding points is in this area, spanning the four central districts of Hoan Kiem, Dong Da, Ba Dinh, and Hai Ba Trung, with population densities ranging from 24,000 to 40,000 people/km^2. With a high proportion of concrete surfaces and only 5% green space [29], Hoan Kiem District is prone to frequent flooding, especially during prolonged heavy rainfall. These areas mainly exhibit a moderate susceptibility to flooding (Figure 4-15b). Based on the investigation results, this is due to prolonged heavy rainfall overwhelming the outdated drainage system and causing flooding in low-lying residential areas and/ or water concentrated at traffic intersections. In addition, field observations revealed numerous lakes and ponds in this area, most of which are concrete lined, isolated, and are not connected to the river network. These water bodies do not effectively retain rainwater and can contribute to flooding as water can only drain through the urban surface water drainage system.

According to Hanoi's urban planning map for 2030, there are plans to develop green corridors and intersperse green spaces within urban residential areas. Using the flood susceptibility map, areas prone to flooding can be identified for the appropriate design of these. This approach will help regulate rainfall and make efficient use of surface water, thereby minimizing flooding in residential areas. As a result, the next phase of flood research in Hanoi will focus on specific areas and calculating the flood risk for various aspects at each specific location.

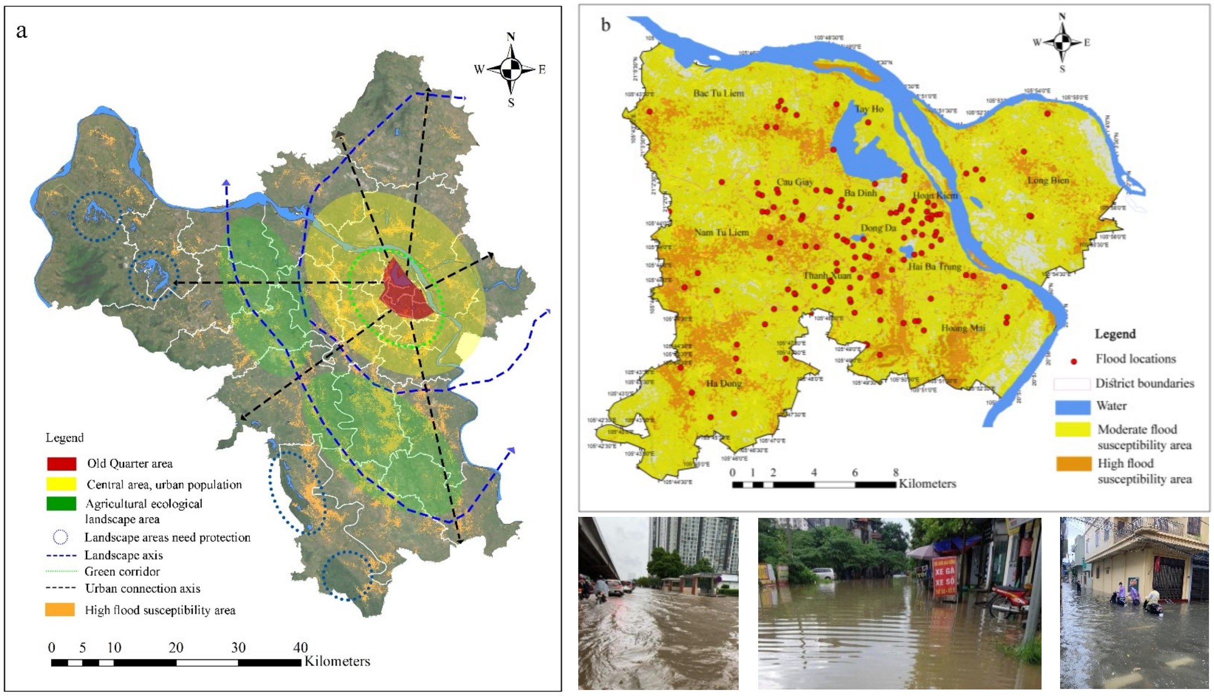

Figure 4-15. (a) Analysis of Hanoi urban planning map 2030. (b) Flood susceptibility map in Hanoi 12 districts central

4.6. Summary

Flood susceptibility maps are widely utilized in flood-related fields and urban development projects [90]. This chapter integrated the Analytic Hierarchy Process (AHP) within a Geographic Information System (GIS) environment to map flood susceptibility at various spatial analysis scales. Nine spatial factors that affect flood susceptibility, including the Topographic Wetness Index (TWI), elevation, slope, precipitation, Land Use and Land Cover (LULC), Normalized Difference Vegetation Index (NDVI), distance from streams, distance from roads, and drainage density, were selected as input data based on overview documents. The study area is Hanoi, Vietnam.

The AHP process involved input from experts in relevant fields, such as management, urban planning, physical geography, and environmental engineering, to create a comprehensive and stable estimation method. The research findings indicate that LULC and distance from roads are the most influential factors in regulating flood susceptibility, while slope and drainage density have a lower priority in relation to flood susceptibility in this area.

In the flood susceptibility map, a majority of the study area is classified as having a moderate susceptibility to flooding, accounting for 65%, and a very small portion is classified as having a very high susceptibility to flooding. The performance of the method was evaluated using the ROC curve and the AUC value. The AUC result of 87.3% demonstrates that the model can reasonably predict the level of flood susceptibility in the study area.

Despite producing an effective analysis and significant validation results in mapping flood susceptibility areas with limited flood data, the study has several limitations regarding data preparation and the specificity of urban locations.

Appendix

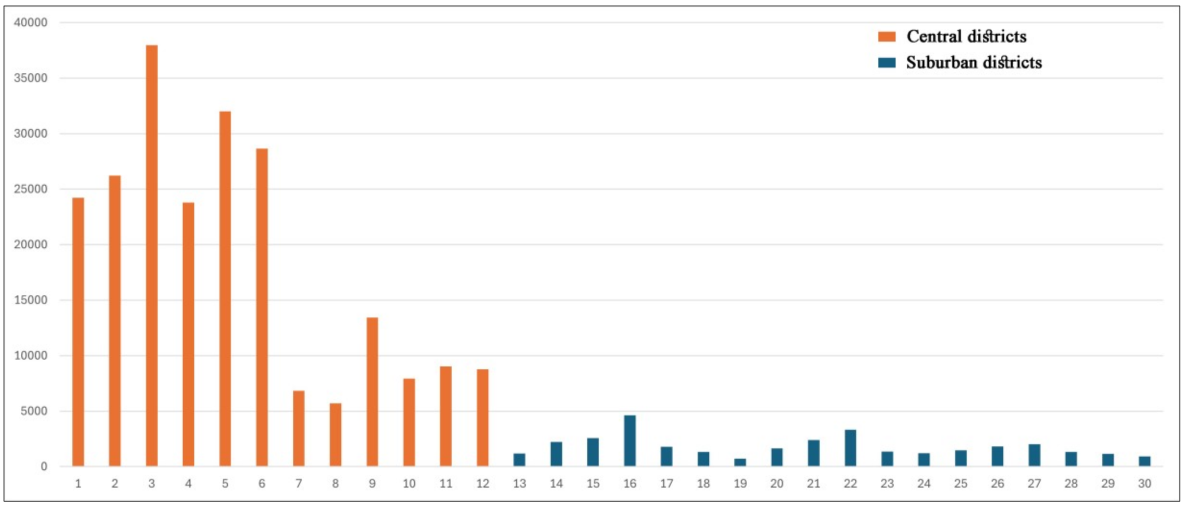

Figure 4-1. Population density by the districts of Hanoi in 2020 (person/km2)

Source: Hanoi Statistical Yearbook 2023

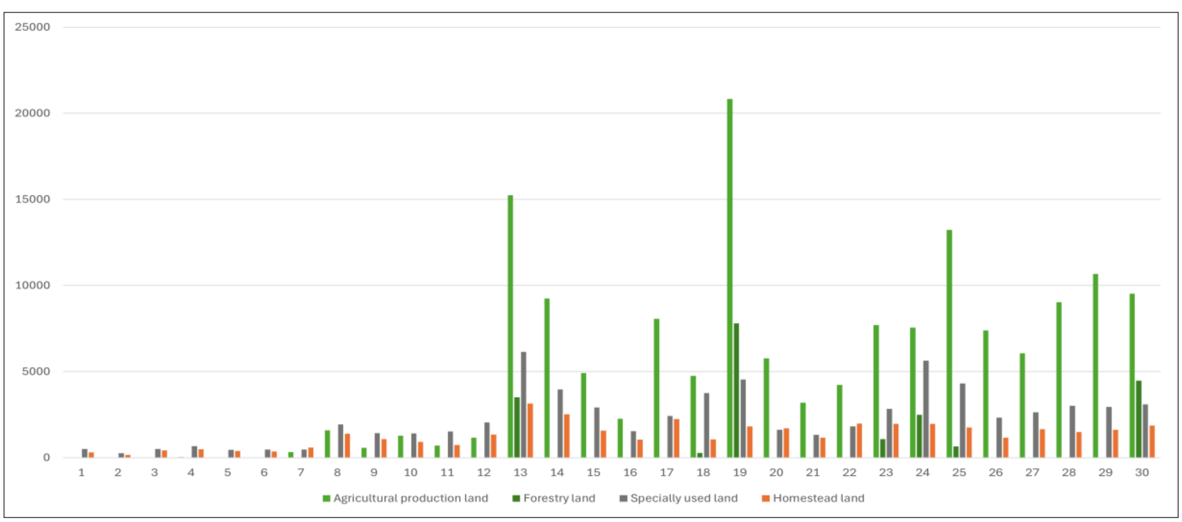

Figure 4-2. Land use status by the districs of Hanoi in 2022 (Ha)

Source: Hanoi Statistical Yearbook 2023

Central districts: 1— Ba Dinh; 2— Hoan Kiem; 3— Dong Da; 4— Cau Giay; 5— Thanh Xuan; 6— Hai Ba Trung; 7— Tay Ho; 8— Long Bien; 9— Hoang Mai; 10— Bac Tu Liem; 11— Nam Tu Liem; 12—Ha Dong.
Suburban districts: 13— Soc Son; 14— Dong Anh; 15— Gia Lâm; 16— Thanh Trì; 17— Mê Linh; 18— Son Tay; 19— Ba Vi; 20— Phu Tho; 21— Dan Phuong; 22— Hoai Duc; 23— Quoc Oai; 24— Thach That; 25— Thanh Oai; 26— Chuong My; 27— Thuong Tin; 28— Phu Xuyen; 29— Ung Hoa; 30— My Duc.

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Chapter 5

SPATIAL FLOOD RISK ASSESSMENT FOR HANOI CITY.

Chapter 4 identifies flood-prone areas and also discovers that flooding in the central areas of Hanoi occurs at many localized points due to the urban surface being concreted and the inefficiency of the drainage system during prolonged heavy rainfall. In this chapter, urban flood risk will be qualitatively assessed based on various natural and social factors. The purpose of this chapter is to determine the level of flood risk that Hanoi is facing.

5.1. Flood Exposure Analysis

Flood exposure criteria, including land use categories, population density, and distance to culverts criteria are shown in Figure 5-1. The weights of criteria and sub-criteria are derived from the AHP model. The distance from culverts is acquired from river and stream network data, it is classified into five categories: less than 250m from stream systems, 250–500 m, 500–1000 m, 1000- 10.000m and greater than 10.000 m. Areas near culverts are at a higher susceptibility of flooding (Chapter 4), and therefore, these areas have higher exposure compared to other regions. The closer it is to streams, the more dangerous it is when exposed to floods. The higher score is given to closer distance to the stream system.

The land use/ land covers are reclassified into agricultural land, settlement, water bodies and wetland, and base soil and vegetation. Due to the significant impact of flooding on residences and infrastructure and its direct effect on people, the settlement criterion is assigned the highest relative weight. Agricultural land follows with the second highest weight, given its importance to community livelihoods. Vegetation and water bodies are assigned the lowest weights since they do not directly threaten human safety.

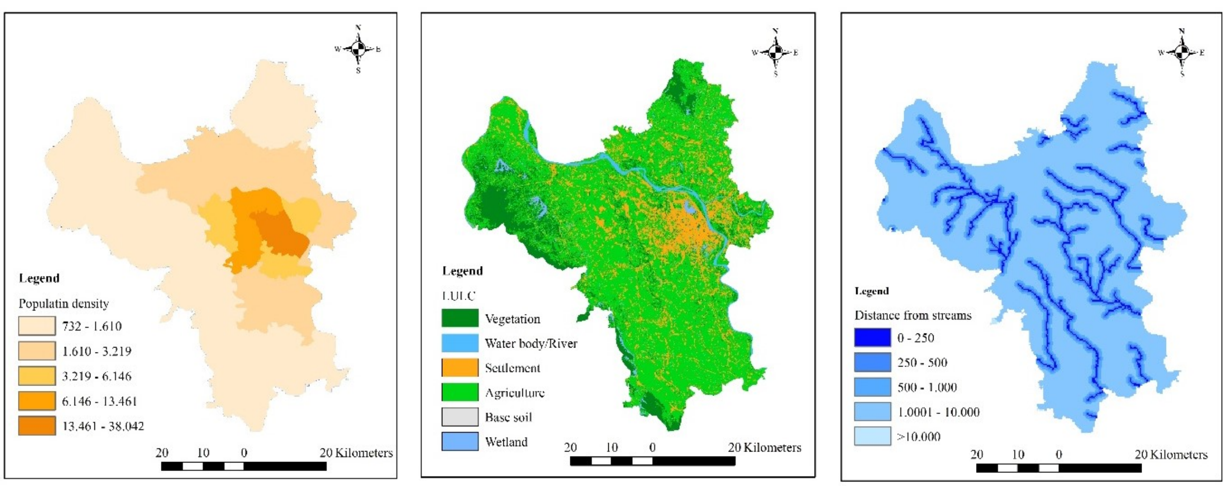

Figure 5-1. Flood exposure criteria distribution, including land use/ land cover, population density, and distance to streams

Population density is deemed the most critical criterion as it directly correlates with human impact. Higher population density results in a correspondingly higher weight distribution (see Table 5-1).

Table 5-1. AHP model for flood exposure criteria

Component	Criteria	Weight	Sub-Criteria	Rating
Flood Exposure	Population density	62.5	<1500	1
			1500- 3000	2
			3000- 8000	3
			8000- 15000	4
			>15000	5
	Distance to streams	23.8	>10000	1
			1000 - 10000	2
			500 - 1000	3
			250 - 500	4
			< 250	5
	Land use/ land cover	13.7	Vegetation	3
			Base soil	2
			Agriculture	4
			Settlements	5
			Water body	1

5.2. Flood Vulnerability Analysis

Flood vulnerability can be assessed by the susceptibility of the exposed elements to the flood hazard [1]. Based on the available data in the research area, we considered flood vulnerability indicators including poverty number [2], distance from roads [3], the number of health facilities [4] and the number of children and women. Thematic maps of flood vulnerability indicators are presented in Figure 5-2.

Poverty rates and flood vulnerability are linked in Vietnam [5]. Higher poverty rates will give greater importance to flood vulnerability. Besides, women and children are also more vulnerable to floods. Therefore, the higher the number of women and children, the higher the vulnerability index. In addition, transportation systems and medical facilities are important factors in flood relief. Therefore, areas with more medical facilities are less vulnerable, while areas farther from the road are more vulnerable. Magnetic distances are classified into 5 classes including less than 100m, 100- 500m, 500- 1500m, 1500m- 5000m and greater than 5000m (Table 5-2)

Table 5-2. AHP model for flood vulnerability criteria

Component	Criteria	Weight	Sub-Criteria	Rating
Flood vulnerability	Poverty number	39.9	0 ~ 84	1
			84 ~ 266	2
			266 ~ 562	3
			562 ~ 892	4
			892 ~ 1702	5
	Distance to roads	14.2	>5000	5
			1500 - 5000	4
			500 - 1500	3
			100- 500	2
			< 100	1
	Number of children	12	60.3- 65.9	1
			65.9- 76.5	2
			76.5- 95	3
			95- 103.8	4
			103.8- 131.5	5
	Number of women	9.1	72.6-92.1	1
			92.1-115.5	2
			115.5-155.5	3
			155.5- 181	4
			181-271.3	5
	Number of health facilities	24.7	12~18	5
			18~22	4
			22~25	3
			25~29	2
			29~38	1

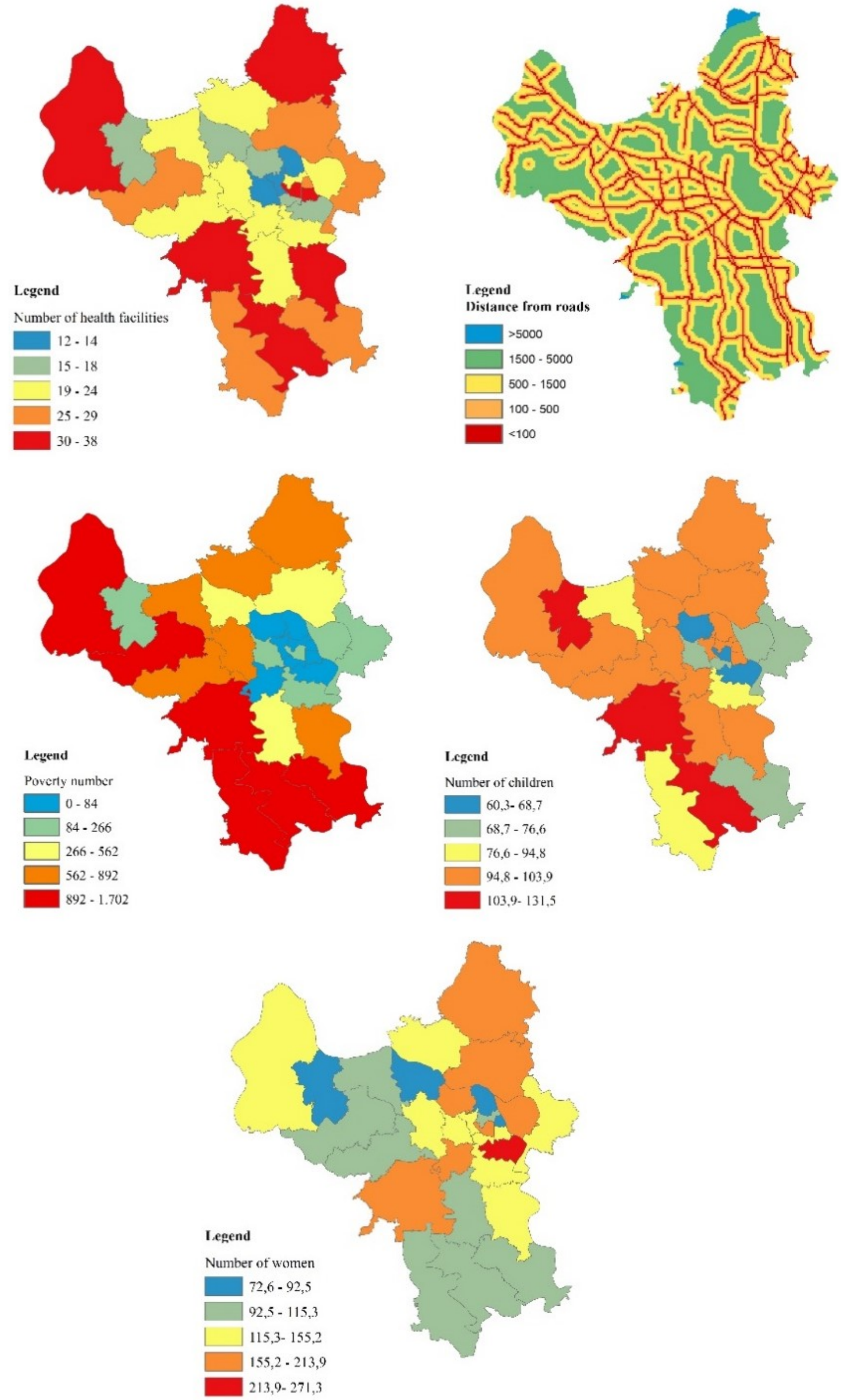

Figure 5-2. Flood vulnerability criteria distribution. including poverty number, distance from roads, number of children, number of women and number of health facilities.

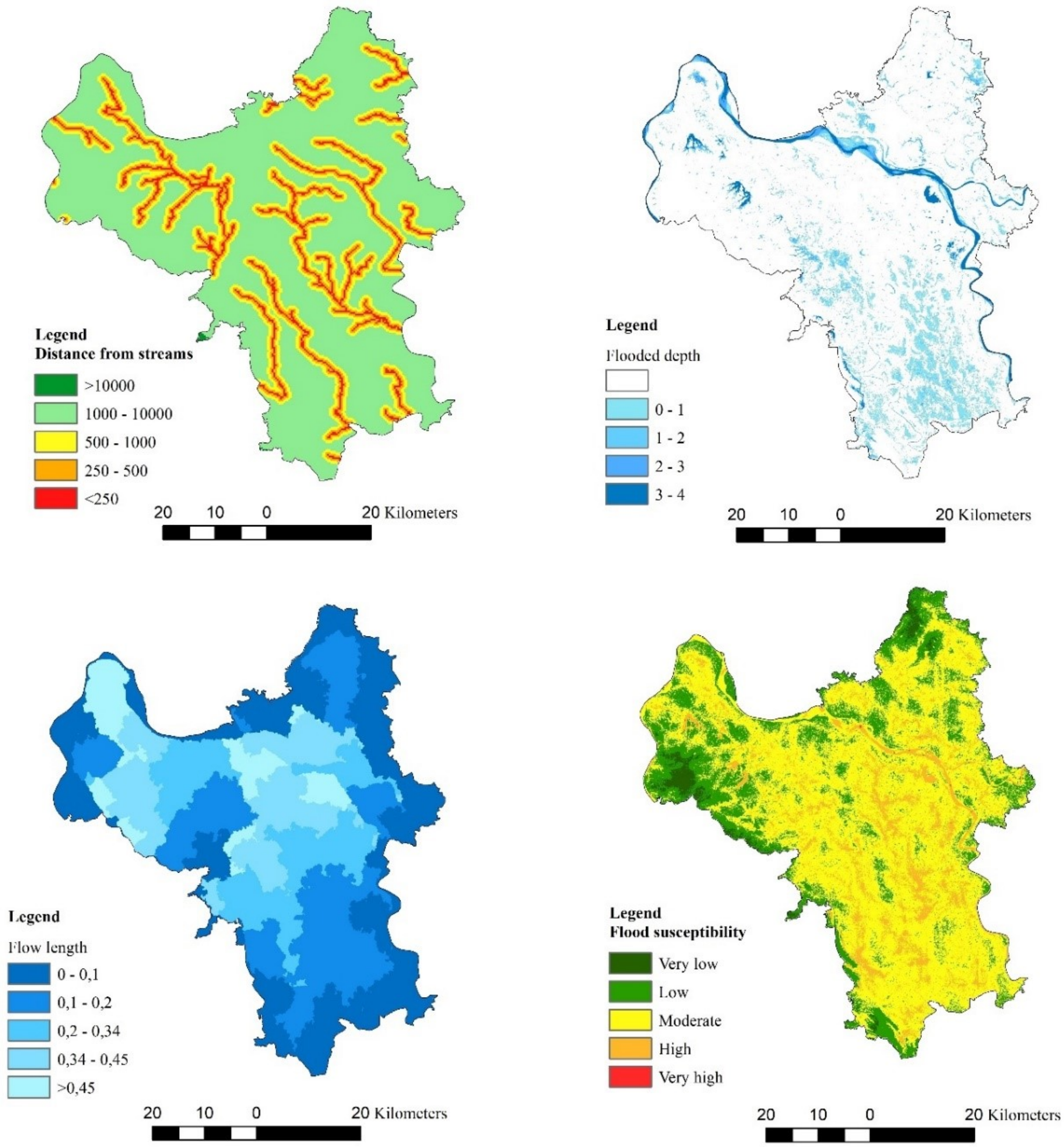

Figure 5-3. Flood hazard criteria distribution

5.3. Flood Hazard Analysis

Flood hazard depends on susceptibility [6], distance from streams, flooded depth, and flow length. We use the flood susceptibility map calculated in chapter IV. A flooded map is built based on DEM data and old flood data. (Figure 5-3).

Susceptibility refers to how likely an area is to experience flooding based on its topography, soil type, land use, and historical flood data. Areas with high susceptibility have characteristics that make them more prone to flooding, such as low-lying terrain, poor drainage, or impermeable surfaces. High susceptibility increases the likelihood of flooding in an area, making it a crucial factor in assessing flood risk.

Proximity to streams or rivers significantly affects flood risk. Areas closer to water bodies are more likely to be inundated when these water bodies overflow during heavy rains or snowmelt. The closer an area is to a stream or river, the higher the risk of flooding due to the potential for overflow and runoff accumulation.

A flooded depth indicates how deep the water can get during a flood event. This factor is critical for assessing the severity and potential damage of flooding. Greater flood depths increase the potential for damage to infrastructure, and property, and can pose significant risks to human safety. Areas that are predicted to experience deeper flooding are at higher risk. Flow length refers to the distance water travels over the surface before reaching a stream or river. It is influenced by the slope and terrain of the area. Locations closer to drainage points are often more susceptible to flooding disasters including flood susceptibility, distance from streams, flood depth and flow length.

Table 5-3. AHP model for flood hazard criteria

Component	Criteria	Weight	Sub-Criteria	Rating
Flood hazard	Flood susceptibility	55.6	Very high	5
			High	4
			Moderate	3
			Low	2
			Very low	1
	Distance to streams	11.5	<250	5
			250- 500	4
			500- 1000	3
			1000- 10000	2
			>10000	1
	Flooded depth	24.9	0 ~ 1	2
			1 ~ 2	3
			2 ~ 3	4
			3 ~ 4	5
	Flow length	8.1	0 ~ 0.1	5

	0.1 ~ 0.2	4
	0.2 ~0.34	3
	0.34 ~ 0.45	2
	>0.45	1

5.4. Flood risk assessment.

Flood hazard, exposure and vulnerability maps are generated using Weighted Overley technique in ArcGIS software. The results of flood hazard, vulnerability, and exposure are displayed in Figure 5-4. In component maps, values are divided into five levels ranging from very low to very high, where very low represents the least danger, least vulnerability, and lowest exposure, and vice versa.

Some studies have focused on flood risk assessment in terms of combining flood vulnerability and flood hazard [7,8,9]. However, flood risk is often considered by the combination of hazard, exposure, and vulnerability, which fully reflects aspects of flood risk. This approach has been applied in many studies at both global [10,11,12] and local scales [13,14,15].

The flood risk assessment result is displayed in Figure 5-5. In the map, the flood risk level is normalised within the range of five class. Areas in the central part of Hanoi and along the Red River are at a higher risk of flooding. The majority of the city's area is at medium risk, accounting for nearly 67% of the total area (approximately 25,715 km2), while areas with high and very high risks constitute less than 1% of the city's area. The results indicate that although Hanoi does not have a high risk of inundation, it is not considered safe from urban flooding. With the rapid urban development combined with current climate change trends, urban areas may face higher risks in the future.

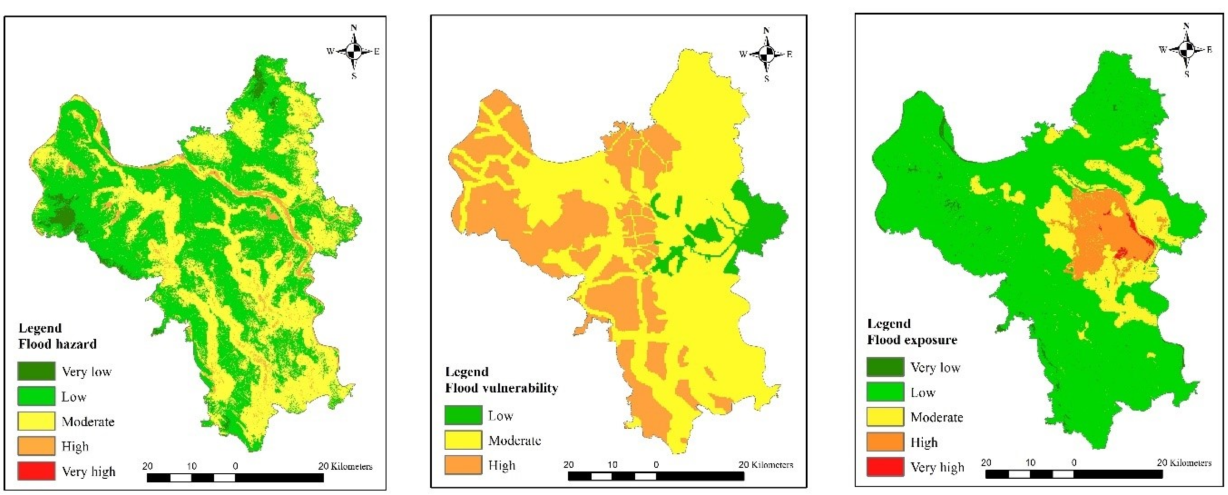

Figure 5-4. Spatial analysis of flood hazard, exposure and vulnerability for Hanoi

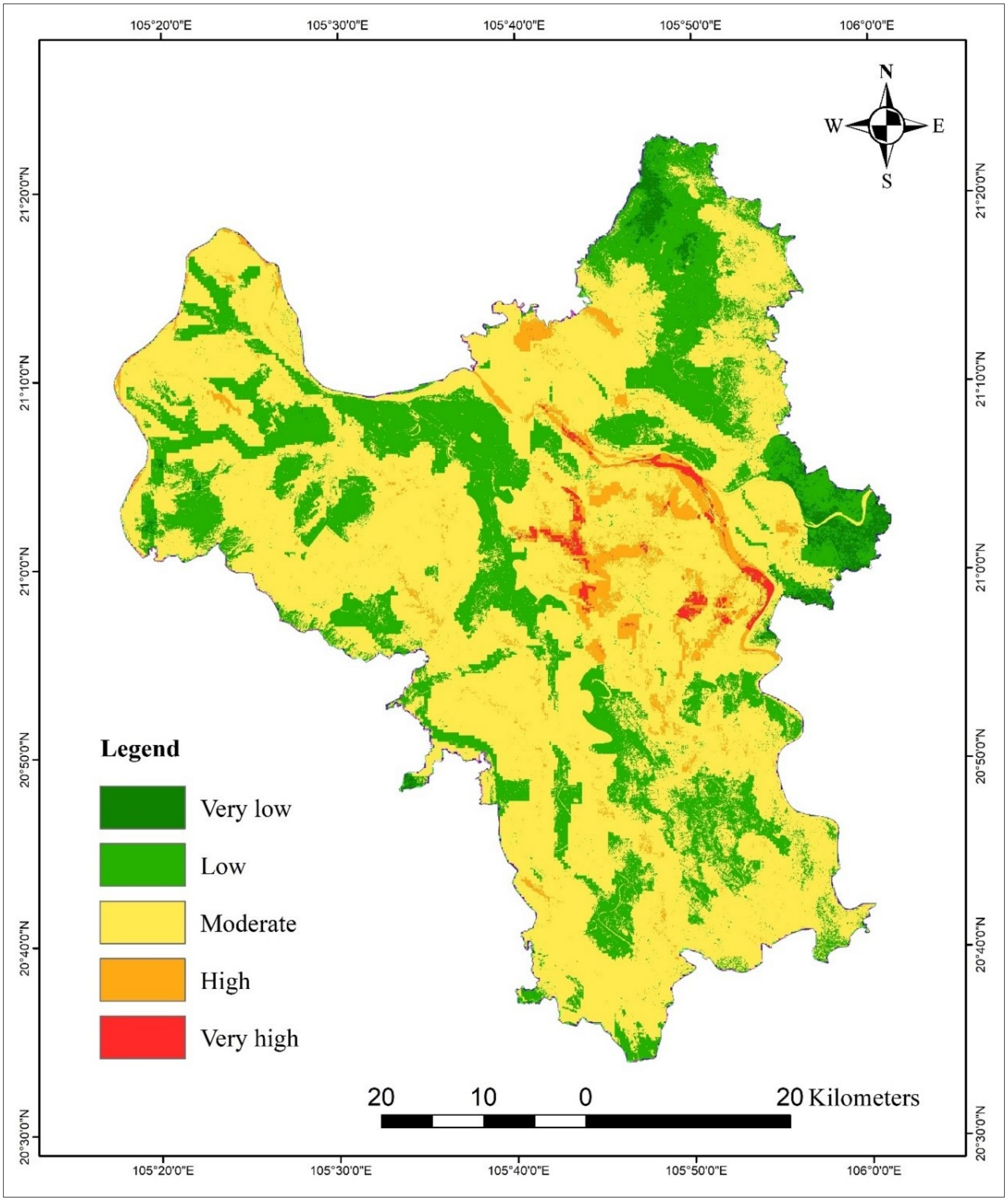

Figure 5-5. Spatial flood risk assessment of Hanoi city

which is combined with three components: flood hazard, exposure, and vulnerability.

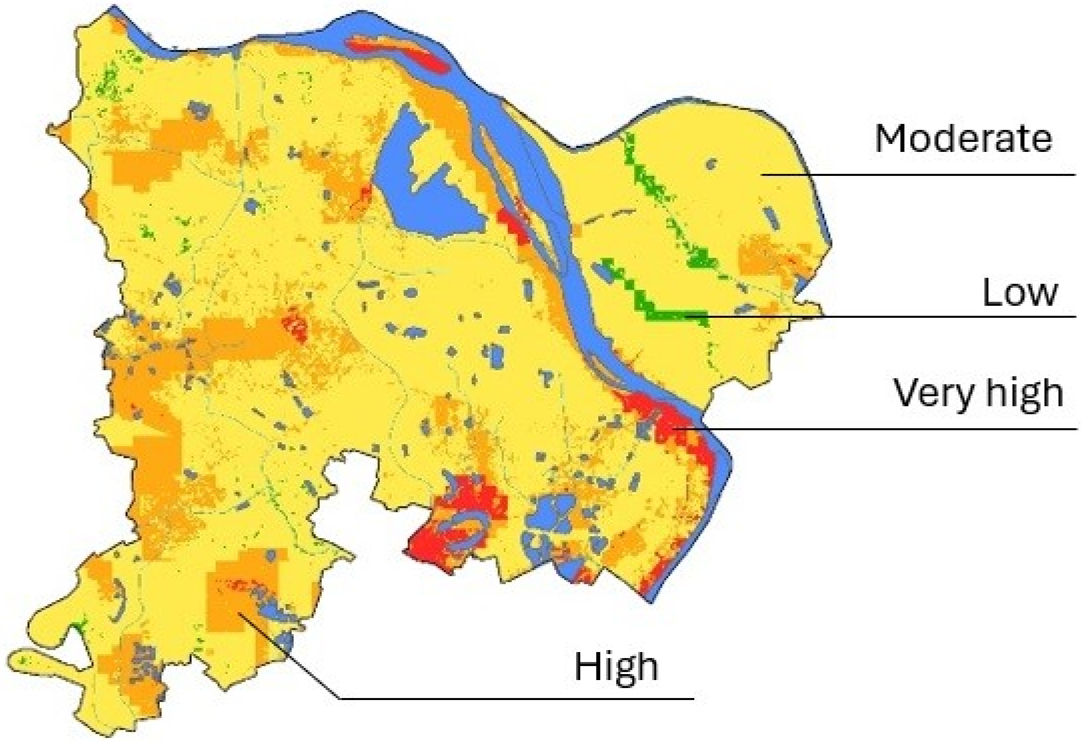

Figure 5-6. Spatial flood risk assessment of Hanoi central districts

According to the results, the level of risk of flooding in the central area of Hanoi is mostly at an average level, but low-risk areas account for a small and insignificant proportion. This indicates that while extreme flood events might not be frequent, the central region still faces considerable flood risk that warrants effective mitigation strategies.

5.5. Summary

This chapter provides a new approach to assess the flood risk for Hanoi city. The study used a combination of hazard, vulnerability and flood exposure data to create flood risk assessment map using spatial multicriteria decision analysis techniques. In the flood risk map, the majority of the study area is classified as having moderate flood risk, accounting for 67%, and a very small part is classified as having very high flood risk. Detailed flood risk assessment maps can support the implementation of specific strategies and actions by government agencies to control, reduce and transfer flood risk. The framework developed in this study can provide a method to rapidly simulate flood risk assessment maps using data available in local areas, especially in areas There is insufficient data for hydraulic models. Additionally, this is a potential way to engage local decision makers in the approach and framework of this study to further investigate and validate flood risks in the study area.

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Chapter 6

BLUE-GREEN INFRASTRUCTURE IN THE CENTRAL OF HANOI

The previous chapter presented findings related to risks from urban flooding. It shows the distribution of the city's hazard levels, vulnerabilities, and exposure levels caused by flooding. It identified that the central area of Hanoi, where high population density is concentrated, has a higher flood risk and is more vulnerable. This chapter provides research on urban blue-green infrastructure and builds a BGI network for stormwater management using a geospatial approach in the central of Hanoi. BGI is one of the methods of interest in surface water management as an alternative to traditional management methods. To do this, the following areas will be explored in this chapter:

- collect information on urban green spaces and water surfaces.
- suitability analysis and mapping for BGI.
- form a BGI network for the research area.

6.1. Suitability analysis for blue-green infrastructure suitability map.

Suitability Analysis is a GIS-based technique that overlays various informational layers to comprehensively determine the best locations for development [1]. In his 1969 publication Design with Nature, Ian McHarg proposed incorporating seven key subject areas into Suitability Analysis: Geophysical, Biological/Ecological, Demographic, Economic, Political, Cultural, and Infrastructure [2]. This method has been applied in the current study to address critical site issues such as stormwater disposal and groundwater recharge by integrating specific criteria: Geophysical, Cultural, and Infrastructure. The selected criteria for the study include Slope, Hydrologic Soil Group (HSG), Drainage Density (DD), Land Cover, and Proximity to Roads. These five attributes were chosen based on their effectiveness in identifying optimal locations for blue-green infrastructure in Hanoi and the availability of open-source data [2].

6.1.1. Suitability layer.

The degree of slope is a critical factor in determining the suitability for blue-green infrastructure (BGI), as it influences the effectiveness of BGI practices in managing runoff during rainfall events [3]. Practices such as permeable pavements and bioswales are most effective on slopes of less than 5%. For rain gardens, a gentle slope of around 5% is ideal, but in some cases, slopes between 5% and 10%, and up to 15%, can also be considered [4-6]. In this study, the slope raster data ranges from 0° to 51°, which has been reclassified into categories of 0–2°, 2–5°, 5–10°, 10–15°, and greater than 15°.

Drainage density measures the natural topography to identify areas susceptible to flooding during rainfall [7]. Regions with high drainage density are more prone to waterlogging, making them suitable for BGI installation. The study area's potential drainage density (DD) was calculated using the line density analysis tool in a GIS environment, based on a drainage network layer derived from a Digital Elevation Model (DEM) using hydrology tools [8]. The resulting drainage density was classified into five categories: less than 0.25 km/km², 0.25–0.5 km/km², 0.5–0.75 km/km², 0.75–1 km/km², and more than 1 km/km².

Land cover data provides spatial information on both natural and built environments, which helps determine the perviousness and imperviousness of the land [9,10]. For designed landscapes, converting impervious surfaces like roads, pavements, plazas, parking lots, and roof terraces into BGI practices such as permeable pavements, rain gardens, and bioswales is beneficial. A supervised classification using the maximum likelihood classifier on Landsat images was performed to identify three land cover types: Built-Up, Vegetation, and Water.

Soil types, which have varying drainage capacities, naturally allow water to pass through at different rates. The United States Department of Agriculture (USDA) Natural Resource Conservation Service [11] classifies soils into four hydrologic soil groups based on infiltration rates: A, B, C, and D.

- Group A: Soils with high infiltration rates (low runoff potential), primarily deep, well-drained sands or gravelly sands.
- Group B: Soils with moderate infiltration rates, typically moderately deep, well-drained soils with moderately fine to coarse textures.
- Group C: Soils with slow infiltration rates, generally having a layer that impedes water movement or fine textures.
- Group D: Soils with very slow infiltration rates (high runoff potential), including clays with high shrink-swell potential, high water tables, or nearly impervious layers.

Group A soils, with the highest infiltration rates and lowest runoff potential, are most suitable for BGI practices like rain gardens, permeable pavement, and bioswales [12]. For Hanoi, the soil map from FAO/UNESCO indicates that the central area contains Fluvisols and Gleysols, corresponding to hydrologic groups B and C.

For effective long-term BGI management and accessibility, public-owned lands are preferred over private lands. Roads and transportation rights-of-way (ROW) offer easier access for implementing and maintaining various BGI practices [13,14]. Consequently, this study considered major roads and an average of 30 m ROW along transportation networks as suitable for BGI implementation. The road network was mapped using OpenStreetMap data.

6.1.2. Blue-green infrastructure suitability map.

The spatial information from the selected criteria was categorized into suitable classes as previously discussed and then ranked on a scale from 1 to 5 (with one being the lowest suitability and five being the highest) following the methodology described in [7,14,9]. However, after discussions with experts in the field and drawing from the authors' experience and understanding of the impact of each criterion and its sub-classes on the successful implementation of a BGI network for stormwater management, the criterion ranks from the literature were adjusted to fit the study area's context (see Table 6-1).

The slope layer, ranging from 0° to 51°, was reclassified into five classes: 0–2°, 2–5°, 5–10°, 10–15°, and more than 15°, as previously mentioned. Slope classes of 0–2° and 2–5° were ranked as the most suitable, while slopes over 15° were ranked as the least suitable. The second criterion, potential drainage density, was divided into five categories: very low, low, medium, high, and very high. Areas with very high drainage density were ranked as the most suitable, while areas with low drainage density were ranked as the least suitable. The road layer and land use/land cover (LULC) layer were merged in a GIS environment to identify five land cover surface types. Highly developed built-up areas were considered the least suitable, whereas less developed areas, vegetation, water surfaces, and roads were considered the most suitable.

For the hydrologic soil group criterion, soils were classified into two types: those belonging to hydrologic groups B and C. Group B soils were ranked as highly suitable, while Group C soils were given a lower suitability ranking. Using the Euclidean Distance tool in a GIS environment, land covers of water and vegetation areas were ranked as the most suitable for implementing BGI, with all other values ranked as the least suitable. The data are presented in Figure 6-1.

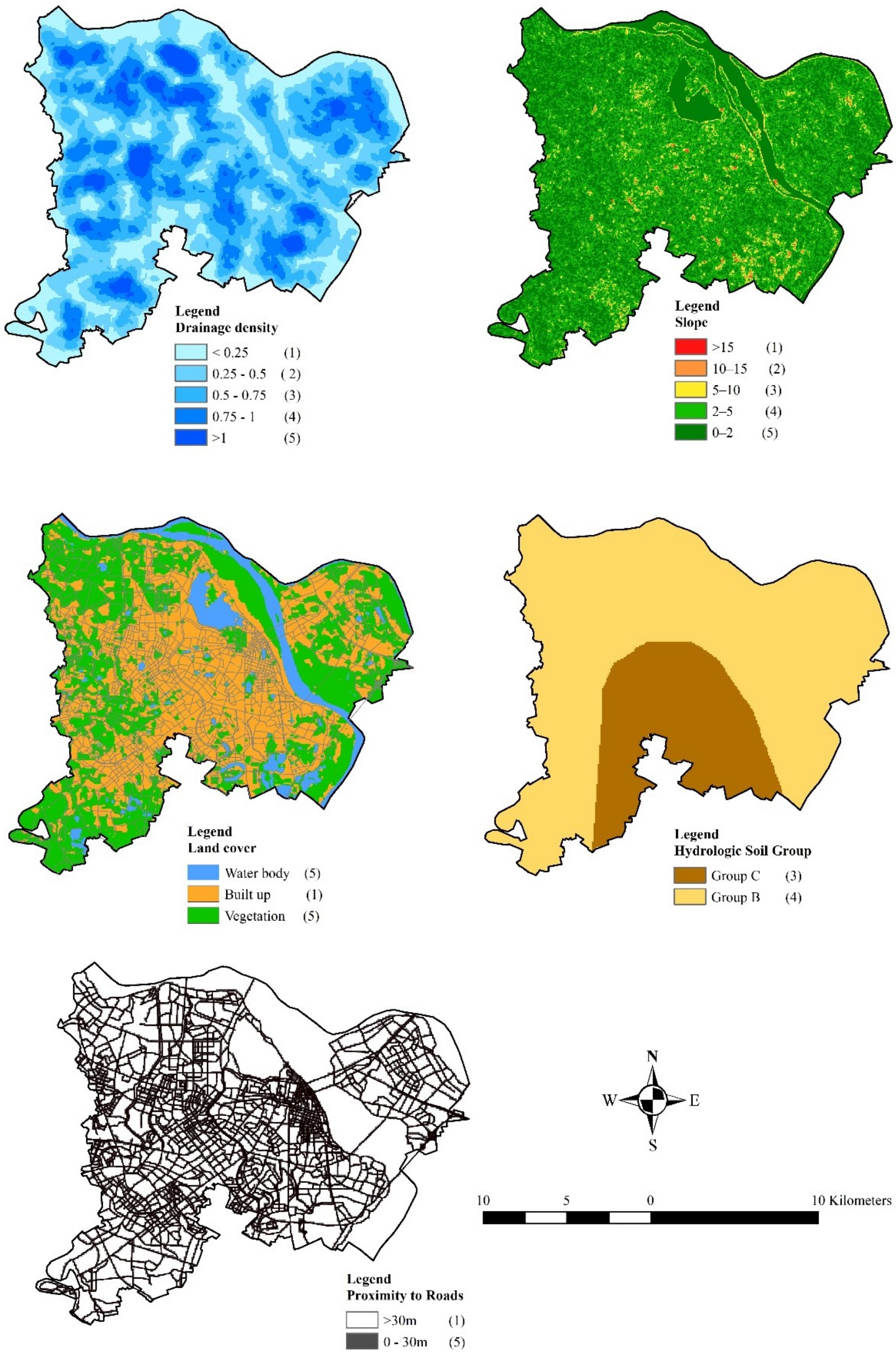

Figure 6-1. Five criteria used to identify the areas suitable for BGI implementation in Hanoi

Table 6-1. Suitability criteria and ranks

Ranking Score	**1**	**2**	**3**	**4**	**5**
Slope	>15	10–15	5–10	2–5	0–2
Drainage density	< 0.25	0.25 - 0.5	0.5 - 0.75	0.75 - 1	> 1
Land cover	Built up	—	—	—	Water, vegetation
Soil	—	—	C	B	—
Road	>30m	—	—	—	0–30m

For a Suitability Analysis, it is necessary to give weight to each criterion and Analytical Hierarchy Process (AHP) is one of the most effective approaches to assign the weights to the criteria without any bias. Table 6-2 shows the weights of the evaluation criteria after implementing the AHP process and the consistency ratio is accepted.

Table 6-2. Criterion weights

Criterion	**Weights**
Slope	32.8
Drainage density	29.4
Land cover	20.4
Hydrologic Soil Group	11.6
Proximity to Roads	5.8

The slope criterion received the highest weight because sites near slopes tend to accumulate more stormwater, making BGI practices for a water-sensitive environment most effective in these areas. Following slope, drainage density (DD) was deemed important and given the second highest weight, as high-density drainage areas are more prone to waterlogging, influencing the selection of suitable areas. Next in importance was the land cover criterion, crucial for implementing BGI in Hanoi. While the Hydrologic Soil Group is essential for the correct functioning of most BGI due to its impact on infiltration rates, it received less weight in this study because of the limited variation in soil types within the study area. Lastly, roads and their surrounding areas were identified as the most suitable land use types for BGI development. Although proximity to roadways is advantageous, it is not mandatory, so it was given a lower weight compared to other criteria. The final BGI suitability map was generated by multiplying each reclassified raster map with its assigned weight and then summing them together using the following formula in GIS.

The final suitability map, which integrates all the five criteria, shows overall suitability for blue-green infrastructure implementation in the study region (Figure 6-2). The suitability is represented by colors, ranging from red (high) through yellow (medium) to green (low). The result shows that out of total study area of 340 km2, an area of about 14 km2 (4%) has low suitability, around 180 km2 area (53 %) has moderate suitability, about 134 km2 area (39 %) has the high suitability and more than 3 % of the area has the highest suitability for the implementation of BGI.

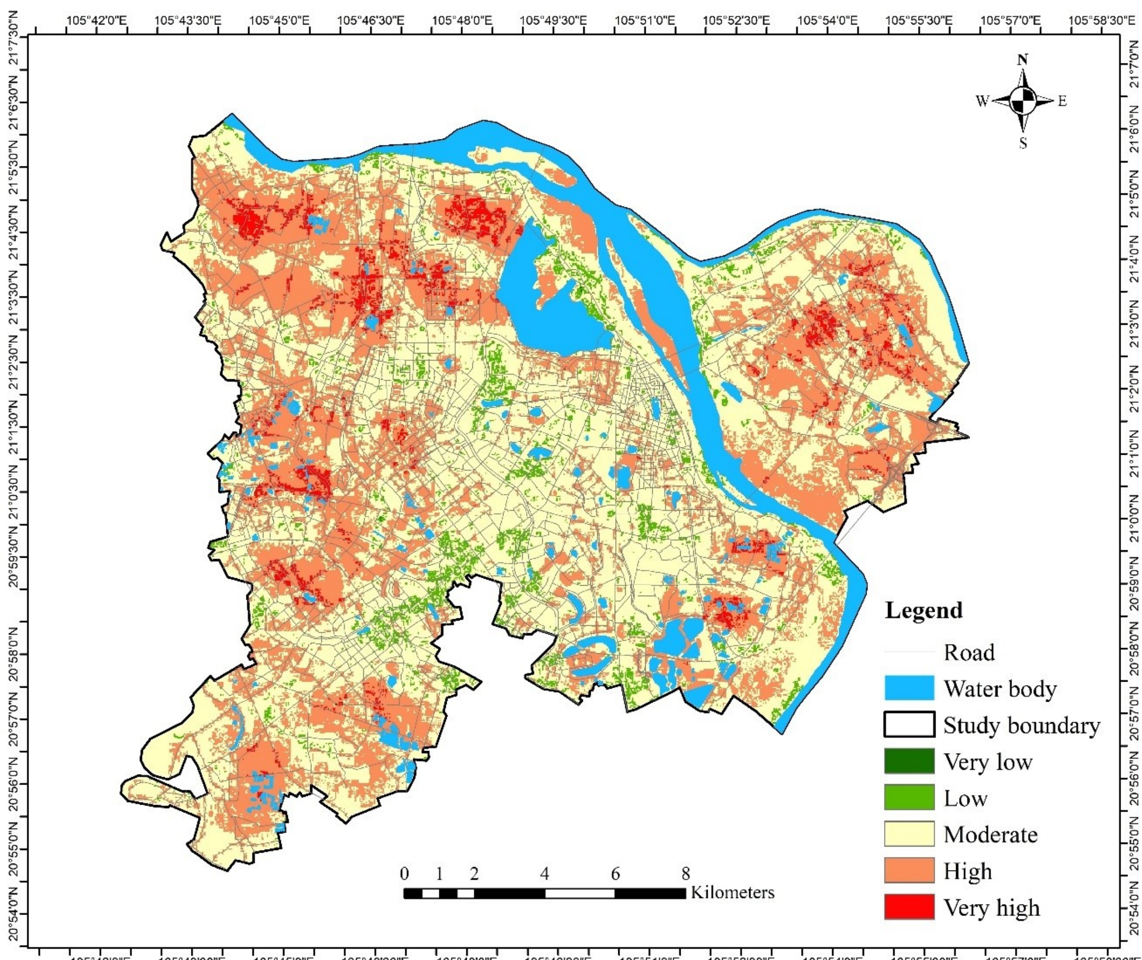

Figure 6-2. The BGI suitability map of the study region

Hanoi city features a relatively flat terrain, with its center located near the Red River basin. The Red River serves as the primary drainage channel for the smaller rivers running through the city. This physical characteristic of the study area was leveraged in this research by identifying a BGI network designed to mimic the natural drainage patterns of the region.

The study capitalizes on Hanoi's physical characteristics by identifying a BGI network that mirrors the natural drainage patterns of the area. BGI practices such as bioswales, filter strips, permeable pavements, wetlands, and rain gardens require a gentle slope of less than 5% to be effective. However, in some cases, even slopes of 0–2% may be too flat and ineffective. The slope map revealed that slopes of 0–2% and 2–5% make up 53% and 40.6% of the total study area, respectively. These slopes are prevalent throughout the region, suggesting the potential for a widespread and efficient BGI network to complement the primarily underground gray stormwater drainage system.

Climate change increased impervious surfaces, and insufficient gray infrastructure are major causes of flooding in central Hanoi. Implementing various BGI types can alleviate flood risks by capturing rainwater at its source. Built-up areas, which cover 47% of the study region, dominate the land cover, followed by vegetation and water bodies. Core urban areas have limited and scattered green infrastructure and water spaces, many of which are polluted. Integrating BGI practices in unplanned areas, road networks, and linking them with existing blue-green spaces can reduce the city's impermeability.

Soil permeability is crucial when selecting BGI types for specific land use scenarios. For instance, areas with heavy clay soil and poor infiltration rates may not be suitable for rain gardens and permeable pavements. The study area's swampy and alluvial soils pose no significant obstacles to implementing green infrastructure in open spaces. Natural topography must also be considered to determine where water naturally accumulates. The potential drainage density criterion identifies areas most susceptible to flooding, highlighting where BGI would be most beneficial. Chapter Four findings indicate that high drainage density areas are at greater flood risk, making them priorities for BGI implementation.

In addition to technical factors like soil and topography, public land availability is prioritized for BGI implementation due to its accessibility and ease of use. Because data on land ownership (public/private) is lacking, roads and pathways are considered the most suitable land cover types for BGI implementation in this study.

Integrating BGI practices into urban planning helps manage flood risks, enhances urban resilience, improves water quality, and contributes to urban ecosystem well-being. By prioritizing areas with high drainage potential and considering soil permeability and public land availability, effective BGI strategies can be developed to mitigate urban flooding and create sustainable urban environments.

6.2. Blue- green infrastructure networks

6.2.1. Core patch identification.

Urban theory conceptualizes the landscape as a network of points and lines, where the points represent patches (nodes) of blue and green spaces, and the lines (corridors) represent the connectivity between these patches [15]. In this study, patches are defined as existing blue and green spaces in the city with a minimum area of 2 hectares (Figure 6-3) [13]. These existing spaces were initially identified from the parks and gardens map in the Hanoi status map. Additionally, Landsat satellite imagery was used to enhance the core patches map, incorporating green areas within the green belt, riverside greenery, cantonments, graveyards, burial grounds, institutional greens, playgrounds, and railway/roadside greens, as well as blue spaces such as lakes, ponds, and rivers.

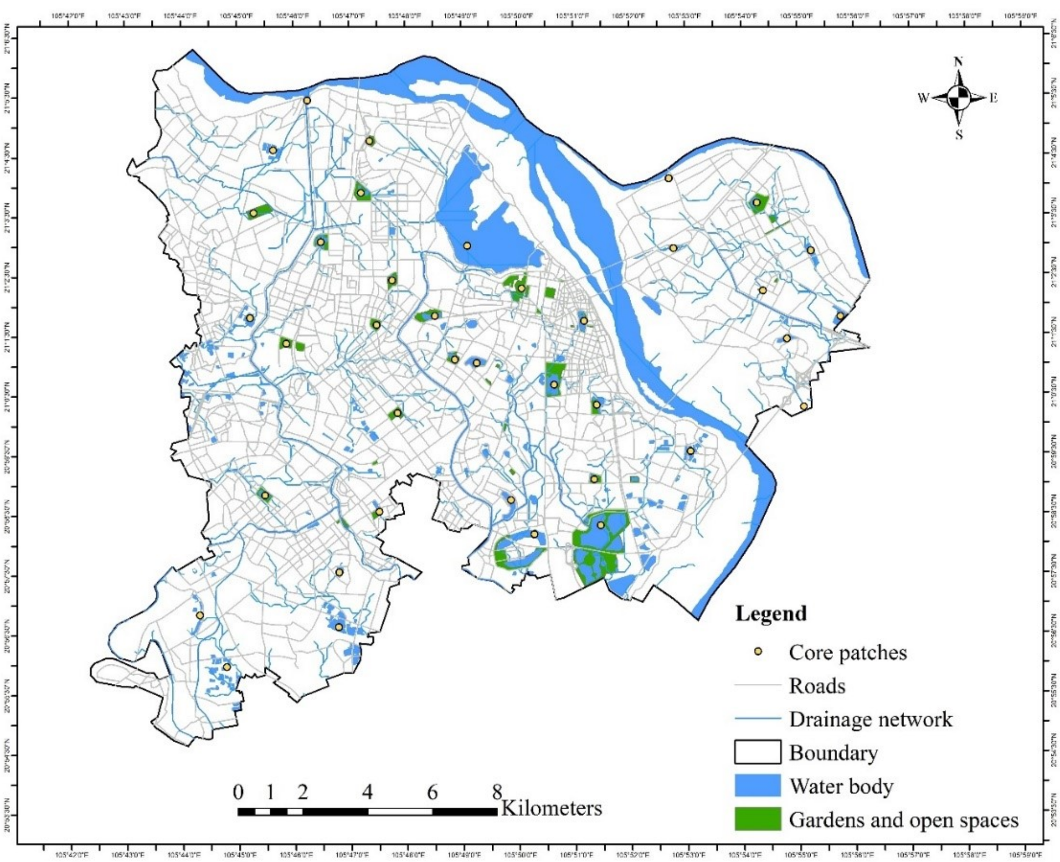

Figure 6-3. The map of the Core patches (Nodes) > 2ha of the study area

6.2.2. Establishing node-corridor matrix by least-cost path analysis

The least cost path method in GIS is effective for identifying the most efficient routes between two nodes by representing the landscape as a cost surface [16]. Researchers in landscape conservation, such as Kong et al. [17], have used the least-cost path function to define green corridors connecting habitat patches in urban environments for biodiversity conservation. In this study, least cost path analysis was conducted in a GIS environment to define a blue-green network in central Hanoi for stormwater management. The BGI suitability map served as the cost surface for the least cost path function. The cost distance and cost path tools in the GIS environment were then used to create least cost corridors connecting the identified nodes in the study region.

Using the cost path tool in the GIS environment identified the most cost-effective routes, indicating high suitability for developing blue-green corridors between established nodes. Utilizing the BGI suitability map as a cost surface resulted in a network of 463 potential corridors connecting 38 nodes on either side of the Red River (Figure 6-4).

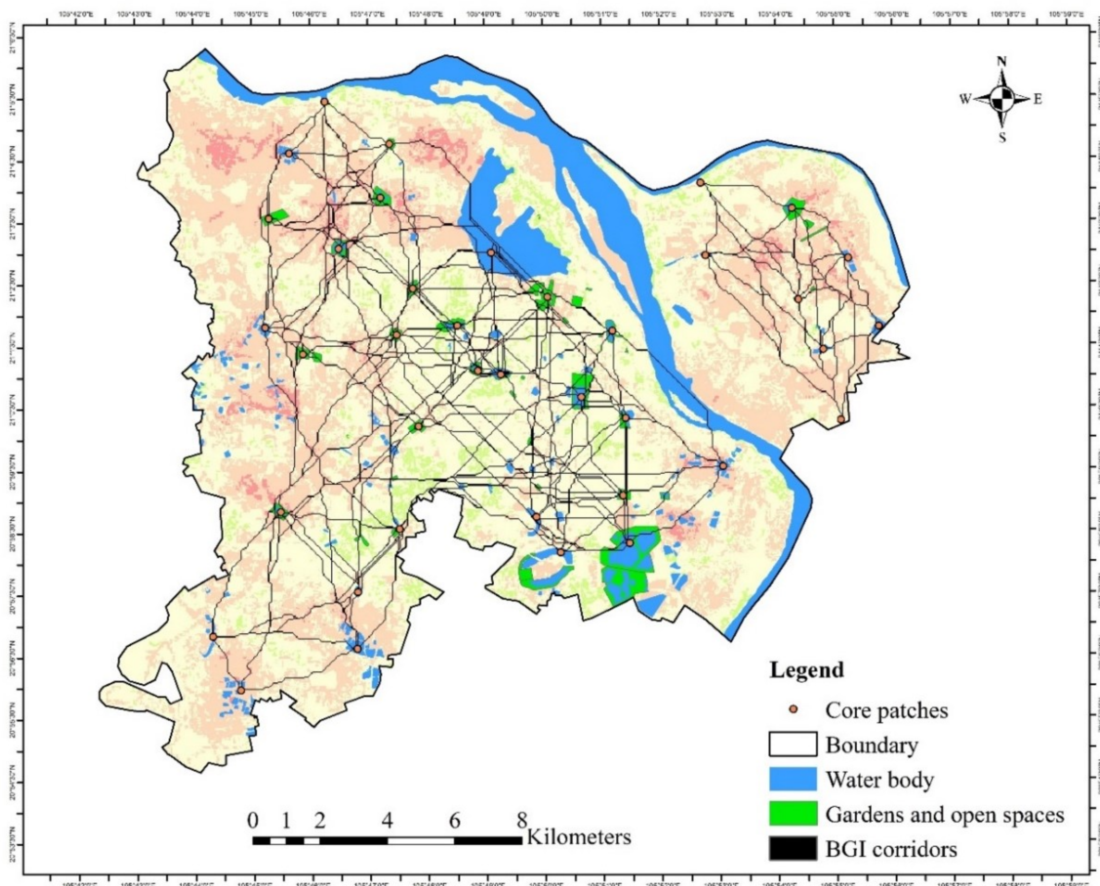

Figure 6-4. The map of BGI corridors linking the nodes generated by the least cost path analysis

6.2.3. Assessment of corridors using gravity model

In this chapter, the study focuses on selecting BGI routes in the central area of the city. 30 nodes in the west of the study area relative to the Red River and 435 BGI routes will be calculated in the gravity model. The Land cover map will be used as the cost surface for calculation. The impedance value of a node and a corridor as mentioned above is deduced from the authors' experience to assess the additional effort required to convert a particular landcover type under the node and the corridor into a blue-green network (Table 6-3).

Table 6-3. Land cover types are used to calculate impedance value for patches and corridors (node and edge weights).

Land Cover	Description	Impedance
Built-Up	Areas with impervious surfaces and structures such as buildings.	5
Road	Primary, secondary and tertiary roads.	1
Vegetation	Areas having tree cover, shrub cover, grass or lawn cover, agriculture	1
Water	Lakes, rivers, streams, and other water features.	1

Table 6-4 statistics the green surface and surface water area and the impedance of 30 nodes. According to formula (10), the weight of a node is determined by dividing its area by the total impedance values of all land cover types within that node. For corridors between nodes, as stated in formula (11), the impedance value is obtained by adding the impedance value of each cell along the corridor and then dividing the sum by its highest impedance value (Figure 6-5) [18].

Table 6-4. Area and impedance of survey nodes

No	Water surface area (ha)	Green surface area (ha)	Impedance
1	5.03	17	2
2	37.41	0	1
3	13.09	0	1
4	5.41	9.2	2
5	44.08	0	1

6	6.47	0	1
7	5.5	3.93	2
8	61.1	36.35	2
9	153.57	135.96	2
10	15.87	0	1
11	4.29	6.76	2
12	15.92	0	1
13	8.86	9.56	2
14	30.25	32.41	2
15	0	11.83	1
16	13.22	3.65	2
17	5.18	6.93	2
18	10.67	6.93	2
19	0	38.44	1
20	8.28	14.49	2
21	1.36	8.7	2
22	566.74	0	1
23	4.36	7.03	2
24	0	19.66	1
25	14.95	0	1
26	10.07	9.46	2
27	0	20.43	1
28	16.57	0	1
29	0	7.46	1
30	5.74	0	1

	A	B	C	D	E	F	G	H	I	J	K	L
1	Corridor	point i	point j	Ni*Nj	Water body *1	build up*5	vegestation*1	Lmax	Lij	Dij	Dij2	Gij
2	12	11.015	37.41	0.41207115	18	110	368	550	936	1.701818182	2.896185124	0.142280667
3	13	11.015	13.09	0.14418635	7	116	325	580	912	1.572413793	2.472485137	0.058316367
4	14	11.015	7.305	0.080464575	8	69	241	345	594	1.72173913	2.964385633	0.027143761
5	15	11.015	44.08	0.4855412	21	135	298	675	994	1.472592593	2.168528944	0.223903491
6	16	11.015	6.47	0.07126705	8	118	270	590	868	1.471186441	2.164389543	0.03292709
7	17	11.015	4.715	0.051935725	32	128	172	640	844	1.31875	1.739101563	0.029863538
8	18	11.015	48.725	0.536705875	80	209	133	1045	1258	1.203827751	1.449201255	0.370345991
9	19	11.015	144.765	1.594586475	94	154	174	770	1038	1.348051948	1.817244055	0.877475137
10	110	11.015	15.87	0.17480805	88	189	110	945	1143	1.20952381	1.462947846	0.119490282
11	111	11.015	5.525	0.060857875	83	152	140	760	983	1.293421053	1.672938019	0.036377842
12	112	11.015	15.92	0.1753588	83	149	136	745	964	1.293959732	1.674331787	0.104733603
13	113	11.015	9.21	0.10144815	81	89	128	445	654	1.469662921	2.159909102	0.046968713
14	114	11.015	31.33	0.34509995	88	55	129	275	492	1.789090909	3.200846281	0.107815221
15	115	11.015	11.83	0.13030745	22	111	105	555	682	1.228828829	1.510020291	0.086295165
16	116	11.015	8.435	0.092911525	63	83	86	415	564	1.359036145	1.846979242	0.050304585
17	117	11.015	6.055	0.066695825	10	84	91	420	521	1.24047619	1.538781179	0.043343281
18	118	11.015	8.8	0.096932	80	41	113	205	398	1.941463415	3.76928019	0.025716316
19	119	11.015	38.44	0.4234166	75	13	84	84	224	2.666666667	7.111111111	0.059542959
20	120	11.015	11.385	0.125405775	7	61	75	305	387	1.268852459	1.609986563	0.07789243 6
21	121	11.015	5.03	0.05540545	3	50	87	250	340	1.36	1.8496	0.029955369
22	122	11.015	566.74	6.2426411	47	11	67	67	169	2.52238806	6.362441524	0.981170684
23	123	11.015	5.695	0.062730425	8	27	68	135	211	1.562962963	2.442853224	0.025679163
24	124	11.015	19.66	0.2165549	6	49	105	245	356	1.453061224	2.111386922	0.102565237
25	125	11.015	14.95	0.16467425	6	29	135	145	286	1.972413793	3.890416171	0.042328184
26	126	11.015	9.765	0.107561475	7	22	32	110	149	1.354545455	1.834793388	0.058623208
27	127	11.015	20.43	0.22503645	4	18	93	93	187	2.010752688	4.043126373	0.05565902
28	128	11.015	16.57	0.18251855	10	11	75	75	140	1.866666667	3.484444444	0.052380961
29	129	11.015	7.46	0.0821719	3	18	34	90	127	1.411111111	1.991234568	0.041266811
30	130	11.015	5.74	0.0632261	3	0	98	98	101	1.030612245	1.062161599	0.059525876
31	23	37.41	13.09	0.4896969	12	9	33	45	90	2	4	0.122424225
32	24	37.41	7.305	0.27328005	16	42	120	210	346	1.647619048	2.714648526	0.100668668
33	25	37.41	44.08	1.6490328	3	3	111	111	129	1.162162162	1.350620891	1.220944242
34	26	37.41	6.47	0.2420427	12	18	119	119	221	1.857142857	3.448979592	0.070178061
35	27	37.41	4.715	0.17638815	10	51	140	255	405	1.588235294	2.522491349	0.069926166
36	28	37.41	48.725	1.82280225	19	175	182	875	1076	1.229714286	1.512197224	1.205399812
37	29	37.41	144.765	5.41565865	27	195	222	975	1224	1.255384615	1.575990533	3.436352274

Figure 6-5. Excel file summarizes and calculates impedance for 435 corridors

The gravity model is employed to prioritize 435 corridors located in the city center, into a sustainable network that ensures landscape connectivity, crucial for effective stormwater management. By calculating the interaction value between nodes along the corridors, only those corridors with an interaction value G<0.1 were selected for the final network, resulting in 229 potential corridors out of the original 435 (Figure 6-6).

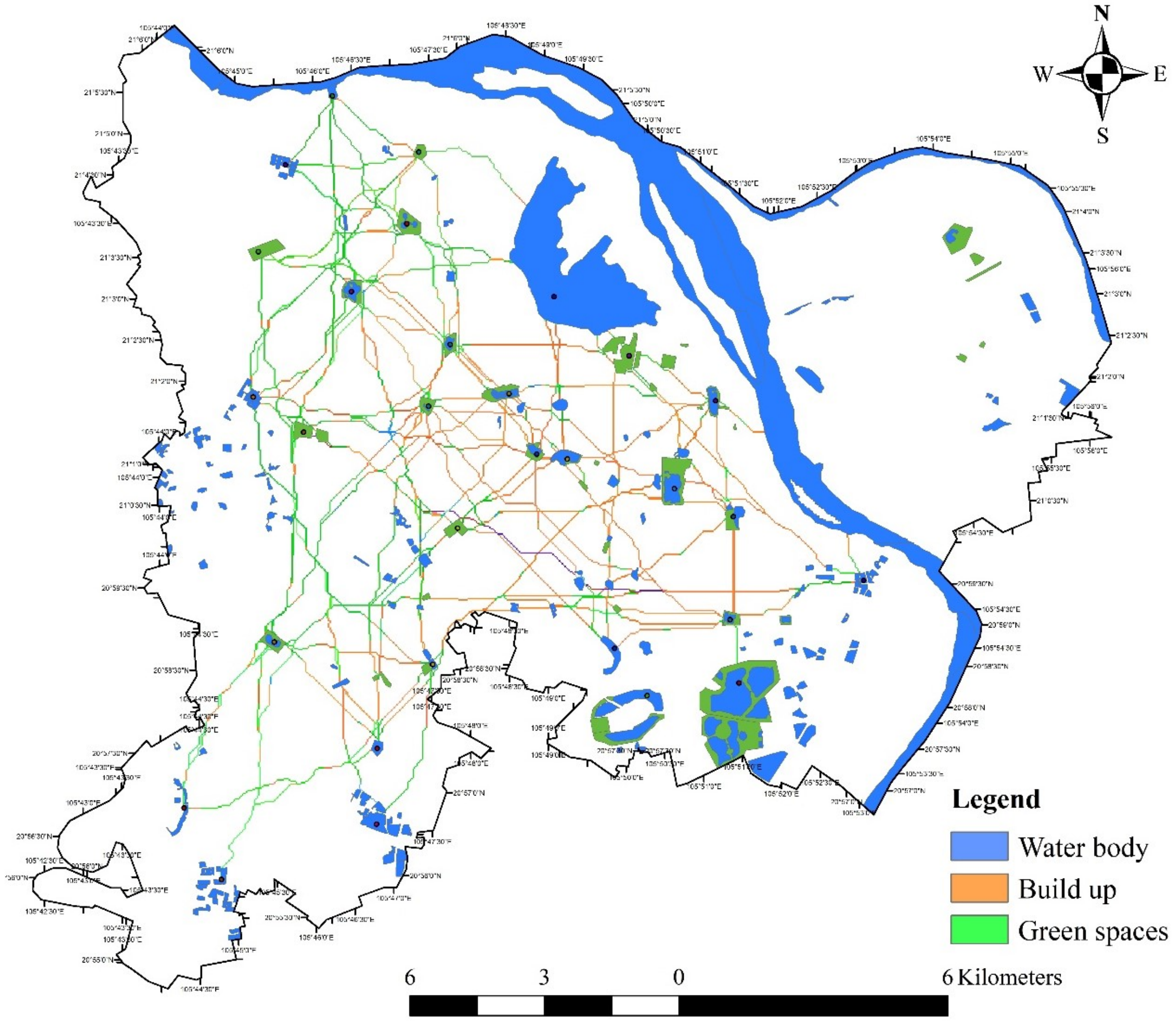

Figure 6-6. Map of BGI corridors after gravity model

A geospatial approach has been developed to supplement the stormwater management system in downtown Hanoi by integrating BGI infrastructure with the existing grey infrastructure. Three steps are applied to provide a suitable approach to identify potential BGI networks. This study has a higher applicability in the context of developing regions with scarce data, especially in Asian countries. The proposed BGI development network aims to improve localized flooding points. The design, combined with the grey system along the road system, helps alleviate the pressure on traditional drainage system design.

The central of Hanoi, with an average elevation ranging from -6 to 31 meters, is considered a flat area. The Red River divides the city into eastern and western parts, and the natural drainage system flows from north to south. This physical characteristic of the study area is exploited in this study by identifying the BGI network to simulate the natural drainage model of the study area. BGI activities such as bioretention, filter strips, permeable pavements, wetlands, and rain gardens require a very gentle slope of less than 5% to function effectively.

6.2.4. BGI design example

Based on the BGI network built above, the author provides an example of an appropriate BGI design orientation (Figure 6-7).

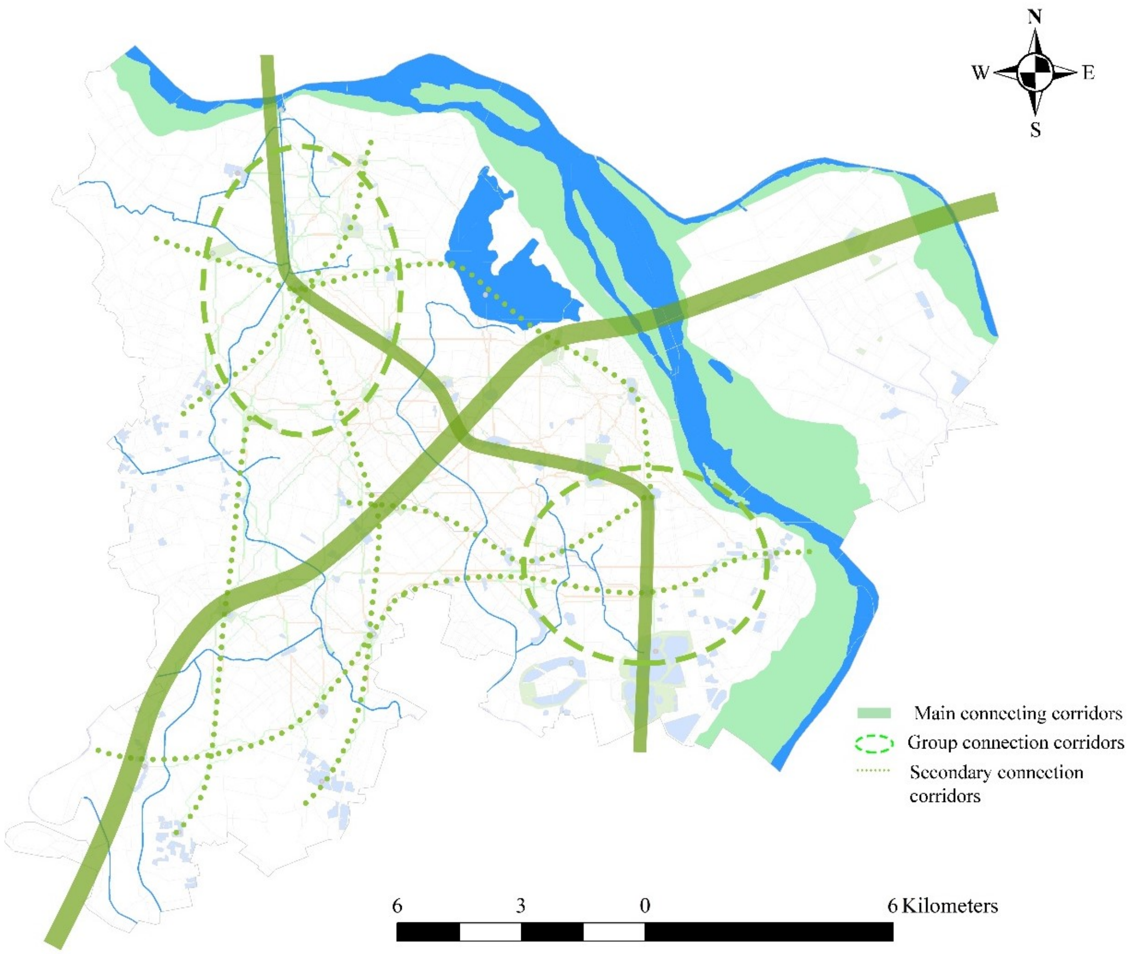

Figure 6-7. Blue – green infrastructure network idea

Most of the flooding points in the center of Hanoi are located at traffic junctions and low-lying areas that have been concreted. Although Hanoi is in a delta region with flat terrain, the rapid urban development process without prior disaster countermeasures has led to this situation. Green spaces and water surfaces in the central areas have gradually shrunk and are difficult to restore. Flooding points appear frequently, and although they do not cause significant damage, they have considerable impacts on the environment.

This Blue-Green Infrastructure framework provides an overall connectivity framework, making it clear where BGI corridors can be formed. Besides regulating water in flooded areas, these corridors can also bring greenery into urban areas, helping to reduce urban heat.

By applying a natural drainage system-centered approach, the development process will aim to maintain and enhance the grey water drainage system in combination with the natural drainage system. The use of the green infrastructure network will ensure the capability to channel water from locally flooded areas to water storage locations, areas in need of water, and allow for sustainable development.

This will enable the utilization of floodwater as a benefit by effectively repurposing it. North-South and East-West connections will be enhanced, and the two groups of nodes will provide opportunities to enhance accessibility and activation.

Focus areas

1) Sustainable Drainage Solutions

2) Portability

3) Accessibility

4) Ecology

5) Effective using

Focus 1: Sustainable Drainage Solutions

A major influence in the design and layout of the BGI network has been understanding flood risk and embracing the existing water resources and blue corridors within the site. The approach is to regenerate existing catchments on the site, preventing any increase in flooding by redirecting surface water and using Sustainable Urban Drainage (SuDs).

Soft Landscaping SUDs Examples (Figure 6-8)

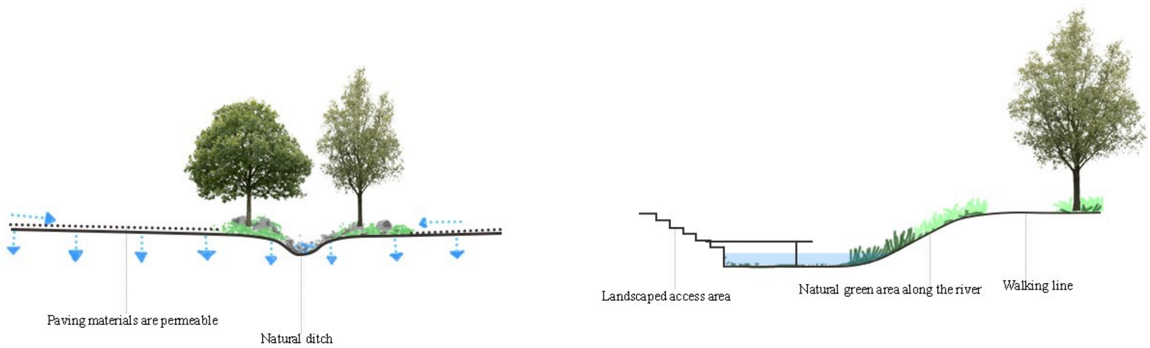

Figure 6-8. Example of sustainable urban drainage along the route

Focus 2: Portability

For an effective BGI network, the portability of the system is crucial. This means that with a BGI network designed to channel surface water from locally flooded areas to green spaces that need water or water retention areas, it is necessary to ensure that the network operates naturally (Figure 6-9). This requires calculating the system's factors such as elevation, slope, and permeability of the area. Besides channeling water, the BGI corridors also serve as water reception and absorption areas, reducing flooding pressure on the corridors.

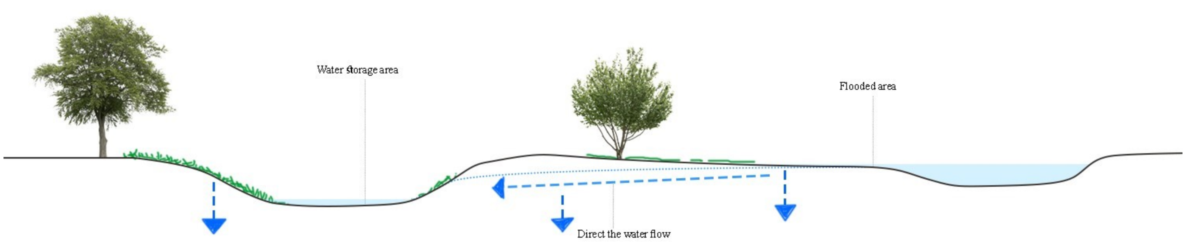

Figure 6-9. Example of the portability in BGI

Focus 3: Accessibility

The Blue-Green Infrastructure (BGI) network proposes new connections and upgraded routes to enhance connectivity and improve access quality across the entire area. These BGI routes link public spaces, serving as connections between residential areas and open green spaces. This approach encourages increased engagement with nature and fosters environmental stewardship among residents.

Focus 4: Ecology

The ecological strategy emphasizes retaining existing habitats and achieving biodiversity gains. This involves creating ecologically valuable, diverse, and connected habitats. Currently, surface water bodies like lakes and rivers in central Hanoi are polluted. Restoring these ecosystems will transform them into environmental access points for residents and ensure the sustainability of the BGI network. Designing parks, gathering areas, and water retention zones must consider ecological factors to enhance and purify surface water through natural filtration. Additionally, ecological considerations should align with local climate and weather conditions.

Focus 5: Effective Use

The BGI network integrates green spaces (parks, gardens, natural landscapes) and blue spaces (rivers, lakes, wetlands) into a cohesive system. This network facilitates natural water movement and absorption, reduces flood risks, and delivers multiple environmental, social, and economic benefits.

While traditional greywater drainage systems collect and dispose of water to prevent flooding, the BGI network promotes the efficient use of surface water. BGI corridors not only convey water but also absorb it, creating green environments within the landscape. Water retention features, such as park lakes, are designed for natural water filtration, supporting recreational activities, flower gardens, and green spaces.

Figure 6-10 illustrates the process of cleaning and utilizing circulating water. Surface water is brought to parks, treated, and utilized for various park activities, offering numerous benefits.

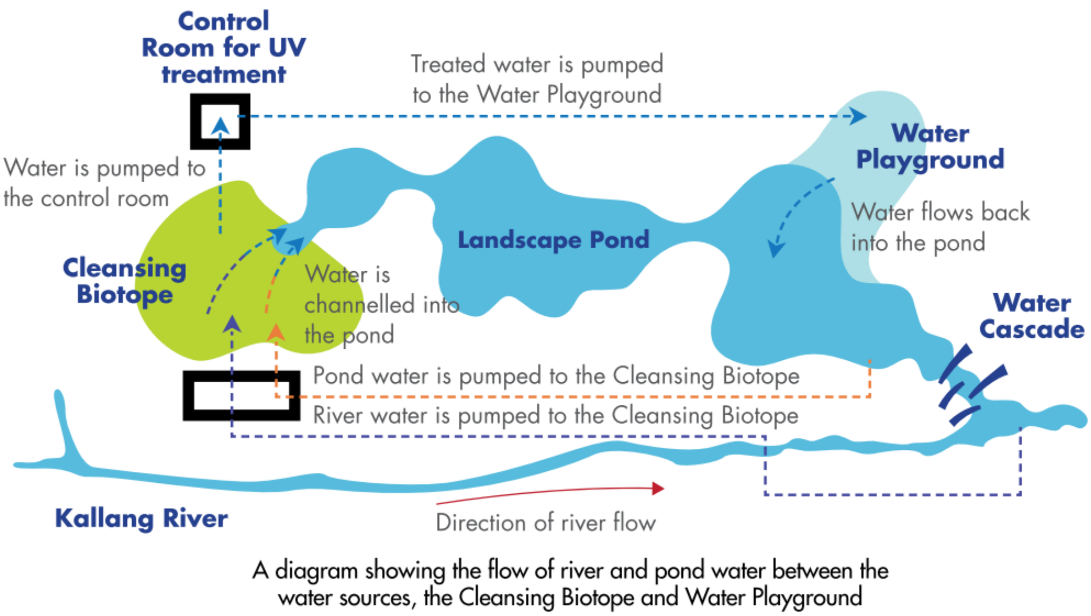

Figure 6-10. Using circulating water in Bishan Ang Mo Kio Park, Singapore

Figures 6-11 present a case study of two typical BGI routes for the central area of Hanoi. These two routes connect open spaces along the East-West and North-South axes of the central area. Based on the previously calculated corridors, the design orientation for the corridors is divided into four tasks:

1, Corridor along the river

In this area, it is necessary to renovate the riverbank areas, prioritizing the natural riverbanks and vegetation. Expanding the riverbank access areas for residents is crucial.

The central area of Hanoi has two main rivers: the Nhue River and the To Lich River. However, these two rivers are currently heavily polluted due to becoming the main receivers of domestic wastewater. Additionally, most of the riverbanks have been concreted, creating a barrier between the rivers and urban residents. Integrating BGI with these rivers requires addressing river issues, prioritizing natural development, and promoting the connection between the rivers and the people.

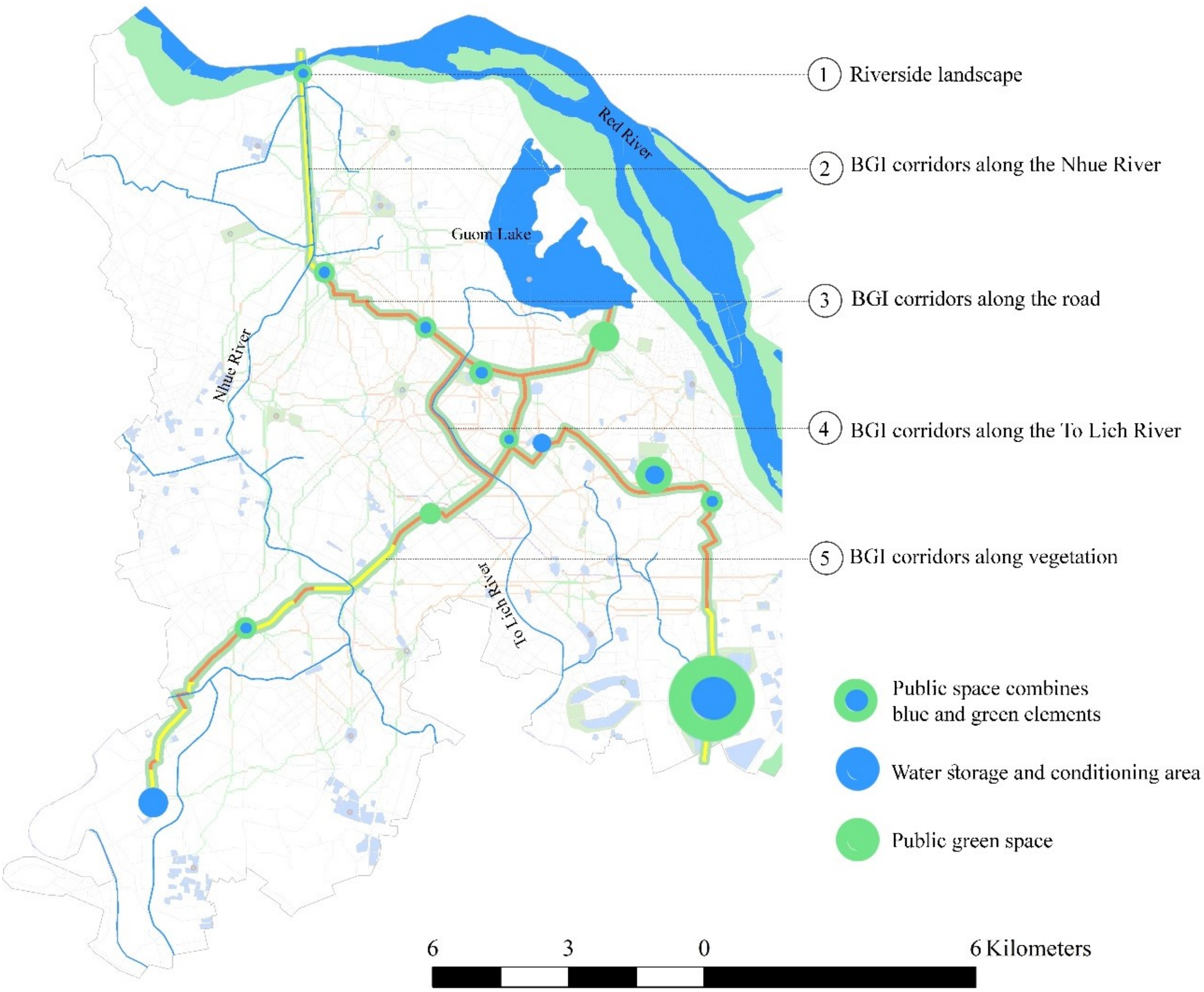

Figure 6-11. Orientation for development of BGI route

2, Corridor along the road

Most of the central area of Hanoi is concrete, and the population density is high. Due to the scarcity of land for developing BGI, the study considers streets as one of the suitable options for building BGI routes. With traditional street design, the land allocated for streets is often used for decorative green spaces or shade trees. However, in many streets in the central area, these green spaces are often encroached upon or not truly beneficial for the environment, and many streets lack green spaces (Figure 6-12).

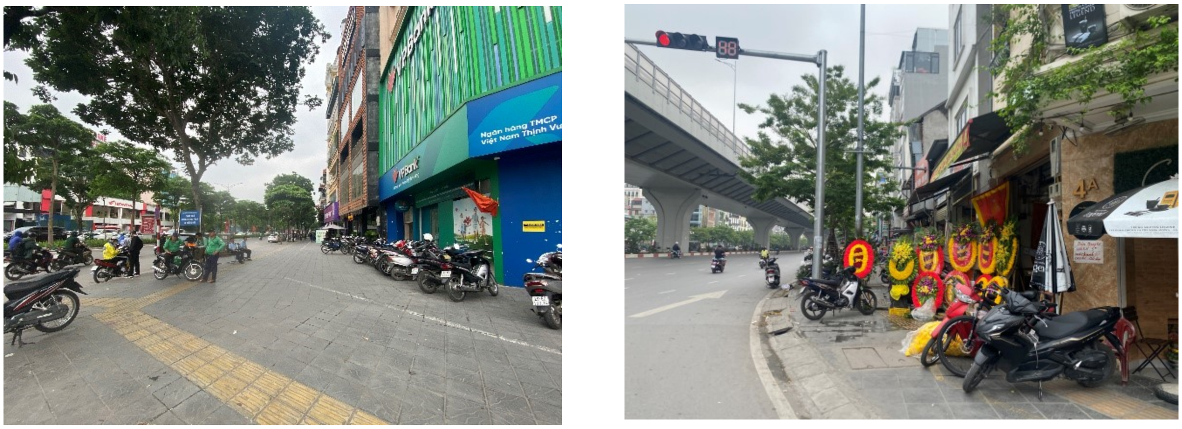

Figure 6-12. Status of Nguyen Khanh Toan and Minh Khai streets

In addition, there are some streets that already have green corridors along them, but these primarily serve a landscaping purpose. (Figure 6-13)

Figure 6-13. Status some streets in Cau Giay district

Therefore, the priority choice for designing BGI routes combined with streets is to supplement sustainable drainage systems to support the underground greywater system (Figure 6-14)

Combining BGI with streets also helps reduce urban heat and mitigates noise and pollution from traffic.

3, Corridor in the vegetation area

For vegetation areas, it is important to utilize these spaces rationally. Utilize the landscape to create new blue-green points. Expand natural design approaches to create water retention areas. Additionally, surface water can be used for irrigation or to create green landscapes.

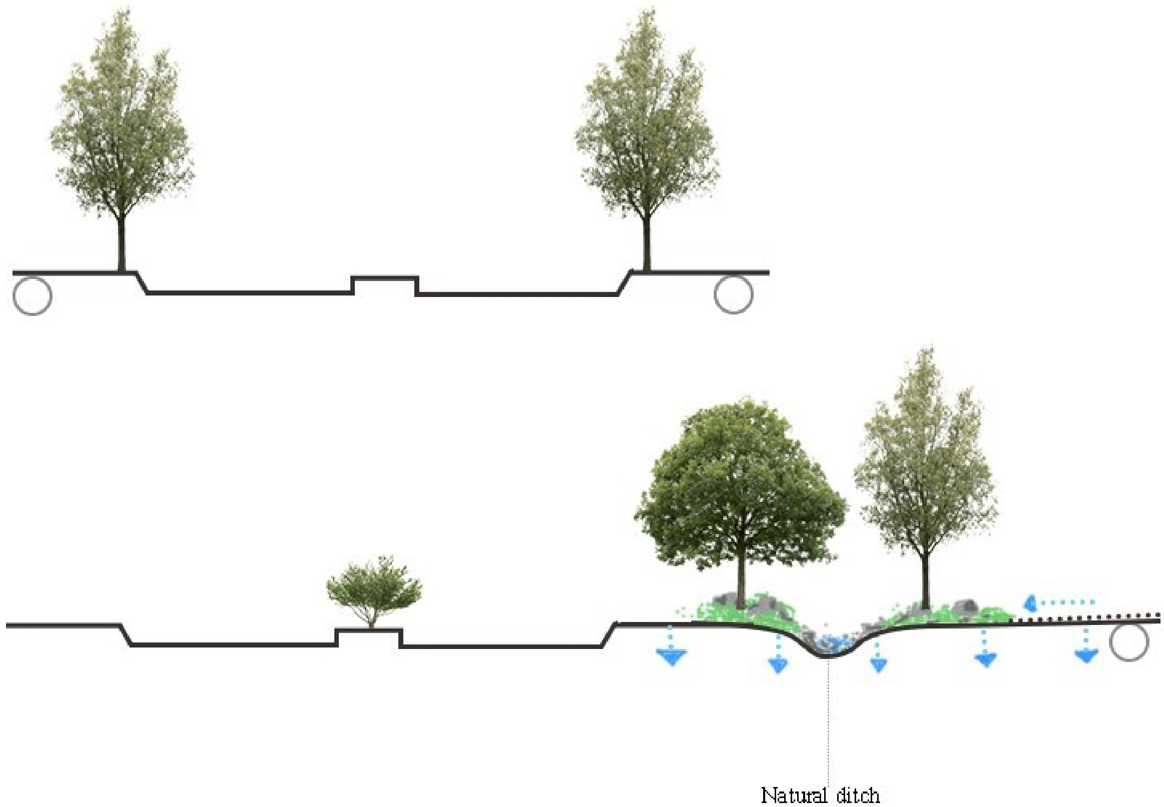

Figure 6-14. Example of design combining BGI and street

4, Point space

In the central area of Hanoi, the main features are green parks and artificial lakes, with some lakes heavily concreted. To develop these points into BGI features, efforts should focus on restoring the natural landscape of these areas. There needs to be a harmonious transformation between water bodies and natural vegetation spaces. Combine recreational areas for residents by utilizing surface water. These points will become passive water retention areas, creating a diverse ecological environment.

6.3. Summary

The geographic approach proposed for identifying BGI networks demonstrates a practical, easily implementable approach with openly accessible datasets. The landscape conservation approach promotes the concept of green-blue infrastructure on a grey background for sensitive urban design and planning with water in Hanoi.

Five spatial factors influencing suitability for BGI were utilized, including Slope Degree, Drainage Density, Land cover, Hydrologic Soil Group, and Proximity to Roads, to generate a map assessing suitability for BGI. In the BGI suitability map, the majority of the study area falls within the moderately suitable category, at 53%, with a high suitability rating covering 39%. This indicates that the potential for constructing BGI in central Hanoi is significant.

The locations most appropriate for the implementation of BGI within the city of Hanoi central have been determined with Suitability Analysis by integrating five identified criteria in GIS environment. Further analysis identified critical core habitat patches for stormwater management and modeled a network of green and blue spaces using the suitability map as base reference map. The resulting blue-green infra- structure corridors may reduce the water logging conditions and enhance the groundwater potential in the study region.

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Chapter 7

CONCLUSION AND PROSPECT

7.1. Summary of Findings

This study delved into urban flood risk in Hanoi, Vietnam, and explored the viability of Blue-Green Infrastructure (BGI) as a sustainable approach to mitigate these risks. Through a meticulous analysis of the city's flood dynamics, infrastructure, and environmental attributes, several critical insights were gleaned.

Firstly, the investigation generated flood susceptibility maps by examining diverse factors such as land cover, soil type, slope degree, and proximity to water bodies and roads. Results indicated varying degrees of flood susceptibility across different areas, with certain locales exhibiting heightened vulnerability due to their geographical characteristics. While Hanoi does not face severe susceptibility to catastrophic flooding, it is notably prone to moderate flooding across a significant portion of its landscape, with approximately 65% of the city exhibiting moderate flood susceptibility. Particularly, the central and southern districts, characterized by lower elevations, face higher flood risks compared to northern regions, with suburban agricultural areas also demonstrating considerable susceptibility. Areas with high drainage density were identified as particularly vulnerable.

Land use and proximity to roads emerged as pivotal factors influencing urban flooding. Despite the model's robust performance, localized flood points in the city center often reside within areas classified as moderately susceptible to flooding rather than highly susceptible. These localized inundation spots are typically situated at major traffic intersections or within densely populated residential zones, attributable to rapid urbanization, insufficient drainage systems, and extensive urban concrete.

Secondly, flood risk was assessed by considering flood hazard, vulnerability, and exposure factors. Through comprehensive analysis integrating natural, demographic, and socio-economic data, various areas with distinct flood risk levels were identified. A significant portion of the city (approximately 67%) falls within the category of moderate flood risk. Central urban districts face higher flood risks compared to other areas. Population density, poverty rates, and flood occurrence probabilities emerged as crucial factors contributing to flood risk, providing valuable insights for urban planning and disaster management efforts.

Lastly, BGI suitability maps and networks were developed to pinpoint suitable locations and designs for BGI interventions in Hanoi. By integrating spatial factors such as slope degree, drainage density, land cover, soil type, and proximity to roads, areas with high potential for BGI implementation were identified. Results indicated a substantial area suitable for BGI development in Hanoi, with 39% of the land exhibiting high suitability and 53% demonstrating moderate suitability. These findings offer valuable insights for policymakers and urban planners to optimize land use and enhance urban resilience to flooding, thereby improving the overall urban environment.

With the specific nature of floods in Hanoi's urban center, constructing even a large BGI project is difficult. Therefore, the BGI network model is chosen to connect open spaces and create a surface water regulation network. The BGI network is the result of connecting 38 green space and water surface points in the inner-city area of Hanoi, based on their suitability for BGI. A total of 463 potential corridors have been formed. In the inner-city area, a gravity model is used to select the most suitable corridors based on land use surfaces.

The available land in the central area is very limited for construction, and the utilization of land according to the traffic network is highly valued in this area. The author has provided an example of the design of this BGI corridor.

7.2. Prospects

Looking ahead, several prospects for further research and implementation based on the study's findings emerge. Firstly, continued monitoring and assessment of flood susceptibility and risk are imperative to adapt to evolving environmental conditions and urban development dynamics. This entails incorporating new data sources and advanced modeling techniques to enhance the accuracy and reliability of flood risk assessments.

Furthermore, prioritizing the development and expansion of BGI networks is essential to mitigate the impacts of flooding and enhance urban recovery capabilities. Future research could focus on optimizing BGI designs and integrating nature-based solutions to maximize their effectiveness in flood prevention and water management and can be extended to larger areas.

Moreover, stakeholder engagement and community involvement are paramount for successful and sustainable BGI implementation. Collaborative efforts between government agencies, academic institutions, and local communities can facilitate the adoption of BGI strategies and raise awareness of flood risk mitigation measures.

Overall, this study lays the groundwork for informed decision-making and proactive measures to address flood risks in Hanoi. By integrating scientific analysis with practical solutions, we can build a more resilient and sustainable urban environment for current and future generations.

Limitations

Data Availability and Quality: The accuracy and comprehensiveness of the flood susceptibility and risk maps depend heavily on the quality of available data. In areas with limited or outdated data, the analysis might not fully capture the current flood dynamics.

Limited Consideration of Climate Change: While the study assesses current flood risks, it may not fully account for future changes in flood patterns due to climate change, which could alter precipitation patterns, sea levels, and flood frequencies.

Urbanization Factors: Rapid urbanization and changes in land use can quickly render the results outdated. The study may not fully capture the dynamic nature of urban development and its impact on flood risk.

Model Limitations: The use of spatial multicriteria decision analysis techniques, while robust, may not encompass all variables affecting flood risk. Certain local factors and nuanced environmental interactions might be oversimplified.

Implementation Challenges: While the study identifies suitable areas for BGI, actual implementation might face practical challenges such as land ownership issues, funding constraints, and public acceptance.

Interdisciplinary Integration: The study might not fully integrate interdisciplinary approaches, including social, economic, and political factors that influence flood risk management and BGI implementation.