



Faculty of Architecture

Department of Urban Architecture and Waterscapes

Doctoral Dissertation

**Planning Nature-Based Solutions for Urban Flood
Resiliency in European Cities through Integrating Spatial,
Technical and Social Aspects**

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Abstract

Climate change is increasing and causing more adverse effects. One consequence is the rising flood risk in cities. This is particularly noticeable in European cities due to their high concentration of populations and infrastructure. Conventional hard engineering solutions and grey infrastructure, though effective in controlling and mitigating risks, are often costly, inflexible, and may cause environmental harm in the long run. As climate change impacts intensify and become more unpredictable, flexible approaches are essential. Recently, nature-based solutions (NbS) have gained much attention. In line with resilience theory, NbS aim not only to control and mitigate but also to adapt while providing co-benefits beyond reducing flood risk. This PhD dissertation is based on six publications focused on this research problem, with the goal of developing an integrated conceptual framework for planning NbS in European cities for flood resilience. The research narrative begins with a review paper (paper I) on the urban flood risk mitigation model (UFRM) of the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) software suite. This publication identified current research gaps and trends and posed questions that subsequent papers address. The next paper (paper II) examined physical properties of urban form that affect flood risk and how their interplay influences runoff accumulation. Building on this hydrological understanding, the third study (paper III) integrates the InVEST model with a multi-objective genetic algorithm to identify near-optimal locations and configurations of NbS while considering multiple planning objectives and spatial constraints. Subsequent studies (papers IV, V, VI) extend the analysis to the social dimension of urban resilience by examining NbS distribution in relation to socioeconomic conditions, social vulnerability, environmental quality, accessibility, and spatial quality. Across seven European cities, the research combines geospatial analysis, hydrological modeling, optimization, socioeconomic assessment, and accessibility analysis. The findings show that effective NbS planning depends on the interaction of spatial, technical, and social conditions and cannot rely on hydrological performance or spatial availability alone. The thesis thus contributes an integrated conceptual decision-support framework for more context-sensitive, effective, and socially equitable NbS planning in European cities.

Keywords:

Nature-based solutions; Urban flooding; Urban planning; Decision support; Social vulnerability; Environmental justice; Distributive justice

Publications Forming the Basis of the PhD Thesis

The publications are presented in the sequence in which they contribute to the scientific narrative of the dissertation.

Number	Authors, Publication Title, DOI	Journal	Year Published	Ministerial Points
I	Anahita Azadgar, Lucyna Nyka, Stefano Salata <i>Advancing Urban Flood Resilience: A Systematic Review of Urban Flood Risk Mitigation Model, Research Trends, and Future Directions</i> doi.org/10.3390/land13122138	Land	2024	70
II	Anahita Azadgar, Andrea Benedini, Stefano Salata, Peter Lacoere, Joanna Badach, Lucyna Nyka <i>Flood-sensitive land take (FSL) analysis: A new way to read how urban sealing shapes flood risk</i> doi.org/10.1016/j.jenvman.2026.129513	Journal of Environmental Management	2026	200
III	Anahita Azadgar, Artur Gańcza, Sina Razzaghi Asl, Stefano Salata, Lucyna Nyka <i>Optimizing nature-based solutions for urban flood risk mitigation: A multi-objective genetic algorithm approach in Gdańsk, Poland</i> doi.org/10.1016/j.scitotenv.2024.178303	Science of The Total Environment	2025	200
IV	Anahita Azadgar, Giulia Luciani, Lucyna Nyka <i>Spatial allocation of nature-based solutions in the form of public green infrastructure in relation to the socio-economic district profile—a GIS-based comparative study of Gdańsk and Rome</i> doi.org/10.1016/j.landusepol.2024.107454	Land Use Policy	2025	140
V	Sina Razzaghi Asl, Anahita Azadgar, Lucyna Nyka <i>Green privilege? Exploring the spatial relations between nature-based solutions and social vulnerability in Nordic cities</i> doi.org/10.1080/13549839.2026.2639069	Local Environment	2026	100
VI	Anahita Azadgar, Marichela Sepe, Artur Gańcza, Piotr Lorens, Giulia Luciani, Lucyna Nyka <i>Integrating AI and spatial analysis for resilient and inclusive 15-minute cities: A case study of Gdańsk</i> doi.org/10.1016/j.cities.2026.107011	Cities	2026	100

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List of abbreviations

Abbreviation	Full version
EbA	Ecosystem-based Adaptation
ES	Ecosystem Services
FSL	Flood-Sensitive Land Take
GI	Green Infrastructure
GIS	Geographic Information System
GSVI	Google Street View imagery
HEC-HMS	Hydrologic Engineering Center-Hydrologic Modelling System
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
IUCN	International Union for Conservation of Nature
LID	Low Impact Development
LISA	Local Indicators of Spatial Association
LUC	Land Use Change
LULC	Land Use and Land Cover
NbS	Nature-based Solutions
NbSI	Nature-based Solutions Index
NDVI	Normalized Difference Vegetation Index
NWASI	Normalized Water Accumulation Sensitivity Index
PCA	Principal Component Analysis
PNbS	Publicly Accessible Nature-based Solutions
SoVI	Social Vulnerability Index framework developed by Cutter et al. (2003)
SUDS	Sustainable Urban Drainage Systems
SVI	Social Vulnerability Index
SWMM	Storm Water Management Model
UFRM	Urban Flood Risk Mitigation
WASI	Water Accumulation Sensitivity Index
WSUD	Water-Sensitive Urban Design
FMC	15-Minute City

Glossary

Term	Definition	Source
Nature-based Solutions (NbS)	Actions that protect, manage sustainably, or restore natural and modified ecosystems to address societal challenges. These actions also benefit human well-being, biodiversity, and ecosystem functioning.	(IUCN, International Union for Conservation of Nature, 2020)
Ecosystem-based Adaptation (EbA)	Utilizing biodiversity and ecosystem services as part of a broader adaptation strategy to help people adapt to the negative impacts of climate change.	(Lo, 2016)
Green Infrastructure (GI)	It is defined as network of natural and semi-natural areas strategically designed and managed to provide a broad range of ecosystem services and improve human wellbeing.	(Chatzimontor et al., 2020)
Low Impact Development (LID)	Low impact development (LID) refers to an urban stormwater management approach that uses engineered solutions intended to replicate the natural water cycle.	(Castro et al., 2025)
Sustainable Urban Drainage Systems (SUDS)	Decentralized stormwater-management practices to mimic natural drainage processes and manage runoff through processes such as infiltration and storage.	(Yang and Chui, 2021)
Water-Sensitive Urban Design (WSUD)	An integrated approach to urban water management that combines stormwater management, water conservation and reuse, water-quality management, and urban ecology within urban design.	(Donofrio et al., 2009)
Social Vulnerability	The susceptibility or pre-existing conditions of communities that increase their potential to experience harm when exposed to hazards.	(Rabiei-Dastjerdi et al., 2025)
Flood Resilience	Flood resilience is described as the capacity of a system to resist flooding, absorb shocks, recover, transform, and adapt to changing conditions.	(Takin et al., 2023)
Flood Susceptibility	The tendency of an area to experience flooding based on its physical characteristics.	(Bentivoglio et al., 2022)
Ecosystem Services (EA)	The benefits that people obtain from ecosystems. They are broadly categorized into provisioning, regulating, cultural, and supporting services.	(Nicholson et al., 2009)
Land Use and land cover (LULC) Change Analysis	The analysis of spatiotemporal changes in land use and land cover to identify their patterns, trends, drivers, and potential future development patterns.	(Setiawan et al., 2024)

1. Introduction

1.1 Background and motivation

Climate change is an ongoing and intensifying phenomenon with its effects becoming increasingly pronounced each year. One consequence is the growing frequency and severity of extreme weather events, including short-duration, high-intensity rainfall. Such events may not substantially affect annual average precipitation, but their brief duration and high intensity can generate substantial runoff and increase the likelihood of flooding (Huo et al., 2021; IPCC, 2023). This problem has grown concerning particularly in urban areas where the combination of continued expansion and increasing population density can further increase flood risk (Hamers et al., 2023). The consequences are already evident across Europe. Between 2000 and 2015, more than 2,000 flood events were recorded which caused approximately €48 billion in damage, particularly from 2006 to 2015, with countries including Poland and Norway among those frequently affected (Nones and Guo, 2023). This particular exposure of European cities to flood risk can be attributed to their dense populations, extensive built-up surfaces, and high concentrations of infrastructure and economic assets (Barquet et al., 2024; Othmer et al., 2020).

Traditionally, flood risk management in cities has relied on grey infrastructure, such as dams and hard embankments around water bodies (Cea and Costabile, 2022) and while these approaches have been effective in the past, they are often expensive, unsustainable, and may cause extra environmental problems (Pudar et al., 2020; Seidu et al., 2025). For instance, hard embankments can disconnect floodplains from river flows which can alter water and soil conditions and also influence floodplain ecosystems (Lechowska, 2017). More importantly, however, conventional flood management approaches have historically been grounded in engineering paradigms that are centered on stability, control, and risk reduction. Such approaches performed relatively well under more stable climatic conditions. However, increasing climate uncertainty and the growing frequency of extreme weather events have exposed the limitations of relying solely on rigid mitigation-oriented infrastructure (Milly et al., 2008; Sørensen et al., 2016). As a result, urban flood management increasingly requires adaptive, resilience-oriented approaches. These types of approaches can be capable of responding to dynamic environmental conditions. This is something that conventional grey infrastructure often struggles to deliver.

Moreover, it is important to recognize that cities are complex entities shaped by the interaction of ecological, social, spatial, hydrological, and infrastructural systems. As a result, addressing urban flooding solely through technical and engineering-based approaches may not be fully compatible with the multidimensional nature of urban environments. In response to these limitations, resilience theory and socio-ecological systems thinking have increasingly influenced urban climate adaptation research with early resilience theory, developed by Holling (1973), distinguishing resilience from conventional notions of stability and balance. This approach emphasized the adaptive capacity of systems to absorb disturbances and reorganize in the face of changing conditions. Within this perspective, cities are increasingly understood not merely as

technical or engineered systems, but as interconnected socio-ecological systems shaped by interactions between hydrological, ecological, spatial, and social processes.

It is important to distinguish resilience from concepts such as stability and sustainability. Conventional engineering approaches often emphasize control, predictability, and the maintenance of stable conditions while on the other hand, resilience is more closely associated with flexibility, adaptation, and the capacity to respond to changes. Holling (1973) conceptualized resilience as the capacity of a system to absorb disturbance and reorganize while continuing to maintain its essential functions and building on this perspective, socio-ecological systems should not be understood as stationary systems that simply return to a fixed equilibrium after disturbance but instead, in accordance with the adaptive-cycle perspective, they should be analyzed as systems that move through phases of growth, conservation, release, and reorganization. This notion highlights the importance of change, renewal, and adaptation over time (Gunderson and Holling, 2002).

This understanding provides an important basis for considering nature-based solutions (NbS) within urban resilience. Urban systems are complex and continuously changing, therefore approaches based solely on rigid control may have limited capacity to accommodate changing climatic, hydrological, and spatial conditions. NbS, by contrast, work through ecological processes such as infiltration, retention, evapotranspiration, and vegetation-based water regulation. By making use of these processes rather than relying exclusively on engineered control, NbS can contribute to the capacity of urban socio-ecological systems to absorb disturbances and adapt to changing conditions which consequently makes their relevance to resilience lie not only in being environmentally beneficial or multifunctional, but also in their potential to work with the adaptive capacities of socio-ecological systems (Zhou et al., 2024).

NbS are increasingly recognized as promising and adaptable strategies for addressing urban flood risk. They offer multifunctional and multi-beneficial approaches, providing a range of co-benefits beyond flood mitigation (Kabisch et al., 2022; Pancewicz et al., 2023). These benefits fall into three main categories: social, economic, and environmental. Socially, NbS foster communities, boost mental and physical health, enhance recreation and aesthetics in urban spaces. They are also reported to support cultural and educational values (Kabisch et al., 2016; Nesshöver et al., 2017; Raymond et al., 2017). Economically, they are often more cost-efficient than grey infrastructure and have lower maintenance costs. They may increase property values, create green jobs, create local opportunities, and deliver ecosystem services (EA) with economic value (Boyle and Kuhl, 2021; Mutlu et al., 2023; Radfar et al., 2024; Raymond et al., 2017). For the environmental benefits, they can enhance biodiversity and habitat restoration, improve water quality and natural filtration. They can also support climate change mitigation through carbon sequestration. Moreover they can contribute positively to climate adaptation by reducing flood risk and erosion, improving air quality, and decreasing the urban heat island effect (Ghaedi et al., 2026; Rey et al., 2026; Zhou et al., 2024).

Despite the growing interest in NbS, multiple obstacles and research gaps remain. From a social perspective, inclusiveness and environmental justice remain important challenges in NbS planning, particularly regarding the equitable distribution of benefits across urban populations (Kabisch et al., 2022). In addition, existing tools and frameworks are largely focused on risk assessment rather than on supporting decision-making for selecting and prioritizing NbS alternatives (Gallois et al., 2026a; Gonzalez-Ollauri et al., 2023; Sedighkia et al., 2026). This limits planners' ability to evaluate trade-offs among environmental, social, and economic criteria. Furthermore, there is still a limited understanding of how urban form and land-use dynamics affect the effectiveness of NbS, notably in complex urban contexts (Marzio et al., 2026). These gaps point to the need for more integrated and holistic approaches capable of linking hydrological performance, land-use dynamics, spatial planning, and socioeconomic considerations within NbS planning and implementation. Figure 1 illustrates the main research problem outlined in the above.

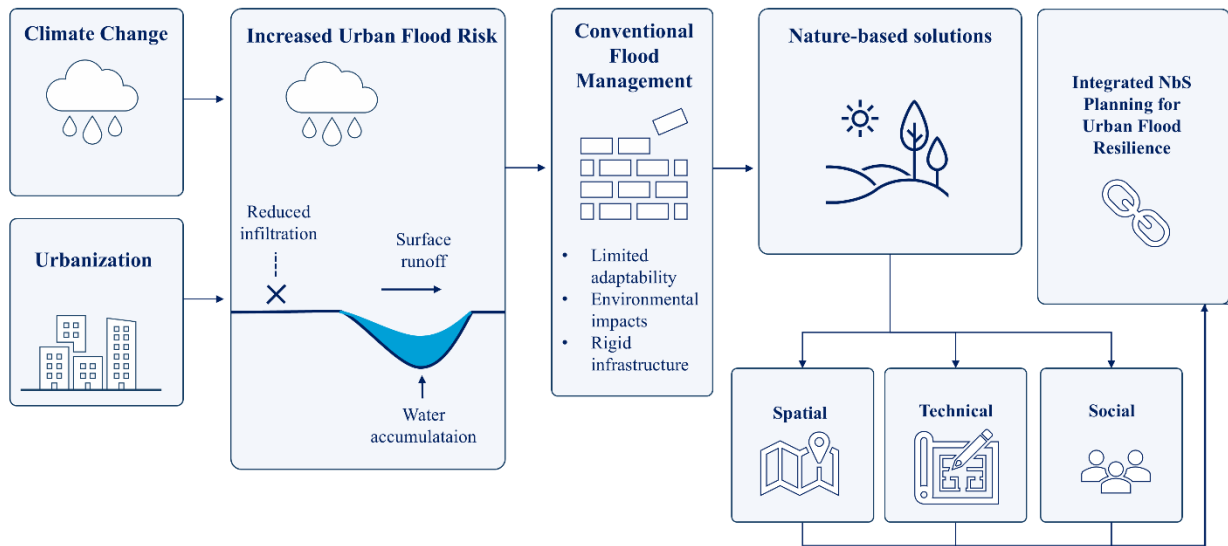


Figure 1. Conceptual overview of the drivers of urban flood risk and the need for integrated NbS planning.
Source: Author's own illustration

In response to the identified research gaps and the increasing risks posed by climate change in Europe, particularly urban flooding, there is a need for a more comprehensive understanding of nature-based solutions for reducing flood risk in European cities. This research addresses this limitation by adopting an interdisciplinary approach that combines insights from spatial, technical, and social perspectives. Rather than relying on a single analytical lens, the study is structured around multiple complementary investigations that contribute to a broader understanding of NbS. These components, when combined, inform the development of a holistic framework for urban flood risk management. Furthermore, given the context-specific nature of NbS performance, this research incorporates multiple case studies across different European cities. In doing so, the study enhances the transferability and generalizability of the proposed

framework. This ensures that the proposed framework will not be limited to a single context but can also be adapted and applied across a wide range of urban environments.

In this thesis, spatial, technical, and social are the three main analytical dimensions of NbS planning. The spatial dimension covers land-use change, urban form, spatial distribution and allocation, and spatial feasibility. The technical dimension involves hydrological assessment and modeling, runoff and retention performance, flood sensitivity, optimization, and decision-support methods. The social dimension includes socioeconomic conditions, social vulnerability, distributive and environmental justice, accessibility, inclusiveness, and how different groups can access and benefit from NbS. More specific terms like hydrological, socioeconomic, environmental, and planning-related considerations are used throughout the thesis to describe particular aspects within these broader dimensions.

1.2. Research goal

The main goal of this research is to contribute to the development of a comprehensive, multi-dimensional decision-support approach for the planning, prioritization, and implementation of NbS for urban flood resilience in European cities, by integrating spatial, technical, and social considerations.

1.3. Research objectives

To achieve the overall aim of this research, the following objectives were established:

RO1: To critically review existing approaches, tools, and research trends related to NbS and urban flood risk. This is done with a particular focus on the InVEST Urban Flood Risk Mitigation (UFRM) model and its applications.

RO2: To investigate the relationship between land-use change, urban form, and urban flood risk in urban environments.

RO3: To evaluate and optimize the spatial allocation and selection of NbS for managing urban flood risk using decision-support approaches.

RO4: To examine the socioeconomic and environmental justice dimensions of nature-based solutions, including distributive justice, spatial inequality, and social vulnerability.

RO5: To explore how inclusive urban planning concepts can contribute to climate resilience, accessibility, and equitable distribution of NbS.

1.4. Key research questions

The main questions which lead this research are as follows:

RQ1: What tools, approaches and research trends exist in relation to NbS and urban flood risk and what are the strengths and limitations of the InVEST UFRM in this regard?

RQ2: In what ways do land-use change, urban form, and spatial characteristics affect urban flood risk and runoff retention within urban environments?

RQ3: How can spatial analysis and decision-support methodologies facilitate the identification, prioritization, and implementation of nature-based solutions for mitigating urban flooding?

RQ4: What relationships exist between the socioeconomic characteristics of urban environments and the quantity, and quality of NbS within those settings?

RQ5: How can inclusive urban planning principles support the accessible and equitable implementation of NbS for urban flood resilience?

1.5. Research theses

RT1: The flood-mitigation relevance of land-use change in cities is not determined by the extent of urban sealing alone, but by the type of land-use transition, local soil and drainage conditions, and urban morphology. This means that equally-sized land-use conversions can produce noticeably different increases in runoff and water accumulation.

RT2: Spatial planning of NbS in urban areas using digital approaches capable of considering multiple criteria and constraints simultaneously leads to more efficient and effective flood risk reduction in cities.

RT3: Socio-spatial equity in nature-based flood resilience cannot be inferred from the quantity or spatial presence of NbS alone: distributive inequalities in access and ecological quality persist even in cities with strong welfare and environmental governance.

1.6. Research structure

The present PhD thesis is formed into 8 main chapters, starting with Chapter 1, which addresses the research problem, background, motivation, main goal, research objectives, and research questions. Chapter 2 presents a literature review of the relevant research and explores the main theoretical themes, including urban flooding, land-use change, NbS, and socio-economic considerations. Chapter 3 summarizes the methods used in the articles on which this PhD is based, ranging from spatial analysis within geographic information system (GIS) through

technical decision-making support using optimization algorithms, to the examination of links between social vulnerability and NbS quality and quantity using a composite social vulnerability index and cluster analysis. Chapter 4 is the most critical and important part of the current thesis, as it goes through each article individually and summarizes the findings in a way that exhibits the interconnectedness among the articles. Every subchapter in chapter 4 ends with research questions that the article posed, which will be answered by the next paper in the next subchapter. Chapter 5 binds together the findings and implications of the articles and conceptually links them to create a final framework, informed by the research conducted within this paper-based PhD dissertation. Chapters 6, 7, and 8, respectively, present the limitations and suggested future research directions, general conclusions, and a summary. The overall research structure of this PhD dissertation has been summarized visually in figure 2.

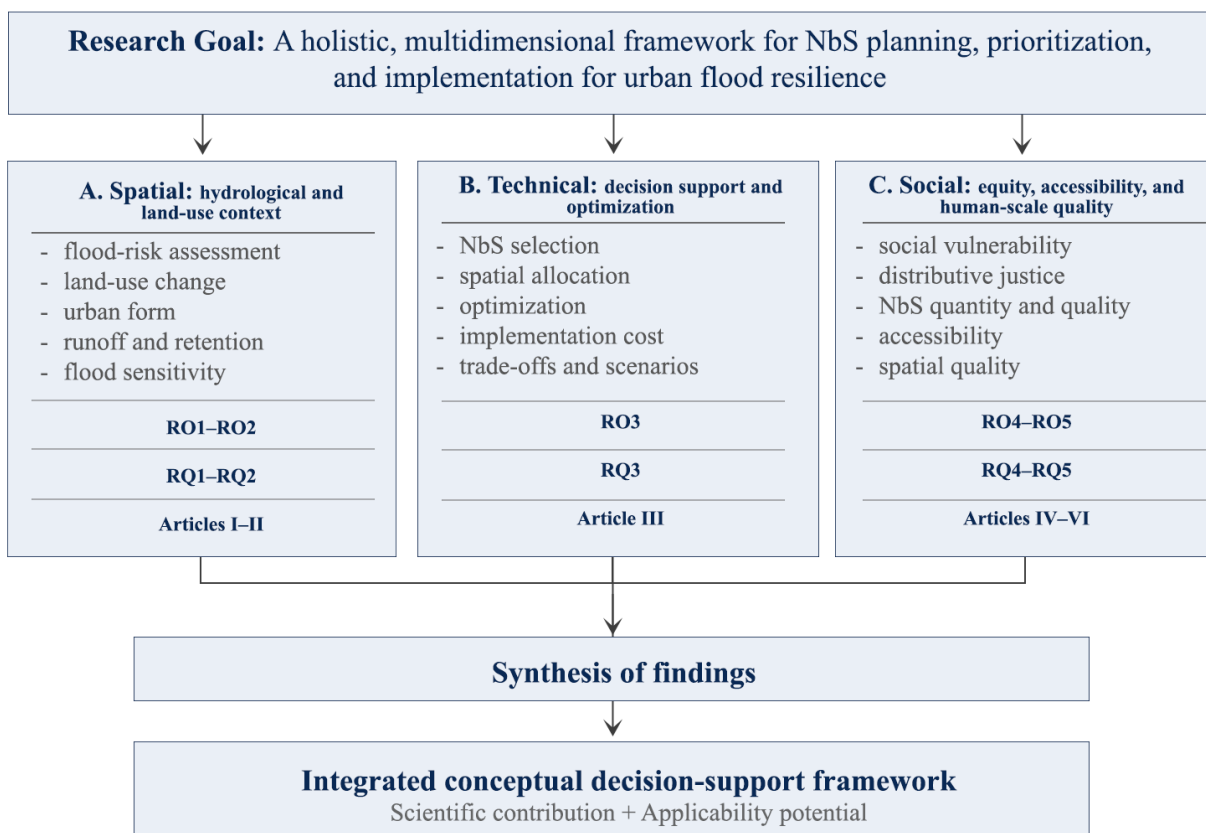


Figure 2. Research architecture of the thesis linking the overall research goal, analytical dimensions, research objectives, research questions, articles, and thesis-level synthesis. Source: Author's own illustration

2. Literature review

This chapter reviews the main theoretical and methodological foundations related to urban flood resilience and NbS, examining how spatial, technical, and social dimensions interact in urban flood mitigation which provides the basis for the dissertation. Accordingly, the chapter starts by outlining the challenges of urban flood risk and how changes in land use and city layouts affect runoff and flood risk. It then looks at the role of NbS in reducing urban flooding and investigates the existing decision-support and optimization methods for planning and implementing NbS. Additionally this chapter also takes into account the social and justice dimensions of NbS, including social vulnerability, fair distribution, and inclusive urban planning. Finally, it ends by pointing out the key research gaps that the subsequent chapters will address.

2.1. Urban flood risk, urbanization, and land use change

Flooding is one of the most damaging of all natural hazards. According to the European Environment Agency, between 1998 and 2002 Europe suffered about 100 serious floods. These floods led to approximately 700 deaths and forced the displacement of almost 500,000 people. In addition, they also caused insured economic losses that went beyond €25 billion (Dankers and Feyen, 2009). In recent decades the problem of urban flooding has worsened as a result of the combined impact of climate change and rapid urbanization. In short, the mechanism that these two components cause increased flooding risk is this: climate change causes greater rainfall intensity, more frequent extreme precipitation events and increased climate variability while urban expansion modifies natural hydrological processes and decreases the capacity of landscapes to hold and infiltrate stormwater (Huong and Pathirana, 2013; Miller and Hutchins, 2017).

Urban flood risk refers to the probability and potential consequences of flooding that occurs within urban environments, including impacts on infrastructure, ecosystems, economic activities, and human well-being (European Parliament and Council, 2007). Urban floods that mostly affect urban environments can be categorized into four major types: fluvial, groundwater, coastal, and pluvial flooding. The first type, Fluvial flooding, occurs when rivers exceed their channel capacity (Abebe et al., 2018). The second type, groundwater flooding, can occur when groundwater levels rise due to increased recharge of aquifers with limited storage capacity, reduced groundwater pumping, or high river levels that raise groundwater levels in connected aquifers. (Abboud et al., 2018). The third type, coastal flooding, is associated with storm surges and sea-level rise in coastal regions and lastly, the fourth type, pluvial flooding, which represents the primary focus of this PhD research, occurs when intense rainfall exceeds the infiltration and drainage capacity of urban environments. This leads to rapid surface runoff accumulation (Abebe et al., 2018). Due to a mix of factors (increasing urbanization, expanding of impervious surfaces, and climate-induced extreme rainfall events), pluvial flooding has become an increasingly

significant component of urban flood risk in cities all over the world (Huang et al., 2020; Rosenzweig et al., 2018).

Urbanization transforms land surfaces by replacing natural and permeable areas with impervious surfaces that may include roads, buildings, parking areas, and other types of sealed infrastructure. These types of surfaces can prevent water infiltration into the soil which will accelerate surface runoff and increase the volume and speed of stormwater flows. Consequently this can cause the urban areas often experience higher flood peaks, reduced infiltration capacity, and greater runoff accumulation during heavy rainfall events (Błaszczak-Bąk et al., 2025; Jamtsho et al., 2025). Land use and land cover (LULC) change is therefore considered one of the main drivers of changing urban flood dynamics in the cities. Land use refers to the human use of land for activities such as residential, industrial, commercial, agricultural, or recreational purposes, while land cover describes the physical materials present on the land surface, including vegetation, soil, water, and built surfaces. LULC change may directly affect the hydrological behavior by altering evapotranspiration, infiltration, interception, and runoff processes (Dumdumaya and Cabrera, 2023; Shukla et al., 2023).

In the context of pluvial flooding, several hydrological processes are particularly important. Surface runoff refers to the portion of rainfall that does not infiltrate into the soil or evaporate, but instead flows across the land surface (Zhang et al., 2025). Surface runoff increases when rainfall intensity exceeds the infiltration capacity of the ground or when surfaces are impermeable, such as in case of asphalt or concrete (Fletcher et al., 2024; He et al., 2024). Infiltration is the process through which water penetrates the soil surface and moves into the ground, thereby reducing the amount of surface water accumulation (Chunilal, 2025). Interception refers to the temporary capture of rainfall by vegetation, especially tree canopies and plant surfaces, before the water reaches the ground (Anys and Weiler, 2024). Evapotranspiration combines evaporation from land and water surfaces with transpiration from plants, both of which contribute to reducing excess surface water (Ghiat et al., 2021). Together, these processes regulate the movement and storage of water within urban environments and strongly influence flood generation and mitigation.

The relationship between vegetation, soil, infiltration, and runoff generation is illustrated in Figure 3. The figure demonstrates how natural systems regulate rainfall through canopy interception, evapotranspiration, infiltration, and delayed runoff processes, whereas impervious urban surfaces accelerate runoff accumulation and reduce water retention capacity.

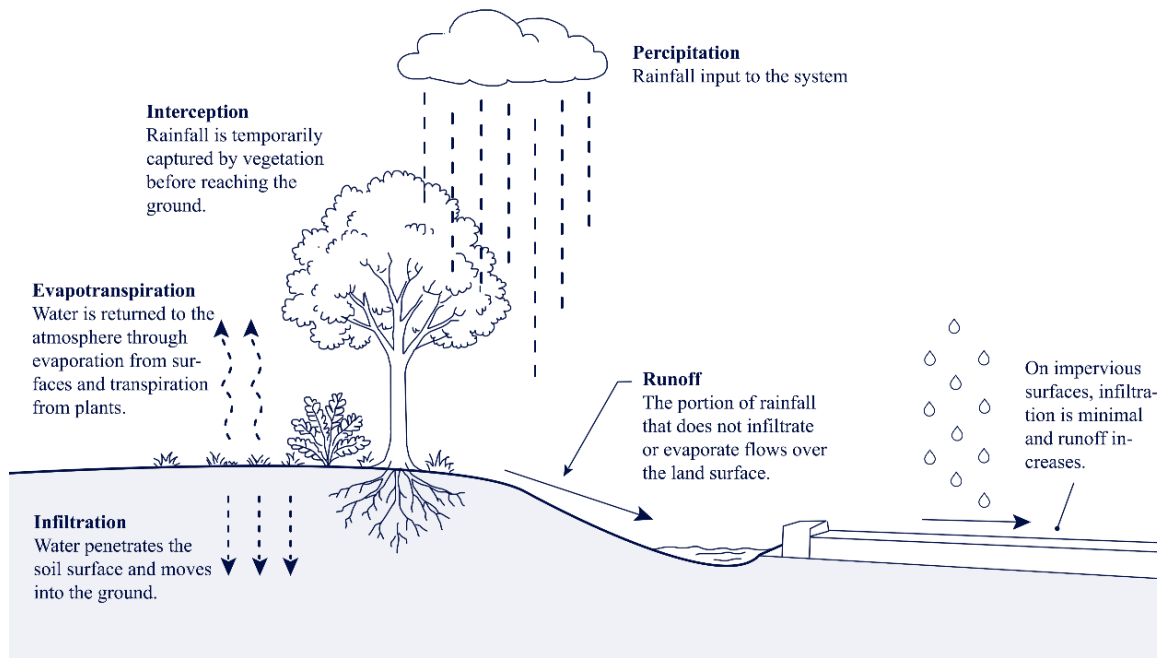


Figure 3. Conceptual illustration depicting the responses of various urban land surfaces to rainfall.
Source: Author's own elaboration based on Fletcher et al. (2024) and Anys and Weiler (2024).

Given the intensification of flood risk and the necessity to understand the effects of urbanization on hydrological processes outlined above, which impact the increase or mitigation of flooding in cities, urban flood risk assessment has become an important research area within urban planning and environmental management. Various approaches have been developed to assess runoff dynamics and identify vulnerable urban areas with GIS-based spatial analysis commonly used to integrate topographic, hydrological, and land use datasets in order to map runoff susceptibility and flood-prone zones (Bishikwabo et al., 2025). Hydrological models such as Storm Water Management Model (SWMM) and Hydrologic Engineering Center-Hydrologic Modelling System (HEC-HMS) simulate rainfall-runoff relationships, stormwater flow, and drainage system responses under different precipitation scenarios (Prakash et al., 2024). Remote sensing techniques using satellite imagery and aerial data enable the monitoring of urban expansion, vegetation cover, impervious surfaces, and flood inundation patterns over large spatial extents (Shastry et al., 2023). In parallel, ecosystem service assessment frameworks evaluate the capacity of vegetation, soils, wetlands, and green infrastructure to regulate water storage, infiltration, and runoff reduction within urban environments (Wübbelmann et al., 2022). At a more detailed level, hydrodynamic models such as Hydrologic Engineering Center River

Analysis System (HEC-RAS) and MIKE FLOOD provide highly accurate simulations of flood depth, velocity, and inundation extent (Silwal et al., 2026).

Although highly detailed hydrodynamic models provide accurate simulations of flood processes, they often require extensive datasets, specialized expertise, and substantial computational resources (Chaudhuri et al., 2021; Fraehr et al., 2024). Consequently, increasing attention has been directed toward developing approaches that balance analytical capability with practical usability in urban planning and flood adaptation contexts (Mahmood et al., 2025).

2.2. Nature-based solutions for urban flood mitigation

NbS have become an important concept in climate adaptation, environmental management, and urban resilience research over the last two decades. The World Bank first introduced this term in 2009, and organizations such as the International Union for Conservation of Nature (IUCN) and the European Commission later further developed it (Marino et al., 2025). While definitions of NbS differ, most emphasize using natural processes and ecosystem functions to address social and environmental problems, thereby providing ecological, social, and economic benefits. The IUCN (2020) defines NbS as “actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits.” The European Commission also describes NbS as solutions inspired and supported by nature that are cost-effective, resource-efficient, and offer environmental, social, and economic benefits (Faivre et al., 2017). Related concepts that overlap with NbS may include green infrastructure (GI), ecosystem-based adaptation (EbA), sustainable urban drainage systems (SUDS), low-impact development (LID), and water-sensitive urban design (WSUD). While these concepts have different backgrounds and scopes, they all emphasize the importance of integrating ecological processes into urban planning and infrastructure (Hamidiaala et al., 2026). Green infrastructure, for example, means carefully planned networks of natural and semi-natural areas that provide ecosystem services and help cities become more resilient (Zahoor et al., 2023). Examples of urban NbS are green roofs, rain gardens, bioswales, urban wetlands, retention ponds, permeable pavements, and urban forests (Battisti et al., 2024).

NbS are now widely recognized as effective ways to reduce urban flooding because they can enhance natural water processes such as rainfall regulation, infiltration, runoff retention, and water storage. Unlike traditional grey infrastructure, which mainly moves stormwater quickly out of cities, NbS aims to slow, store and absorb using natural methods (Koedijk and Schwartz, 2026), for instance Plants and permeable soils help water soak into the ground, while trees and green roofs capture rainwater and reduce runoff. Wetlands, detention basins, and restored floodplains temporarily hold water and reduce flood risk during heavy rain (Kasprzyk et al., 2022).

A 2024 systematic review of 76 NbS case studies found that NbS generally reduce runoff volume and peak flow, and that combinations of measures often outperform single interventions with empirical case studies reporting runoff reductions ranging from 32% to 96% and peak-flow reductions of up to 65,5% when multiple NbS measures were combined (Esraz-UI-Zannat et al., 2024). NbS also generates multiple co-benefits beyond flood regulation. This may include biodiversity enhancement, heatwave mitigation, carbon sequestration, landslide protection, and socio-economic benefits for local populations (González-García et al., 2025). Because of these advantages, NbS are increasingly being promoted in European and international climate adaptation plans as alternatives or additions to traditional grey infrastructure.

Even though empirical evidence shows the positive performance of NbS, it is important to note that their effectiveness depends not only on the individual performance of specific interventions but also on their relationship with surrounding land-use patterns, urban morphology, hydrological conditions, and spatial connectivity. As a result the flood mitigation capacity of NbS is strongly influenced by how they are spatially distributed and integrated within the broader urban fabric (Chen et al., 2023; Esraz-UI-Zannat et al., 2024; Su et al., 2024). In rapidly urbanizing environments, land-use change, surface sealing, and infrastructure expansion reshape urban hydrological dynamics, affecting both flood risk and NbS performance (Zhou et al., 2024), therefore, NbS should be integrated not only within the spatial structure of cities, but also into ordinary planning processes concerned with land-use allocation, site selection, intervention prioritization, and implementation, rather than being treated as isolated site-specific measures (Corgo et al., 2024; Esraz-UI-Zannat et al., 2024). Such integration also depends on coordination within existing planning and institutional arrangements (Hölscher et al., 2023), although governance mechanisms themselves are beyond the analytical scope of this thesis.

Despite the increasing recognition of NbS as effective approaches for urban flood mitigation, several important research gaps and implementation challenges are remaining (Esraz-UI-Zannat et al., 2024; Zhou et al., 2024). With existing research being primarily focused on the hydrological and ecological performance of NbS, while in comparison less attention is being paid to broader spatial, social, and governance dimensions (Zhou et al., 2024). Particularly, there is still limited understanding of how urban form, land-use dynamics, and spatial characteristics influence the effectiveness of NbS within complex urban environments, especially in rapidly urbanizing and waterfront cities (Louarn et al., 2025; Su et al., 2024) and although numerous methods have been developed to assess NbS performance and suitability, guidance for context-specific selection, prioritization, and implementation remains limited. All of these together highlights the need for more integrated decision-support approaches (Gallois et al., 2026b; Kuller et al., 2022; Mrówczyńska et al., 2021). Recent literature also highlights the growing importance of considering accessibility, inclusiveness, social vulnerability, and equitable distribution of NbS benefits within urban planning processes (La Rosa and Pappalardo, 2020; Zhou et al., 2024). These emerging social and spatial dimensions of NbS will be discussed further in the following section.

2.3. Socioeconomic dimensions of nature-based solutions

Although NbS are widely recognized for their environmental and hydrological benefits, recent attention has focused on their social and socioeconomic dimensions. Urban flooding and climate hazards do not affect all populations equally because exposure, sensitivity, and adaptive capacity vary across social groups and neighborhoods and in this context, social vulnerability with it referring to how susceptible individuals or communities to harm from environmental hazards due to socioeconomic factors (such as income, age, education, health, housing quality, employment, and access to resources and services) are, has become important in urban climate adaptation research. refers to how susceptible. Socially vulnerable populations often have lower adaptive capacity and fewer financial, institutional, or social resources to respond to and recover from floods. This makes them disproportionately exposed to climate risks in urban areas (Shehzad et al., 2026). The accessibility and distribution of urban infrastructure can further shape the ability of vulnerable groups to participate in and benefit from urban environments (Ptak-Wojciechowska et al., 2025), therefore, evaluating NbS only through technical indicators like runoff reduction or infiltration capacity is insufficient because their effectiveness also depends on how benefits are distributed among social groups.

These concerns are also closely connected with the general idea of environmental justice. Environmental justice emphasizes fairness tied to distributing environmental benefits and burdens across society. This should be regardless of socioeconomic status, ethnicity, age, or demographic background (Resnik, 2022). within NbS research, it is commonly examined through the lens of distributive justice, which refers to the spatially fair allocation of resources such as green infrastructure, ecosystem services, and climate adaptation benefits among urban populations (Mohtat and Khirfan, 2022). In practice, distributive justice looks at whether all residents have equal opportunities to benefit from green spaces, flood protection measures, recreational areas, and other environmental improvements (Kato-Huerta and Geneletti, 2023).

Yet a number of studies have shown that both NbS and urban green infrastructure are generally unevenly distributed throughout cities, richer neighborhoods usually getting more access to high-quality green spaces and environmental facilities while disadvantaged communities have less access and a lower ability to adapt (Rigolon, 2016). The unequal spatial distribution has in recent years been addressed using ideas such as 'green privilege' and 'green inequity', since urban greening efforts can inadvertently strengthen existing social and spatial inequalities. In certain instances, large-scale greening measures can also lead to green gentrification, which involves environmental improvements raising property values and living costs and possibly forcing lower-income residents out of the areas that have been regenerated (Anguelovski et al., 2022).

2.4 Research gaps

To sum up, the literature review revealed a number of closely related research gaps which shaped the present PhD research and helped to establish its originality, scientific relevance, its contribution to the advancement of knowledge, and its practical applicability. The main research gap is the lack of integration of the spatial, technical, and social dimensions within a coherent decision-support framework for the planning and prioritization of NbS for urban flood resilience. Currently, most research looks at these different aspects separately, whereas NbS planning calls for a greater understanding of how they are related. This main gap includes five other interrelated research gaps. The five interconnected research gaps identified through literature review are summarized in figure 4.

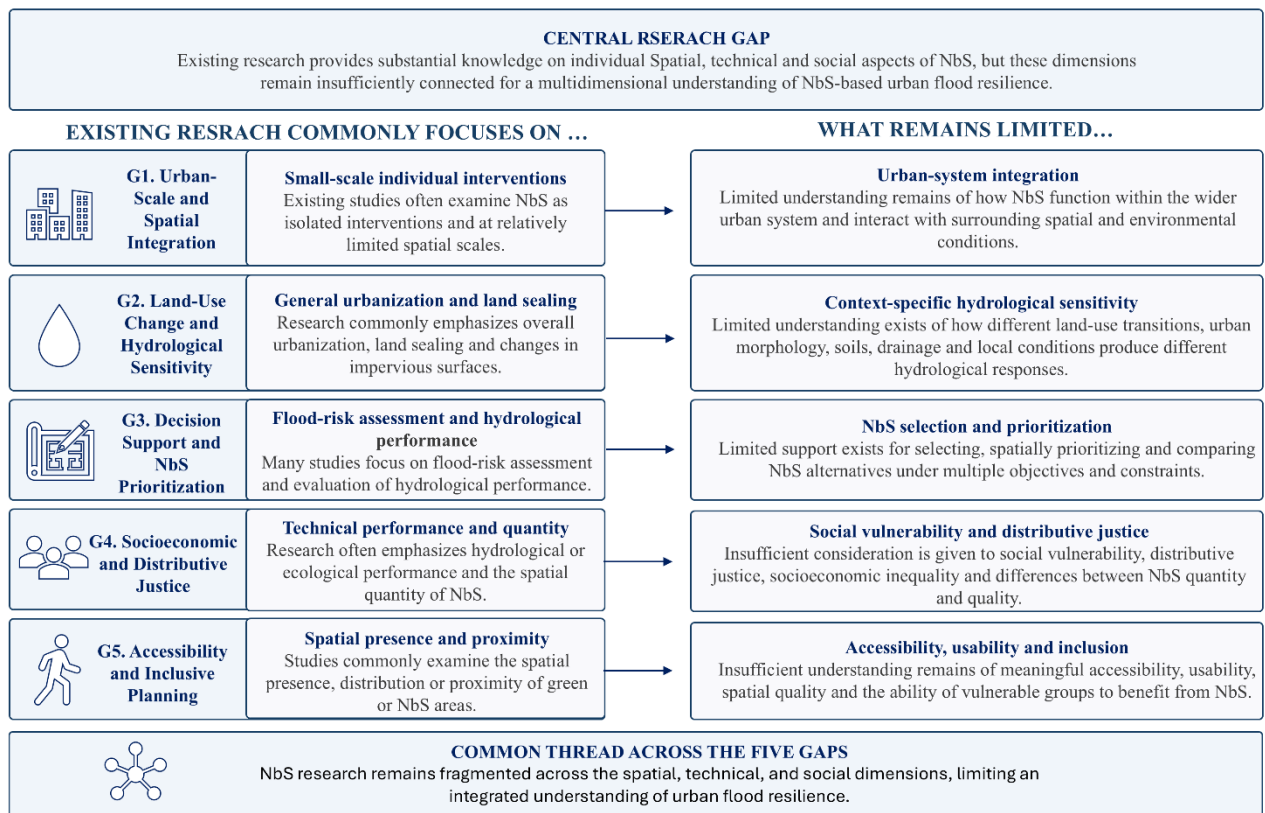


Figure 4. Key research gaps identified in the literature on NbS-based urban flood resilience. Source: Author's own illustration

G1. Urban-scale and spatial integration gap

Many studies tend to look at NbS as separate projects within cities. They are usually evaluated one by one and on a small scale, which makes it hard to see how they function together in the larger urban system. To better understand how NbS can reduce urban flood risk, research needs to examine them at a city-wide scale and consider how they interact with their surroundings.

G2. Land use change and hydrological sensitivity gap

Another gap is that we do not fully understand how changes in land use, urban form, and local environmental factors affect urban flood risk and water retention. More research is needed to understand how different land use changes interact with soil, drainage, climate, and city structure, rather than assuming urbanization is the same everywhere. This calls for a more detailed look at how different development patterns lead to different levels of flood risk.

G3. Decision-support and NbS prioritization gap

While there are numerous tools for assessing flood risk and water management, less focus has been placed on aiding in choosing, prioritizing, and implementing NbS. Most current methods still mainly assess risk, rather than guiding decisions between different NbS options.

This makes it challenging to consider factors like hydrological effectiveness, cost, spatial fit, and land-use compatibility simultaneously. There is a need for decision-support tools that go beyond merely assessing flood risk and help identify, allocate, prioritize, and compare different NbS options.

G4. Socioeconomic and distributive justice gap

Another crucial, less explored area is that most studies mainly examine the hydrological and ecological results of NbS, but pay less attention to their wider social and economic impacts. Evaluating NbS mostly by technical measures like runoff reduction is not sufficient, since individuals in cities face different levels of flood risk, social vulnerability, ability to adapt, and access to resources.

Therefore, it is essential to look at not just where NbS are placed, but also who gets to benefit from them and whether these benefits are shared equitably among different neighborhoods and communities. This gap is especially about justice and the difference between how much NbS is provided and how good or beneficial it is. Focusing only on the amount or area of NbS can hide differences in quality, function, access, and real benefits for different communities in urban spaces.

G5. Accessibility and inclusive planning gap

Another identified gap is the insufficient consideration of accessibility, usability, and inclusiveness in NbS planning. Proximity to NbS does not guarantee equal use or benefit for all individuals.

If assessments focus only on how much NbS there is, where it is, or how close it is, they may miss real differences in access, quality, mobility, and whether vulnerable groups can actually use and benefit from NbS. This shows the need to look beyond just physical presence and move toward a more people-centered view of accessibility, inclusion, and daily use.

Altogether, these five gaps show a bigger problem in the literature: the spatial, technical, and social dimensions of NbS planning are rarely studied together in a single framework. An integrated, multi-dimensional decision-support system is needed to bring these areas together and help identify, assess, prioritize, and plan NbS in cities in a way that is more sensitive to context, effective, and equitable. Addressing these gaps advances scientific understanding of the interconnections among urban development, hydrological sensitivity, NbS performance, spatial factors, and social equity. This research also enhances the practical utility of such knowledge for urban flood resilience planning. The principal contribution of this thesis lies not only in its methodologies and findings but also in the integration of these diverse domains into a coherent and unified framework. For analytical clarity, table 1 presents the five identified research gaps and the publications that address them.

Table 1. Summary of identified research gaps and publications addressing them.

Gap	Description	Thesis Publications addressing the gaps
G1	NbS are often examined as individual interventions and at relatively small spatial scales, with limited consideration of how they interact with the wider urban system and surrounding spatial conditions.	Articles II and III
G2	Limited understanding of how different land-use transitions, urban form, soil, drainage, climatic conditions, and spatial context influence runoff generation, water retention, and flood sensitivity.	Article II
G3	Existing approaches are frequently focused on flood-risk assessment rather than supporting the selection, spatial prioritization, and comparison of NbS alternatives under multiple objectives and constraints.	Articles I and III
G4	NbS research remains strongly focused on hydrological and ecological performance, with comparatively limited consideration of social vulnerability, socioeconomic inequality, distributive justice, and differences between NbS quantity and quality.	Articles IV and V
G5	The spatial presence or proximity of NbS does not necessarily ensure meaningful or equitable access. Accessibility, spatial quality, usability, and the needs of vulnerable groups remain insufficiently integrated into NbS planning.	Article VI

3. Methodology

3.1. Overall research design

To address the research gaps identified in the previous chapter, this thesis uses a multi-dimensional and interdisciplinary research design comprising several complementary studies. Each study considers a particular aspect of the posed research problem and collectively supports the advancements of understanding of flood risk dynamics in urban setting and development of an integrated approach for nature-based solutions and urban flood resilience in European cities. The selected methodologies reflect the three overarching dimensions of this thesis which are spatial, technical, and social; through the integration of geospatial analysis, hydrological

modeling, optimization techniques, socioeconomic assessment, and integrative planning approaches.

List of research articles developed within the PhD research process:

- I. Azadgar, A.; Nyka, L.; Salata, S. Advancing Urban Flood Resilience: A Systematic Review of Urban Flood Risk Mitigation Model, Research Trends, and Future Directions. *Land* 2024, 13, 2138, <https://doi.org/10.3390/land13122138>.
- II. Azadgar, A., Benedini, A., Salata, S., Lacoere, P., Badach, J., Nyka, L., Flood-sensitive land take (FSL) analysis: A new way to read how urban sealing shapes flood risk, *Journal of Environmental Management*, Volume 404, 2026, 129513, <https://doi.org/10.1016/j.jenvman.2026.129513>.
- III. Azadgar, A., Gańcza, A., Razzaghi Asl, S., Salata, S., Nyka, L., Optimizing nature-based solutions for urban flood risk mitigation: A multi-objective genetic algorithm approach in Gdańsk, Poland, *Science of The Total Environment*, Volume 963, 2025, 178303, <https://doi.org/10.1016/j.scitotenv.2024.178303>.
- IV. Azadgar, A., Luciani, G., Nyka, L., Spatial allocation of nature-based solutions in the form of public green infrastructure in relation to the socio-economic district profile—a GIS-based comparative study of Gdańsk and Rome, *Land Use Policy*, Vol. 150, 2025, 107454, <https://doi.org/10.1016/j.landusepol.2024.107454>.
- V. Asl, S. R., Azadgar, A., & Nyka, L. (2026). Green privilege? Exploring the spatial relations between nature-based solutions and social vulnerability in Nordic cities. *Local Environment*, 1–22, <https://doi.org/10.1080/13549839.2026.2639069>.
- VI. Azadgar, A., Sepe, M., Gańcza, A., Lorens, P., Luciani, G., Nyka, L. (2026) Integrating AI and spatial analysis for resilient and inclusive 15-minute cities: A case study of Gdańsk, *Cities*, Volume 173, 2026, 107011, <https://doi.org/10.1016/j.cities.2026.107011>.

Each of these articles has employed a distinct methodology but, at the same time, is harmonious with the main research goal of this dissertation in order to find responses to the research questions and cover research gaps derived from the literature review. Table 2 demonstrates the utilized methodologies within each paper and their alignment with research components of the overall dissertation (research questions, gaps, objectives, and theses), along with their analytical role and their contribution to the overall dissertation. Conceptual diagrams, schematic illustrations, and other visual representations presented in this thesis were created by the author using Microsoft PowerPoint and Adobe Photoshop.

Table 2. Alignment of research questions, articles, methodological approaches, and contributions to the overall thesis.

Paper	Analytical role	Research question	Research gap	Research objective	Research theses	Methodological response	Contribution to overall thesis
I	Research review and gap identification	RQ1	G3	RO1	---	A systematic review and bibliometric analysis	Identifies the research trends and gaps in relation to flood risk and NbS with particular focus on InVEST UFRM
II	Spatial dimension: hydrological and land-use context	RQ2	G1	RO2	RT1	GIS-based land use change analysis combined with the InVEST Urban Stormwater Retention Model	Establishes the relationship between urbanization, land take, and flood sensitivity through developing water accumulation sensitivity index (WASI) and normalized WASI (NWASI) indicators as the hydrological foundation for flood-sensitive urban planning
III	Technical dimension: decision support and optimization	RQ3	G1; G3	RO3	RT2	InVEST Urban Flood Risk Mitigation model integrated with a multi-objective genetic algorithm optimization framework	Translates hydrological assessment into operational NbS planning strategies through spatial prioritization and decision-support approaches
IV and V	Social dimension: socioeconomic equity, distributive justice, and vulnerability	RQ4	G4	RO4	RT3	GIS spatial analysis, Pearson correlation analysis, Social Vulnerability Index (SVI), principal component analysis (PCA), and spatial clustering methods	Expands flood resilience assessment beyond hydrological performance to include distributive justice, social vulnerability
VI	Social dimension: accessibility and human-scale spatial quality	RQ5	G5	RO5	RT3	spatial quality assessment, network-based accessibility analysis, and InVEST UFRM	Advances NbS planning toward more inclusive, accessible, and human-centered planning approaches

3.2. Case study selection

The case studies in this research were selected to represent a broad range of European urban contexts, environmental conditions, planning systems, and flood-related challenges linked to NbS. The research adopted a comparative multi-case approach across different European regions instead of focusing on a single city or country. Following the comparative and transferability-oriented approach common in European urban and environmental research, geographically and climatically diverse case studies were chosen to test the applicability, robustness, and transferability of the proposed methodologies across various urban, hydrological, socioeconomic, and governance conditions. This diversity was necessary to understand how different climatic conditions, urban morphologies, hydrological systems, planning traditions, and socioeconomic structures influence the implementation, performance, accessibility, and spatial distribution of NbS and flooding risk in different European cities. Expanding the research across multiple urban contexts also strengthened the potential applicability of the developed frameworks and findings for broader European planning and policy contexts.

The selected case studies include Gdańsk, Milan, Rome, Oslo, Helsinki, Stockholm, and Ghent, representing coastal, Mediterranean, continental, and Nordic urban environments with different urbanization trajectories and environmental pressures. The inclusion of specific cities varied across papers, depending on each study's objectives and methodological needs. For example, Gdańsk, Milan, Oslo, and Ghent were selected for comparative land-take and hydrological sensitivity analyses because they represent contrasting flood drivers, land use transitions, and planning approaches. In contrast, Oslo, Helsinki, Stockholm, and Rome were included in studies on environmental justice, social vulnerability, accessibility, and green privilege due to the availability of high-quality spatial and socioeconomic datasets and their differing approaches to NbS planning and welfare-oriented urban development. In this way, these case studies enabled both context-specific investigation and broader comparative analysis, supporting the development of more scalable and transferable conclusions about the role of nature-based solutions in improving urban flood resilience across Europe.



Figure 5. Study areas. Source: Author's own illustration

3.3. Description of data sources

In order to fulfill the objectives of the dissertation, each article was tasked with different methodologies, and each of them, in order to produce results, needed different types of data. Table 3 summarizes the data sources and features of the input data within each publication.

Table 3. Summary of characteristics of input data in the publications of this thesis along with their sources.

Article	Data type	Source	Spatial/temporal resolution	Purpose	Method using the data
I	Scientific publications to be included in the review study	Scinapse and Google Scholar	Papers published 2019-2024; searches conducted February 2024	Identify studies applying UFRM and examine the applications, limitations and research gaps	PRISMA guided screening and full text review of 21 papers
II	LULC	Copernicus Urban Atlas (European Environment Agency, 2020, 2016)	2012 and 2018 for comparison; minimum mapping unit 0.25 ha	Detect where natural/semi-natural/agricultural land became artificial or sealed	GIS clipping, intersection and cross-tabulation to identify land-use transitions and land take
	Hydrologic soil groups	HYSOGs250m (Ross et al., 2018)	250 m raster; static	Represent soil runoff/infiltration characteristics	Combined with LULC in the InVEST biophysical parameterization
	Annual precipitation	ERA5 (Hersbach et al., 2023) , accessed via Google Earth Engine	Mean annual precipitation	Provide climatic forcing for long-term water balance	Input to InVEST Urban Stormwater Retention Model; also used to normalize WASI into NWASI
	Road centerlines	OpenStreetMap contributors (2025)	Vector network	Represent transport-related impervious surfaces	Included in the spatial representation of sealed urban infrastructure
III	LULC	Copernicus Urban Atlas (European Environment Agency, 2020)	2018, minimum mapping unit 0.25 ha	Describe existing land cover and determine runoff characteristics and where specific NbS can be installed	Input to InVEST UFRM and starting raster for the genetic-algorithm optimization
	Soil hydraulic properties / hydrologic soil groups	ESDAC 3D Soil Hydraulic Database (Tóth et al., 2017)	250 m raster	Classify soil into hydrological groups A-D and represent infiltration/runoff behaviour	Combined with land-cover data in InVEST UFRM
	Curve Numbers	NRCS Curve Numbers / USACE HEC Curve Number Tables (USACE, n.d.)	Non-spatial lookup table	Assign runoff potential for each land-use × soil-group combination	SCS-Curve Number calculation within InVEST UFRM and genetic algorithm objective calculations

	NbS implementation costs	Mix of literature and expert consultation with a local engineering firm (SPB Contech Sp. z o.o. in Gdańsk); worst-case costs used in optimization	Local cost estimates; principally current to study period, no spatial resolution	Represent economic cost of interventions	One of the objective functions in the multi-objective genetic algorithm
IV	Gdansk green space data	Geoportal.gov.pl	Citywide spatial layers; analysed at district level; accessed January 2024	Quantify the area and density of publicly accessible NbS (PNbS) in each district	District-level PNbS area and density calculation
	Rome green space data	Roma Capitale – Statistics and Data Portal, based on Environmental Protection Department data	District level; 2022	Quantify the area and density of PNbS in each district	
	Gdansk socio-economic data	City of Gdańsk District Portal / BIP; SonarHome (2024); Gdańsk municipal open-data portal	District level; housing prices 2024; unemployment 2016; population/district data from municipal sources	Characterize district socio-economic conditions and examine their relationship with PNbS distribution	GIS mapping, Pearson correlation and priority index
	Rome socio-economic data	City of Rome Statistics and Data Portal; ISTAT (2021); Mapparoma / OMI (Lelo et al., 2016)	District level; population 2022; household income 2020; education 2021; housing prices 2018	Characterize district socio-economic conditions and assess distributive justice in PNbS allocation	
V	Data for constructing nature-based solutions index (NbSI)	Urban Atlas 2018 (Copernicus Land Monitoring Service, 2018); population data from Helsinki Map Service (2023), Oslo Kommune (2024), and Sweco (2022); Sentinel-2 Level-2A imagery via Copernicus Open Access Hub	Urban Atlas: 2018; population data: sub-district level; Sentinel-2: cloud-free growing-season imagery from 17–28 May 2024, summarised as mean NDVI per sub-district	Represent the quantity, relative availability, and ecological condition of NbS across sub-districts	Calculation and equal-weighted combination of NbSI indicators
	Data for constructing SVI	Oslo Kommune (2022–24); Helsinki Map	Sub-district level; Oslo 2022–24, Helsinki 2022–23, Stockholm 2021–22	Represent social vulnerability through socioeconomic and	PCA-based construction of SVI

		Service (2022–23); Sweco (2021–22)		demographic characteristics related to capacity to cope with environmental and social risks	
VI	Amenities, public transport, green/recreational spaces and street network	OpenStreetMap data accessed through QuickOSM in QGIS	Vector point/network data; data availability checked June 2024	Assess 15-minute walking accessibility to essential amenities, recreational spaces and public transport	QNEAT3 network analysis of 15-minute accessibility
	Google Street View images	Google Street View (GSV) Static API	600 randomly generated locations; after removing duplicates/non-landscape images, 198 panoramic images remained; availability checked June 2024	Assess public-space quality, including infrastructure, greenery, visual quality, identity and users	Machine learning-based assessment of public-space quality
	Input data for InVEST UFRM	UFRM Urban Atlas 2018 (EEA, 2021); ESDAC 3D Soil Hydraulic Database (European Commission JRC, 2017; Tóth et al., 2017); NRCS TR-55 biophysical table	Urban Atlas: 2018 vector land-cover data; ESDAC soil data: 250 m raster; TR-55: non-spatial Curve Number/biophysical lookup table	Estimate water-retention capacity and identify areas with greater physical susceptibility to surface- water accumulation/flooding	to calculate spatial water- retention capacity within InVEST UFRM

3.4. The overview of the used methods

3.4.1. Systematic literature review

The first step in the PhD research was a literature review that resulted in the paper “Advancing Urban Flood Resilience: A Systematic Review of Urban Flood Risk Mitigation Model, Research Trends, and Future Directions”. A systematic literature review was used to collect and evaluate research on urban flood risk mitigation model published between 2019 and 2024, since UFRM, the focus of this review, was introduced in 2019. Initially, papers matching the keywords “Integrated Evaluation of Ecosystem Services and Trade-offs” were included. Then, papers containing any of the keywords “flood”, “flooding”, or “floods” were added. In Google Scholar, the phrases “Integrated Valuation of Ecosystem Services and Trade-offs” AND “Urban Flood Risk Mitigation model” were searched. After removing duplicates and screening titles, abstracts, and keywords, 21 relevant studies were selected for detailed full-text analysis (see figure 6 for a breakdown of steps). Next, the bibliometric analysis was applied to examine patterns in the literature, including publication trends, citation counts, journals, affiliations, funding sources, and geographic distribution of case studies. This helped identify which countries, institutions, and journals were most active in UFRM research. Finally, the keyword co-occurrence and network analyses using VOSviewer was conducted. By analyzing how keywords co-occurred across the selected studies, it was possible to generate thematic clusters revealing the field's major research areas.

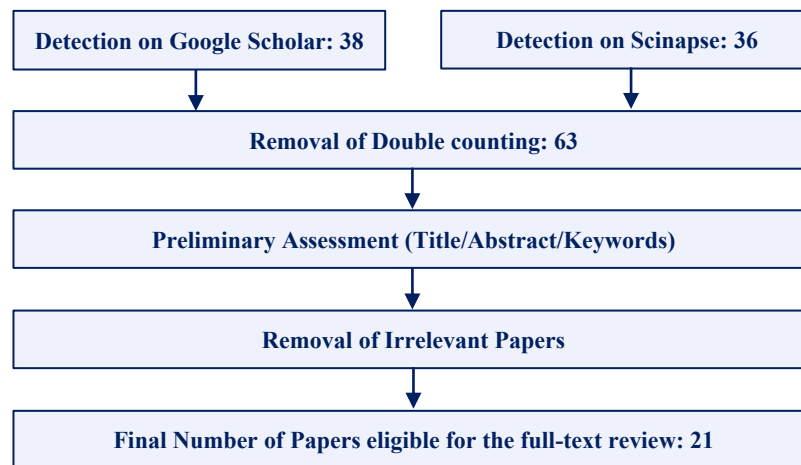


Figure 6. Exploration approach of peer-reviewed articles. Source: Author’s own illustration

3.4.2 Spatial and hydrological assessment

This section presents the spatial and hydrological methods used to investigate the relationships between urban development, land-use change, flood risk, and NbS. The analytical framework combines GIS-based spatial analysis, hydrological modeling, and sensitivity assessment to examine how urbanization influences runoff generation, water accumulation, and flood

susceptibility across different urban contexts. The methodology evolved from large-scale comparative assessments of land use transitions and hydrological sensitivity to intervention-oriented modeling focused on evaluating and optimizing NbS flood-mitigation performance in urban environments.

Land use change analysis

To understand how different land use types affect flood risk and how various land use changes influence flood risk, a GIS-based LUC analysis was conducted to examine urban transitions as the first step in this PhD research. The LUC analysis followed a consistent GIS procedure. It involved clipping land use layers to administrative boundaries, intersecting 2012 and 2018 maps to identify changes, classifying transition types, and calculating absolute and relative area changes for cross-city comparison.

Flood risk and runoff modelling

One main theme of this research is flood risk modelling and spatial analysis to find links between flood risk and urban characteristics in a city. Based on this and the literature review of possible tools and methods, I chose to use InVEST's flood risk assessment models: UFRM and the Urban Stormwater Retention Model. In this thesis, modeled runoff was used as a proxy indicator of flood susceptibility, with higher runoff values interpreted as indicating greater hydrological susceptibility to flooding under the analyzed conditions.

In the land take paper, my objective was to understand how urbanization and land-use transitions alter the hydrological sensitivity of cities over time. For this reason, the InVEST Urban Stormwater Retention Model was the most appropriate tool because it is designed to evaluate long-term stormwater retention and water accumulation through an annual water balance framework. The model estimates how land cover change affects infiltration, evapotranspiration, interception, and runoff generation across urban systems, making it particularly suitable for comparative analysis of land take patterns between cities. The paper explicitly states that the model was selected because it supports “comparative urban studies focused on runoff generation and retention capacity”.

By contrast, the optimization paper addresses a different problem: how to spatially allocate NbS to reduce pluvial flood risk in vulnerable urban areas. This required a model capable of evaluating storm-event runoff dynamics and flood mitigation performance under specific rainfall conditions. Therefore, the InVEST UFRM model was more appropriate because it directly estimates runoff during storm events using the SCS-Curve Number method. The paper explains that UFRM is suitable for assessing “water retention during storm events,” quantifying “reductions in floodwater volume,” and evaluating the flood mitigation potential of NbS interventions. Unlike the Stormwater Retention Model, which is primarily diagnostic and

comparative, the UFRM model is operational and intervention-oriented. It allowed integration with the genetic algorithm optimization framework to test alternative NbS configurations under explicit hydrological constraints.

Integrated land take-runoff Sensitivity analysis

In paper II, an integrated analytical framework combining land-use change detection and runoff sensitivity modeling was developed to evaluate the hydrological impacts of urban land take. The innovative methodology developed in this paper, called Flood-Sensitive Land Take (FSL) analysis, examined how transitions from natural, agricultural, and semi-natural land to artificial urban surfaces influenced water accumulation and runoff sensitivity between 2012 and 2018. Land use and land cover transitions were identified using Urban Atlas datasets through GIS-based overlay and intersection analysis. Hydrological responses were modeled using the InVEST Urban Stormwater Retention Model. After modelling, water accumulation outputs were extracted for each land take transition zone to compare pre- and post-development hydrological conditions.

To quantify the sensitivity of different land use transitions to runoff generation, the Water Accumulation Sensitivity Index (WASI) was developed as the ratio of the change in total accumulated water volume to the corresponding land take area. This indicator measured the marginal hydrological impact of each land conversion type, allowing direct comparison of how different forms of urbanization influence runoff sensitivity. To support comparisons across cities with different climates, the WASI was further normalized using annual precipitation data to create the Normalized Water Accumulation Sensitivity Index (NWASI). These indicators enabled the identification of land use transitions with the highest runoff sensitivity and provided a quantitative basis for flood-sensitive spatial planning, targeted mitigation strategies, and evaluation of nature-based solutions for urban flood resilience.

3.4.3. NbS planning and optimization approaches

In Article III, I explored the problem of spatially selecting and distributing NbSs in a case study of Gdańsk. Given the complexity of flood protection measures and the multifunctionality of NbS, selecting and allocating them required an approach that considers multiple objectives simultaneously. Therefore, a multi-objective optimization approach was necessary. Such optimization problems can be approached in several ways, from optimizing a linear combination of objectives to searching for a pareto front of best-fitting solutions. Methods focusing on the latter yield a collection of solutions, each optimal in at least one selected measure (Arora, 2004).

Such a framework is well-suited for genetic algorithms, i.e., methods solving optimization problems using techniques inspired by mechanisms of natural evolution. These methods operate on a collection of possible solutions, called a population, and iteratively refine them through repeated stages of selection, crossover, and mutation. In the optimization of NbS placement, a

single solution is represented by a matrix of land use codes. First, the collection of randomly generated solutions is prepared. Next, they are evaluated in terms of runoff reduction and implementation cost. Then, they are organized in so-called Pareto fronts according to the procedures described in (Fonseca and Fleming, 1993). Candidates to the new population are selected via stochastic universal sampling and are then subject to uniform crossover and mutation (Goldberg and Deb, 1991) to generate the new population of solutions. Throughout the iterations, the best solutions are kept to increase probability of finding the algorithm find the optimal solutions. This procedure is stopped after an experimentally selected number of iterations, large enough to guarantee convergence.

To ensure computational feasibility of the process and to reduce the intervention cost, only the areas characterized by the highest rainfall depth in the InVEST UFRM simulation are selected for optimization. Selection is performed by classifying rainfall depth scores into five categories using the k-means clustering (Hastie et al., 2009), which can be interpreted as regions with very low, low, medium, high, and very high rainfall depth. Areas belonging to the last two were selected for optimization.

3.4.4. Evaluating NbS quantity and quantity

Quantity of NbS were evaluated in articles IV and V. Article IV evaluates the quantity of NbS mainly through the density of public NbS (PNbS), calculated by dividing the area of publicly accessible green spaces in each district by the district's total area. I used GIS spatial analysis to map and compare the distribution of parks, forests, playgrounds, sports fields, and waterfront greenery across districts in both cities. In Rome, district-level PNbS data came directly from municipal datasets, while in Gdańsk the data came from Geoportal.

Article V evaluates the quantity and quality of nature-based solutions (NbS) using a more comprehensive Nature-based Solutions Index (NbSI), which combines multiple indicators related to both the amount and quality of urban green infrastructure. We measured NbS quantity through NbS density, calculated as the total area of NbS within each sub-district divided by the sub-district's total area, and NbS per capita, which measures the amount of NbS available for each resident. In addition, we incorporated NDVI (Normalized Difference Vegetation Index) derived from Sentinel-2 satellite imagery to assess vegetation health and ecological quality. To define NbS spatially, the study used Urban Atlas 2018 land-cover classes such as green urban areas, grasslands, wetlands, and arable land. All indicators were normalized and combined into the composite NbSI.

Accessibility and spatial quality

Throughout the research process, the assessment framework evolved from focusing on the quantity and spatial distribution of NbS to a more integrated evaluation of both quantity and

quality. Articles IV and V concentrated on the ecological presence and spatial coverage of NbS. The final article (VI), though, expanded the analysis to the lived accessibility and usability of NbS within everyday urban environments. This was done through a combined machine-learning-based spatial quality assessment and network-based accessibility analysis. This evaluated not only whether green and public spaces exist but also whether they are realistically accessible, inclusive, and attractive for daily use by citizens. Public space quality was assessed through AI-driven semantic segmentation and object detection applied to Google Street View imagery (GSVI). This enabled automated evaluation of spatial characteristics such as greenery, walkability, lighting, seating, visual diversity, and overall environmental quality using deep learning models, including DeepLabv3 (Chen et al., 2017) and Faster R-CNN (Ren et al., 2016). Simultaneously, network analysis using the QNEAT3 (Qgis Network Analysis Toolbox 3) plugin assessed accessibility through actual pedestrian routes rather than Euclidean distance. It incorporated slower walking speeds to better reflect the mobility needs of vulnerable populations, including elderly people, children, and individuals with reduced mobility. This approach shifted the evaluation beyond the simple presence of NbS on the map to an understanding of the actual conditions of access, movement, and inclusivity.

3.5.5. Socioeconomic assessments

The socioeconomic assessment conducted throughout the research evolved in complexity and methodological depth across papers IV and V. In article IV, represented by the comparative study of Gdańsk and Rome, the assessment focused on examining the relationship between the spatial distribution of publicly accessible nature-based solutions and the socioeconomic characteristics of urban districts through the use of selected socioeconomic variables, including housing prices, unemployment rate, education level, household income, and population density. These variables were separately and individually analyzed in relation to the density and allocation of public green infrastructure in order to identify patterns of distributive and environmental justice. In the next article, however, the socioeconomic assessment was further developed into a more comprehensive and systematic approach by constructing a Social Vulnerability Index (SVI).

Social vulnerability

The Social Vulnerability Index (SVI) developed in article V was constructed to capture the multidimensional socioeconomic and demographic characteristics influencing the vulnerability of urban communities in relation to access to nature-based solutions. The methodology followed a deductive indicator-based approach adapted from the Social Vulnerability Index (SoVI) framework proposed by Cutter et al., 2003. The index incorporated eleven variables at the subdistrict scale, including average taxable income, housing conditions, gender distribution, foreign population, household structure, age groups, education level, and unemployment rate.

Variables expected to have an inverse relationship with vulnerability, such as income and housing conditions, were reverse-coded prior to analysis. To reduce dimensionality and identify latent socioeconomic structures, principal component analysis (PCA) was applied. Components with eigenvalues equal to or greater than one were retained and aggregated to produce the final SVI score for each subdistrict. This approach enabled the transformation of multiple socioeconomic indicators into a single composite index reflecting the relative concentration of social vulnerability across the study areas.

Statistical and spatial correlation analysis

To investigate the relationships between NbS and socioeconomic characteristics, statistical correlation methods and spatial analytical techniques were applied in articles IV and V. The approach evolved from statistical correlation analysis in paper IV to more advanced spatially explicit analyses in article V. Pearson correlation analysis examined linear relationships between socioeconomic variables and NbS distribution, while spatial statistical approaches, including Local Indicators of Spatial Association (LISA), identified localized spatial patterns, inequalities, and variations in the relationships between social vulnerability and NbS characteristics.

Pearson correlation coefficient

In paper IV, Pearson correlation analysis was used to evaluate the strength and direction of linear relationships between NbS indicators and socioeconomic variables. Pearson correlation coefficients assessed associations between the density of publicly accessible nature-based solutions and district-level socioeconomic characteristics such as population density, housing prices, education level, household income, and unemployment rate. The analysis followed the integration of spatial and census data within ArcGIS. Correlation calculations were performed in Microsoft Excel. The Pearson correlation coefficient, ranging from -1 to $+1$, identified both negative and positive relationships between variables, supporting the interpretation of distributive and environmental justice patterns in the two cities.

Spatial clustering and local spatial analysis

In Article V, spatial analytical methods investigated localized relationships between social vulnerability and the distribution and quality of nature-based solutions. The analysis used LISA and Moran's I statistics to identify spatial autocorrelation and significant spatial clusters between the Nature-based Solutions Index (NbSI) and the Social Vulnerability Index (SVI). Unlike global correlation methods, these approaches detected localized socio-spatial inequalities and identified areas with varying combinations of NbS provision and social vulnerability. Bivariate LISA cluster analysis classified urban districts into spatial patterns linked to green privilege, environmental injustice, ambivalent conditions, and equity potential. This approach provided a

spatially explicit understanding of how NbS quantity and quality intersect with social vulnerability patterns across Oslo, Helsinki, and Stockholm.

Chapter 4: Summary of the appended articles

This chapter provides a summary of each paper on which the PhD research is based. The summary includes the background, motivation, and most important finding of each paper. The papers are introduced in a sequence aligned with the overall research narrative. Each article attempts to resolve the question posed by the previous one and ends by posing the research questions the next paper will address. In this way, all these papers form a cohesive narrative that shape the final guide. In the broader sense and in the context of the overall dissertation, each of the presented publications acts as a piece of a puzzle. At the end of this chapter, all of these pieces are brought together; this will help synthesize the findings of each publication in order to produce the final integrated framework, which will be presented in Chapter 5 in detail.

4.1. Article I

Advancing Urban Flood Resilience: A Systematic Review of Urban Flood Risk Mitigation Model, Research Trends, and Future Directions

This paper provides a systematic literature review of the UFRM within the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) software suite. The research addresses the increasing demand for practical, spatially explicit tools that integrate into flood risk assessment and climate adaptation planning, particularly in contexts with limited data availability and technical capacity. Summary of this article is presented in figure 7.

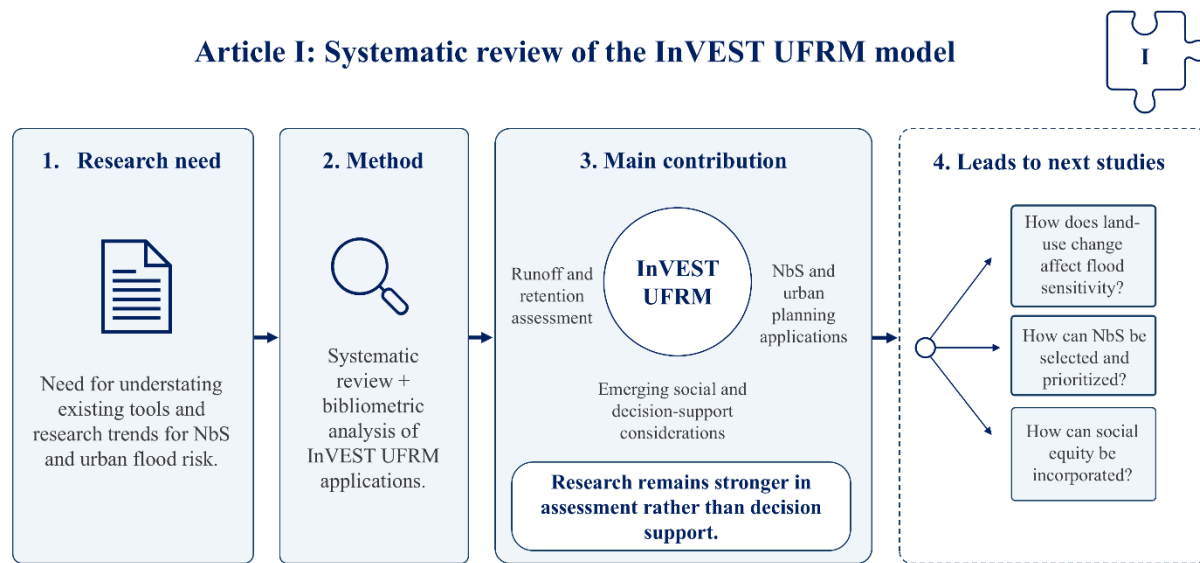


Figure 7. Visual summary of article I. Source: Author's own illustration

4.1.1. Background and summary of findings

Prior to this paper, a broader examination of urban flooding approaches and NbS was conducted. This initial analysis indicated that many available tools are either excessively complex and data-intensive or serve mainly as conceptual and informational frameworks rather than as operational planning instruments (Voskamp et al., 2021). In this context, the InVEST UFRM model was identified as a promising alternative due to its combination of accessible data requirements and capacity to generate spatially explicit analyses of runoff retention and flood-prone areas. This balance of analytical capability and usability informed its selection as the primary focus of the review.

To get an overall picture of the research landscape of the reviewed papers, a bibliometric keyword analysis was conducted using VOS viewer software based on keyword co-occurrence in publications. The extracted keywords were grouped into five thematic clusters representing the main research directions of studies that used UFRM. The visualization network used node size to

represent keyword frequency, link strength to indicate relationships between keywords, and color to distinguish clusters (please see figure 7 in the article).

The first and largest cluster focused on urban planning and NbS, including themes such as climate change, ecosystem services, GIS, land management, urban green spaces, and urban design. Studies within this cluster mainly evaluated the role of green infrastructure and ecosystem-based planning in reducing urban flood risks. Papers in this cluster demonstrated that NbS, such as forested green areas, sponge city strategies, and urban green spaces, significantly improve runoff retention and support climate adaptation.

The second cluster emphasized urbanization, land use and land cover (LULC) change, sustainable development, and flood control. Studies from Brazil, Sweden, Italy, and China showed that rapid urban growth and expanding impervious surfaces increase runoff and reduce flood regulation capacity, while preserving green spaces improves ecosystem service delivery and flood mitigation. Several studies highlighted the importance of integrating spatial planning and sustainable land management into urban flood prevention strategies.

The third cluster focused on the economic and social dimensions of flood mitigation, including ecosystem valuation, runoff, natural hazards, and flood risk reduction. Research demonstrated that UFRM can support cost-benefit analysis and evaluate trade-offs between urban development, agriculture, and ecosystem services. Studies assessing green roofs, bioswales, and other NbS found that the economic benefits of flood mitigation frequently exceeded implementation costs, especially under future climate scenarios.

The fourth cluster addressed adaptation and risk management, concentrating on mitigation strategies, ecosystem resilience, and climate adaptation planning. Research from Turkey, Sweden, and China applied UFRM to identify vulnerable urban areas, evaluate runoff during extreme rainfall events, and support adaptive urban planning. The fifth cluster focused on resilience, vulnerability, adaptive management, and pluvial flooding, emphasizing the importance of improving urban resilience through ecosystem-based flood management and spatial adaptation strategies.

4.1.2. Limitations, research gaps and future directions

The reviewed literature demonstrates that the UFRM model has become an important tool for assessing ecosystem services, runoff retention, and the role of NbS in urban flood management. The growing number of studies applying UFRM across a range of climatic and urban contexts shows its flexibility and strong potential to support sustainable urban planning and climate adaptation strategies. At the same time, the reviewed papers reveal several emerging research directions that can further expand the practical applications of UFRM and boost its contribution to urban resilience planning.

A major focus of recent research involves improving the understanding of how urbanization and land use change influence flood risk and ecosystem service provision. Multiple studies demonstrated that increasing impervious surfaces and rapid urban growth significantly affect runoff generation and water retention capacity, while green infrastructure and ecosystem-based planning are able to enhance flood mitigation. They emphasize the importance of investigating how different land use configurations, landscape patterns, and urban development scenarios alter flood dynamics and the supply of ecosystem services over time, thus indicating a growing need for more detailed spatial analyses linking land use transformation processes to urban flooding patterns.

Another important direction identified in the literature concerns integrating UFRM into practical urban planning and adaptation processes. Existing studies successfully use the model to identify areas at risk, evaluate ecosystem services, and assess the benefits of nature-based solutions such as green roofs, bioswales, sponge city strategies, and urban green spaces. Future research increasingly aims to move beyond assessment toward more direct support for planning and decision-making processes. Several authors emphasized the importance of developing approaches that can compare alternative planning scenarios, evaluate multiple adaptation strategies simultaneously, and support the spatial prioritization of flood mitigation interventions within specific urban contexts.

The reviewed papers also highlight increasing interest in combining UFRM with advanced geospatial analysis, climate modeling, remote sensing, sewer network analysis, and ecosystem accounting frameworks. These interdisciplinary approaches contribute to more comprehensive evaluations of urban flood resilience and offer opportunities to integrate hydrological, environmental, and socioeconomic dimensions into adaptation planning. In addition, studies such as Hamel et al. (2021) demonstrate the growing relevance of environmental justice and spatial equity considerations within ecosystem service modeling, particularly in identifying areas where green infrastructure can simultaneously reduce flood vulnerability and improve social well-being.

Based on these emerging research directions presented in article I, three key research questions guide the following papers presented in this PhD:

- 1) How do different land-use and land-cover changes influence urban flood risk and runoff retention in urban areas? (explored in paper II).
- 2) How can InVEST UFRM based analyses support spatial decision-making and the identification of optimal nature-based solutions for urban flood mitigation? (explored in paper III)
- 3) How can NbS for flood protection in cities contribute to socially equitable, inclusive, and resilient urban environments? (explored in paper IV, V and VI)

4.2. Article II

Flood-sensitive land take (FSL) analysis: A new way to read how urban sealing shapes flood risk

Building on the review article and motivated by the aim of understanding how land use changes influence urban flood risk, I co-authored the article “Flood-sensitive land take (FSL) analysis: A new way to read how urban sealing shapes flood risk.” In this work, we sought to challenge conventional views of land-use change and flooding. While the link between land sealing and increased flood risk is well established (Kudas et al., 2024), the specific effects of different sealing types have not been thoroughly investigated. Through a sensitivity analysis, we sought to close this research gap. Also, in order to develop a framework applicable to diverse European urban contexts, we chose four cases from four countries, each with distinct planning systems and climates.

In this study, we applied a comparative GIS-based methodology, along with InVEST’s stormwater retention model, to analyze how land use change influences urban water accumulation and flood sensitivity across four European cities between 2012 and 2018. Using harmonized Urban Atlas land-use data, spatial transitions from natural or agricultural land to artificial surfaces were identified through GIS overlay and cross-tabulation techniques. Hydrological impacts were then assessed using the InVEST Urban Stormwater Retention Model, which estimates long-term water accumulation based on annual water balance processes, including infiltration, evapotranspiration, runoff, and groundwater recharge. The model combined land use data, hydrologic soil groups, precipitation records, and transport infrastructure information within a consistent parameter framework to ensure cross-city comparability. Building on these outputs, the study developed the Flood Sensitive Land Take (FSL) framework, which links specific land use transitions to changes in modeled water accumulation. Two indicators were introduced: the Water Accumulation Sensitivity Index (WASI), measuring hydrological change per unit of converted land, and the Normalized WASI (NWASI), which adjusts results for climatic variability using annual precipitation. Visual summary of paper II is presented in figure 8.

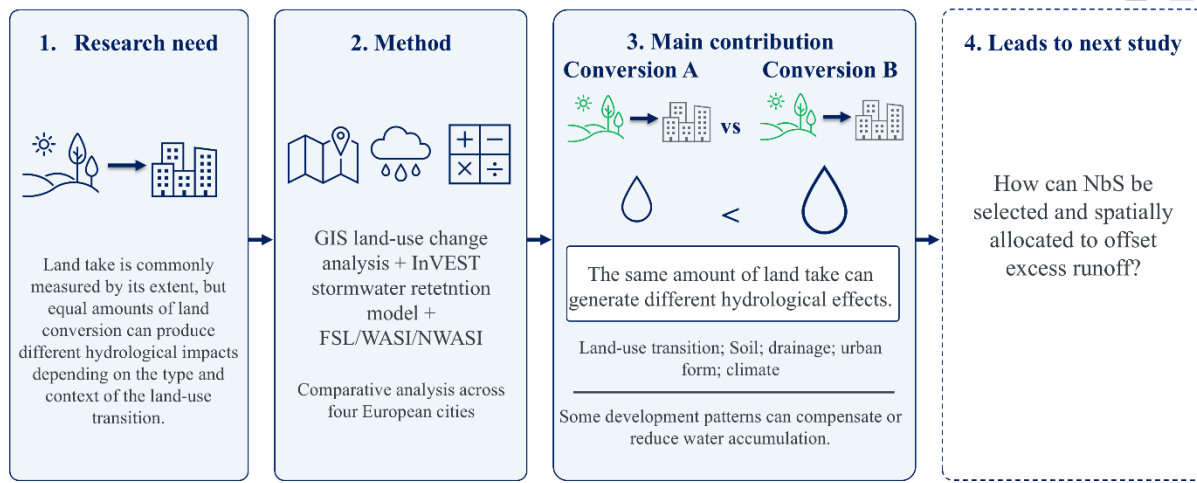


Figure 8. Visual summary of article II. Source: Author's own illustration

4.2.1. Comparative patterns of land take and hydrological sensitivity

The results (please see figures 3-7 in the article) reveal noticeable differences in how land take affects urban water accumulation across our case studies. Gdańsk showed the most intensive urban expansion compared to the other studied cities. This expansion is mainly driven by residential, commercial, and industrial growth on agricultural land, which corresponds with strong increases in water accumulation in newly urbanized districts. Milan showed more moderate but widespread hydrological impacts associated with redevelopment and infrastructure expansion around the Expo 2015 area, though some locally implemented green projects reduced water accumulation. Oslo recorded minimal land take overall, yet even limited conversion of forests and agricultural land generated relatively high hydrological sensitivity, highlighting the possible vulnerability of Nordic landscapes to sealing processes. Ghent presented a more intriguing trajectory, where parts of the land take were directed toward new urban parks and green infrastructure, resulting in reduced water accumulation and negative WASI values in some areas. The case of Ghent demonstrated that even though land take may include the conversion of natural land uses to urban land uses, if the urbanization involves green infrastructure, it can have positive effects on water management in that area. This showcases the importance of a balanced urban planning approach that incorporates green infrastructure implementation in order to compensate for the sealing of natural landscapes. In a more general sense, the findings demonstrate that the hydrological consequences of land take depend not only on its extent but also on the type of land conversion, with industrial and transport-related developments consistently increasing water accumulation, while green infrastructure can mitigate or even reverse these effects.

4.2.2. Implications of land take and flood risk dynamics for future research

This chapter demonstrated that flood sensitivity emerges from the interaction between land use transitions, local conditions, and the spatial configuration of urban development. By proposing and applying the novel indices WASI and NWASI across four European cities, the study moved beyond conventional land sealing indicators and provided a spatially explicit assessment of how different forms of land use contribute to surface water accumulation. The results highlighted that the same amount of land take can produce very different hydrological outcomes depending on soil conditions, drainage systems, and the type of urban development involved. The analysis also showed the importance of integrating flood risk management with land use planning and revealed that existing planning approaches often insufficiently account for the cumulative hydrological impacts of urban expansion. In this context, the WASI and NWASI indicators offer a practical basis for identifying hydrologically sensitive areas and supporting more targeted, performance-oriented planning strategies.

At the same time, the findings demonstrated that the hydrological impacts of land take can be compensated through integrating green infrastructure and nature-based interventions into urban planning processes. The comparative analysis highlighted how different cities apply varying approaches to stormwater management, retention, and infiltration, while also showing that implementation remains uneven and often lacks spatial prioritization. Consequently, understanding the dynamics and spatial patterns of land use change is a necessary prerequisite for designing effective flood-mitigation strategies. Before prescribing solutions, it was essential to identify which types of urban development generate the greatest hydrological pressures, where these pressures spatially concentrate, and how local environmental conditions influence runoff generation and water retention.

Without this understanding, mitigation measures risk being implemented in locations where they are less effective or insufficiently adapted to the dominant hydrological processes of a given urban context. The findings of this chapter showed that flood sensitivity is not uniform across cities or land use transitions, but instead depends on the interactions among sealing intensity, land use typology, soils, and existing drainage systems. At the same time, the results showed that green infrastructure and ecological compensation can partially offset or even reverse some of the hydrological impacts associated with urbanization. Carefully considering all findings and analyses from the second article in this PhD research, the following research question was posed: after understanding the dynamics of land-use change and urban flooding risk in cities, how can we effectively design and plan solutions to offset excess runoff caused by urban development?

4.3. Article III

Optimizing nature-based solutions for urban flood risk mitigation: A multi-objective genetic algorithm approach in Gdańsk, Poland

The previous chapter focused on a paper exploring the dynamics between land use change and flood risk. It produced mapped flood risk results for Gdańsk and raised the question of how to address flood risk using NbS. To explore responses and address the scarcity of decision-support frameworks for NbS in flood risk mitigation identified earlier in the second chapter, I began preparing a new research project.

The first step was to explore all the possible NbS suggested in the literature for flood risk mitigation. I conducted a systematic literature review to identify these NbS. Then, I focused on addressing the challenge of decision support. In prescribing solutions for cities, multiple, sometimes contradictory, criteria, constraints, and limitations must be considered.

Given all these factors, it seemed that a successful framework needed to be geographically and spatially explicit, while accounting for multiple competing and contradictory criteria and constraints. This meant that the nature of the task was deeply interdisciplinary. Creating such a framework seemed impossible unless it was done with the help of computer scientists. Therefore, I teamed up with the Faculty of Electronics Telecommunications and Informatics to create a decision-support system that leveraged the NbS I had identified during my literature review. Consultation with computer scientists revealed that this could be achieved effectively using a multi-objective genetic algorithm. This resulted in writing the paper titled “Optimizing Nature-Based Solutions for Urban Flood Risk Mitigation: A Multi-Objective Genetic Algorithm Approach in Gdańsk, Poland”. Figure 9 summarizes paper III visually.

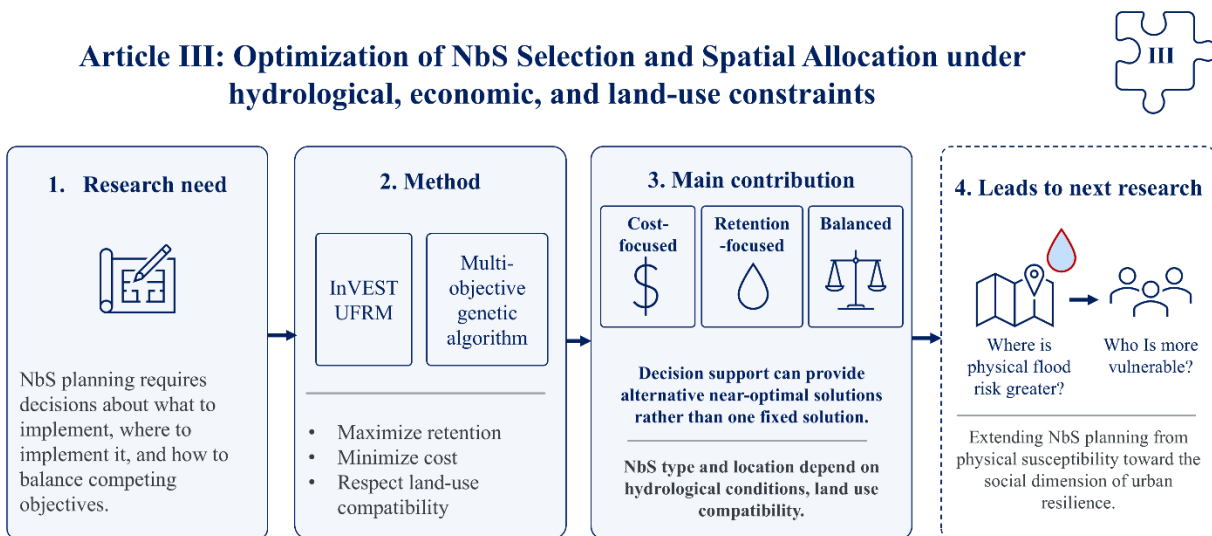


Figure 9. Visual summary of article III. Source: Author's own illustration

4.3.1. Developing the optimization framework for selection and placement of NbS

The resulting paper produced an analytical framework to optimize the spatial allocation and selection of NbS for urban flood risk mitigation in Gdańsk, Poland. By integrating the InVEST Urban Flood Risk Mitigation model with a multi-objective genetic algorithm, the research identified areas of the city with low water retention capacity and high susceptibility to pluvial flooding. The framework optimized the placement of 14 different NbS, simultaneously considering objectives such as maximizing water retention, minimizing implementation costs, and ensuring compliance with land use compatibility constraints (for the full steps and detailed methodology, see Figure 2 in the paper).

4.3.2. Optimization results and its spatial implications and decision-support contributions

The optimization process produced three alternative scenarios: a cost-minimization scenario, a maximum-retention scenario, and a balanced scenario that reconciled environmental performance with economic feasibility. The cost-minimization scenario prioritized reducing implementation costs, resulting in fewer spatial interventions and modification of approximately 49 304 cells, yet still achieved a 14,6% improvement in water retention. The maximum-retention scenario focused on maximizing water retention capacity, proposing interventions in approximately 107 375 cells and achieving the highest retention improvement of 15,5%. The balanced scenario represented a compromise between cost and environmental performance, modifying approximately 105 263 cells to achieve a 14,9% retention improvement while reducing costs relative to the most expensive solution.

The findings revealed noticeable spatial patterns in the effectiveness of NbS implementation across the city. Densely urbanized areas with high levels of impervious surfaces, particularly industrial and central urban districts, exhibited the lowest water retention capacities and benefited most from optimized interventions. Highly urbanized areas had average retention values of approximately 16,3 m³, while greener and less urbanized areas, such as forests and agricultural lands on the outskirts of Gdańsk, showed average retention levels of approximately 24,8 m³. Citywide, the average retention level predicted by the InVEST UFRM model was approximately 20,9 m³, with substantial spatial variation across land-use categories. Very low-retention areas comprised approximately 33,3% of the city, with average retention levels as low as 12,3 m³, whereas very high-retention areas accounted for only 14,6% of the city and demonstrated average retention values of approximately 28,9 m³.

Results also demonstrated that different NbS fulfilled distinguishing roles depending on land use conditions and spatial context (see Figure 11 in the article). Rainwater harvesting cisterns were frequently selected in continuous urban fabric and industrial areas due to their high effectiveness and moderate implementation costs. Permeable pavements and infiltration trenches were commonly allocated to industrial and transportation-related land uses, given their suitability for managing runoff from impervious surfaces. In contrast, vegetated swales, wildflower meadows, and concave green lands were more often assigned to recreational and open urban spaces where

larger-scale ecological interventions were feasible. These findings underscore the need to tailor NbS implementation strategies to local land-use characteristics and hydrological conditions rather than applying uniform interventions citywide.

The paper also highlighted the trade-offs between implementation cost and environmental effectiveness. Lower-cost solutions, such as retention ponds and concave green lands, provided noticeable retention improvements, while more complex interventions, including green roofs and vegetated swales, generally achieved higher runoff reduction at substantially greater costs. The optimization framework demonstrated the value of decision-support systems that balance multiple, sometimes conflicting, criteria. Instead of producing a single optimal solution, the genetic algorithm generated a range of near-optimal alternatives, enabling planners and policymakers to select scenarios aligned with their priorities, budgetary constraints, and environmental objectives.

4.3.3. Future research direction: Extending NbS flood risk mitigation from susceptibility to vulnerability

Articles II and III were primarily concerned with the physical dimensions of urban flooding. Article II sought to identify where in a city the greatest volumes of runoff are generated and, consequently, where flood risk is the highest. The analysis focused exclusively on the physical dimensions of runoff risk, treating urban areas as physical spaces without considering the people who live there or their diverse socioeconomic characteristics.

As a natural progression from assessment to solution development, article III examined configurations for the placement and selection of nature-based solutions that could reduce runoff while maintaining economic efficiency. Like article II, however, article III focused mainly on the physical characteristics of the city and largely overlooked its socioeconomic systems and residents.

As explained earlier in this thesis, the overall PhD research is situated within the discourse of urban resilience. Resilience cannot be adequately assessed by focusing only on physical susceptibility. Therefore, the findings of article III provided the basis for reframing the research question in the subsequent study from “Where in the city is flood risk greatest?” to “Who in the city is most at risk?” Answering this question requires an analysis of the socioeconomic characteristics of urban districts and their relationship with existing NbS, which are intended to reduce flood risk in those areas. This approach makes it possible to identify which parts of the city are vulnerable to flooding, rather than merely physically susceptible to it.

4.4. Article IV

Spatial allocation of nature-based solutions in the form of public green infrastructure in relation to the socio-economic district profile—a GIS-based comparative study of Gdańsk and Rome

The paper discussed in this subchapter was the first attempt to address the social dimension of NbS. Consequently, this research aimed to find correlations between the socio-economic status of municipal districts in the cities of Rome and Gdańsk and the quantity of publicly accessible nature-based solutions (PNbS). Figure 10 visualizes the summary of article IV.

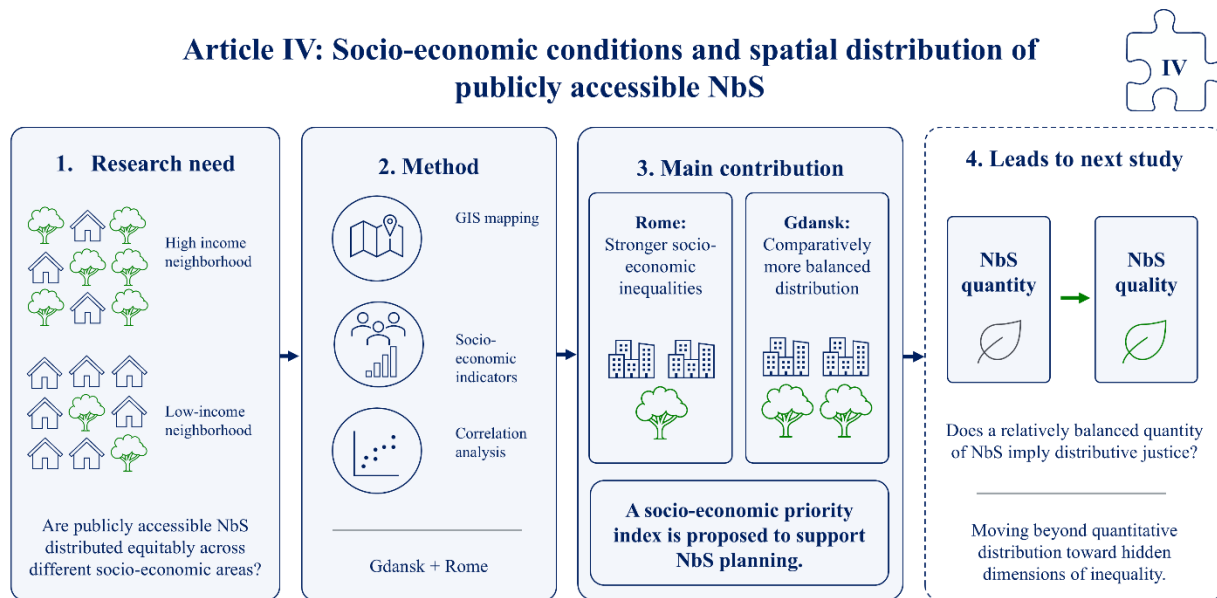


Figure 10. Visual summary of article IV. Source: Author's own illustration

4.4.1. Background and motivation

This paper investigates the spatial distribution of publicly accessible nature-based solutions and their relationship with socio-economic conditions in Gdańsk and Rome. The study was motivated by growing concerns about environmental justice and the unequal distribution of green infrastructure benefits in urban areas. Although nature-based solutions are promoted as key tools for climate adaptation, flood mitigation, and urban resilience, previous research shows access to green infrastructure is often uneven across social groups. The paper also addresses a geographical research gap, as most studies on environmental justice and green infrastructure focus on North America, while comparative European studies are limited. By comparing two cities with different geographical, historical, and urban development patterns, the research aims to better understand how socio-economic conditions influence the spatial allocation of public nature-based solutions.

4.4.2. Main findings

The study uses a GIS-based comparative methodology combining spatial analysis, descriptive mapping, and statistical correlation analysis. Publicly accessible nature-based solutions such as parks, forests, playgrounds, sports fields, waterfront green areas, and other public green spaces were mapped and analyzed at the district level in both cities. Several socio-economic variables were examined in relation to PNbS density. In Rome, the analysis included population density, household income, education rate, and housing prices. In Gdańsk, available district-level data included population density, unemployment rate, and housing prices. Pearson correlation analysis examined relationships between socio-economic indicators and PNbS density. GIS mapping identified spatial patterns and priority districts for future green infrastructure interventions.

The results revealed spatial inequalities in the distribution of public nature-based solutions, especially in Rome. Districts with higher household incomes, educational attainment, and housing prices generally had higher PNbS density, indicating a strong link between socio-economic advantage and access to green infrastructure. In contrast, districts with lower socio-economic conditions often had less public green space. Gdańsk showed a more balanced distribution of PNbS, although some districts with lower environmental quality and weaker socio-economic conditions also had a relatively more limited access. The comparative analysis showed that socio-economic disparities in access to nature-based solutions were stronger in Rome than in Gdańsk. Based on these findings, the study identified priority districts for future green infrastructure interventions and emphasized integrating environmental justice into urban planning and climate adaptation strategies.

4.4.3. Future research directions: Beyond the quantitative assessment of NbS

This research, especially the detailed analysis of results from Gdańsk, revealed new curiosity about hidden dimensions of distributive justice related to NbS in cities. At first glance, Gdańsk showed a relatively balanced distribution of PNbS compared to Rome. Some less affluent districts had lower availability of green spaces, but the disparities did not seem severe enough to indicate urgent spatial inequality or strong environmental injustice. However, this observation revealed an important limitation of the study. The analysis mainly focused on the quantitative dimension of nature-based solutions, examining the amount and spatial distribution of public greenery while largely overlooking qualitative aspects.

This realization raised a broader question: does spatial equality in quantity necessarily translate into equitable access to high-quality urban environments? It suggested that underlying forms of environmental injustice may remain hidden when analysis is limited to numerical distribution alone. Consequently, the findings of this paper served as a starting point for further investigation into the qualitative dimensions of nature-based solutions and urban green infrastructure.

4.5. Article V

Green privilege? Exploring the spatial relations between nature-based solutions and social vulnerability in Nordic cities

This paper builds on the findings and limitations identified in the previous article. While the earlier study examined the quantitative distribution of publicly accessible nature-based solutions in relation to selected socio-economic indicators, results from Gdańsk suggested that balanced spatial distribution does not guarantee environmental justice or equitable access to high-quality urban green spaces. Therefore, this paper advances the research by investigating both the quantity of NbS and their ecological quality, as well as their spatial relationships with social vulnerability. The study introduces a more comprehensive and spatially detailed approach to understanding distributive justice in urban green infrastructure by integrating multiple socio-economic dimensions, finer-scale spatial analysis, and spatial clustering techniques. Through this progression, the research moves beyond simple statistical comparisons toward a more nuanced understanding of how environmental inequalities are produced and spatially embedded within cities. Figure 11 demonstrates the visual summary of article V.

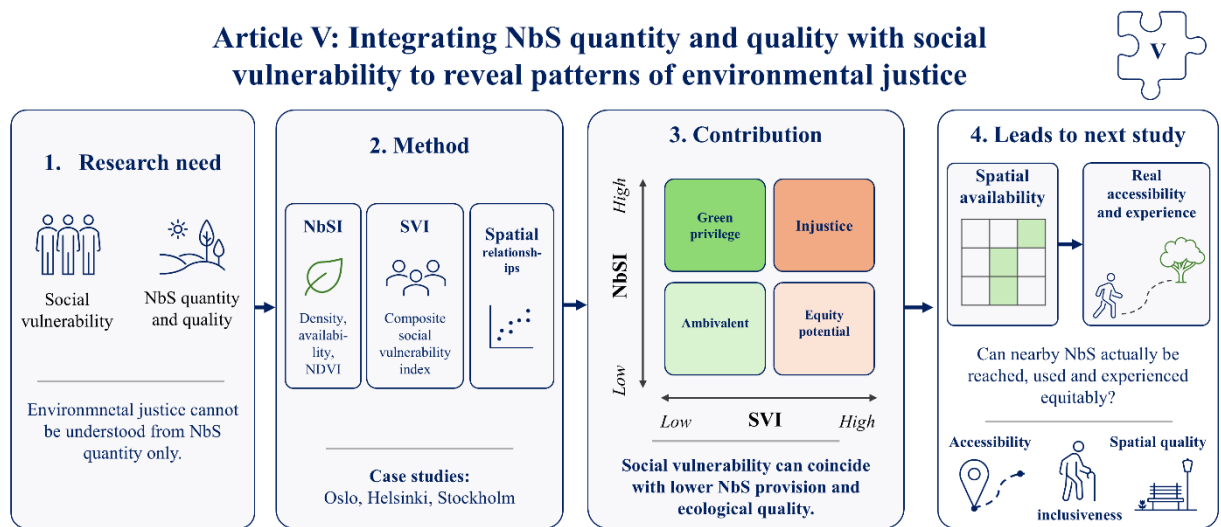


Figure 11. Visual summary of article V. Source: Author's own illustration

4.5.1. Background and motivation

The paper investigates the spatial relationship between nature-based solutions and social vulnerability in Oslo, Helsinki, and Stockholm. The selection of these case studies was motivated by several factors. First, the three cities share similar climatic conditions, strong environmental policies, welfare-oriented governance systems, and long-standing commitments to sustainable urban planning, allowing meaningful comparison across comparable urban contexts. At the same time, the cities differ in planning traditions, approaches to NbS implementation, urban

morphology, and socio-spatial development patterns. Importantly, these Nordic cities are often internationally seen as models of environmental governance and social equity. Rather than assuming these cities are inherently equitable, the study critically examines whether socio-spatial inequalities in access to nature-based solutions persist under advanced welfare and planning systems. This makes them valuable test cases for investigating hidden forms of environmental injustice and “green privilege.”

The study was motivated by methodological and conceptual gaps identified in previous research. Existing studies on environmental justice and green infrastructure often focus on the quantity or accessibility of green spaces while overlooking qualitative dimensions like vegetation condition and ecological performance. Furthermore, many studies rely on broad administrative scales and limited socio-economic indicators, which may conceal localized disparities and complex vulnerability patterns. In response, this paper advances the previous article in four ways: first, it evaluates both the quantity and quality of NbS; second, it incorporates spatial correlation and clustering analysis instead of relying solely on traditional statistical relationships; third, it applies analysis at a finer sub-district scale, reducing the chance that inequalities remain hidden within aggregated urban units; and fourth, it replaces simplified socio-economic indicators with a multidimensional Social Vulnerability Index (SVI) that integrates several demographic and socio-economic factors into a more comprehensive representation of vulnerability.

4.5.2. Main findings

The study applies a comparative GIS-based methodology combining spatial analysis, composite indexing, Principal Component Analysis (PCA), Local Indicators of Spatial Association (LISA), and inequality analysis using Gini coefficient. To assess nature-based solutions, the research developed a Nature-based Solutions Index (NbSI) capturing both quantitative and qualitative dimensions of urban greenery. The NbSI integrates three indicators: NbS density, representing the spatial concentration of green infrastructure within each sub-district; NbS availability per capita, reflecting the relative accessibility of green spaces to residents; and NDVI values derived from Sentinel-2 satellite imagery, representing vegetation health and ecological condition. Six vegetation-related land-cover classes from the Urban Atlas dataset were included, such as green urban areas, grasslands, and wetlands.

To evaluate social vulnerability, the study constructed a Social Vulnerability Index (SVI) using a deductive framework adapted from prior research. Eleven socio-economic and demographic indicators were included, such as taxable income, housing conditions, immigration status, unemployment, educational attainment, age structure, household composition, and family characteristics. PCA was used to reduce dimensionality and identify dominant vulnerability components within each city. Unlike the previous article, which relied mainly on direct statistical relationships between selected socio-economic variables and green infrastructure density, this study also employed spatial correlation analysis and bivariate LISA cluster analysis to identify

geographically significant relationships between NbS characteristics and social vulnerability patterns. Using sub-district-level spatial units enabled a finer-scale analysis of socio-spatial inequalities and reduced the chance that localized disparities would remain concealed within larger administrative boundaries.

The results revealed noticeable socio-spatial inequalities in both the quantity and quality of NbS across all three cities. Socially vulnerable districts frequently coincided with areas of lower NbS coverage and lower vegetation quality, demonstrating that environmental inequalities persist even within Nordic cities characterized by strong welfare systems and progressive environmental policies. The study identified four recurring spatial patterns: green privilege, where affluent areas concentrated high-quality NbS; injustice, where vulnerable communities lacked adequate green infrastructure; ambivalent zones, where relatively high NbS coexisted with social vulnerability; and equity potential zones, where future equitable interventions could be prioritized. Helsinki had the highest inequality in NbS distribution, as measured by the Gini coefficient, while Oslo and Stockholm also showed significant disparities.

4.5.3. Future research directions: From spatial availability to real-life accessibility

This study showed that evaluating the quantity and ecological quality of nature-based solutions provides important insight about patterns of environmental inequality and social vulnerability. However, several limitations emerged from the analysis. First, NDVI mainly reflects vegetation's biophysical condition and does not capture the social or experiential aspects of green space quality, such as comfort, safety, walkability, attractiveness, or perceived environmental quality. Second, although spatial availability of nature-based solutions is often used as a proxy for accessibility, physical proximity alone does not guarantee meaningful or equitable access. Structural barriers, street connectivity, mobility limitations, and socio-economic conditions can greatly affect different population groups' ability to benefit from nearby green spaces.

These limitations indicate the need for future research to move past static distributional analysis toward more human-centered understandings of urban environmental quality. In particular, there is a growing need to examine how accessibility, inclusiveness, and street-level spatial experience influence the actual usability and social value of urban green infrastructure. Consequently, the question posed by this paper for future research direction is as follows:

How can accessibility, inclusiveness, and street-level spatial quality assessment contribute to a more comprehensive evaluation of urban green infrastructure?

4.6. Article VI

Integrating AI and spatial analysis for resilient and inclusive 15-minute cities: A case study of Gdańsk

This paper builds on previous studies by extending the investigation from the spatial distribution and ecological quality of nature-based solutions to questions of accessibility, inclusiveness, and everyday spatial experience. It focuses on how urban greenery can support resilient and livable neighborhoods within the 15-minute city concept through accessibility analysis and AI-assisted spatial quality assessment. Figure 12 presents the visual summary of paper VI.

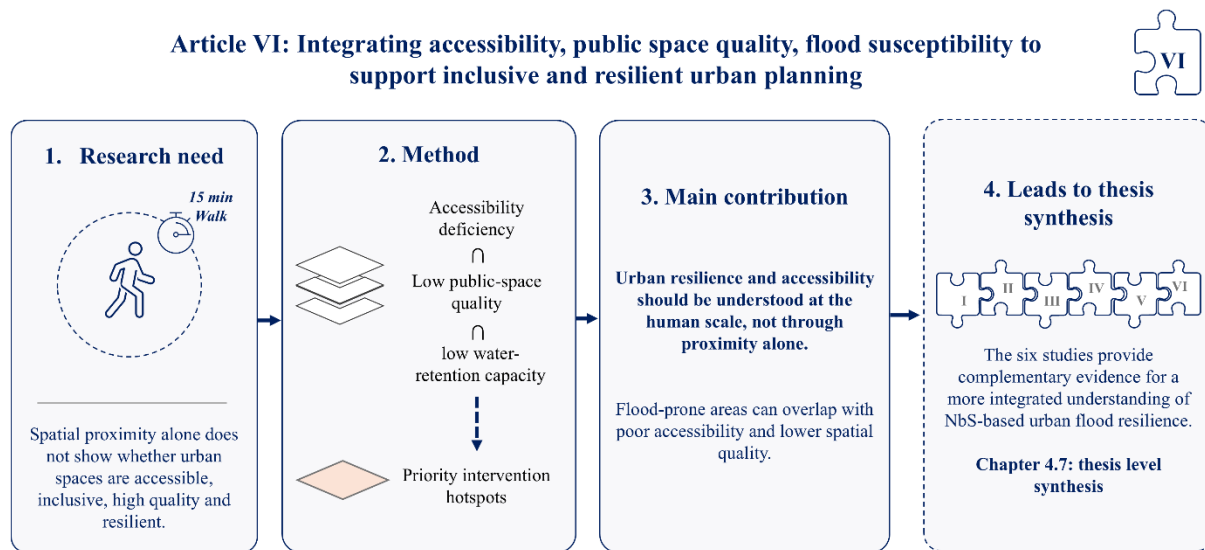


Figure 12. Visual summary of article VI. Source: Author's own illustration

4.6.1. Background and motivation

The 15-minute city (FMC) is a compact urban planning approach that has gained much attention in recent years. Its core idea is to plan urban areas in a way that all necessary amenities are within a 15-minute walk for citizens. Because the concept is flexible and lacks a universal definition, several papers have tried to answer questions about its applicability. These include how to assess it in cities and which essential services should be included in the framework. However, despite growing literature, several research gaps remain. These include inclusivity, environmental resilience, public space quality, and methodological approaches. Existing FMC studies mainly focus on proximity and accessibility metrics, often overlooking the mobility needs of vulnerable groups such as elderly people, children, and individuals with disabilities. Meanwhile, qualitative aspects of public spaces, like safety, comfort, greenery, aesthetics, and pedestrian experience, are insufficiently integrated into accessibility assessments. Also, climate-related challenges, especially flooding and stormwater vulnerability, are rarely included in FMC frameworks despite their direct impact on urban accessibility and the usability of public spaces.

Moreover, current research often treats accessibility, environmental resilience, and social inclusivity separately, lacking integrated frameworks that evaluate these dimensions simultaneously.

This paper addresses these gaps by developing an integrated framework to evaluate resilient and inclusive 15-minute cities through combined assessments of accessibility, public space quality, and environmental susceptibility. Using the Young City district in Gdańsk as a case study, the research integrates GIS-based network analysis, AI-driven spatial quality assessment, and flood modeling to go beyond conventional proximity-based FMC evaluations. The study considers the needs of vulnerable groups by applying a lower walking speed in network analysis and evaluates the qualitative characteristics of pedestrian environments through machine-learning-based image analysis. Flood-prone areas are also integrated into the accessibility framework to examine how environmental risks affect urban usability and resilience. By combining social, spatial, and environmental dimensions in one methodological approach, the paper offers a more comprehensive and operational framework for inclusive, climate-resilient, and people-centered urban planning. It also responds to questions raised in previous papers in this thesis about moving beyond purely ecological assessments of nature-based solutions toward evaluating spatial quality and real-life accessibility. Specifically, the study examines accessibility to urban green spaces through the actual urban network of streets, pedestrian paths, and walkable connections that shape how citizens experience and reach these spaces daily, rather than evaluating accessibility solely based on the spatial presence or distribution of urban greenery in cities.

4.6.2. Main findings

Findings show that evaluating 15-minute cities only through proximity and accessibility metrics is insufficient to understand real urban livability, inclusivity, and resilience. By integrating spatial quality assessment, network-based accessibility analysis, and environmental flood susceptibility modeling, the study identified clear spatial inequalities within the Young City district of Gdańsk. The results revealed that although some central redevelopment areas had good accessibility to amenities and public transportation, many surrounding areas, especially former fence-line communities, remained underserved in public space quality, greenery, accessibility, and environmental resilience. The study also showed that flood-prone areas often overlapped with zones of low spatial quality and limited amenity access, demonstrating how climate vulnerability can reduce effective accessibility and usability of urban spaces. By overlaying several analytical layers, the paper developed hotspot maps highlighting areas of high priority for interventions (see figure 16 in article VI). Additionally, the paper showed that machine learning-based image analysis and GIS methods can provide scalable and efficient tools for evaluating urban quality and identifying priority intervention areas.

4.6.3. Future research direction

Paper VI suggests several directions for future research to improve the 15-minute city framework, digital urban assessment methods, and climate-resilient planning. One key direction is integrating additional environmental risks beyond flooding, such as urban heat islands, air pollution, and other climate-related hazards, to create more comprehensive environmental resilience assessments. The study also recommends expanding the use of alternative data sources, including drone imagery, IoT sensors, and crowdsourced data. This would overcome the limitations of GSVI and improve the evaluation of non-road public spaces, such as parks and pedestrian areas. Another direction is developing dynamic, real-time monitoring systems to evaluate how public spaces change over time following urban interventions. The paper also emphasizes the need for participatory, community-centered planning approaches that involve local residents in co-designing regeneration strategies, especially in historically marginalized neighborhoods. Finally, the study highlights the importance of adapting the proposed framework to diverse urban contexts and environmental conditions across cities worldwide to test its replicability and transferability.

4.7. From individual articles to thesis-level synthesis

The six articles explored different but related research topics, starting with urban flood processes and land use sensitivity, and moving toward NbS optimization, distributive justice, social vulnerability, accessibility, and spatial quality. Figure 13 shows how these articles connect as parts of the overall research. Each study offers its own methodological and scientific viewpoint, and together they form the foundation for the thesis-level synthesis developed in chapter 5. As mentioned earlier in the beginning of this chapter, each of these individual publications functions as an individual puzzle piece that is a building block of the final integrated framework, which will be presented in the next chapter. Figure 13 brings all of these pieces together and demonstrates them within the broader analytical dimensions of the present dissertation.

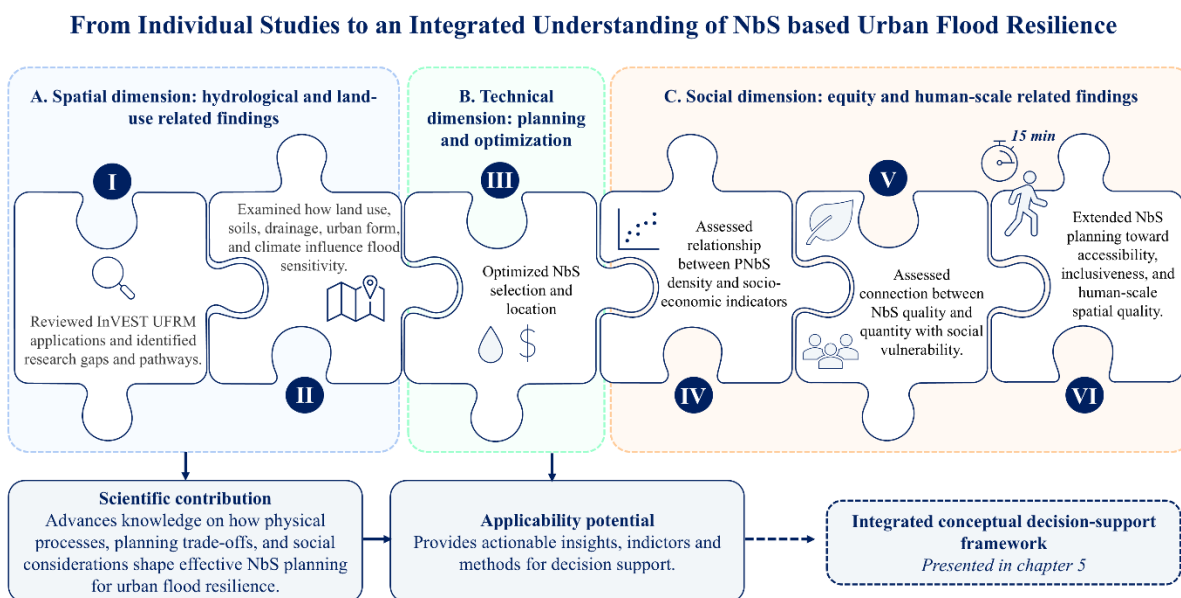


Figure 13. Progression of articles I-VI toward an integrated understanding of NbS-based urban flood resilience. Source: Author's own illustration

Chapter 5: Cross-study synthesis and presenting the integrated NbS planning framework

5.1. Synthesizing findings across the studies

This chapter synthesizes the findings of the six articles and explains how they shape the thesis's overall contribution. It begins with the spatial and technical dimensions of urban flood resilience, examining how land use change and local environmental conditions influence flood susceptibility. Then it moves from flood assessment to selecting and spatially optimizing nature-based solutions, considering hydrological effectiveness, cost, and land use compatibility. Finally, it expands the analysis to social vulnerability, distributive justice, accessibility, and spatial quality. It concludes by identifying the key principles that inform the final integrated decision-support framework.

5.1.1. Urbanization and the spatial production of flood risk

Urban flooding is increasingly recognized as a major environmental challenge in cities, and the growing body of evidence reviewed in article I demonstrates a strong relationship between urbanization, climate change, and increased flood risk. However, article II was not primarily concerned with simply reaffirming that urbanization increases runoff and flood susceptibility, as this relationship is already extensively documented in existing literature. Instead, the article sought to move beyond this established understanding by examining why the hydrological impacts of urbanization differ across urban contexts and land-use transitions.

Through comparative analysis of runoff dynamics between 2012 and 2018 across four European case studies, the findings showed that increases in runoff are not determined solely by the extent of urban expansion but by the interaction of multiple environmental and spatial factors. The application of the InVEST Urban Stormwater Retention Model highlighted the role of climatic conditions, soil characteristics, drainage infrastructure, land use configuration, and urban morphology in shaping hydrological responses within cities. Different combinations of these variables produced different runoff patterns and flood sensitivities across the studied urban environments.

While previous studies emphasized the importance of environmental conditions in influencing runoff generation, article II further explored the role of urban morphology and specific characteristics of land-use transitions. In this context, the development of the WASI was an important conceptual contribution because it enabled assessment of how sensitive different forms of land-use change are to runoff generation, rather than focusing solely on the quantity of urban expansion. The findings showed that different types of land conversion can produce different hydrological consequences even when the total amount of urbanized land remains comparable.

This has important implications for urban planning and flood resilience strategies. In complex urban environments with competing land use demands, financial limitations, and multiple

planning priorities, understanding the hydrological sensitivity of different urban transitions is particularly valuable. Rather than distributing resources uniformly, sensitivity-based approaches like WASI can support more targeted, spatially prioritized interventions by identifying locations where flood mitigation measures will yield the greatest resilience benefits.

More importantly, the findings align closely with broader resilience-oriented approaches to urban flood management. Conventional flood mitigation strategies have historically emphasized control, standardization, and risk reduction through relatively rigid engineering interventions, often without fully accounting for contextual variability and urban sensitivity. By contrast, the WASI framework shows that urban environments respond differently to land use transitions depending on local environmental, hydrological, and spatial conditions. This reinforces the importance of adaptive and context-sensitive planning approaches that respond to the specific characteristics and vulnerabilities of individual urban systems.

From this perspective, resilience emerges not through uniform mitigation measures but through the capacity to understand, anticipate, and adapt to varying levels of hydrological sensitivity across urban landscapes. Consequently, the findings further support the growing relevance of nature-based solutions within urban flood resilience planning, as NbS offer flexible, multifunctional, and context-responsive approaches that can be adapted to the specific environmental and spatial conditions of different urban areas.

5.1.2. From hydrological assessment to NbS planning and optimization

Article II demonstrated that urban flood risk is shaped by the interaction of multiple environmental, hydrological, and spatial components rather than a single factor. The analysis showed that different combinations of land use change, soil conditions, climatic characteristics, drainage infrastructure, and urban morphology produce varying levels of runoff and flood sensitivity across urban contexts. This finding highlighted the role of trade-offs in urban flood resilience planning. In cities, where environmental, economic, spatial, and infrastructural priorities interact continuously, reducing one risk or pressure may depend on several competing and non-competing factors at the same time. As a result, planning effective responses to flood risk is a complex task that requires more than identifying where runoff increases.

The findings reinforced the importance of moving beyond rigid and standardized flood mitigation strategies. As discussed in chapter 1, conventional flood management often relies on fixed engineering interventions designed to control or reduce risk. However, the varying sensitivities identified in article II suggest cities require more adaptive and context-sensitive approaches. NbS are particularly relevant because they align closely with resilience thinking. Rather than functioning only as technical mitigation measures, NbS can be adapted to different spatial, environmental, and hydrological conditions while providing multiple ecological and social benefits. However, urban flood resilience cannot be achieved by implementing isolated NbS interventions. If NbS are treated as individual projects disconnected from broader urban

development, their long-term effectiveness is limited. Instead, NbS need to be embedded in conventional urban planning and integrated into regular spatial decision-making. The question is not only whether NbS can reduce runoff, but also where they should be implemented, which types are most suitable, and how they can be prioritized under real urban constraints.

This need created the foundation for article III. Article I showed that despite numerous flood modelling tools with strong assessment capabilities, fewer tools support practical decision-making, especially for spatial selection and implementation of NbS. Building on this gap, article III focused on optimizing the placement and selection of different NbS types while addressing multiple trade-offs and competing planning objectives. The optimization approach was important because urban planning must balance several objectives at once, including flood mitigation performance, implementation cost, land use compatibility, spatial feasibility, and long-term resilience. Rather than producing a single fixed solution, the optimization framework could offer a flexible decision-support approach capable of generating near-optimal alternatives under different planning priorities. In this way, article III translated the understanding of flood sensitivity from article II into a more operational planning process. Understanding flood sensitivity alone is insufficient unless this knowledge is transformed into practical strategies that identify where, how, and under what conditions NbS should be implemented. Through the optimization approach developed in article III, NbS could be positioned not only as flood mitigation measures but as active components of urban decision-making and resilience-oriented planning. This represents an important step from hydrological assessment toward strategic NbS planning, where interventions are selected and allocated according to the specific sensitivities, constraints, and opportunities of the urban context.

5.1.3. The social dimension of NbS-based flood resilience

While article III demonstrated the importance of spatial prioritization and optimization in NbS planning, it also raised a broader question about the social consequences of resilience interventions. If nature-based solutions are planned solely on the basis of effectiveness, implementation cost, and spatial and technical feasibility, their social distribution and justice implications risk being insufficiently addressed. The transition from article III to articles IV and V marked an important conceptual shift in the thesis: from asking where NbS should be implemented to reduce runoff, to asking who benefits from NbS and whether these benefits are distributed equitably across urban populations. This shift was further extended in article VI, which moved the analysis from spatial distribution toward accessibility, usability, and the everyday experience of urban resilience. This shift is important because urban flood resilience is not only a technical or environmental challenge, but also a social one. Climate risks, environmental amenities, and adaptation benefits are not experienced equally by all urban residents. Socioeconomic status, age, income, education, housing conditions, mobility, all influence the capacity of different groups to prepare for, respond to, and recover from

environmental hazards. Therefore, evaluating NbS solely through hydrological indicators, such as runoff reduction or water retention, provides an incomplete understanding of their role in urban resilience. A socially meaningful assessment must also consider whether NbS are distributed fairly and whether vulnerable communities can also benefit from them.

Article IV addressed this issue by examining the spatial distribution of publicly accessible nature-based solutions in relation to socioeconomic characteristics in Gdańsk and Rome. The findings showed that the distribution of public NbS is connected to broader socio-spatial structures within cities. In Rome, districts with higher income, education levels, and housing prices generally had greater access to public NbS, showing a stronger link between socioeconomic advantage and green infrastructure provision. Gdańsk showed a more balanced distribution, but some districts with weaker socioeconomic and environmental conditions still had limited access to public green infrastructure. These findings show that the spatial allocation of NbS cannot be understood separately from urban inequality and distributive justice.

However, article IV revealed an important limitation: evaluating the quantity of publicly accessible NbS alone is not enough to fully assess environmental justice. A district may appear well supplied with green space by area or density but still lack high-quality, ecologically valuable, accessible, or socially beneficial green infrastructure. This recognition became the starting point for article V, which expanded the analysis from quantity to a more comprehensive assessment of both quantity and quality. By combining NbS density, NbS per capita, and vegetation quality through the Nature-based Solutions Index, and comparing these patterns with a multidimensional Social Vulnerability Index, article V provided a more detailed understanding of how green infrastructure intersects with social vulnerability.

The findings from article V showed that socio-spatial inequalities in NbS provision persist even in Nordic cities often associated with strong welfare systems, progressive environmental policies, and high urban planning standards. Socially vulnerable areas frequently had lower quantity or quality of NbS, while more advantaged areas benefited from better green infrastructure. This finding is important because it challenges the assumption that environmentally progressive or welfare-oriented cities are automatically equitable in access to high-quality nature-based solutions. Instead, the results suggest hidden forms of green inequality remain embedded within urban systems, even where overall environmental performance appears strong. The concept of green privilege helps interpret these findings. Green privilege refers to situations where socially advantaged groups have greater access to high-quality green infrastructure and ecosystem services, while vulnerable communities receive fewer or lower-quality environmental benefits. In NbS planning, this is important because NbS are often promoted as universally beneficial climate adaptation measures. However, the thesis findings show these benefits are not automatically distributed equally. Without explicit attention to vulnerability and justice, NbS implementation may unintentionally reproduce existing inequalities or concentrate resilience benefits in already advantaged urban areas.

Article VI extended this justice perspective by showing that environmental justice in NbS planning cannot be assessed only through distribution or ecological quality. Even when green infrastructure exists in an urban area, it may not be accessible or usable for all residents. By integrating network-based accessibility analysis, spatial quality assessment, and flood susceptibility, article VI shifted the focus from the presence of NbS to their lived accessibility and practical usability. This is especially important for vulnerable groups, whose ability to benefit from NbS may be limited by walking conditions, mobility barriers, poor public-space quality, safety concerns, or environmental risks. Therefore, articles IV, V, and VI together show that socially just NbS planning requires attention not only to who has access to NbS and their quality, but also whether people can realistically reach, use, and benefit from these spaces in everyday life.

Consequently, the findings from articles IV, V and VI altogether show that environmental justice must be a core dimension of urban flood resilience planning, not a secondary or optional consideration. NbS planning should ask not only where interventions are hydrologically effective but also where they are socially needed, who benefits, and whether they reduce or reinforce existing inequalities. It should also ask whether NbS are accessible, usable, and capable of improving everyday urban life for different social groups. This requires integrating social vulnerability, distributive justice, accessibility, and spatial quality into NbS planning and prioritization. In this way, the thesis moves beyond a purely technical understanding of flood resilience toward a more socially embedded and justice-oriented approach.

5.2. Synthesizing the articles' findings into an integrated decision-support framework

This chapter synthesizes the findings of the articles in this thesis and explains how they collectively constitute the basis for an integrated decision-support framework for nature-based solution planning. While each article addressed a specific research question, the thesis's overall contribution lies in connecting these studies into a coherent planning logic for flood-resilient and socially equitable urban planning. The framework brings together the knowledge, methods, and planning insights from the six articles at a conceptual level. It does not aim to be a single computational model that combines all the methods and indicators from the individual studies. Instead, it shows how their different insights can help inform the interconnected aspects of planning and decision-making for NbS.

The dissertation started with the recognition that urban flood risk cannot be understood only as a technical or hydrological problem. Flooding in cities results from the interaction of climate conditions, land-use change, urban form, soil characteristics, infrastructure, and social vulnerability. Effective flood mitigation requires approaches beyond conventional risk assessment, including spatial planning, environmental performance, economic feasibility, and social equity.

Article I provided the theoretical and methodological basis for the thesis by reviewing the application of the InVEST Urban Flood Risk Mitigation model in urban flood resilience research. The review showed that InVEST-based models are increasingly used to evaluate runoff, ecosystem services, green infrastructure, and nature-based solutions. However, it revealed that many studies remain focused on assessment rather than decision support. This finding highlighted the need to move from identifying flood-prone areas to supporting the selection, prioritization, and implementation of NbS in urban planning. Building on this gap, article II examined the relationship between land use change and flood sensitivity in European cities. The findings showed that the hydrological impacts of urbanization are not determined only by the amount of land converted to artificial surfaces. Instead, flood sensitivity depends on the type of land use transition, soil conditions, urban morphology, climatic context, and local drainage characteristics. The development of the Water Accumulation Sensitivity Index (WASI) enabled evaluation of which land use changes cause greater increases in water accumulation. This shifted the analysis from general land take measurement to a more targeted understanding of flood-sensitive urban planning.

Article III translated this understanding into a more operational planning process by developing a multi-objective optimization approach for NbS allocation in Gdańsk. The study integrated the InVEST UFRM model with a genetic algorithm to optimize the selection and spatial placement of different NbS types. The optimization considered runoff reduction, implementation cost, and land use compatibility. The results showed that NbS planning involves trade-offs between hydrological effectiveness and economic feasibility. Instead of producing a single fixed solution, the optimization generated alternative scenarios, allowing planners to choose between cost-effective, high-retention, and balanced strategies.

However, the following articles showed that flood-resilient NbS planning should not be limited to hydrological and economic criteria. Article IV introduced distributive justice by examining the spatial allocation of publicly accessible NbS in relation to socio-economic conditions in Gdańsk and Rome. Article V expanded this justice-oriented perspective by examining the relationship between NbS quantity, NbS quality, and social vulnerability in Nordic cities. Together, these articles showed that NbS distribution can reflect broader patterns of social and spatial inequality, and that socially vulnerable areas may experience lower NbS provision or lower ecological quality.

Article VI further developed this line of thinking by moving from spatial presence to real accessibility and public space quality. The study showed that the presence of green or public spaces on a map does not mean they are accessible, inclusive, safe, or attractive in everyday life. By combining network-based accessibility analysis, AI-based spatial quality assessment, and flood susceptibility modeling, the article demonstrated that urban resilience should be understood at the human scale.

Taken together, the articles demonstrate a clear progression. The thesis begins with flood risk and land use sensitivity, moves toward NbS optimization, and then expands the analysis to

include distributive justice, social vulnerability, accessibility, and spatial quality. This progression shows that NbS planning for urban flood resilience should not rely only on hydrological effectiveness; it should also consider where interventions are most needed from a social and spatial justice perspective.

Although the six articles followed different research paths, their findings can be organized around the three overarching analytical dimensions of this thesis: spatial, technical, and social. This grouping does not mean that each study followed the same analytical steps. Instead, it helps show how the different research directions in the thesis work together as parts of a broader approach to NbS planning.

The spatial dimension focuses on identifying flood risks, land use impacts, and the locations where interventions might be needed. The technical dimension looks at how to choose, place, and compare different NbS strategies, as well as their feasibility and optimization. The social dimension considers issues such as equity, social vulnerability, accessibility, and the quality of public spaces for citizens. Even though, these dimensions were studied using different methods and case studies, the current dissertation demonstrates how they are closely linked to each other in NbS planning.

Figure 14 brings together these research directions in a single framework and shows how they help with decision support. The spatial and social dimensions provide complementary evidence for identifying and prioritizing areas for intervention, while the technical dimension supports the selection, allocation, and comparison of NbS strategies under different objectives and constraints. They show both where environmental pressures are highest and where social needs should guide planning. The technical and planning dimension helps decide which interventions are suitable, where they can be carried out, and how different strategies work under various objectives and constraints. This framework combines findings and planning logic, rather than merging all the methods from the six articles into one mathematical or computational model.

Integrated Decision-Support Framework for NbS-Based Urban Flood Resilience

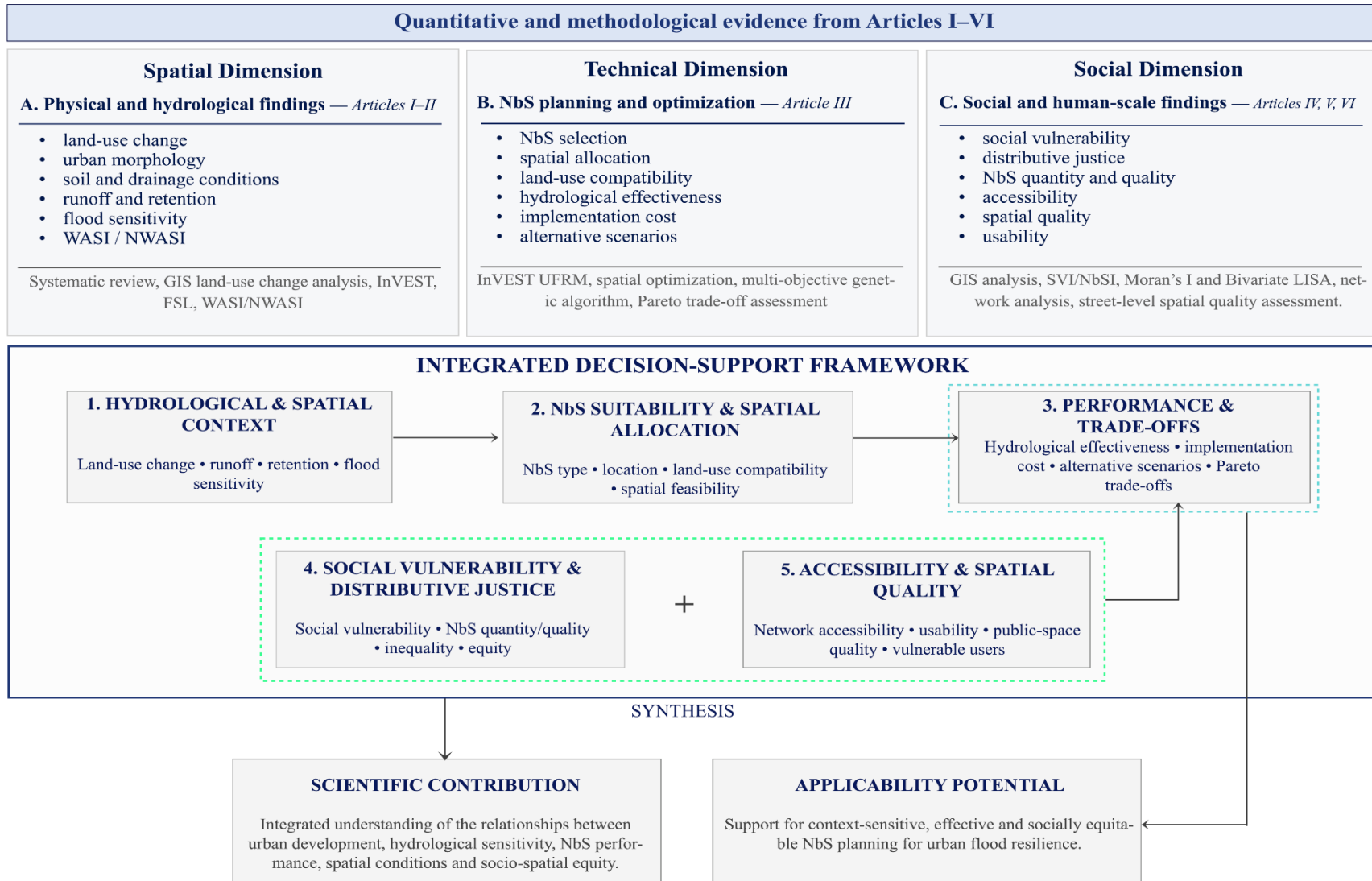


Figure 14. Conceptual progression: article findings as building blocks of the integrated decision-support framework. Source: Author's own illustration

At the decision-support level, the framework translates the combined findings of the six studies into several planning principles. Priority should be given to areas where hydrological sensitivity overlaps with social vulnerability. NbS selection should reflect local environmental, hydrological, and land use conditions, while balancing objectives such as runoff reduction, cost, spatial feasibility, equity, ecological quality, and accessibility. Alternative implementation scenarios can then be compared to make trade-offs explicit and support context-specific planning decisions. Overall, NbS should be integrated into broader urban planning rather than treated as isolated flood-mitigation measures.

Beyond its practical decision-support value, the framework also reflects the scientific contribution of the thesis. By combining the different methods, indices, and analyses developed across the six studies, the research helps reveal important relationships among the spatial, technical, and social dimensions that shape flood risk and NbS planning. These relationships help identify which factors are important, how they influence one another, and where potential trade-offs emerge. Such understanding is essential for defining the relevant criteria, objectives, and constraints that could be incorporated into optimization-based decision support. In this way, the thesis provides not only practical guidance for planning, but also a knowledge base for determining what should be considered in more integrated NbS decision-making and how these considerations relate to one another.

5.3. Achievement of the research goal, objectives, questions, and theses

By putting together the findings of articles I–VI, it becomes evident that the overall research goal presented at the beginning of this doctoral dissertation was fully achieved through the realization of each research objective, with each of them dealing with one of the dimensions of the final framework. The study achieved RO1–RO5, addressed RQ1–RQ5, and supported RT1–RT3 within the scope of the conducted studies. Accordingly, figure 15 summarizes this alignment and shows how the individual research components contribute to the integrated conceptual decision-support framework. By taking a logical route starting from the review paper, which shed light on current research gaps and shaped the subsequent research, it became possible to carry out each publication responsible for answering the outlined research questions. Article I helped find the InVEST UFRM model as a useful tool for mapping runoff within an urban setting, and it also showed the areas and ways in which it could be utilized in order to cover the present research gaps. Subsequently, in article II, it became possible not only to provide an answer to the second research question and find how different conditions and land use changes in cities cause runoff accumulation, but it also led to creating the novel indices of WASI and NWASI that could help plan NbS in cities in locations that are more sensitive to runoff accumulation. Article III next addressed the third question by building and testing a multi-objective optimization framework, demonstrating a positive effect and noticeable runoff reduction when choosing to utilize digital tools for planning NbS while having to balance multiple competing objectives and also

considering constraints. The next two papers (articles IV and V) delve more into the social dimension of this research and examined the quantity and quality aspects of NbS in cities and their possible correlation with socio-economic conditions and social vulnerability of urban districts. Lastly, paper number VI showcased the overlaying of different essential aspects in urban life for citizens, such as quality of urban spaces, walking distance to essential amenities, and presence of green spaces, as well as areas with high runoff potential to showcase hotspots in need of interventions which could benefit from implementing new NbS there due to their multifunctionality properties. All of the papers were pieces of the bigger intended picture. Chapter 5 in the current dissertation brought all of these pieces together to construct the final integrated framework, which not only can be utilized in a practical sense, but also has the scientific merit of sharing lesser-known aspects of NbS for flood resilience in cities, especially through a multidimensional lens.

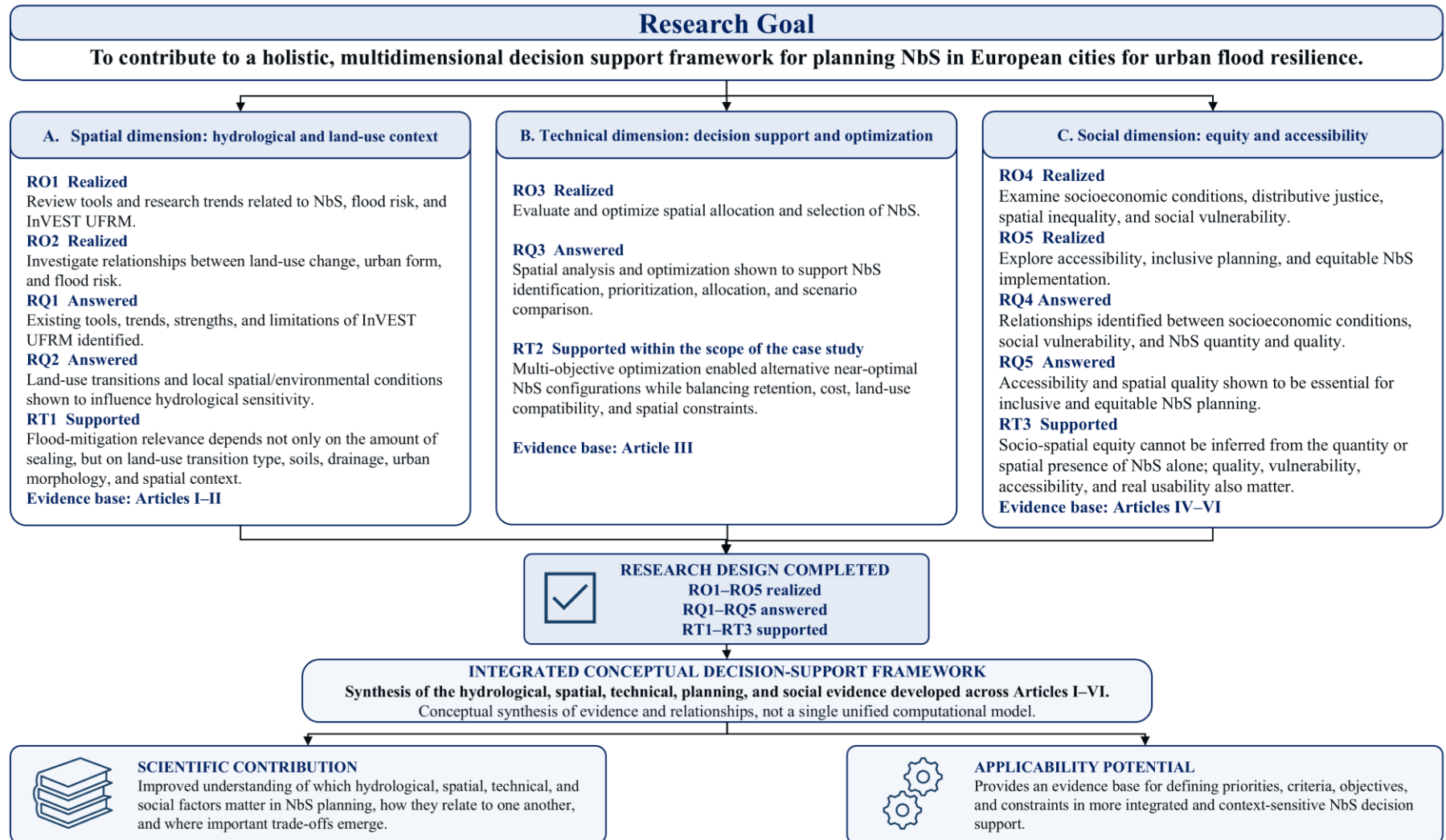


Figure 15. Addressing the research questions and achieving the overall research goal. Source: Author's own illustration

Chapter 6: Limitations and recommendations for future research

From a methodological perspective, the main limitations of this research concern the scale, resolution, and granularity of the input data. The urban land use and land cover datasets, which formed the backbone of several InVEST-based analyses in this thesis, were derived from the Urban Atlas dataset. Although this dataset provides a harmonized and comparable basis for cross-city analysis, its minimum mapping unit and generalized classification may obscure fine-scale urban features, mixed-use patterns, small green spaces, and micro-scale variations in imperviousness. This is particularly relevant in dense urban areas, where small changes in land cover can significantly influence hydrological performance, accessibility, and the distribution of ecosystem services. Therefore, the spatial resolution and thematic generalization of the input data may have affected the precision and granularity of the model outputs. A second limitation relates to the use of InVEST models. The InVEST Urban Stormwater Retention Model used in the thesis is a static, spatially explicit, empirical model rather than a dynamic hydrological simulator. It estimates long-term water accumulation potential but does not simulate flow routing, runoff timing, hydrographs, or event-based flood dynamics. Consequently, the results should be interpreted as relative indicators of runoff and retention potential rather than precise predictions of flood events. This limitation is particularly important for article II and the flood-sensitive land take analysis, where the model was used to compare hydrological sensitivity across different land use transitions and urban contexts. The paper itself notes that the model outputs should be understood as accumulated water volume potential rather than event-based flood dynamics. The InVEST UFRM model used in article III also depends heavily on the accuracy and quality of the input data, especially land use maps and soil characteristics. Any inaccuracies in these datasets can propagate through the model, affecting the reliability of the results. In addition, both the UFRM and stormwater retention models are less forgiving of inconsistencies or simplifications in input layers, which can lead to disrupted or distorted outputs. This sensitivity is important because several analyses in the thesis rely on publicly available datasets that may vary in precision across cities and contexts. The article III limitations section specifically states that UFRM accuracy is highly dependent on land use and soil data quality.

The optimization component of this research is subject to several limitations. The genetic algorithm employed in article III effectively balanced multiple objectives, including implementation cost, water retention capacity, land use compatibility, and the placement of NbS. However, similar to other heuristic optimization methods, it may not consistently converge to the global optimum in complex solution spaces. Consequently, the results should be interpreted as near-optimal rather than definitive optimal configurations. Additionally, the computational demand of the method increases substantially with higher spatial resolution of input data. Scaling the analysis to finer-resolution maps would require further improvements in computational efficiency. Another significant limitation is that the optimization process was static rather than dynamic. It did not incorporate future urban growth, evolving land use patterns, climate change projections, or anticipated changes in rainfall intensity. This restricts the capacity of the

optimized NbS scenarios to account for long-term urban and climatic uncertainties. Future research should integrate urban growth scenarios, climate projections, infrastructure constraints, land availability, construction feasibility, long-term maintenance costs, and ongoing performance monitoring of NbS. Article III explicitly acknowledges that future urban growth and climate change are dynamic factors not included in the optimization process, yet they could substantially influence the long-term effectiveness of NbS implementation.

Article IV, which compared the spatial allocation of public nature-based solutions in Gdańsk and Rome, is subject to several limitations. The comparison between the two cities was constrained by differences in data availability, municipal systems, and the number of spatial units. Rome provided data for 15 districts, whereas Gdansk included more than twice as many units, reducing the direct comparability of statistical results. Additionally, the socio-economic indicators available for each city were not identical. Five datasets were used for Rome; PNbS density, population density, housing prices, education rate, and household income; while four datasets were used for Gdansk, namely PNbS density, population density, housing prices, and unemployment density. These discrepancies reflect the limitations of available municipal data and should be taken into account when interpreting the comparative findings.

Another limitation of article IV involves the use of Pearson correlation. While Pearson correlation offered an initial indication of relationships between PNbS density and socio-economic variables, its effectiveness is limited when the sample size is small, as in Rome, with only 15 districts. The paper suggests that future research could employ alternative correlation measures, such as Kendall's Tau, which may be more appropriate for smaller samples. It also advises caution in comparing Rome and Gdańsk due to the unequal number of data points. Furthermore, the article IV analysis primarily addressed the density of public nature-based solutions, rather than their actual accessibility, quality, usability, or ecological performance. Real accessibility is influenced not only by the quantity or spatial density of green spaces, but also by factors such as park size, entrance locations, barriers, amenities, safety, maintenance, recreational opportunities, and public availability. The paper notes that evaluating real accessibility requires further research, as park size, quality, amenities, and organized recreation can vary significantly. Additionally, article IV highlights a critical spatial justice limitation. Addressing inequalities in public green space distribution cannot be reduced to identifying areas lacking green spaces. New or improved green amenities may increase land attractiveness, housing prices, and the overall cost of living, potentially contributing to eco-gentrification and displacement. This issue is directly related to urban rent theory, as public amenities can generate differential rent by increasing land values in improved areas. Consequently, green interventions intended to enhance spatial justice may unintentionally intensify social exclusion if not accompanied by housing protection, participatory planning, affordability measures, and anti-displacement strategies. The paper explicitly warns that quality green spaces can increase surrounding housing prices and cost of living, and that participatory approaches are necessary to mitigate these risks.

This limitation extends to articles IV and V more broadly. Spatial justice cannot be fully understood solely through the equal spatial distribution of nature-based solutions or green amenities. A more comprehensive analysis must consider how urban rent, land value, property markets, redevelopment pressure, and displacement processes influence the social outcomes of urban greening. For example, a district may gain additional green space, yet vulnerable residents may lose access to these benefits if rising land values result in displacement. Accordingly, the thesis recognizes that its quantitative spatial justice indicators capture distributive patterns but do not fully explain the political-economic mechanisms by which green amenities can reshape urban inequality.

Article V, which investigated the relationship between nature-based solutions and social vulnerability in Nordic cities, is also subject to limitations regarding the use of NDVI as a proxy for quality. While NDVI effectively captures vegetation density and can indicate ecological quality, it does not fully represent the social, experiential, cultural, aesthetic, or functional qualities of green spaces. For instance, NDVI does not provide information about whether a green space is safe, accessible, well-maintained, socially inclusive, or meaningful to residents. Consequently, the quality dimension in article V should be interpreted primarily as ecological or vegetation related quality, rather than as a comprehensive measure of public space quality. The quantitative tools employed in article V also have interpretive limitations. Gini coefficient and LISA cluster analysis can reveal spatial inequality, concentration, and clustering patterns, but they do not establish causality. The observed inequalities in access to or quality of nature-based solutions may be influenced by deeper historical, institutional, political, and socio-economic processes that were beyond the article's scope. Similarly, the Social Vulnerability Index simplifies complex social realities into a composite quantitative indicator. While valuable for comparison and spatial analysis, it may obscure the complexity of lived vulnerability, local histories, intersectional disadvantage, and community capacities.

Article VI, which utilizes GSVI and AI-based methods to assess public space quality within the 15-minute city framework, is constrained by the characteristics of the image source. GSVI is primarily collected from roads, resulting in the underrepresentation of off-road spaces such as parks, pedestrian boulevards, internal courtyards, informal paths, and certain waterfront or recreational areas. Consequently, the analysis may more accurately capture the quality of street-facing public space than the full spectrum of public and semi-public spaces. The article suggests that future research could incorporate drone imagery, crowdsourced data, and additional image sources to enhance the comprehensiveness and accuracy of public space quality assessments. Another limitation is that AI-based public space assessment depends on pre-trained models and visible physical indicators. Although semantic segmentation and object detection enable efficient and scalable analysis, they may not fully capture subjective experiences, social meaning, perceived safety, cultural identity, or temporal variations in public space use. The paper therefore recommends supplementing image-based analysis with additional data sources, such as real-time

sensors, participatory methods, and performance metrics, including dwell time, user diversity, and ecological impact.

Chapter 7: Conclusions

This research examined the role of NbS in reducing urban flood risk by integrating spatial, technical, and social dimensions across European cities. To achieve this, six research papers were developed, each focusing on a particular research question; together, they helped develop a more integrated approach to urban flood resilience.

The findings demonstrated, firstly, that the InVEST modeling suite, specifically the Urban Flood Risk Mitigation and Urban Stormwater Retention models, can serve as useful and efficient tools for assessing runoff and identifying areas logically sensitive in urban areas. The research also showed that runoff generation and retention are affected not only by soil characteristics, drainage conditions, and current land use, but also by the type of land use change and its spatial setting. Some combinations of land use transition and local environmental conditions were found to result in a higher level of hydrological sensitivity than other combinations.

When shifting from assessment to intervention planning, the research found that optimization techniques, especially genetic algorithms, are able to help identify near-optimal NbS configurations while at the same time taking into account multiple objectives and spatial constraints. Meanwhile, the social analyses indicated that the spatial provision of NbS cannot be judged merely on the basis of quantity or hydrological performance; differences in socioeconomic conditions, accessibility, spatial quality and vulnerability affect who can actually access and benefit from NbS. The findings thus revealed that being near green or public spaces does not always translate into having meaningful accessibility or being more resilient, especially in cases where there is poor spatial quality, environmental hazards, or barriers that impact vulnerable groups.

The output of all of the developed research articles collectively reveal that urban flood resilience planning cannot be viewed merely as a hydrological or technical issue. On the contrary, effective planning involves first identifying both hydrological sensitivity and social vulnerability, then selecting suitable nature-based solutions in light of the local environmental and land use conditions, and afterwards assessing various configurations by taking into account runoff reduction, cost, spatial feasibility, equity, ecological quality, and accessibility. It is also necessary to compare different implementation scenarios in order to make the trade-offs between these objectives clear and to aid context-sensitive decision-making. Lastly, nature-based solutions should be integrated into wider urban and spatial planning rather than being introduced as separate flood mitigation measures.

From this synthesis, the thesis's key contribution is an integrated planning framework aimed at improving urban flood resilience through nature-based solutions. The guide addresses the fragmentation found in the current literature, where the spatial, technical, and social aspects are frequently studied in isolation. By integrating these different aspects, the thesis shifts from a primarily physical approach that focuses on flood susceptibility and technical performance to a more comprehensive planning approach that also takes into account social vulnerability, distributive justice, accessibility, and spatial quality. Thus, the research makes a theoretical contribution to the understanding of NbS planning and also offers a framework that has practical value for assisting urban planning and decision-making in European cities.

It should still be noted that there are a number of limitations. These primarily involve the spatial resolution, consistency, and availability of the input data; the fact that the hydrological models employed are simple and static; and how the outcomes of both the model and the optimization depend on the quality of the basic datasets and the assumptions made. Moreover, the optimization procedure produced near-optimal solutions rather than globally optimal ones and did not include dynamic processes such as future urban expansion or climate change. Also, the variation in the availability of data among the case-study cities had an effect on the direct comparability of certain socioeconomic analyses. Lastly, the quantitative measures of vegetation, social vulnerability, accessibility, and spatial justice are unable to fully take into account the lived, cultural, political, and experiential aspects of urban space. The proposed planning approach should therefore be tested and refined in future research by making use of higher-resolution and more consistent spatial data, dynamic climate and urban-development scenarios, and more detailed depictions of infrastructure and the various implementation constraints. Future studies might also combine quantitative spatial analysis with participatory and qualitative methods in order to better reflect perceived accessibility, the quality of public space, community needs, and the broader social effects of urban greening. Special attention should also be paid to processes such as changes in land value, eco-gentrification, and displacement to make sure that improvements to green infrastructure do not inadvertently reinforce existing inequalities.

The thesis as a whole shows that planning NbS for urban flood resilience is most successful when hydrological performance, spatial conditions, implementation feasibility, social vulnerability, equity, and accessibility are regarded as interconnected aspects of the planning process. By incorporating these aspects into a coherent planning guide, the study offers a route from the identification of flood-prone areas to the creation of more effective, context-appropriate, accessible and socially equitable nature-based solutions.

Chapter 8: Summary

8.1. Summary in English

Climate change is an ongoing issue, and its consequences have created significant challenges, particularly in cities due to their large populations and extensive infrastructure. One major challenge is the increased risk of urban flooding. Traditionally, this issue has been addressed primarily through grey and engineering solutions. Although these approaches can be effective, they often have drawbacks, including high costs, potential environmental harm, and limited flexibility. Therefore, addressing urban flooding only through technical solutions risks overlooking the complexity of urban environments. In response, resilience theory and socio-ecological systems thinking have gained attention and shape urban climate adaptation research. Holling's (1973) resilience theory emphasized systems' ability to adapt and reorganize after disturbances, rather than just maintaining stability. Cities are thus viewed as interconnected socio-ecological systems, influenced by hydrological, ecological, spatial, and social processes. This has increased interest in nature-based solutions that use natural processes like infiltration, retention, and evapotranspiration. Although interest in NbS is growing, significant gaps remain in their planning and implementation. Current methods usually pay only limited attention to social equity and environmental justice, and most available tools focus mainly on risk assessment rather than helping select and prioritize different NbS options. Moreover, the impact of urban form and land use changes on NbS effectiveness is not well understood. These limitations show the need for an integrated planning approach that combines hydrological performance, spatial and land use factors, and socioeconomic criteria.

To address rising climate-related flood risks in European cities and the gaps in NbS research, this thesis uses a multi-dimensional and interdisciplinary research design made up of several related research papers. Each study examines a specific part of the research problem, and together they help us better understand flood risk in cities and develop an integrated approach to NbS and urban flood resilience in European cities. The chosen methods reflect the complex mix of spatial, technical, and social factors by combining geospatial modeling, optimization, spatial analysis, and planning techniques. Building on this comprehensive methodological framework, the research employed a comparative multi-case approach across seven European cities representing diverse climatic, urban, socioeconomic, and planning conditions. Different case-study combinations were used according to the objectives of individual analyses, allowing the research to examine context-specific issues while assessing the transferability of the developed methods and findings across different European urban contexts.

Findings reveal that NbS effectiveness depends on how spatial, technical, and social conditions interact. The InVEST models provided an efficient way to identify runoff patterns and hydrologically sensitive areas. The analysis found that changes in land use and the spatial context of these changes have a noticeable impact on hydrological sensitivity. Moreover, genetic algorithms were used to identify near-optimal NbS configurations while accounting for multiple

objectives and spatial constraints. The social analyses indicated that the benefits of NbS depend not only on physical features or hydrological performance but also on accessibility, socioeconomic vulnerability, spatial quality, and environmental conditions. Overall, the findings show that achieving urban flood resilience requires an integrated planning approach that considers hydrological performance, spatial feasibility, cost, ecological quality, social vulnerability, equity, and accessibility. The thesis therefore serves as a comprehensive planning guide to support more context-sensitive, effective, and socially equitable NbS decisions in European cities.

8.2. Summary in Polish

Zmiany klimatu stanowią proces ciągły, którego konsekwencje generują istotne wyzwania, szczególnie w miastach, ze względu na wysoką koncentrację ludności oraz rozbudowaną infrastrukturę. Jednym z zasadniczych wyzwań jest wzrost ryzyka powodzi miejskich. Tradycyjnie problem ten rozwiązywano przede wszystkim za pomocą szarej infrastruktury i rozwiązań inżynierskich. Choć podejścia te mogą być skuteczne, wiążą się one z licznymi ograniczeniami, w tym z wysokimi kosztami, potencjalną szkodliwością dla środowiska oraz ograniczoną elastycznością. W konsekwencji ograniczanie się wyłącznie do rozwiązań technicznych w przeciwdziałaniu powodziom miejskim niesie ryzyko pominięcia złożoności środowiska miejskiego. W odpowiedzi na te wyzwania pojawiły się nowe teorie, takie jak teoria odporności (resilience) czy podejście oparte na myśleniu w kategoriach systemów społeczno-ekologicznych, które zyskują na znaczeniu i kształtują współczesne badania nad adaptacją miast do zmian klimatu. Teoria odporności Hollinga (1973) akcentuje zdolność systemów do adaptacji i reorganizacji po zakłóceniach, nie zaś jedynie do utrzymywania stabilności. Miasta są zatem postrzegane jako wzajemnie powiązane systemy społeczno-ekologiczne, kształtowane przez różne procesy, w tym hydrologiczne i przestrzenne. Przyczyniło się to do wzrostu zainteresowania rozwiązaniami opartymi na przyrodzie (Nature-based Solutions, NbS), które wykorzystują naturalne procesy, takie jak infiltracja, retencja i ewapotranspiracja. Pomimo rosnącego zainteresowania rozwiązaniami opartymi na przyrodzie, nadal istnieją istotne luki w zakresie ich planowania i wdrażania. Obecnie stosowane metody zazwyczaj w ograniczonym stopniu uwzględniają kwestie sprawiedliwości społecznej i środowiskowej, a większość dostępnych narzędzi koncentruje się przede wszystkim na ocenie ryzyka, zamiast wspierać wybór i ustalanie priorytetów wśród różnych wariantów NbS. Ponadto wpływ formy urbanistycznej oraz zmian użytkowania terenu na skuteczność NbS nie został dotychczas dostatecznie rozpoznany. Ograniczenia te wskazują na potrzebę opracowania zintegrowanego podejścia planistycznego, które łączy efektywność hydrologiczną, czynniki przestrzenne i związane z użytkowaniem terenu oraz kryteria społeczno-ekonomiczne.

W odpowiedzi na rosnące ryzyko powodzi związanych ze zmianą klimatu w europejskich miastach oraz zidentyfikowane luki badawcze dotyczące NbS, w niniejszej rozprawie zastosowano wielowymiarowy i interdyscyplinarny schemat badawczy, bazujący na kilku powiązanych ze sobą artykułach naukowych. Każdy z nich analizuje określony aspekt problemu badawczego, a łącznie przyczyniają się one do lepszego zrozumienia ryzyka powodziowego w miastach oraz opracowania zintegrowanego podejścia do NbS i budowania odporności europejskich miast na powódzie. Dobór metod odzwierciedla złożone współzależności między czynnikami przestrzennymi, technicznymi i społecznymi poprzez połączenie modelowania geoprzestrzennego, optymalizacji, analiz przestrzennych oraz technik planistycznych. Na podstawie tych kompleksowych ram metodologicznych przeprowadzono porównawczą analizę wielu przypadków, obejmującą siedem europejskich miast reprezentujących zróżnicowane uwarunkowania klimatyczne, urbanistyczne, społeczno-ekonomiczne i planistyczne. W zależności od celów poszczególnych analiz studiowano różne kombinacje przypadków, co umożliwiło zbadanie zagadnień specyficznych dla danego kontekstu, a jednocześnie ocenę możliwości zastosowania opracowanych metod i wyników w różnych realiach miejskich występujących w Europie.

Uzyskane wyniki wskazują, że skuteczność NbS zależy od sposobu, w jaki oddziałują na siebie uwarunkowania przestrzenne, techniczne i społeczne. Modele InVEST umożliwiły efektywną identyfikację przestrzennych wzorców wpływu powierzchniowego oraz obszarów wrażliwych pod względem hydrologicznym. Analiza wykazała, że zmiany użytkowania terenu oraz kontekst przestrzenny, w jakim zachodzą, mają zauważalny wpływ na wrażliwość hydrologiczną. Ponadto zastosowano algorytmy genetyczne w celu identyfikacji sub-optymalnych konfiguracji NbS, uwzględniających wiele celów i ograniczeń przestrzennych. Analizy społeczne wykazały, że korzyści wynikające z zastosowania NbS zależą nie tylko od cech fizycznych czy efektywności hydrologicznej, lecz także od dostępności, podatności społeczno-ekonomicznej, jakości przestrzennej oraz warunków środowiskowych. Całościowo wyniki dowodzą, że osiągnięcie odporności powodziowej miast wymaga zintegrowanego podejścia planistycznego, uwzględniającego efektywność hydrologiczną, możliwości realizacji w określonych warunkach przestrzennych, koszty, jakość ekologiczną, podatność społeczną, sprawiedliwość społeczną oraz dostępność. Niniejsza rozprawa stanowi zatem kompleksowy przewodnik planistyczny wspierający podejmowanie decyzji dotyczących NbS w europejskich miastach, które w większym stopniu uwzględniają lokalne uwarunkowania, są skuteczniejsze i bardziej sprawiedliwe społecznie.

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