HIGOR COSTA DE BRITO

URBAN HYDROLOGICAL CHALLENGES

SPATIAL INTERRELATIONS BETWEEN LULC AND WATER RESOURCES

FEDERAL UNIVERSITY OF CAMPINA GRANDE - UFCG
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CAMPINA GRANDE
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SPATIAL INTERRELATIONS BETWEEN LULC AND WATER RESOURCES

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Written in Portuguese

Aos meus padrinhos, Maria e Francisco (*in memoriam*), pilares da minha formação como ser humano. Aos meus pais, Elza e Deusdet, que jamais mediram esforços para tornar minha carreira acadêmica um sonho possível.

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À minha família, pelo amor incondicional, pelo apoio contínuo e pelos inúmeros sacrifícios feitos para me oferecerem sempre o melhor. Vocês são minha base, meu exemplo de luta e resiliência. Sem a força de vocês, eu não teria chegado até aqui.

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Written in Portuguese

A todos do Laboratório de Gerenciamento do Risco Climático para a Sustentabilidade Hídrica (GRC) da Universidade do Ceará, por me receberem tão calorosamente em Fortaleza.

Ao meu companheiro de quatro patas, Dobby, por me lembrar, mesmo nos dias mais exaustivos, da importância do afeto simples, da pausa e da alegria espontânea.

Ao Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), pelo suporte financeiro que possibilitou a realização desta pesquisa, e à Fundação Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES), pela bolsa de mobilidade.

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"A maior armadilha é acreditar que o futuro será uma simples continuação do presente."

(Michel Godet)

PREFACE

Era uma vez, em uma terra quente e seca do Sertão, um menino que nasceu onde a terra rachava de sede e o céu custava a chorar. Ele era neto de raízes fortes — pessoas que liam com as mãos e escreviam com enxadas — e filho de quem nunca pôde tirar férias, mas conhecia bem o valor do trabalho e da resistência.

Esse menino cresceu em meio terra seca. Mas em sua memória, as maiores alegrias vinham quando os açudes sangravam e os rios dançavam entre as pedras. Era nesses momentos que ele virava peixe por um dia — como se ali, por um instante, tudo fosse abundância.

Ele foi criado pelos padrinhos num bairro humilde, dividia seu tempo entre a escola, os estudos e as brincadeiras na rua. Ali, com uma lousa comprada por um pai que, mesmo sem ter estudado, sabia a importância da educação, o menino ensinava matemática aos amigos, como quem aprende ensinando. Curioso, desmontava brinquedos, rádios e ventiladores — acumulando choques e descobertas em partes iguais.

Ele nunca quis ser o melhor. Queria apenas compreender mais. Queria, desde cedo, fazer perguntas que talvez ninguém ali soubesse responder.

E assim, o menino cresceu. Virou estudante, virou engenheiro, virou pesquisador. Mas jamais deixou de ser o menino que espera a água cair do céu. Agora, ele estuda como as cidades crescem e sufocam a água, como a terra muda de roupa e o céu muda de humor. Ele traça mapas, simula futuros e conversa com dados.

Hoje, esse menino entende: seu percurso não foi um desvio, mas um rio em formação. Um rio que nasceu na seca, correu por pedras, desviou por curvas, e agora busca, por meio da ciência, traçar novos caminhos.

Aprendeu que água e educação têm mais em comum do que se imagina: ambas percorrem, conectam, transformam. São forças silenciosas que, quando bem conduzidas, têm o poder de mudar vidas.

Porque ele sempre soube, mesmo sem palavras para isso, que a água não é apenas um recurso — é memória, é justiça, é vida.

ABSTRACT

As urbanization accelerates globally, cities face increasing challenges in managing water resources amid changes in land use and land cover (LULC), climate pressures, and social inequalities. While some regions struggle with water scarcity, others contend with recurrent flooding, underscoring the urgency of addressing water-related vulnerabilities through integrated urban planning and resource management. In this context, this thesis investigates urban hydrological challenges arising from the spatial interrelations between LULC changes and water resources, specifically through the analysis of two contrasting urban contexts: Campina Grande (Brazil), characterized by water scarcity, and Washington, D.C. (USA), known for recurrent urban flooding. The objective is to assess how LULC changes affect water availability and increase urban flood vulnerabilities. In Campina Grande, water scarcity issues are explored through sentiment analysis, highlighting the social and structural impacts of droughts. Spatial analysis and simulation methods are used to estimate domestic water demand under demographic changes and urbanization pressures. A sensitivity analysis of LULC models identifies the factors influencing urbanization dynamics and their implications for water resource availability and quality. In Washington, D.C., the research evaluates flood hazards exacerbated by LULC transformations, employing spatial autocorrelation techniques to identify clusters of vulnerability and assess sustainable urban drainage systems. These practices are further analyzed from an environmental justice perspective, examining spatial disparities in infrastructure distribution. The cross-city analysis emphasizes a fundamental premise: regardless of development levels or water availability, urban areas worldwide face challenges in sustainably managing the LULC–water nexus, whether addressing scarcity (as in Brazil) or flooding (as in the USA). The integration of case studies enables reflection on how territorial transformations associated with urbanization differentially influence water resources in contexts with diverse socio-environmental realities, offering replicable methodologies and support tools for sustainable urban planning and the development of more resilient cities in the face of climate pressures and the challenges of integrated water management.

Keywords: Urban Hydrology; Land Use and Land Cover; Water Availability; Sustainable Urban Drainage Systems; Environmental Justice.

RESUMO

À medida que a urbanização acelera em todo o mundo, as cidades enfrentam desafios na gestão dos recursos hídricos em meio a mudanças nos padrões de uso e na cobertura da terra (LULC), pressões climáticas e desigualdades sociais. Enquanto algumas regiões enfrentam escassez de água, outras lutam contra inundações recorrentes, o que ressalta a urgência de abordar as vulnerabilidades relacionadas à água por meio do planejamento urbano integrado e da gestão de recursos. Nesse contexto, esta tese investiga os desafios hidrológicos urbanos decorrentes das inter-relações espaciais entre as mudanças no LULC e os recursos hídricos, especificamente por meio da análise de dois contextos urbanos contrastantes: Campina Grande (Brasil), caracterizada pela escassez de água, e Washington, D.C. (EUA), conhecida por inundações urbanas recorrentes. O objetivo é avaliar como as mudanças no LULC afetam a disponibilidade de água e aumentam as vulnerabilidades urbanas às inundações. Em Campina Grande, as questões de escassez de água são exploradas por meio da análise de sentimentos, destacando os impactos sociais e estruturais das secas. A análise espacial e os métodos de simulação estimam a demanda doméstica de água sob mudanças demográficas e pressões de urbanização. Uma análise de sensibilidade dos modelos LULC identifica os fatores que influenciam a dinâmica da urbanização e suas implicações para a disponibilidade e a qualidade dos recursos hídricos. Em Washington, D.C., a pesquisa avalia os perigos de inundação exacerbados pelas transformações do LULC, empregando técnicas de autocorrelação espacial para identificar grupos de vulnerabilidade e avaliar os sistemas de drenagem urbana sustentável. Essas práticas são analisadas ainda sob uma perspectiva de justiça ambiental, examinando as disparidades espaciais na distribuição da infraestrutura. A análise entre as cidades enfatiza uma premissa fundamental: independentemente dos níveis de desenvolvimento ou da disponibilidade de água, as áreas urbanas em todo o mundo enfrentam desafios para gerenciar o nexo LULC – água de forma sustentável, seja abordando a escassez (como no Brasil) ou as inundações (como nos EUA). A integração dos estudos de caso permite uma reflexão sobre como as transformações territoriais associadas à urbanização influenciam diferencialmente os recursos hídricos em contextos com realidades socioambientais diversas, oferecendo metodologias replicáveis e ferramentas de apoio para o planejamento urbano sustentável e o desenvolvimento de cidades mais resilientes diante das pressões climáticas e dos desafios da gestão integrada da água.

Palavras-chave: Hidrologia Urbana; Uso e Cobertura do Solo; Disponibilidade Hídrica; Sistemas Sustentáveis de Drenagem Urbana; Justiça Ambiental.

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LIST OF ABBREVIATIONS

ACC	Accessibility
ACS	American Community Survey
AHP	Multi-Criteria Analytic Hierarchy Process
ANN	Artificial Neural Network
ANOVA	Two-way Analysis of Variance
AR6	IPCC Sixth Assessment Report
BMP	Best Management Practice
BSR	Brazilian Semiarid Region
CA-ANN	Cellular Automata Based on Artificial Neural Networks
CAGEPA	Paraíba Water and Sewage Company
CRS	Geographic Coordinate Reference System
DEFRA	Department for Environment, Food & Rural Affairs
DNIT	National Department of Transport Infrastructure
DOEE	Department of Energy & Environment
DSM	Digital Surface Model
EPA	Environmental Protection Agency
FEMA	Federal Emergency Management Agency
FN	False Negatives
FP	False Positives
GeoDa	Geographic Data Analysis Software
GI	Green Infrastructure
GIS	Geographic Information System
GSI	Green Stormwater Infrastructure
HIFLD	Homeland Infrastructure Foundation-Level Data
HR	Hazard Rating
IBGE	Brazilian Institute of Geography and Statistics
ICM	Integrated Catchment Model
InfoWorks ICM	InfoWorks Integrated Catchment Model
INSA	National Semi-arid Institute
IPCC	Intergovernmental Panel on Climate Change
IPCC SREX	IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation
JSI	Jaccard Similarity Index
LID	Low-Impact Development
LiDAR	Light Detection and Ranging
LISA	Local Indicators of Spatial Association
LISA	Local Indicators of Spatial Association
LULC	Land Use and Land Cover
LULCC	Land Use and Land Cover Change
Manning's n	Manning roughness coefficient

Mapbiomas	Annual Mapping of Land Cover and Land Use in Brazil
MOLUSCE	Modules for Land Use Change Assessment
NEB	Brazilian Northeast
NLCD	National Land Cover Database
NOOA	National Oceanic and Atmospheric Administration
NPDES	National Pollutant Discharge Elimination System
NRC	National Research Council of Canada
OA	Overall Accuracy
ONU	United Nations Organization
PA	Producer's Accuracy
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
PUC	Proximity to Urban Centers
SAB	Brazilian Semi-arid Region
SDG	Sustainable Development Goals
SEBAL	Surface Energy Balance Algorithms for Land
SLO	Slope
SO	Specific Objective
SNIS	National Sanitation Information System
SUDENE	Northeast Development Superintendence
SUDS	Sustainable Urban Drainage Systems
TP	True Positives
UA	User's Accuracy
UEZ	Urban Expansion Zones
UN-Habitat	United Nations New Urban Agenda
VBLA	Percentage of the population identifying as 'One race: Black or African American'
VEDU	Percentage of the population aged 25 and over with a bachelor's degree or higher
VPOV	Percentage of individuals whose income in the past 12 months was below the poverty level
VVAL	Median value of owner-occupied housing units
VWHI	Percentage of the population identifying as 'One race: White'

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1 INTRODUCTION

English

This introductory chapter addresses the complexity of water cycle dynamics in urban environments, highlighting the continuous interaction between social, built, and natural subsystems. It highlights the amplification of this complexity by accelerated urbanization and changes in land use and cover, redefining the spatial and temporal patterns of water flows and presenting challenges in managing urban water resources. It also presents the driver questions that motivated the dissertation and its hypothesis, objectives, contributions, and structure.

Portuguese

Este capítulo introdutório aborda a complexidade da dinâmica do ciclo da água em ambientes urbanos, destacando a interação contínua entre os subsistemas sociais, construídos e naturais. Destaca a ampliação dessa complexidade pela urbanização acelerada e pelas mudanças no uso e na cobertura do solo, redefinindo os padrões espaciais e temporais dos fluxos de água e apresentando desafios na gestão dos recursos hídricos urbanos. Apresenta também as questões norteadoras que motivaram a tese, sua hipótese, objetivos, contribuições e estrutura.

1.1 GENERAL BACKGROUND

The water cycle dynamics in urban environments are intrinsically complex, reflecting the continuous interaction between social, built, and natural subsystems. This complexity is amplified by accelerated urbanization and changes in land use and land cover (LULC), which redefine the spatial and temporal patterns of water flows, leading to significant challenges in managing urban water resources (Yang; Yang; Xia, 2021). Recent studies highlight that mass migration to urban areas, now home to more than half of the global population (UN-Habitat, 2022), puts unprecedented pressure on infrastructure and public services, requiring adaptive approaches to urban water management (Bach *et al.*, 2014).

The growing focus on urbanization and LULC reflects a paradigmatic shift in water resources research, shifting some of the attention from global climate change to how the configuration and management of urban space can mitigate or exacerbate water-related risks such as floods and droughts (Alexander, 2016; Hao; Singh, 2020; Trenberth *et al.*, 2014). The complexity of these extreme events in urban contexts, often exacerbated by the interaction of multiple factors, highlights the need for interdisciplinary approaches and multifunctional solutions in water management (Zscheischler *et al.*, 2018; Zscheischler; Lehner, 2022).

In response to these challenges, this research emphasizes applying spatial analysis techniques and using geospatial data to understand and quantify the impacts of urbanization on water resources. The increasing availability of remote sensing data offers unprecedented opportunities to monitor urban water systems in a more holistic and integrated way, going beyond the limitations of traditional ground observations (AghaKouchak *et al.*, 2015; Chawla; Karthikeyan; Mishra, 2020).

Therefore, this dissertation aims to identify and apply key geospatial databases to scenarize urban hydrology, bringing scientific innovations in GIS science applied to water resources and predictive scenarios. By analyzing the impact of anthropization and changes in LULC on water resources in urban areas, this research aims to provide insights and replicable tools for sustainable water management in cities around the world, thus contributing to water safety and more resilient and adaptive water infrastructure for facing urban hydrological challenges.

1.2 RATIONALE OF THE STUDY

Water challenges constitute a global issue, increasingly exacerbated by rapid urbanization and climate variability. Around the world, urban areas face pressures from complex hydrological phenomena, ranging from water scarcity to recurrent urban flooding

(Raymond *et al.*, 2020). These challenges are particularly acute in cities due to their high population density, intensified land-use transformations, and growing infrastructure demands, amplifying vulnerability and socio-environmental inequalities (Ribot, 2014). Water scarcity and flooding frequently impact urban settings worldwide, underscoring the universal necessity for integrated water management strategies.

Urbanization directly influences the dynamics between LULC and water resources, modifying natural hydrological cycles, water availability, quality, and distribution. The socio-economic and political factors inherent in urban areas shape how extreme weather events translate into human and environmental disasters, further complicating the response capacity of affected populations (Lahsen; Ribot, 2022). Given this complexity, it is imperative to understand and address these urban hydrological challenges through comprehensive, interdisciplinary approaches that integrate land-use planning and water resource management.

This dissertation addresses the central research question: "**How do LULC changes driven by urbanization impact water resources across different geographical contexts – including both growing cities and well-established urban centers – and which integrated water resource management strategies, coupled with spatial data, can effectively mitigate these impacts, promoting urban resilience and water sustainability?**" This question arises from the necessity to develop proactive urban planning frameworks capable of anticipating and adapting to diverse climatic futures and urban development trajectories (Zevenbergen *et al.*, 2008).

The analysis between Campina Grande, Brazil, and Washington, D.C., US, chosen for their distinct hydrological issues – water scarcity and urban flooding, respectively – highlights urban water challenges' global relevance and diversity. This comparative approach underscores the universal nature of urban water vulnerabilities, irrespective of the socioeconomic context or development level. By examining these two distinct cases, this research uniquely positions itself to offer comprehensive insights into managing the LULC-water nexus, promoting replicable methodologies applicable to urban settings globally.

The central hypothesis guiding this research is that urbanization catalyzes LULC transformations, impacting urban water resources by reducing water availability and increasing vulnerability to extreme weather events. It argues that adopting integrated water management strategies and adaptive land-use practices can mitigate these adverse effects. Implementing such strategies is critical for enhancing urban resilience and ensuring the sustainable and equitable management of water resources over the long term.

Thus, the dissertation contributes scientific insights to the urban hydrology field by applying advanced spatial analysis techniques and geospatial databases. Leveraging increasing accessibility to remote sensing data and GIS technologies, the study quantifies the complex interplay between urbanization and water resources, providing actionable, evidence-based tools that support sustainable urban water management worldwide. This research aims to enhance urban resilience, promote equitable water governance, and advance sustainable urban planning practices internationally.

1.3 OBJECTIVES

The general objective of this study is to evaluate, through geospatial analysis, how changes in LULC affect water availability and increase urban vulnerabilities to flooding in different socio-economic contexts.

The Specific Objectives (SO) are:

SO1. Characterize and quantify LULC changes in different urban contexts, highlighting temporal and spatial patterns and their main influencing factors;
SO2. Analyze how the urbanization process and territorial transformations impact the water availability;
SO3. Compare the socio-environmental implications of LULC changes, with a special focus on the most vulnerable groups or regions, promoting reflections on equity and environmental justice;
SO4. Evaluate the role of modeling and projection tools (including spatial analysis and scenario methods) in predicting the impacts of different urban growth scenarios on water resources;
SO5. Propose spatial methodologies capable of supporting public policies and urban planning practices that ensure greater water resilience in different urban contexts.

1.4 RESEARCH QUESTIONS

The research questions guiding this plan include:

- How does water shortage affect local communities in social, emotional, and structural terms, and what factors have amplified water access inequalities? (SO1, SO2, SO3)
- How can predictive land-use modeling, integrated with demographic data and spatial analysis, estimate future domestic water demand in urban areas undergoing rapid expansion? (SO2, SO4, SO5)
- How do the explanatory variables used in LULC modeling influence the accuracy of spatial simulations, and what are their interactions in representing urban dynamics? (SO2. SO4)
- How can integrating urban planning and water management promote a more equitable distribution of investments? (SO3, SO5)

- How are LULC changes shaping urban flood hazards and patterns, and what urban planning and stormwater management strategies can mitigate these hazards supported by future scenarios? (SO4, SO5)
- How do Sustainable Urban Drainage Systems (SUDS) contribute to mitigating flooding impacts while promoting environmental justice and providing social and environmental benefits? (SO4, SO5)

1.5 SCIENTIFIC AND TECHNOLOGICAL CONTRIBUTIONS

The main contribution of this dissertation is the development of spatial methodologies that connect LULC changes to hydrological processes in urban environments. By integrating different modeling and analytical techniques, the study demonstrates how LULC transformations directly influence the increase in water demand and contribute to the intensification of flood hazards. These methodologies were applied in contrasting urban contexts, reinforcing their relevance for understanding and addressing hydrological challenges related to both water scarcity and urban flooding. These findings unfold into the following scientific and technological contributions:

- Integration of sentiment analysis with water crisis narratives, bridging data science and environmental justice;
- Development of a replicable workflow using publicly available audiovisual content to analyze urban crises;
- Integration of land use simulation and water demand modeling, using spatial data and demographic variables to forecast urban water consumption in semi-arid regions;
- Development of a replicable geospatial methodology combining cellular automata with open datasets, enabling predictions in data-scarce cities;
- Identification of the main LULC drivers through sensitivity analysis, revealing the most influential variables in modeling urban growth patterns in a city in the semiarid region;
- Refinement of spatial modeling approaches, assessing the impact of each explanatory variable on simulation accuracy, supporting more targeted and realistic LULC planning;
- Integration of spatial data science with environmental justice, revealing how green infrastructure reflects and reinforces historical patterns of racial and socioeconomic exclusion;
- Evidence of "green gentrification" and infrastructural selectivity, revealing that certain sustainability solutions are implemented in ways that deepen urban inequality.
- Integration of future LULC simulations with hydrodynamic flood modeling to project how urban land use changes will reshape flood exposure and intensity;
- Development of a spatially explicit risk assessment framework, combining hazard rating, LULC projections, infrastructure datasets, and community-reported flood data;
- Integration of SUDS into flood simulations, demonstrating their partial effectiveness in reducing flood volume and hazard under current land use, while revealing their limited impact under future high-imperviousness scenarios;

- Development of a spatial methodology to assess socio-hydrological trade-offs, uncovering how SUDS can unintentionally redistribute flood risk.

1.6 STRUCTURE OF THE DISSERTATION

The dissertation is organized into two sections and nine chapters. **Chapter I** introduces the overall context of the study, highlighting the research problem, motivation, hypotheses, and justification, as well as the general and specific objectives and guiding questions. **Chapter II** then outlines the theoretical framework, addressing concepts related to urbanization, water resource management, environmental justice, land use and land cover prediction models, and other topics that underpin the study.

The dissertation is divided into two main sections: **Section I** corresponds to the studies conducted in Campina Grande (Brazil), presented in Chapters III, IV, and V; while **Section II** encompasses the investigations carried out in Washington, D.C. (US), covered in Chapters VI, VII, and VIII.

Chapter III marks the beginning of the practical application, discussing the challenges of water availability in Campina Grande, followed by the analysis of spatial data in **Chapter IV**, which presents the methodology and simulation of water demand. **Chapter V** delves into the driving factors behind land use and land cover changes, consolidating the results obtained for the Brazilian context.

Chapter VI transitions to the Washington, D.C. scenario, illustrating the distinct urban and environmental challenges faced in a developed setting, while **Chapter VII** specifically addresses flood risks, their modeling, and projections within the North American context. **Chapter VIII** discusses solutions based on green infrastructure and sustainable urban drainage, linking them to aspects of environmental justice.

Finally, **Chapter IX** presents the general conclusion and a geospatial analysis between the two studied contexts, highlighting recommendations, limitations, and potential future developments for water management across diverse urban realities.

2 THEORETICAL FRAMEWORK

English

This theoretical framework chapter offers a holistic view of urbanization, water sustainability, and climate change challenges. It begins by discussing urbanization as a global historical process, highlighting its nuances in different contexts, such as Brazil and the United States. It delves into water sustainability issues amid urbanization, highlighting the transformation of natural landscapes into urban ones and their environmental impact. It addresses the challenges of climate change in cities and the complex interaction between land use and water resources. Finally, it focuses on the importance of urban resilience in facing emerging environmental risks and disasters, underlining the need for adaptive strategies to ensure the sustainability of cities.

Portuguese

Este capítulo de referencial teórico oferece uma visão holística sobre os desafios da urbanização, sustentabilidade hídrica e mudanças climáticas. Inicia-se com a discussão da urbanização como um processo histórico global, destacando suas nuances em diferentes contextos, como Brasil e Estados Unidos. Aprofunda-se nas questões de sustentabilidade hídrica em meio à urbanização, ressaltando a transformação das paisagens naturais em urbanas e seu impacto ambiental. Aborda-se os desafios relacionados às mudanças climáticas nas cidades e a complexa interação entre uso da terra e recursos hídricos. Por fim, enfoca-se na importância da resiliência urbana para enfrentar riscos ambientais emergentes e desastres, sublinhando a necessidade de estratégias adaptativas para garantir a sustentabilidade das cidades.

2.1 URBANIZATION AS A HISTORICAL PROCESS

Urbanization is a global historical process involving increased population living in cities and other urban settlements. This process is closely linked to human development, as it influences and is influenced by economic, social, environmental, and political aspects (Mehmood; Ullah; Lal, 2021). Therefore, urbanization has diverse origins and manifests differently across various world regions (Randolph; Storper, 2023).

Contrary to the traditional notion that primarily associates urbanization with the Industrial Revolution, Fox (2012) argues that urbanization should be understood as a process driven by population dynamics related to technological and institutional changes. This perspective challenges the view that urbanization is merely a byproduct of economic development, highlighting the importance of health and food availability.

In the 20th century, urbanization intensified due to technological advances and economic growth. United Nations (2018) indicated that the proportion of the world's population residing in urban areas increased substantially—from 30% in 1950 to 55% in 2018—and is projected to reach 68% by 2050, reflecting changes in living patterns, work, and mobility. Urban expansion, especially in developing countries, is often associated with disordered growth and challenges such as social inequality, environmental problems, and pressures for infrastructure and public services (Kuddus; Tynan; McBryde, 2020).

Urbanization has been linked to globalization and technological advancement in the last century. These factors contribute to the emergence of large cities and the integration of urban networks at regional scales, influencing the economy, politics, and environment (Acuto; Leffel, 2021). In contemporary times, urbanization also raises questions about urban sustainability and resilience, driving discussions about urban development models that balance economic growth, social justice, and environmental protection (Santamaria, 2019).

Thus, urbanization as a global historical process reveals the interaction between human development, economic transformations, technological advancements, and socio-environmental challenges (Deppisch; Yilmaz, 2021). This ongoing and dynamic process shapes the landscape of contemporary societies and poses challenges for urban planners and policymakers.

2.1.1 Urbanization process in Brazil

The urban growth in Brazil is a result of rapid industrialization and an increase in the urban population. Understanding how the urban system evolves from population growth and the social, economic, and ecological implications of these developments has become essential (Meirelles *et al.*, 2018).

Throughout the urban development process in Brazil, two periods were significant for the growth of industrialization and provided historical patterns of urbanization. The first period, around the mid-1800s, includes the country's independence in 1822, the opening of markets to international trade, the increase in coffee production, and the beginning of industrialization. (Hummell; Cutter; Emrich, 2016). The second period, starting in the 1930s, was marked by political innovations such as changes in economic policy, government interventions to support coffee prices, and the promotion of economic diversification (Santos, 1996).

According to Oliven (2010), four factors triggered the urbanization of Brazilian society: i) the insertion of capitalist relations in the countryside, leading to the proletarianization of poor farmers; ii) sanitary and hygienic improvements that reduced infant mortality in rural areas, causing an increase in the rural population, which was not supported due to physical and social limitations; iii) expansion of agricultural frontiers, where small farmers and indigenous people were forced to migrate in search of new lands; iv) the search for better living and working conditions in cities, driven by the diffusion of news through mass media.

According to Santos (2008), urbanization in Brazil has evolved in an unequal and complex manner, reflecting socioeconomic and technological conditions across different historical periods. During the colonial and imperial periods, the urban process was selective and concentrated in coastal cities such as Salvador and Rio de Janeiro, which played administrative and commercial roles within an economy oriented toward the export of agricultural products. However, starting in the 20th century, especially with industrialization and the mechanization of the territory, urbanization intensified and spread, creating new urban centers and regional networks.

The transition to an industrial economy, accelerated during the 1930s and 1940s, marked a new phase of the urban process. The import substitution policy promoted the growth of industrial cities, particularly in the Southeast. São Paulo stood out during this period as the main industrial metropolis, attracting internal migratory flows from the Northeast and other regions of Brazil. This movement was accompanied by the concentration of infrastructure and services, as well as the expansion of the tertiary sector in major cities (Villaça, 2001).

The rural exodus, which intensified from the 1960s onward, was a turning point in the Brazilian urbanization process, driven by agricultural modernization and land concentration, which limited economic opportunities in rural areas (Matos, 2012). From the 1980s, a relative deconcentration of economic activities can be observed, marked by the strengthening of medium-sized cities in the interior and the formation of urban networks connecting major centers to smaller localities (Braga, 2006). This trend highlights a networked urbanization influenced by factors such as industrial decentralization and advances in transportation and communication.

Brazilian urbanization has been a driving force for economic and social progress, fostering greater territorial integration and development opportunities across various regions of the country. However, as with many urban processes, challenges persist, particularly regarding socio-spatial inequalities. In some areas, gaps in urban infrastructure and access to public services remain, but progress has been made through housing policies and investments in sustainable urbanization (Albuquerque; Ribeiro, 2020; Penna; Ferreira, 2014).

Concerns about environmental vulnerability and urban sustainability are gaining prominence in academic discussions and public policies, contributing to innovative and inclusive solutions. These efforts underscore the resilience of the country and its ongoing pursuit of ways to improve urban quality of life, reduce inequalities, and create more welcoming cities for all (Bittencourt; Faria, 2021; Véras, 2010).

The urbanization process in Brazil, while presenting challenges, stands out as an opportunity to promote social inclusion and urban sustainability. Housing programs and infrastructure investments aim to balance urban growth with the reduction of socio-spatial inequalities and environmental preservation (Muianga; Kowaltowski, 2024). Moreover, the cultural and economic diversity of Brazilian cities serves as a catalyst for innovation, integrating public policies and community actions that seek to transform vulnerable areas into resilient and inclusive spaces (Portugal *et al.*, 2021; Stålhammar; Brink, 2021).

2.1.2 Urbanization process in the United States

The urbanization process in the United States reflects a trajectory marked by economic, technological, and social transformations. Historically, American urbanization was influenced by multiple factors, including industrialization, migration, and technological innovations (Balk *et al.*, 2018; Silva, 2014).

The initial phase of urbanization in the United States can be traced back to the Industrial Revolution in the 19th century (Bairoch; Goertz, 1986). This period was characterized by the transition from an agricultural to an industrial economy, driven by the expansion of industries, technological innovations, and the growth of infrastructures such as railways (Jones; Balk; Leyk, 2020). Consequently, the rural population was migrating to urban areas, motivated by employment opportunities in growing urban industries and the promise of a better life in cities (Boustan; Bunten; Hearey, 2014).

This movement was characterized by rapid population growth concentrated in cities of the Northeast and Midwest, such as Chicago and New York, which became crucial industrial and commercial hubs. Recent studies highlight that, although economic factors were the primary drivers of this initial process, social and cultural dynamics also played an essential role in shaping spatial organization and urban living patterns (Boustan; Bunten; Hearey, 2013).

During the 20th century, American urbanization took on new configurations, marked by suburbanization and the development of metropolitan areas (Kilper, 2018). This movement was largely supported by public policies such as the Federal Highway Act of 1956, which financed extensive interstate highways, and the availability of affordable housing loans through programs offered by the Federal Housing Administration. However, suburbanization was not merely an economic or infrastructural phenomenon but also a reflection of cultural shifts (Goldfield, 1990).

The growth of suburbs was accompanied by the consolidation of lifestyle ideals that emphasized private spaces, security, and access to modern services—elements that transformed the relationship between urban centers and their peripheries. The search for quality of life, lower population densities, and accessible housing led to expanding suburban areas (Zhou; An; Yao, 2022). Simultaneously, cities faced challenges such as deindustrialization, a declining economic base, and social problems, resulting in urban restructuring (Balk *et al.*, 2018).

Since the 1970s, the phenomenon of counterurbanization has emerged as a counterforce to traditional urbanization, reflecting a population movement back to rural or less densely populated areas, particularly in response to issues such as urban congestion, high living costs, and environmental degradation (Frey, 1993). This settlement pattern, combined with urban growth in lower-density areas, has introduced new challenges for sustainable urban planning. Additionally, the acceleration of technological processes, such as the proliferation of digital platforms for remote work, has intensified these trends, enabling greater flexibility in choosing residential locations and reducing dependence on traditional urban centers (Wu *et al.*, 2011).

At the same time, the environmental impact of urbanization has received growing attention, especially in regions experiencing rapid metropolitan expansion, such as the Sun Belt. Studies emphasize that urban area growth has led to changes in land use, with direct effects on local ecology and climate resilience (Alig; Kline; Lichtenstein, 2004; Foody, 2003). Furthermore, these structural changes in land use directly affect climate resilience, increasing vulnerability to extreme events such as hurricanes and floods, which disproportionately impact low-income communities in densely populated urban areas (Shi; Moser, 2021).

From an economic perspective, the urbanization process in the United States also reflects a spatial reorganization of productive activities and capital accumulation. The decentralization of industries, the strengthening of financial and technological services, and the rise of new urban economies based on innovation and creativity have redefined the role of cities (Sun *et al.*, 2023). However, these transformations have also exacerbated regional inequalities, creating disparities between global cities like New York and San Francisco and economically declining urban areas, particularly in the Rust Belt (Hackworth, 2019; Miraftab; Wilson; Salo, 2015).

In summary, the urbanization process in the United States is characterized by an interaction of historical and contemporary forces, spanning from industrial beginnings to postmodern dynamics of counterurbanization and dispersed urbanization. The spatial, economic, and social changes observed throughout the 20th and 21st centuries underscore the need for urban planning approaches that balance growth, sustainability, and social equity (Fiack *et al.*, 2021; Hess; McKane, 2021).

2.1.3 Urbanization in cities with different levels of development

Urbanization is a global process that reflects diverse economic, social, and environmental dynamics, shaped by factors such as the level of development, resource availability, and local history (Gu, 2019). Although urban growth is often associated with modernization and economic progress, it can also lead to challenges such as social inequalities, environmental degradation, and pressure on infrastructure (Zhang, 2016). In countries with varying levels of development, the urbanization process exhibits both similarities and differences, which can be illustrated through the analysis of specific cases.

The urbanization process reflects interactions between population density and the physical development of cities. As observed by Carra and Barthelemy (2019), this process can be divided into three main phases: an initial growth stage, characterized by the simultaneous increase in population and the number of buildings; a second phase of saturation, during which the population declines while the number of buildings remains constant, often due to the conversion of residential to non-residential uses; and, finally, a phase of re-densification, where both the population and the number of buildings resume growth.

In cities located in developing countries, like many found in Brazil, urbanization frequently unfolds rapidly, propelled by a significant migration flow from rural to urban zones

(Brockerhoff; Jones; Visaria, 1998). This expansion, often outpacing the scope of adequate urban strategies, reflects a range of underlying orders – from economic forces drawing populations to certain locales, to the dynamics of urban space production and speculation (Campolina Diniz; Vieira, 2016). Consequently, this form of urbanization culminates in a landscape marked by socioeconomic disparities, including challenges like insufficient infrastructure, unequal access to essential public amenities and housing, along with environmental concerns (Marques, 2021; Sousa Filho *et al.*, 2022).

In some cases, the speed of urbanization may surpass the capacity for urban planning to fully address the demands of growing populations, resulting in uneven development and persistent disparities. Issues such as inadequate infrastructure and environmental concerns are not uncommon and require innovative policies to foster inclusive and sustainable urban growth (Henderson; Turner, 2020).

Conversely, in consolidated urban areas, as is the case in several cities in the United States, the urbanization process has typically unfolded over a longer timeframe. This gradual trajectory has allowed for more structured urban planning, often incorporating sustainability initiatives, technological advancements, and measures to enhance urban resilience (Antrop, 2000; Sutton-Grier *et al.*, 2018). However, even in these contexts, challenges such as urban sprawl, social inequality, and environmental degradation persist, demonstrating that no urban system is immune to pressures associated with growth and modernization (Talen; Wheeler; Anselin, 2018).

Hendricks and Dowtin (2023) emphasize that, historically, urbanization has involved extensive replacement of natural landscapes with impervious materials such as concrete, metals, and plastics. This extensive use of impervious materials has disrupted natural hydrological processes, decreasing infiltration capacity and elevating stormwater runoff. Gray infrastructure systems – engineered structures such as gutters, pipelines, and drainage channels built primarily from impermeable materials – have traditionally been employed to manage stormwater runoff. However, such systems are increasingly inadequate due to escalating urban development and changing climatic conditions that amplify stormwater volumes and exacerbate flooding issues. The authors further argue that addressing these challenges requires a strategic combination of traditional gray infrastructure with green infrastructure solutions. Integrating nature-based solutions such as bioswales, rain gardens, permeable pavements, and urban forestry can enhance stormwater management, reduce runoff volumes, and improve overall urban resilience.

The patterns of urbanization also vary according to economic structures. Industrialized countries tend to create "production cities" focused on industrial and technological activities, whereas resource-exporting countries often develop “consumption cities” centered around service-oriented economic activities (Gollin; Jedwab; Vollrath, 2016). Despite these economic differences, urban inequalities persist globally, manifesting uniquely across different contexts (Brelsford *et al.*, 2017).

In the United States, for instance, marginalized communities often have limited access to affordable housing and quality urban services, underscoring that issues of inequality are not exclusive to developing contexts (Koschinsky; Talen, 2015). Similarly, in Brazil, various cities have implemented initiatives to integrate low-income populations into the urban fabric, such as land regularization projects and the urbanization of informal settlements. These efforts demonstrate that urbanization in these countries is not inherently chaotic or problematic but rather reflects historical and structural dynamics (Prouse, 2019; Riley; Fiori; Ramirez, 2001).

Finally, when analyzing urbanization processes, it is necessary to acknowledge the similarities and differences in terms of challenges and opportunities. While cities in the United States grapple with issues such as modernization and sustainability in already established systems, cities in Brazil are at the forefront of creative solutions to promote social inclusion and sustainability amid rapid growth (Culligan, 2019; Portugal *et al.*, 2021). This diversity highlights the complexity of the urban phenomenon, emphasizing that both developing and developed countries have lessons to offer in the management of cities in an increasingly urbanized world (Teklemariam, 2022).

2.2 CHALLENGES OF WATER SUSTAINABILITY IN URBANIZATION

Amid urbanization, unpaved surfaces, agricultural lands, and natural wetlands are converted into paved and impermeable areas. Thus, the environmental impacts caused by urbanization in the environment are part of the efforts to implement global strategies for sustainable development (Juma; Wang; Li, 2014).

In this context, population growth, accompanied by domestic, agricultural, and industrial needs, has increased water pressure, usually leading to availability and quality issues. Adding to this, the increase in impermeable surface in urbanized areas increases runoff, flooding, and diffuse sources of pollution in watersheds (McDaniel; O’Donnell, 2019).

The changes in LULC caused by urbanization alter the patterns of wastewater and stormwater runoff, which impacts aquatic life in receiving waters. Related to these challenges are the issues of water scarcity and pollution on the planet, among the most significant challenges in the developed world (Hassan Rashid; Manzoor; Mukhtar, 2018).

Urban centers concentrate the water demands of thousands of people in a small area, which would increase stress on the supply of available fresh water in its surroundings. However, as they also represent a concentration of economic and political power, cities, as reported by McDonald *et al.* (2014), began to build water infrastructures to meet their demands, exploring new surface and groundwater sources, often distant from their locality.

The relationship between urbanization and water vulnerability is hotly debated because it shifts across disciplinary perspectives, scales of analysis (from individual plots and neighborhoods to entire cities, river basins, and broader regions) and governance domains that divide authority over state-managed waters, federally regulated waterways, and other jurisdictions. A view generally supported by engineers and hydrologists argues that a lack of water resources rarely limits urban water supply and that water availability for cities can be increased by reallocating water from agricultural uses to human consumption (Garrick *et al.*, 2019). On the other hand, another point of view, usually adopted by geographers and urban planners, argues that many urban centers cannot expand supply to meet demand due to poor governance or inadequate coordination among decision-makers (Vo, 2007).

According to Vo (2007), as cities grow ill-planned without adequate supply infrastructure, they may become dependent on unsustainable water withdrawals (surface or groundwater), further stifling human development. Thus, the lack of water resources can delay development and restrict urbanization (Bao; Fang, 2007).

Therefore, understanding the bidirectional links between urbanization and water resources requires examining the underlying nature of this relationship. According to Srinivasan *et al.* (2013), the relationship between urbanization and vulnerability to water scarcity depends on multiple factors, such as the available water infrastructure, the rate and spatial pattern of urbanization, the adaptability of inhabitants, and local geology.

Emerging countries have lower financial potential to mitigate environmental and water issues globally. The highest number of people affected by water-related problems in urban areas, such as the scarcity of necessary quality water, live in these countries, where gaps in water policies result in the lack of efficient management plans (Mukherjee; Bebermeier; Schütt, 2018).

Consequently, climate and environmental changes must also affect water availability and increase stress on supply (Arnbjerg-Nielsen *et al.*, 2013). According to Romero-Lankao and Gnatz (2016), such changes also affect the recharge capacity of reservoirs and negatively impact urban areas, challenging water managers and stakeholders to develop tools and metrics that can help them assess the challenges to water security imposed by the urbanization process.

Thus, Orlove and Caton (2010) propose that anthropological analyses of water resources should focus on five main themes: value, equity, governance, politics, and knowledge.

2.2.1 Values: natural resources and human rights

How do the environment and society interact in water systems?

Water connects to the environment both directly—through drinking water—and indirectly, as a resource embedded in the production of goods and services (Chini; Konar; Stillwell, 2017). There are trade-offs between allocating water for direct and indirect human uses. According to Forslund *et al.* (2009), the impact on the hydrological cycle of allocating water to natural ecosystems is often positive, as ecosystems improve water quality. However, the direct use of water by developing managed systems (reservoirs, irrigation, dams, etc.) often negatively impacts the hydrological cycle.

In July 2010, the UN General Assembly adopted a resolution recognizing the right to drinking water and sanitation as essential human rights for the full enjoyment of life and all human rights (Ki-moon; General, 2010). However, the debate over the official recognition of the human right to water has a significant political dimension. It raises discussions about water as a human right or economic commodity and, consequently, about the role of public and private actors in its management (Fantini, 2020).

In this context, water is valued as a resource for human well-being and the economy, and therefore, integrates the economic system, but also as an essential good for human life, being part of political systems (Branco; Henriques, 2010). Thus, various social movements claim universal rights to water based on biological needs for quantity and quality; however, these calls for universal water rights are systematically undermined by appeals related to property rights and their exclusive use (Swyngedouw, 2009).

2.2.2 Equity: access and distribution

How should a resource be shared among members of a society?

Unequal LULC patterns across neighborhoods—such as concentrations of impervious surfaces and deficits of green space—directly influence who enjoys reliable water services and who is disproportionately exposed to droughts or floods, placing spatial LULC disparities at the center of environmental justice concerns. Ensuring participatory water resource management guarantees access to essential water services. Many regions of the world face problems related to droughts, floods, scarcity, and lack of access to water. However, the burden of these challenges is not equally shared among population groups, as the economically more vulnerable population ends up having reduced access and suffering more significant environmental consequences (Fletcher *et al.*, 2022).

Despite progress towards the United Nations' 6th Sustainable Development Goal, which sets the target of water and sanitation for all by 2030, it is estimated that 785 million people worldwide still do not have access to water in their homes (UNESCO, 2019). Because neighborhood-scale LULC often mirrors broader socio-economic inequalities, these physical patterns reinforce patchworks of privilege and deprivation in both supply and hazard exposure. However, according to Wilder and Ingram (2018), despite numerous efforts to promote equity in water resource access, water faces a global crisis generated by a lack of governance, which amplifies inequalities in access to the resource.

2.2.3 Governance: organization and rules

How do institutional economics and economic sociology help understand the organizations that manage and distribute water?

Sustainable management of water resources in times of climate uncertainty is one of the most pressing challenges of this century. However, many problems in water management are more associated with governance failures than with the availability of resources, encompassing the complexity of a range of processes and interactions (Pahl-Wostl *et al.*, 2010).

According to the World Water Association, the definition of water governance can be understood as: "Water governance refers to the range of political, social, economic, and administrative systems that are in place to regulate the development and management of water resources and the provision of water services at different levels of society" (Rogers; Hall, 2003, p. 16).

Regarding water resources, the term governance has been used to normatively prescribe or help design specific institutional, organizational, and financial arrangements for decision-making about water (Zwarteveen *et al.*, 2017). Thus, governance can be considered a prerequisite for improving water management (Pahl-Wostl, 2009).

General governance gaps in countries form one of the main challenges for implementing water policies, leading to failure in water service policy implementation (Ménard; Jimenez; Tropp, 2018). Another implementation gap is related to decision-makers behaviors, which can result in elite benefit, third-party opportunism, and corruption, mainly caused by a lack of transparency (Jiménez *et al.*, 2020).

In addition to institutional and behavioral barriers, a major governance challenge in water resource management lies in the lack of harmonization and interoperability among geospatial data sources. Although there is an increasing availability of environmental, demographic, and infrastructure datasets, these often differ in definitions, methodologies, formats, resolutions, and update frequencies. This heterogeneity hampers data integration into comprehensive analyses and undermines the development of effective, spatially informed management strategies. The absence of standardization weakens the reliability of assessments and limits the ability to support sound policy and economic decisions, as emphasized by the inconsistent definitions and methodologies found in global water databases (Dantas; Delzeit; Klepper, 2021).

2.2.4 Politics: discourses and conflicts

How to understand the struggles for water control in society?

Water connects with democratic issues, citizenship, and development. To understand the obstacles in realizing a progressive public vision of water distribution, the concept of participation serves as a starting point for analysis (Razavi, 2019).

Politics plays a fundamental role in water governance. The term governance and its association with the notion of management may presume an agreement among all involved parties about the values of the resource; thus, debates and conflicts encompass the sphere of politics based on a variety of forms of discourse, which include laws and human rights (Orlove; Caton, 2010).

With the advent of new irrigation technologies and infrastructure, the importance of water has been widely underestimated in recent history. However, diminishing supply, potential effects of climate variations, and population growth place water at the forefront of future development and risk analysis (Angelakis *et al.*, 2021).

Thus, promoting holistic water policies that integrate management, coordination, knowledge exchange, and planning can facilitate cooperation and conflict resolution at different scales (Kloos *et al.*, 2013). This underscores the importance of understanding hydrosocial cycles (connections between water and society) rather than focusing solely on analyses of the hydrological cycle (Sultana, 2018).

2.2.5 Knowledge: local and scientific systems

How do different types of knowledge interfere in water management?

An interdisciplinary approach to water research is indispensable for understanding the resource's multifaceted issues. According to (Krueger *et al.*, 2012), knowledge about water resources goes beyond the scientific field, requiring the participation of stakeholders and citizens in research and water management.

In this context, knowledge can disrupt existing wisdom and needs to be destabilized, meaning hydrologists have also started to analyze societal feedback, promoting traditional quantitative methods for hydrology and system dynamics (Krueger *et al.*, 2016).

Transdisciplinary research can provide the missing link between theory and implementation of sustainable water governance. Transdisciplinary knowledge among scientists, users, and decision-makers can be considered an important contribution to more reflective and deliberative water governance (Renner *et al.*, 2013).

Therefore, for viable water management plans for different communities, it is essential to recognize science and local cultural aspects, as the feasibility of drainage, depletion, and supply projects are at stake and involve local governance and collaborative water management (Hayashi *et al.*, 2021). From the interconnection between human, environmental, and climatic systems, an emerging challenge for the academic community is to understand the impacts of climate change and climate policies on sociodemographic and economic development (Howarth; Monasterolo, 2017).

2.3 IMPACTS AND ADAPTATION TO CLIMATE CHANGE IN CITIES

Humans have been modifying the planet for millennia, but only in the last centuries have the impacts of these transformations become visible globally (Steffen *et al.*, 2015). Urban areas are places that drive environmental change on different scales. The material demands of human production and consumption alter LULC, biodiversity, and water resources, producing waste that affects biogeochemical cycles and the climate (Grimm *et al.*, 2008).

According to the IPCC Sixth Assessment Report (AR6), global mean surface temperature is projected to rise by 1.0 to 1.8 °C under a very-low-emissions pathway (SSP1-1.9) and by 3.3 to 5.7 °C under a very-high-emissions pathway (SSP5-8.5) for 2081-2100, relative to 1850-1900. Over the same period, global mean sea level is likely to increase by 0.28 to 0.55 m in SSP1-1.9 and by 0.63 to 1.02 m in SSP5-8.5. Without additional adaptation, these rises are expected to expand the population living in low-elevation coastal zones exposed to at least annual flooding from today's tens of millions to hundreds of millions of people by the end of the century (IPCC, 2023).

The main anthropogenic influences on the climate are the emission of greenhouse gases and changes in LULC, such as urbanization and agriculture. However, separating these two influences becomes complex, as both tend to increase the average daily surface temperature (Kalnay; Cai, 2003).

Recent research shows that cities have become seen as places of strategic action for climate change (Khosla; Bhardwaj, 2019). Therefore, it is relevant to analyze the prominence of urban climate responses, especially in developing countries, where most urban growth occurs, as their climate responses are precarious compared to developed countries, justified by local limitations, data, and governance structures (Nagendra *et al.*, 2018; Romero-Lankao *et al.*, 2018).

According to Gill *et al.* (2007), the urban environment has distinct biophysical characteristics compared to adjacent rural areas; this includes heat islands and hydrological changes, such as increased surface water runoff. These changes are, in part, the result of the alteration of the surface cover caused by the rural-urban transition.

Climate change and other environmental changes have contributed to profound changes in the terrestrial system, including changes in sea level, ecosystems, glaciers, species distribution, and extreme events (Aguiar *et al.*, 2018). Thus, more frequent and intense flooding and drought events will pressure water resources and exacerbate urban pressures caused by growth, such as population expansion, poverty, and pollution (Rosenzweig *et al.*, 2010).

Managing risks by adapting long-term infrastructure to the effects of climate change must become a regular part of water system planning (Rosenzweig *et al.*, 2007). Therefore, it is essential to assess the potential risks of climate change in cities, as surface retention and infiltration are reduced – increasing surface flow during rain events – and the increased demand for resources leads to decreased flows, intensifying the impacts of drought phenomena (Remondi; Burlando; Vollmer, 2016).

2.3.1 Compound events in the Anthropocene

Due to their different spatial and temporal dimensions, assessing the risks of droughts and floods simultaneously has become challenging. Generally, drought occurs gradually and covers a large area, whereas floods start quickly and impact a geographically limited area (Shao; Kam, 2020).

Therefore, compound events can exacerbate adverse impacts, leading to greater impacts on human society and the environment compared to extremes that occur in isolation (Hao; Singh; Hao, 2018). Misrepresenting the dependencies between events can lead to underestimating disaster risk, as the risk is generally much greater than the individual components suggest (Zscheischler *et al.*, 2018).

The IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC SREX) defines a compound event, according to the precepts of climate sciences, as:

> (1) two or more extreme events occurring simultaneously or successively, (2) combinations of extreme events with underlying conditions that amplify the impact of the events, or (3) combinations of events that are not themselves extremes but lead to an extreme event or impact when combined (Seneviratne et al., 2012, p. 118).

Hence, the analysis of compound events is limited by data availability, historical series, and model simulations. Essential vulnerabilities and interactions between managing entities remain exogenous to most assessments of climate extremes; thus, resolving these issues would help to build mechanisms to deal with extreme impacts, understand how they develop, and who is affected when it happens (Raymond *et al.*, 2020).

Therefore, compound events create an additional complication for risk estimation. Changes in climatic patterns can occur in opposite directions, such as an increase in the intensity of rains and floods in a drier basin (Leonard *et al.*, 2014). Thus, such changes create multiple extremes in different regions and seasons, such as drought, heat waves, storms, and floods.

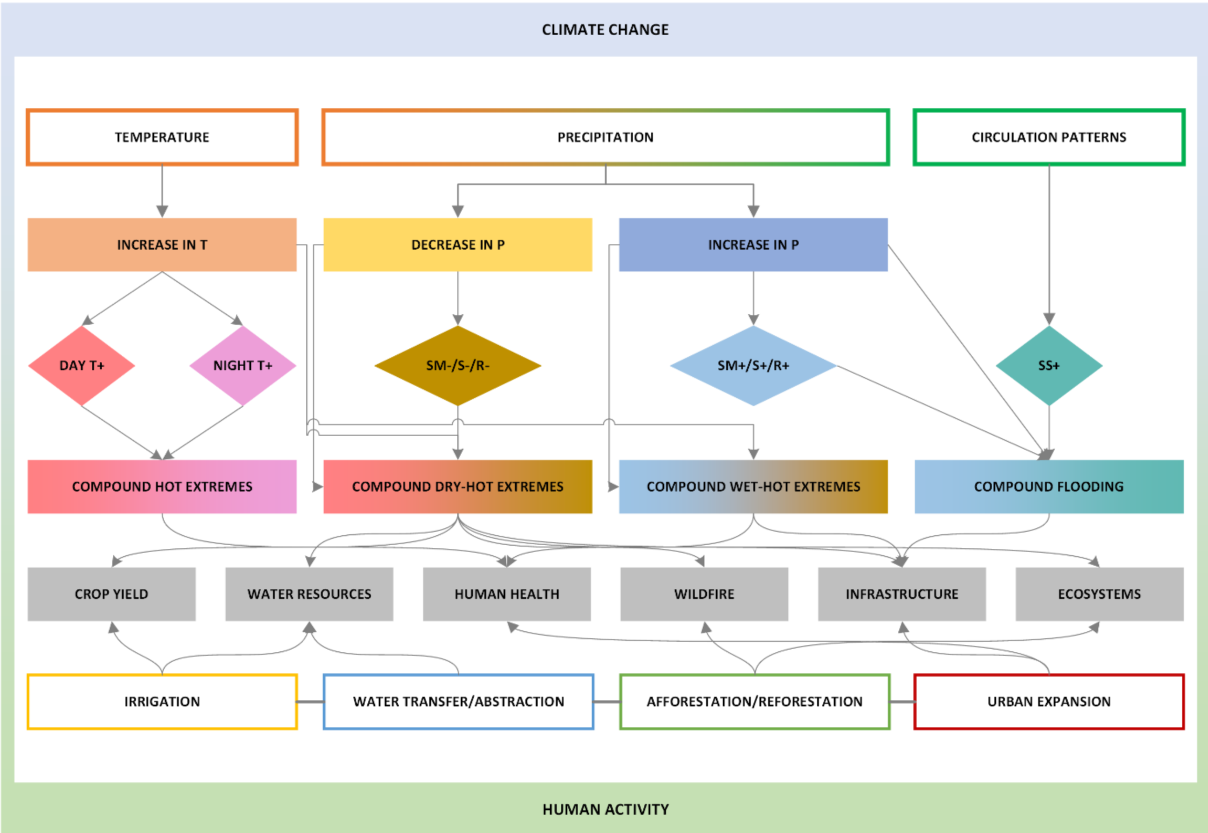
According to Keshavarz, Karami and Vanclay (2013), drought can be considered the most complex natural hazard, affecting more people globally than any other. Drought represents a temporary water shortage in precipitation, groundwater, agriculture, and urban life and can be classified as meteorological, hydrological, agricultural, and socioeconomic (Guo *et al.*, 2019). Socioeconomic drought, in turn, is the only non-physical phenomenon among these four types of drought, characterized by a lack of water to meet demands in industry, irrigation, energy, and the environment (Tu *et al.*, 2018).

In this sense, Zhang *et al.* (2019) classify urban drought as a subtype of socioeconomic drought, representing a temporary water scarcity condition in the urban context, whether due to a sharp drop in supply or a sudden increase in water demand. In contrast, urban environments are also particularly vulnerable to floods caused by heavy rains, which have become increasingly frequent due to climate change and rapid urbanization (O'Donnell; Thorne, 2020). Thus, precipitation is the natural source event that triggers a flood risk.

However, the characteristics and severity of floods also depend on the morphology of the watershed, i.e., how it converts rain into runoff and the consequent flow peaks transported. Therefore, flood control measures are necessary to increase the urban environment's resilience to extreme rain events (Scionti *et al.*, 2018). Thus, the impacts of compound extremes are often substantially and non-linearly influenced by non-physical factors, such as exposure and vulnerability, crossing sectors, and scales (Raymond *et al.*, 2020). Considering the continuous growth of cities, it can be observed that their vulnerability to extreme events and disasters increases proportionally (Borden *et al.*, 2007).

In this context, cities must respond more quickly and effectively to disasters to anticipate and minimize the associated consequences and hazards through improvements in conditions that promote urban resilience (Ribeiro; Gonçalves, 2019).

Figure 1. Compound events and potential impacts



Temperature, precipitation, soil moisture, streamflow, runoff, and storm are abbreviated as T, P, SM, S, R, and SS, respectively. The + and - signs indicate positive and negative anomalies of the contributing variables, respectively.

Source: Adapted from Hao (2022).

2.4 URBAN HYDROLOGICAL CHALLENGES

Urban hydrological challenges represent a set of problems that cities face in water management, influenced by factors such as urbanization – herein understood explicitly as the expansion of impervious surfaces (e.g., asphalt, concrete, rooftops) that replace natural or pervious land cover – climate change, and technology. Firstly, cities face difficulty finding and using new water sources to meet increasing demand while addressing sanitation issues and nutrient recycling from wastewater. Implementing urban agriculture emerges as a potential solution (Niemczynowicz, 1999). Additionally, challenges such as improving short-term rainfall forecasts, restoring water balance, and removing emerging pollutants are exacerbated by uncertainties related to climate change (Fletcher; Andrieu; Hamel, 2013).

Another aspect is hydrological modeling in urban areas, which faces limitations due to incomplete understanding of the interaction between urban and natural systems, high uncertainty, and limited data availability (Salvadore; Bronders; Batelaan, 2015). Because imperviousness alters hydrological connectivity, models must explicitly represent the spatial distribution of impervious materials to produce realistic runoff and pollutant transport estimates. The availability of data and simplified methods has also led to failures in sustainable urban development (Sharma, 2019). In this context, managing urban floods requires constructing flood-resistant infrastructure and local rainwater harvesting for urban regeneration, greening, and resource production.

Therefore, using advanced technologies, such as high-resolution hydrological modeling—computational simulations that represent water movement and distribution across landscapes with fine spatial and temporal detail—can offer more precise tools about water behavior in urban environments and help predict and mitigate problems such as flooding and pollution (Cotton; Strasser, 2012). Consequently, Lara-Valencia et al. (2022) highlight the potential of integrated policies that consider the interaction between urban development, water management, and environmental protection essential for addressing these challenges effectively.

Adaptive management practices, such as the implementation of green and blue infrastructure, are increasingly recognized as effective strategies for sustainable stormwater management and flood risk reduction. Recent studies highlight how green Infrastructure contributes not only to runoff management but also to biodiversity conservation and improved urban livability (Wang *et al.*, 2024). Moreover, integrating blue-green-grey systems offers adaptive and flexible solutions critical for effective flood mitigation (Green *et al.*, 2021). To ensure a sustainable urban future, it is necessary to address these environmental challenges through strategic planning that leverages the co-benefits of green and blue infrastructure for both human and ecosystem health (Kvamsås, 2023).

2.5 INTERRELATIONS BETWEEN LULC AND WATER RESOURCES

LULC changes are an emerging theme in the global environmental and socioeconomic context. These changes reflect the complex interaction between human activities and the natural environment, impacting various aspects of the ecosystem and sustainable development (Mulat, 2020).

Changes in land use, such as urbanization, intensive agriculture, or deforestation, significantly affect the hydrological cycle (Giertz; Junge; Diekkrüger, 2005). Urbanized areas with impermeable surfaces increase surface runoff, reducing soil water infiltration and increasing flood risks. In contrast, areas with dense vegetation, such as forests, facilitate water infiltration, contributing to the recharge of aquifers and the maintenance of river and stream flows (Wang *et al.*, 2008).

Changes in land cover also influence water quality (Mello *et al.*, 2018). Agricultural areas can contribute to water body contamination with pesticides and fertilizers (Karmakar *et al.*, 2019). Urban areas can increase water pollution due to contaminated stormwater runoff. Conversely, natural vegetation zones act as natural filters, improving water quality by removing sediments and pollutants (Sohl; Sleeter, 2012).

Given this problem, analyzing these LULC changes helps to identify critical areas for conservation, prevent the degradation of water resources, and develop strategies to mitigate the negative impacts of urbanization and agriculture (Coskun; Alganci; Usta, 2008; Hussain *et al.*, 2020). It is also helpful in planning water infrastructures, such as dams, urban drainage systems, and water treatment facilities (Matitaputty; Puspita; Isa, 2020).

Thus, LULC changes can aid in understanding how water resources will respond to climate change (Niraula; Meixner; Norman, 2015). Forested areas, for example, play a crucial role in regulating microclimate and maintaining humidity, which can mitigate the effects of climate changes on water resources (Wang *et al.*, 2012).

These analyses help quantify spatial-temporal variability and estimate the role of human activity in environmental changes, which is vital for understanding and mitigating the impacts of anthropogenic alterations on the environment (Brito et al., 2021).

2.5.1 LULC forecasting with cellular automata

LULC forecasting is crucial in studying environmental changes and urban planning (Prestele *et al.*, 2016). Predicting how landscapes will change provides input for sustainable development, economic growth, biodiversity conservation, and mitigation of climate change effects (Han; Yang; Song, 2015). According to Mondal *et al.* (2016), LULC forecasting provides information to understand anthropic interactions and the environment, enabling governments, scientists, and communities to make more assertive decisions.

One of the most used methods for LULC forecasting is using cellular automata (CA). CAs are computational models that simulate the evolution of a system over time through simple rules applied to cells in a grid (Bhattacharjee *et al.*, 2020). They are particularly effective in modeling complex and dynamic systems, such as land use patterns. In this context, the CA-Markov Chain is a notable example, combining the spatial modeling of CA with the temporal modeling of Markov chains to accurately predict future LULC changes (Losiri *et al.*, 2016).

Another approach is using Agent-Based Models (ABM), which simulate the actions and interactions of autonomous agents to assess their effects on the system as a whole. According to Heckbert, Baynes, and Reeson (2010), ABMs help model complex social and ecological phenomena in LULC, considering human behavior and decision-making. Machine Learning techniques, such as Artificial Neural Networks (ANN) and Random Forest Algorithms, have been applied to analyze large LULC data sets, yielding promising results (Shihab; Al-Hameedawi; Hamza, 2020). These techniques can identify complex patterns and trends, making them valuable tools in LULC forecasting (Ullah *et al.*, 2019).

Meanwhile, hybrid models represent another significant innovation in LULC forecasting. They combine different modeling techniques, such as CA and ANN, to add the contributions of each method. This approach allows for more accurate and adaptable modeling of LULC, capable of more precisely representing the complexity and heterogeneity of the planet (Saputra; Lee, 2019). Integrating different methods provides a more holistic understanding of LULC changes, which is essential for effective planning and management approaches (Qin; Fu, 2020).

In addition to these approaches, various CA models have been widely used to simulate and predict LULC changes. For example, the DinamicaEGO model, a flexible environmental modeling software, was used by Soares-Filho *et al.* (2006) to model deforestation in the Amazon. Another model, SIMLANDER, was applied by Rufino *et al.* (2021) to assess urban expansion in Brazilian cities. Additionally, MOLUSCE, a plugin for QGIS, was employed by Muhammad *et al.* (2022) to analyze spatial and temporal changes in LULC, while the LULCC-

R model was used by Aguilar-Tomasini, Escalante e Farfán (2020) to assess the effectiveness of protected natural areas. In this context, the ability to predict and understand LULC changes can assist in assessing and mitigating urban environmental risks and formulating effective risk management strategies (Gomes *et al.*, 2023).

2.5.2 Evaluating uncertainty in LULC models

Sensitivity analysis in LULC models contributes to the validation and improvement of these models. This type of analysis seeks to understand how variations in input parameters affect model outcomes, identifying which parameters are more influential and require greater precision in their estimates (Abijith; Saravanan, 2022; Talukdar *et al.*, 2021).

In this context, "LULC models" refer specifically to land use and land cover change simulation models, such as CA, CA-Markov, CA-ANN, or other spatially explicit models used to predict future landscape scenarios. These are not hydrological models per se, but can inform hydrological or environmental assessments when integrated.

From this perspective, Mohamed and Worku (2020) highlight the importance of sensitivity analysis in understanding past and future dynamics in LULC models, which can facilitate the planning and management of sustainable urban growth. This understanding aids in predicting the long-term effects of LULC changes and implementing effective policies for urban and regional planning.

Talukdar *et al.* (2021) and Sleeter *et al.* (2015) emphasize that sensitivity analysis is essential for identifying parameters that significantly influence the model. This identification allows researchers and planners to focus on the most critical factors impacting the accuracy and reliability of LULC models, thereby ensuring better predictions and planning.

Sensitivity analysis also aids in understanding the effects of physical and socioeconomic variables on LULC patterns (Muhammad *et al.*, 2022). This understanding contributes to developing future scenarios and land management strategies that consider both environmental and socioeconomic aspects.

Metrics such as the *Nash-Sutcliffe efficiency*, *coefficient of determination* (R^2), and *percentage bias* are sometimes applied in the context of LULC models that are coupled with hydrological or environmental models. However, when assessing the accuracy of LULC simulation models alone (e.g., CA-Markov or CA-ANN), spatial agreement metrics such as Kappa index, overall accuracy, or allocation disagreement are typically used (Pontius; Millones, 2011). These methods allow for evaluating the accuracy and reliability of models, quantifying how well the simulations match observed data (Choto; Fetene, 2019).

In addition to these methods, *Hybrid Cellular Automata*, *Markov Chain*, and *Multi-Criteria Analytic Hierarchy Process (AHP)* are techniques used to simulate LULC change dynamics and predict future transformations (Mohamed; Worku, 2020). On the other hand, there are others techniques often used, such as *Random Forest*, which supports vector machine decision-making, and machine learning-based methods, like the Continuous Change Detection and Classification algorithm (Fu; Weng, 2016; Talukdar *et al.*, 2021).

Thus, sensitivity analysis becomes essential for assessing and guiding future land use policies and helping to predict changes in LULC that assist in developing more sustainable and environmentally responsible land management policies (Rahman *et al.*, 2017).

2.6 WATER SECURITY AND EMERGING ENVIRONMENTAL RISKS

Water systems are often altered by widespread changes in land cover, urbanization, industrialization, and water infrastructures such as reservoirs, irrigation, and inter-basin transfers that maximize human access to water (Vörösmarty *et al.*, 2010). Thus, water supply benefits for economic productivity and human consumption are accompanied by damage to ecosystems and biodiversity, highlighting the need for frameworks to diagnose the main threats to water security at various spatial scales (World Water Assessment Programme, 2009).

Water security has received increased attention in recent decades, with multiple definitions promoted by various international organizations (Cook; Bakker, 2012). UNESCO's International Hydrological Programme defines water security as:

> The capacity of a population to safeguard access to adequate quantities of water of acceptable quality for sustaining human and ecosystem health on a watershed basis and to ensure efficient protection of life and property against water-related hazards – floods, landslides, land subsidence,) and droughts (UNESCO, 2012, p. 7).

Water security incorporates a highly complex, multidimensional, and interdependent set of factors in this context. Consequently, increasing pressure on water resources has exacerbated competition for water use, compromising basic needs such as supply, irrigation, hydropower, and industrial uses (Mishra *et al.*, 2021). To analyze water security in the face of emerging risk threats, Kumar (2015) lists two primary challenges: (i) developing the capacity to explore the diverse possibilities of risk, to anticipate their probability and impact, and (ii) exploring new solutions modalities that combine new infrastructures with knowledge-based solutions to increase the range of management, mitigation, and adaptation strategies.

In most developing countries, understanding local climate dynamics and making predictions to respond to climate variability and change has become necessary. This is due to the economies of most of these countries being heavily dependent on climate-sensitive sectors such as water, agriculture, fisheries, energy, and tourism, where climate change poses a severe challenge to social and economic development (Misra, 2014).

Generally, at the urban scale, water security from a risk perspective is more significant due to the high concentration of people. In this context, risk can be characterized as a combination of hazard, exposure, and vulnerability (Garrick; Hall, 2014). Therefore, one city may be vulnerable due to a lack of preparation, while another facing the same hazards may be less vulnerable due to adequate adaptation and greater resilience (Hoekstra; Buurman; van Ginkel, 2018).

Therefore, it is evident that water sector security is a critical element in combating climate change (Babel *et al.*, 2020). The UN's Sustainable Development Agenda established Sustainable Development Goals (SDGs) dedicated to water (SDG 6) as well as to climate change (SDG 13), which reveal the nexus between climate change and water, as addressing issues related to this nexus will require improving water security (ONU, 2022).

Achieving water security depends less on an environmental challenge (availability of resources) and more on a governance issue. The impacts of a lack of water security on food, health, energy, livelihoods, migration, and conflicts demonstrate the crucial role of water as a connector since infrastructures alone will be insufficient and may increase inequalities (Stringer *et al.*, 2021).

2.7 URBAN RESILIENCE

Throughout history, cities have proven to be remarkably resilient complex systems, where millennia-old sites have persevered through natural and human-induced disasters to become stronger and, in some cases, more resilient (Elmqvist *et al.*, 2019). While resilience is a term recently added to the discursive repertoire of planners, it is not a new concept. Originating from the Latin resi-lire, meaning "to leap back," physicists first used resilience to represent the characteristics of a spring and describe the stability of materials and their resistance to external shocks (Davoudi *et al.*, 2012).

According to Leichenko (2011), urban resilience generally refers to the capacity of an urban system to withstand a wide range of stresses, such as climate change and disasters (droughts, floods, thermal stresses, extreme rainfall events). Thus, the definition of urban resilience needs to incorporate conceptual tensions flexibly and inclusively and can be defined as:

> Urban resilience refers to the ability of an urban system-and all its constituent socio-ecological and socio-technical networks across temporal and spatial scales-to

> maintain or rapidly return to desired functions in the face of a disturbance, to adapt to change, and to quickly transform systems that limit current or future adaptive capacity (Meerow; Newell; Stults, 2016, p. 45).

To deal with new urban challenges, planners must develop greater awareness and place mitigation and adaptation policies at the center of the planning process (Jabareen, 2013). Hence, cities must be understood as complex socio-ecological systems where sustainability and resilience involve more than urban form, encompassing a broad set of social and economic issues and strategies (Ahern, 2013).

Consequently, Godschalk (2003) classifies resilience as an important goal for two reasons: i) the vulnerability of technological and social systems cannot be fully anticipated; ii) people and property are expected to cope better with disasters in resilient cities compared to less flexible and adaptable places.

Thus, as societies experience the impacts of drought or flood events, humans respond and adapt to hydrological extremes through a combination of spontaneous processes and deliberate strategies, seeking adaptive responses at individual, collective, and institutional levels (Di Baldassarre *et al.*, 2017; Rufino *et al.*, 2021).

2.8 SUSTAINABLE URBAN DRAINAGE SYSTEMS

SUDS represent a promising approach to managing stormwater in urban areas. These systems aim to mitigate the negative impacts of urban development on the natural water cycle, emphasizing nature-based solutions and green technologies (Abellán García; Cruz Pérez; Santamarta, 2021).

SUDS offers multiple benefits, including flood risk reduction and water quality improvement. Ramos *et al.* (2013) highlight how SUDS can also be integrated into smart water networks to produce energy and efficiently manage water resources.

However, the effective implementation of SUDS requires considering the preferences and opinions of stakeholders. Casal-Campos et al. (2012) demonstrate this through a decision-support process in selecting SUDS in two Spanish cities, emphasizing the importance of stakeholder participation in planning and implementation (Casal-Campos; Jefferies; Perales Momparler, 2012).

In highly urbanized areas, SUDS are essential to mitigate flooding and relieve pressure on sewer networks. Jato-Espino *et al.* (2016) note that SUDS can significantly reduce the volume of water generated after rainfall events, preventing local flooding and drainage network overloads.

From an economic perspective, SUDS proves to be a valid investment. Johnson and Geisendorf (2019) analyzed the economic benefits of SUDS at the neighborhood level, revealing positive net present values and cost-benefit ratios. However, the implementation of SUDS faces challenges, such as uncertainty about their long-term performance and legislative requirements. These issues were addressed by Dierkes, Lucke and Helmreich (2015), who highlighted the need for improved technical approaches and greater clarity in regulatory guidelines for decentralized SUDS.

In this context, SUDS represents an emerging approach to sustainable stormwater management in urban environments. They offer significant environmental, social, and economic benefits, although they face practical and regulatory challenges (Andrés-Doménech *et al.*, 2021).

2.9 ENVIRONMENTAL JUSTICE

> Why, for instance, is a *human-made* phenomenon like global warming – which may kill hundreds of millions of *human beings* over the next century – considered 'environmental'? Why are poverty and war not considered environmental problems while global warming is? (Shellenberger; Nordhaus, 2004, p. 12).

Environmental justice originated as a response to the disproportionate siting of hazardous facilities in low-income and racially marginalized communities, particularly in the United States. A key historical landmark was the 1982 protest in Warren County, North Carolina, where a predominantly African American community mobilized against the siting of a PCB-contaminated landfill. This event, which led to over 500 arrests, catalyzed the environmental justice movement and drew national attention to the correlation between race and environmental hazards (Bullard; Johnson, 2000).

According to Bullard and Johnson (2000), prior to Warren County, localized struggles like the 1979 lawsuit Bean v. Southwestern Waste Management, Inc.—filed by African American residents in Houston—marked one of the first times environmental siting was challenged under civil rights law. These and similar actions laid the groundwork for environmental justice as a grassroots social movement concerned with racial, economic, and environmental inequalities.

In scenarios where marginalized communities are disproportionately affected by environmental issues such as pollution, ecosystem degradation, and lack of access to essential environmental services, ensuring equitable distribution of impacts, benefits, and accessibility to natural resources becomes urgent (Anguelovski, 2013). Therefore, impartiality in decision-making processes related to environmental policies and regulations is crucial to ensure that vulnerable groups do not unjustly bear adverse environmental impacts (Unger, 2008).

According to Scott (2014), environmental justice is a social movement emphasizing the just and equitable distribution of environmental advantages and disadvantages. Environmental justice refers to the principle of ensuring that all individuals, regardless of their social, economic, or demographic backgrounds, have equal and meaningful opportunities to participate in and contribute to the formulation, implementation, and enforcement of environmental legislation, regulations, and policies (Habermann; Gouveia, 2008).

Additionally, environmental justice encompasses the concept of fair allocation of environmental advantages and resources, aiming to mitigate any potential disparities, inequalities, or discriminatory practices that may arise about the distribution of environmental benefits (Loos *et al.*, 2023). Thus, fair treatment implies the absence of any group being burdened with an unbalanced and disproportionate allocation of adverse environmental repercussions from industrial, governmental, and commercial operations or policies (EPA, 2023).

The dimensions of environmental justice in urban ecosystem services focus on distributive, procedural, and recognition aspects (Calderón-Argelich *et al.*, 2021). Distributive justice focuses on fair allocation and access to material resources for all social groups, considering spatial and temporal aspects. Procedural justice highlights the importance of active and inclusive citizen participation in decision-making, prioritizing transparency (Schlosberg, 2013). Recognition of justice involves respecting and allowing individual expression, ensuring access to information, and catering to diverse individual needs and values (Langemeyer; Connolly, 2020).

The First National People of Color Environmental Leadership Summit in 1991 helped formalize these principles, adopting 17 foundational environmental justice principles that emphasized rights to ecological integrity, clean environments, self-determination, and participatory governance (Mohai; Pellow; Roberts, 2009). This summit expanded the scope of environmental justice to include housing, land use, and labor rights, reinforcing its intersectional and global dimensions.

More recently, scholars have highlighted how environmental injustice is embedded not only in the siting of harmful facilities but also in the neglect and degradation of critical infrastructure in marginalized neighborhoods. Hendricks and Van Zandt (2021) emphasize that infrastructure—such as stormwater systems, green spaces, roads, and sewerage—often reflects and reinforces social vulnerability. They argue that environmental inequality is materially expressed in deteriorated built environments and uneven investment patterns that expose low-income and racialized communities to chronic and acute environmental risks.

Broadly, environmental justice is intertwined with a spectrum of concerns or principles that encompass different places, types, and processes of injustice, often examined through a sustainability perspective (Koprowska, 2020). Thus, environmental justice can be understood as a theoretical framework and a civil rights social movement (Schlosberg; Collins, 2014). On the one hand, environmental justice seeks to understand how environmental impacts and benefits are distributed among different urban groups based on ethnicity, race, and socioeconomic status; conversely, it proposes solutions to reduce these disparities (Nadybal *et al.*, 2020; Taylor, 2000).

Importantly, recent EJ scholarship also emphasizes how systemic unknowability—where the lived realities and risks faced by vulnerable communities are invisible or dismissed by dominant institutions—creates moral and political barriers to justice. Dotson and Whyte (2013) argues that addressing these barriers requires not only awareness but structural shifts in how interdependence and ethical relations are conceptualized globally.

SECTION I

CAMPINA GRANDE, PB

a Brazilian case study

Credits: all.accor.com

3 UNDERSTANDING WATER SHORTAGE PROBLEMS IN CAMPINA GRANDE, BRAZIL: AN INTRODUCTION THROUGH SENTIMENT ANALYSIS

How does water shortage affect local communities in social, emotional and structural terms, and what factors have amplified inequalities in access to water?

English

This chapter explores an often-overlooked dimension of water resource management: the emotional and perceptual landscape of communities facing water scarcity. By applying sentiment analysis to televised news transcripts from Campina Grande, Brazil—a semiarid city affected by water shortages—this chapter reveals how collective experiences of drought are shaped not only by infrastructure and climate but also by public discourse, fear and trust. These findings underscore that urban water resilience depends as much on social perception and justice as on technical solutions.

Portuguese

Este capítulo explora uma dimensão frequentemente negligenciada da gestão de recursos hídricos: o cenário emocional e perceptivo das comunidades que enfrentam a escassez de água. Ao aplicar a análise de sentimentos às transcrições de notícias televisionadas de Campina Grande, Brasil – uma cidade semiárida afetada pela escassez de água –, este capítulo revela como as experiências coletivas da seca são moldadas não apenas pela infraestrutura e pelo clima, mas também pelo discurso público, pelo medo e pela confiança. Essas descobertas ressaltam que a resiliência da água urbana depende tanto da percepção social e da justiça quanto das soluções técnicas.

3.1 BACKGROUND

The Brazilian Semiarid Region (BSR), characterized by its irregular rainfall patterns and prolonged droughts, is one of the most critical areas in Brazil in terms of water resource management (Sousa *et al.*, 2023). With an average annual precipitation of less than 800 mm, distributed heterogeneously across time and space, the region faces historical challenges in ensuring water supply for its urban and rural populations (Galdino *et al.*, 2020). Reliance on reservoirs and centralized distribution systems increases the vulnerability of these regions, especially during extended drought periods (Li *et al.*, 2022).

The city of Campina Grande, located within the BSR, stands out as an example of hydrological challenges, where issues of flooding and scarcity disproportionately affect the most vulnerable communities (Alves *et al.*, 2020; Carvalho *et al.*, 2023). Alves *et al.* (2020) indicate that water supply is compromised by management issues in existing systems and by insufficient infrastructure to withstand severe drought periods.

Furthermore, inequalities in water access exacerbate social problems, intensifying perceptions of injustice and frustration among affected populations (Alves; Djordjević; Javadi, 2022). In a qualitative study, Del Grande *et al.* (2016) observed that the normalization of unequal water access reflects a scenario of environmental injustice, where the most vulnerable populations face greater barriers to obtaining water.

In this context, the media plays a critical role in shaping society's perception of water crises (Hyman *et al.*, 2022; Kong, 2022). By disseminating information about water shortages, the media not only highlights the challenges faced by vulnerable communities but also influences public understanding of the causes and potential solutions to these problems. Quesnel and Ajami (2017) suggest that by reporting on supply crises, the media can raise public awareness and foster debates that drive changes in water management practices.

Beyond technical dimensions, public perception of the water crisis involves cultural and social aspects that are fundamental for formulating more inclusive management strategies (Drimili *et al.*, 2019; Santos; Carvalho; Martins, 2023). By exploring emotions associated with scarcity, such as helplessness and the demand for water justice, the media can contribute to social mobilization and the strengthening of public policies aimed at equitable water access (Alonso-Cañadas *et al.*, 2019). Studies suggest that in prolonged crises, such narratives can play a positive role in raising awareness and fostering the pursuit of sustainable solutions (Kelly *et al.*, 2017; Thaker *et al.*, 2019).

In this context, analyzing the emotional impact of news coverage on water shortages can reveal key thematic elements tied to emotions, such as management failures, inequality in water access, and government neglect. This chapter aims to discuss the predominant emotions and the polarity of news reports related to water scarcity in Campina Grande, identifying the most recurring feelings and variations in tone throughout the news. By doing so, the study seeks to highlight the main thematic elements associated with emotions, evaluating the emotional impact of the issue as conveyed by journalists and perceived by the population.

3.2 METHODS AND DATA

This chapter focused on the media and public perception of water shortages in Campina Grande, based on televised news available on YouTube. Initially, searches were conducted on the platform using the terms "water", "shortage", "Campina Grande", "supply", and "new". The selection of videos followed inclusion criteria based on the presence of resident testimonies and the temporal proximity between news, ensuring the representativeness of collective narratives on the topic. It is important to highlight, however, that the availability of journalistic content was limited. In recent years, much of Brazilian news coverage has migrated to social media platforms or paid streaming services, which restricts free and public access to audiovisual archives in YouTube. Consequently, the selection process was constrained by the scarcity of openly accessible materials.

The selected news were transcribed with the help of the TurboScribe platform[1], which uses artificial intelligence to automatically convert audiovisual content into text. The process involved uploading the videos and applying speech recognition models to segment and transcribe dialogues. The transcriptions were manually reviewed to correct potential inconsistencies generated by the tool, ensuring the integrity of the textual data.

The transcribed texts were processed in an R environment using text analysis libraries, including tidytext for tokenization[2] and Syuzhet for sentiment analysis. Initially, the words in the texts were tokenized, removing Portuguese stopwords[3] to focus on semantically relevant

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[1] TurboScribe is an AI-powered transcription platform designed to convert audio and video files into accurate, readable text. It supports multiple languages and provides features such as speaker identification, timestamping, and customizable formatting to suit academic, professional, and media needs.

[2] Tokenization is the process of dividing a text into smaller parts, called tokens, which can be words, phrases or even characters, depending on the purpose of the analysis. This process is essential in textual analysis studies, as it allows for the identification of patterns, word frequencies and emotions. For example, in the sentence "Lack of water in Campina Grande", tokenization would result in the text being separated into words such as "Lack", "of", "water", "in", "Campina" and "Grande".

[3] Stopwords refers to very common words in a language, such as "de", "a", "o", "e" and "em" in Portuguese, which do not carry a semantic meaning relevant to the analysis. These words appear with high frequency in texts, but do not contribute directly to understanding the themes or emotions. Thus, in sentiment or content analysis, removing stopwords makes it possible to focus on terms with a greater informational load, such as "water", "lack" and "protest", which reflect the emotional and semantic content of the text.

terms. Numerical words and other non-textual elements were also excluded. Subsequently, the tokenized words were cross-referenced with the National Research Council Canada (NRC) dictionary, a recognized reference for identifying emotions, previously adapted for Portuguese. This analysis classified words into emotional categories such as joy, sadness, anger, fear, surprise, disgust, trust, and anticipation.

The NRC Emotion Lexicon is widely used in sentiment and emotion analysis. Developed by the National Research Council of Canada, it consists of a set of words associated with different emotional categories and polarities, focusing on identifying specific sentiments in texts (Mohammad; Turney, 2013). Each word in the dictionary is categorized according to the emotions or polarities it is associated with. For example, the word “happiness” may be associated with the emotion “joy” and the polarity “positive”, while the word “chaos” might be linked to the emotions “anger”, “fear”, “sadness”, and the polarity “negative”.

The polarity of the texts was also evaluated using the Syuzhet[4] library, which calculates scores for each sentence, measuring their positive or negative character. The results were presented through bar and line graphs, highlighting the distribution of emotions by news report and across sentences.

3.3 RESULTS

The analysis of the transcribed news, presented in Table 1, revealed an overview of the social, economic, and structural impacts resulting from the water crisis in Campina Grande and its surrounding region. The findings demonstrate the persistence and recurrence of issues related to water supply interruptions, highlighting both deficiencies in water planning and management and the resilience of the affected communities.

The results reveal that the lack of water, caused by events such as a power system failure at the Gravatá Water Treatment Station and operational issues at the Paraíba Water and Sewage Company (CAGEPA), directly impacted basic daily activities, such as personal hygiene, food preparation, and household cleaning. In several news, including testimonials from residents of the Palmeira and Araxá neighborhoods, a reliance on improvised solutions was observed, such as transporting water in buckets and using alternative sources unsuitable for human consumption.

[4] Syuzhet is an R package designed for extracting and analyzing the emotional and sentiment content of textual data. Developed for researchers and data analysts, it provides tools to perform sentiment analysis using lexicon-based methods, as well as narrative arc modeling inspired by literary theory.

Table 1. Characteristics of the selected news in the analysis

News	Translated and original title (*in Portuguese*)	Date	Channel	Duration (min)	URL
re1	The water shortage in Campina Grande continues *(Continua o drama da falta de água em Campina Grande)*	03/21/2019	TV Correio	11:57	Link
re2	Water shortage in Campina Grande reaches its fifth day *(Falta de água em Campina Grande chega ao quinto dia)*	03/20/2019	TV Tambaú	4:08	Link
re3	Residents of the Palmeira neighborhood in Campina Grande complain about the water shortage *(Moradores do bairro da Palmeira em Campina Grande reclamam da falta de água)*	02/18/2019	TV Correio	4:12	Link
re4	The water shortage in Campina Grande has been causing significant disruptions for the city's residents *(Falta de água em Campina Grande, vem causando muitos transtornos aos moradores da cidade)*	03/19/2019	TV Correio	4:13	Link
re5	Water shortage reaches its sixth day in Campina Grande *(Falta d'água chega ao sexto dia em Campina Grande)*	03/21/2019	TV Tambaú	2:26	Link
re6	Residents of Araxá protest against the water shortage in Campina Grande *(Moradores no Araxá protestam pela falta de água em Campina Grande)*	03/20/2019	TV Correio	3:06	Link
re7	The water shortage in Campina Grande and surrounding areas has affected a large number of people *(A falta d'água em Campina Grande e região tem afetado muita gente)*	03/26/2019	TV Correio	2:18	Link
re8	Residents of several neighborhoods in Campina Grande have been without water for over five days *(Moradores de vários bairros de Campina Grande estão há mais de 5 dias sem água)*	10/27/2021	TV Correio	5:02	Link

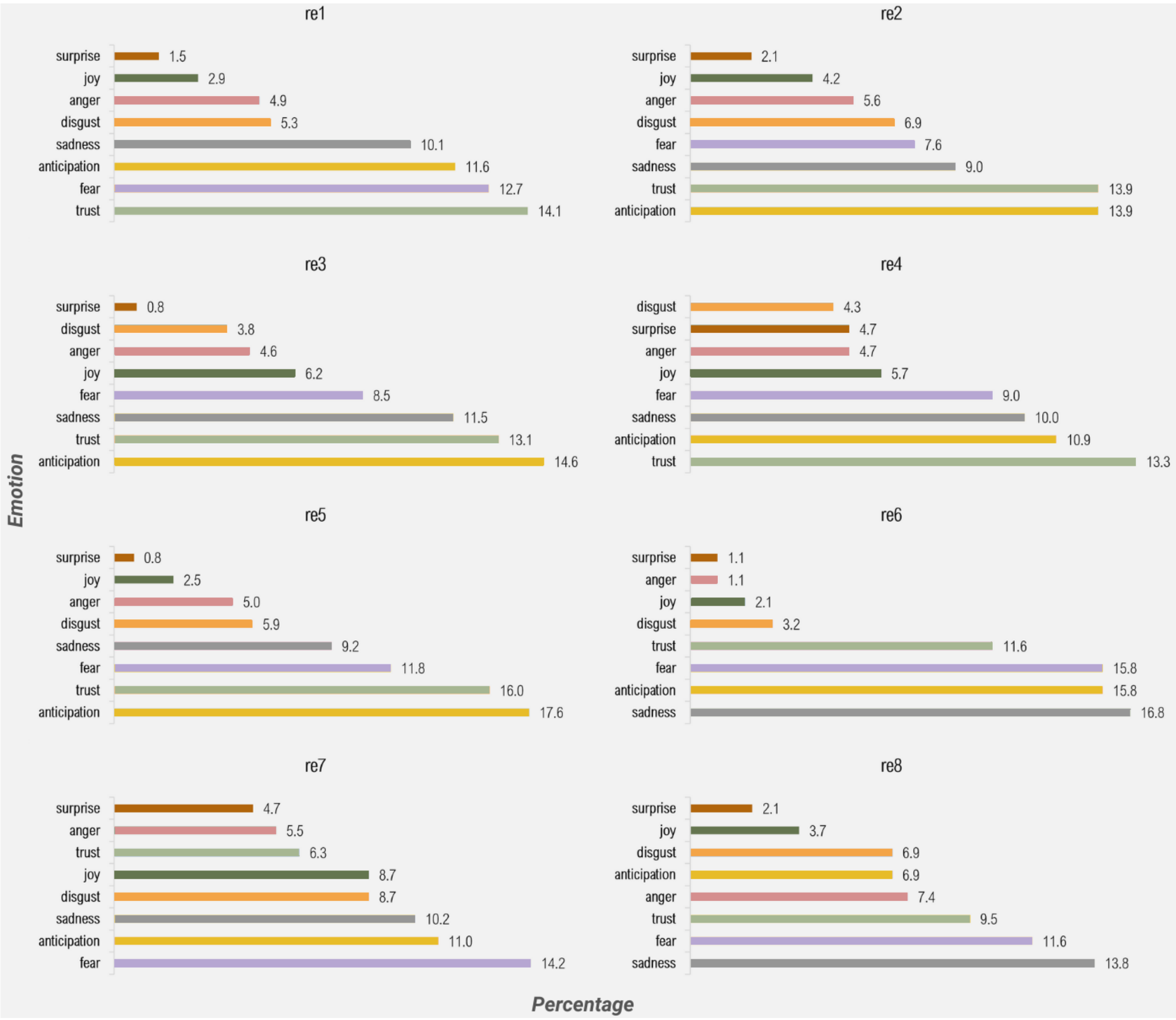
Despite the challenging context, solidarity emerged as a significant element during the crisis. Accounts of residents sharing water from artesian wells or pooling resources to hire water trucks highlight collective strategies to mitigate the effects of the crisis. However, this dynamic also exposed social disparities, as not all residents had access to alternative resources or the financial means to cover additional costs. One account in news re4 stated: "*God provided me with 2,500 liters of water every hour. If He gave me this gift, why not share it with those in need?*".

The absence of emergency planning measures became evident in situations such as reliance on water rotation systems and water trucks, which failed to serve affected areas equitably. As mentioned in news re6: "*In the higher neighborhoods of Campina Grande, it was difficult to pump water; the reservoir at the Gravatá station is operating at only 30% of its total* *capacity due to burnt transformers*" underscoring the connection between infrastructure issues and inequality in water access.

The lack of clear communication with the population was also criticized. Another account from re6 highlighted: "*CAGEPA initially released a supply plan for Campina Grande earlier this week, but this plan has already been changed*". This lack of predictability and transparency generated distrust and frustration among residents.

The analysis of emotions associated with the news, as illustrated in Figure 2, revealed that emotions such as trust, fear, and anticipation were prominent, while feelings like anger, sadness, and disgust appeared in smaller proportions. These emotions reflect dissatisfaction with the authorities' inability to effectively and promptly restore water supply. The lack of transparency and efficient communication from local managers was a recurring theme in the narratives, intensifying the perception of neglect towards the most vulnerable communities.

Figure 2. Percentage of emotions identified in the news



In news re1, trust (14.1%) and fear (12.7%) were the most prevalent emotions, indicating a mix of expectation and apprehension regarding the resolution of the crisis. This dynamic reflects the initial institutional response, which provided timelines for restoring water supply but created uncertainty due to delays. Sadness, at 10.1%, highlights the emotional toll of situations like the closure of healthcare facilities due to the lack of water.

Meanwhile, in re2, the most frequent emotions were trust (13.9%) and anticipation (13.9%), suggesting slight optimism for improvements. However, anger, even at a lower presence of 5.6%, aligns with accounts of dissatisfaction with the arrival of water unsuitable for use: "*It looks like coffee, it looks like hot chocolate, but it's not; this is the water coming out of the tap"*. The predominance of trust and anticipation in this news was primarily tied to the authorities' efforts to provide information, even if the solutions were unsatisfactory.

In re3, trust (13.1%) and anticipation (14.6%) once again led, reflecting residents' hopes for solutions despite evident challenges, such as frequent interruptions in water supply. In this context, sadness (8.5%) and fear (6.2%) appeared less prominently but underscored the insecurity of relying on water available only during nighttime hours: "*We have to stay awake during the night to fill the containers*".

Conversely, re4 demonstrated a balance between trust (13.3%), anticipation (10.9%), and fear (9%), suggesting a context of greater resilience. Acts of solidarity were highlighted, such as residents with access to artesian wells offering water. These acts likely helped mitigate negative emotions, such as anger (4.7%) and disgust (4.3%).

On the other hand, in re5, anticipation (17.6%) reached its highest representation across all news, reflecting the expectations generated by announcements of timelines for restoring water supply. Trust (16%) was also high, while negative emotions, such as sadness (9.2%) and disgust (5.9%), remained moderate. This dynamic reflects the impact of institutional promises and community actions that temporarily alleviated suffering.

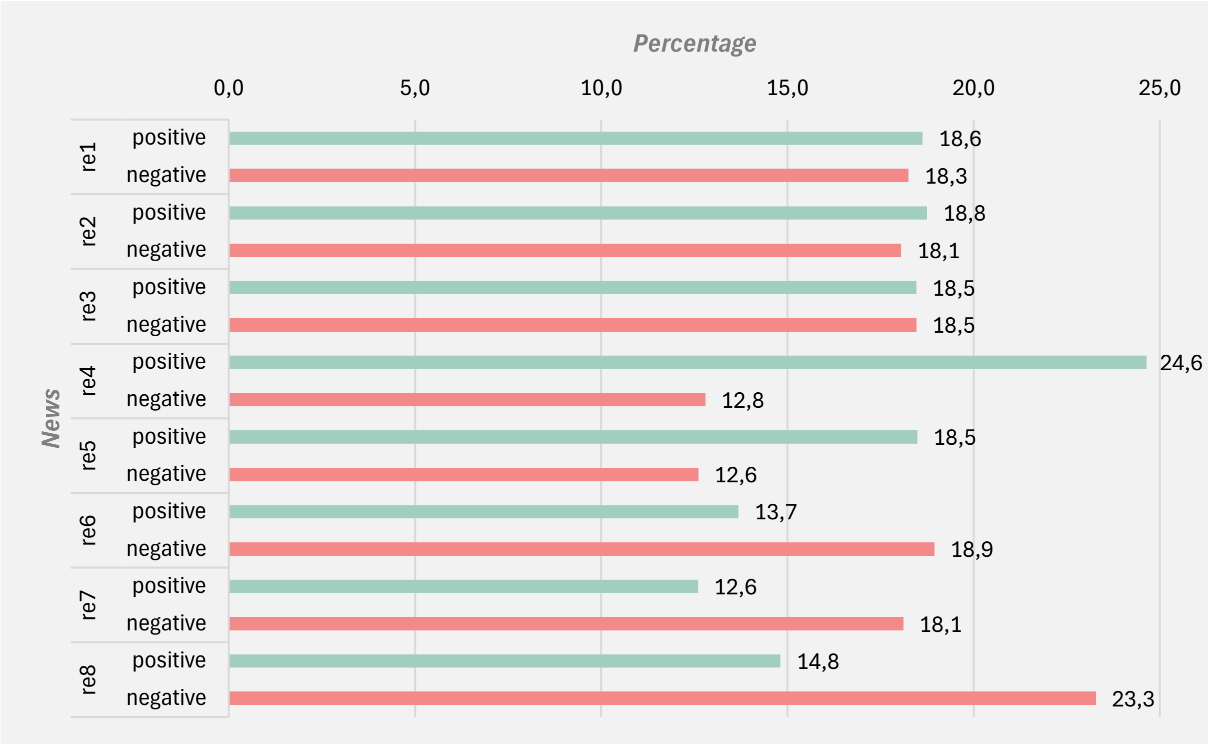
In re6, anticipation and fear shared the lead, both at 15.8%. This indicates a state of alertness and concern, particularly in neighborhoods like Araxá, where pumping difficulties were exacerbated by topography and technical limitations. Despite the predominance of negative emotions, trust (11.6%) was moderate, reflecting the resilience of the residents.

News re7 exhibited a similar distribution, with anticipation (14.2%) and trust (11%) as the primary emotions. Sadness (10.2%) and fear (10%) highlighted the prolonged impact of the crisis in regions like Tião do Rego, where residents had been without water for 12 days.

Finally, in re8, sadness (11.6%) and fear (9.5%) were more pronounced, reflecting the difficulties faced by residents in peripheral neighborhoods who resorted to alternative sources lacking potable standards, such as nearby reservoirs: "*There are people walking kilometers with water cans on their heads*". Trust (9.5%) and anticipation (6.9%) were less frequent, indicating a general feeling of frustration and fatigue due to the prolonged absence of solutions.

In this context, the analysis of polarity in the transcribed sentences from the news reveals a fluctuation between positive and negative sentiments, reflecting the varied experiences of Campina Grande residents during the water crisis. Figure 3 illustrates the percentage of positive and negative polarity in each news.

Figure 3. Polarity of the news analyzed



In news re1, the balance between positive polarity (18.6%) and negative polarity (18.3%) highlights the mixture of emotions at the onset of the crisis. The positive sentiment can be associated with the implementation of emergency measures, such as water trucks and reservoirs, which were emphasized as strategies to mitigate the initial impacts. However, the nearly equivalent negative polarity points to the perception of insufficiency in these measures, particularly in more vulnerable neighborhoods.

In re2, the predominance of positive polarity (18.8%) reflects a sense of expectation fueled by institutional efforts to propose solutions and timelines for water supply restoration. Nonetheless, the negative polarity (18.1%) suggests frustration with the quality of the delivered water and the limitations of the rotation system. Many residents resorted to alternative strategies to meet their needs, reflecting a perception of neglect toward their daily realities.

News re3 shows a balanced distribution of polarities, with 18.5% positive and negative. This parity reflects the population's resilience during the crisis, demonstrated by community actions such as storing water during limited supply periods. However, the challenges of living with constant interruptions explain the equivalent presence of negative sentiments, such as accounts of "*water only arriving during the night*". These frequent challenges have become normalized in discourse, evidencing a feeling of resignation in the face of prolonged structural vulnerability, which generates a normalization of tragedy, as evidenced by Rufino *et al.* (2021).

In re4, the high positive polarity (24.6%) stands out compared to other reports. This positivity is clearly linked to accounts of solidarity and resource-sharing in organized communities, as well as relief brought by specific actions that alleviated the scarcity. Nonetheless, negative polarity (12.8%) persists, reflecting the ongoing inequalities in water access that continued to affect less privileged neighborhoods.

Report re5 shows a slight predominance of positive polarity (18.5%) over negative (12.6%). This balance reflects a scenario where the partial normalization of supply generated optimism but also sustained negative feelings in regions still facing prolonged water shortages. The continued crisis in peripheral areas suggests that institutional promises were insufficient to meet expectations.

In re6, negative polarity (18.9%) surpassed positive polarity (13.7%), marking a moment when the crisis worsened, especially in neighborhoods with elevated topography. The perception of abandonment by authorities, combined with uncertainty about their capacity to address structural pumping issues, resulted in significant dissatisfaction. This situation was exacerbated by the unpredictability of water supply, which eroded public trust in institutional promises.

Report re7 showed a balance between polarities (18.1% positive and 12.6% negative), suggesting that the beginning of supply recovery brought relief to part of the population. However, in areas where supply remained precarious, frustration remained high, particularly in communities reliant on alternative sources to meet basic needs.

Finally, re8 stands out with the highest negative polarity among all reports (23.3%), indicating the prolonged impact of the crisis on peripheral neighborhoods. Positive polarity (14.8%) was low, reflecting a sense of hopelessness among residents who reported extreme conditions, such as long walks to fetch water from alternative sources.

3.4 DISCUSSION

The analysis of the results reveals that the water crisis in Campina Grande transcends resource scarcity, exposing structural inequalities, institutional weaknesses, and the resilience of local communities (Alves *et al.*, 2020). Similarly, David and Hughes (2024) demonstrated how political responses to water crises often exacerbate inequalities, reinforcing existing values and structures. In the local context, the persistence of supply interruptions and the unequal impact between central and peripheral neighborhoods reflect systemic vulnerability, aligning with Millington and Scheba (2021) findings on how precarious infrastructure can intensify crises.

The emotional fluctuations observed in the analyzed accounts — between feelings of trust and fear — also reflect the social impact of the water crisis. Galarce and Viswanath (2012) highlight the role of institutional communication in shaping emotional responses during crises, noting that unmet promises can undermine public trust. In Campina Grande, negative emotions dominate in reports addressing prolonged difficulties, echoing Meng (2022) findings on how urban water crises generate dissatisfaction due to the inefficiency of authorities.

Inequality in water access between peripheral and central neighborhoods also reflects structural limitations. Gallardo (2016) notes that water crises often intensify social and ecological inequalities, particularly in marginalized regions. In Campina Grande, areas such as Araxá and Jeremias face disproportionate challenges due to elevated topography and inadequate infrastructure, emphasizing the urgency of equitable public policies, as also observed in the studies by Cordão *et al.* (2020).

Acts of community solidarity, such as sharing water from artesian wells, partially mitigated the crisis's impacts but also revealed intrinsic social inequalities. In her book *The Price of Thirst*, Piper (2014) argues that community resource management is vital but insufficient without effective state support, particularly in regions where alternative resources are not accessible to everyone.

Finally, the methodological analysis of emotions and polarity in the accounts reveals the complexity of the social impact of water crises. Meehan *et al.* (2024) argue that such crises should not be treated solely as technical problems but as deeply rooted social issues. In Campina Grande, integrating technical and social approaches is crucial to mitigate the effects of the crisis and prevent its recurrence.

3.5 FINAL CONSIDERATIONS

This study investigated the impacts of the water crisis in Campina Grande and its surrounding region, analyzing how water scarcity affected the social, emotional, and structural aspects of local communities. The findings revealed that, beyond technical challenges such as supply system failures and operational limitations, the crisis underscored inequalities in water access, particularly in peripheral neighborhoods. Emotional analysis identified the prevalence of feelings such as trust, anticipation, fear, and sadness, reflecting both adaptability and dissatisfaction of communities facing the crisis. Community solidarity played a significant role in temporarily mitigating the impacts but also highlighted socioeconomic disparities that limit many residents' adaptive capacities.

However, some limitations should be noted. The study's temporal focus, centered on reports from a specific period, may have influenced the results. During the analyzed interval, the water shortage issue was primarily associated with an electrical failure at the Gravatá pumping station, which may limit the generalizability of findings to other contexts of water scarcity, such as those driven by inadequate management or seasonal climate variations. The reliance on reports available on free platforms like YouTube also restricted access to a more diverse database that could include perspectives from communities less covered by mainstream media or information from less accessible regional communication outlets. Additionally, the use of automatic transcription tools, while effective, may have introduced minor inconsistencies in the analyzed text, potentially impacting the accuracy of emotional and polarity analyses. Another important limitation is the focus exclusively on audiovisual content; future studies could incorporate other forms of reporting, such as written news articles, blogs, or social media posts, to capture a wider range of public discourse and narrative structures.

Building on these limitations, future research could deepen the understanding of the emotional and structural dynamics of water crises in broader contexts. Comparative studies could explore changes in public sentiment before and after landmark events, such as the São Francisco River diversion project, analyzing how expectations and perceptions of water supply justice evolve over time. Additionally, future research should consider applying validation techniques for sentiment analysis, such as manual coding of a sample of texts, interrater reliability measures, or comparison with established sentiment dictionaries adapted to regional language use, to ensure greater accuracy and confidence in the interpretations.

This highlights the need to broaden the discussion beyond the analyzed event, exploring how urban growth and LULC dynamics influence both water demand and the capacity of infrastructure systems to meet this pressure. As urban areas expand, often in an ill-planned manner, inadequate territorial planning can exacerbate inequalities in water access and increase the vulnerability of existing systems. In this context, integrating spatial data and LULC projections emerges as a promising approach to forecasting and mitigating future impacts. Thus, the next chapter focuses on investigating how predictive modeling tools and demographic analysis can support water management, offering a technical perspective to address sustainability challenges in a rapidly urbanizing world.

4 USE OF SPATIAL DATA IN THE SIMULATION OF DOMESTIC WATER DEMAND IN CAMPINA GRANDE, BRAZIL

How can predictive land-use modeling, integrated with demographic data and spatial analysis, estimate future domestic water demand in urban areas undergoing rapid expansion, particularly in regions with limited water consumption data?

English

Building on the social perception analysis from the previous chapter, Chapter 4 shifts focus toward forecasting the environmental impacts of urban expansion on water systems, using Campina Grande as a case study. By integrating demographic projections, infrastructural variables, and LULC data, this chapter models future LULC scenarios and estimates their effects on urban water demand by 2040. The results reveal how spatial patterns of densification—especially near accessible areas—are likely to intensify pressure on already fragile water supply systems. This forward-looking approach anticipates emerging vulnerabilities and equips urban planners with spatial tools to intervene before demand outpaces capacity.

Portuguese

Com base na análise da percepção social do capítulo anterior, o Capítulo 4 muda o foco para a previsão dos impactos ambientais da expansão urbana nos sistemas hídricos, utilizando Campina Grande como estudo de caso. Ao integrar projeções demográficas, variáveis de infraestrutura e dados de LULC, este capítulo modela cenários futuros de LULC e estima seus efeitos na demanda urbana de água até 2040. Os resultados revelam como os padrões espaciais de adensamento — especialmente perto de áreas acessíveis — provavelmente intensificarão a pressão sobre os já frágeis sistemas de abastecimento de água. Essa abordagem prospectiva antecipa vulnerabilidades emergentes e equipa os planejadores urbanos com ferramentas espaciais para intervir antes que a demanda supere a capacidade.

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4.1 BACKGROUND

Urbanization changes demographic characteristics and transforms the physical landscape of the environment. Inadequate planning can cause significant impacts on various environmental components, especially soil and water resources (Patra *et al.*, 2018). Economic activities unsustainably exploit land resources, resulting in an imbalance between supply and demand, driven by the urbanization process (Liu, Y. *et al.*, 2017).

As more people migrate to urban areas for a better quality of life, human demands for water, energy, and food exert ecological pressures that contribute to climate change, pollution, biodiversity loss, and land erosion (Ahmed *et al.*, 2020). With the expansion of built-up areas, natural resources become increasingly constrained, necessitating a reevaluation of land-use processes. Policymakers, therefore, must consider scientific studies to formulate appropriate policies (Xu, F. *et al.*, 2020).

The 2016 United Nations New Urban Agenda (UN-Habitat) highlighted the need to adopt more enabling and facilitative approaches to analyzing urban form and extent in developing countries (Caprotti *et al.*, 2017). This movement has stimulated discussions on how best to plan cities, seeking to integrate areas and services, create sustainable population densities, and ensure optimal urban design (Carneiro; Lopes; Espindola, 2021; Yadav *et al.*, 2019). One way to achieve this goal is by analyzing predictive scenarios and anticipating further possible developments for the region studied. This technique helps to understand and project how the region's state will be at a future time and the processes leading up to this projected future (Gaur; Bandyopadhyay; Singh, 2021).

Consequently, several spatiotemporal modeling, simulation, and transition potential techniques have been used to study LULC. Among these are cellular automata, which can effectively simulate and represent spatially stochastic nonlinear land use change processes (Okwuashi; Ndehedehe, 2021). Some cellular automata models successfully used for LULC analyses include Dinamica EGO (Rodrigues; Soares-Filho, 2018), FLUS (Liu, X. *et al.*, 2017), SLEUTH (Saxena; Jat, 2019), Artificial Neural Network-Markov Chain (Pahlavani; Askarian Omran; Bigdeli, 2017), SIMLANDER (Hewitt; Díaz Pacheco; Moya Gómez, 2013) and Cellular Automata-based Artificial-Neural Network (CA-ANN) (Abbas *et al.*, 2021).

Using CA-ANN to predict changes in LULC offers advantages compared to other methods. CA-ANN is excellent at modeling patterns and behaviors, which helps capture the multifaceted dynamics of growth by representing the nonlinear relationships between variables (Gharaibeh *et al.*, 2020). Another benefit is that CA-ANN can adapt well to datasets and scenarios without requiring knowledge of data distribution or assumptions about the data-generating process. Additionally, CA-ANN can easily integrate with models, leading to an understanding of the intricate dynamics behind urban growth patterns (Gantumur *et al.*, 2022).

Such techniques may reflect the increasing demand for water in urban centers, which is attributed to population growth and high urbanization rates. In water-scarce cities, it is crucial to establish reasonable urban boundaries to ensure efficient utilization of limited water resources and encourage sustainable economic and population expansion (Liu *et al.*, 2018). Therefore, this problem generates an even more significant concern in the Brazilian case, especially in the Semiarid Region, where the climatic conditions are already naturally unfavorable for maintaining an adequate water balance.

The BSR, comprising more than 70% of the Northeast Region (NEB), has historically faced challenges such as limited water resources, high rates of internal migration due to drought, and increased poverty and social inequality (Dias de Jesus, 2021; INSA, 2017). Between 1995 and 2000, over 800,000 people left rural areas in the NEB (Delazeri; Cunha; Couto-Santos, 2018). Furthermore, a prolonged drought from 2012 to 2018 resulted in depleted reservoirs and reliance on water supply by tanker trucks in several municipalities (de Brito *et al.*, 2021). Thus, strategic urban nodes emerged in response to intensified migratory movements, fostering significant urban growth in the BSR (Espindola; Carneiro; Façanha, 2017). This region now grapples with climate change impacts, including desertification, which affects not only urbanization but also the overall way of life (Marengo *et al.*, 2020).

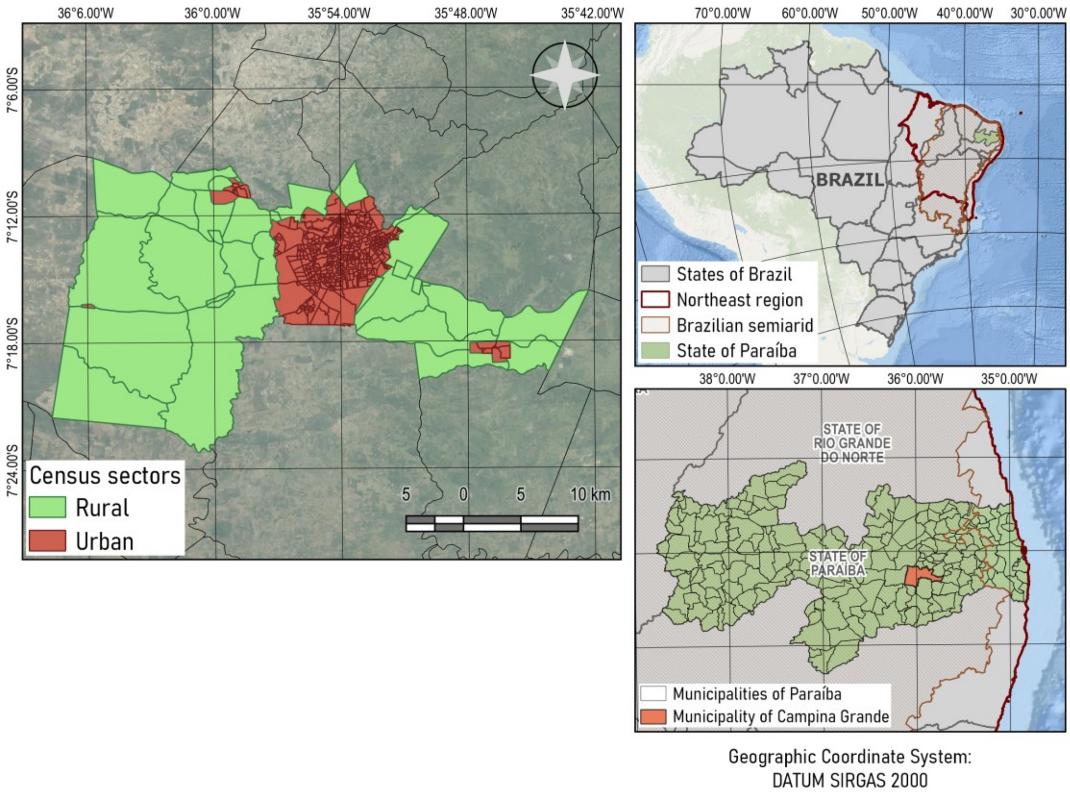
The need for more incisive urban interventions, as emphasized in the New Urban Agenda, is crucial for urban planning research. In this regard, this study aims to develop a domestic water demand forecasting model that considers the population's heterogeneity and urban occupation, contributing to ensuring water availability for future generations in the city of Campina Grande, situated in the BSR. This effort serves as a tool for defining public policies that promote sustainable urban development in municipalities that face the challenge of monitoring water consumption data, thus increasing the capacity for future projections.

4.2 METHODS AND DATA

4.2.1 Study area

The municipality of Campina Grande, located in the semiarid region of the NEB (Figure 4), characterizes itself as the second largest city in the State of Paraíba, both economically and demographically. It stands as one of the largest cities in the interior of the NEB. The city has an urban population of 419,379 inhabitants in 2022, occupying an area of 591.658 km², of which approximately 66.64 km² correspond to the urban zone (IBGE - Instituto Brasileiro de Geografia e Estatística, 2023). The city boasts an average altitude of 551 m and lies about 120 km from the state capital, João Pessoa (IBGE, 2020). According to data from the last demographic census, the municipality was divided into 524 census sectors (territorial units for the collection of census operations), classifying 65 as rural and 459 as urban IBGE, 2010).

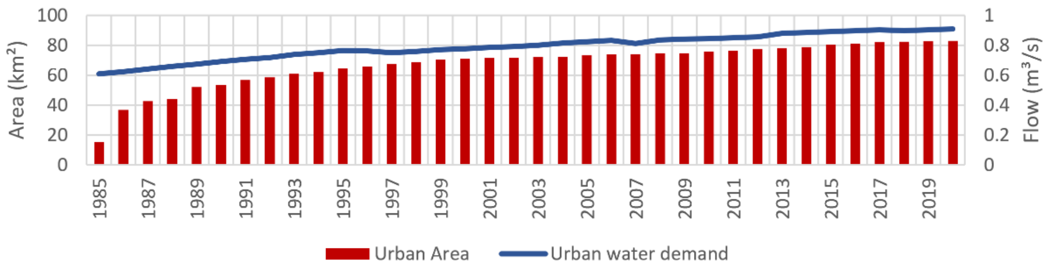
Figure 4. Census sectors in the municipality of Campina Grande



Source: Adapted from IBGE (2010) and SUDENE (2020).

The municipality faces urban water scarcity problems due to growing water demand, hydraulic imbalances, poor management, and poorly planned urbanization processes (Cordão *et al.*, 2020). Therefore, water insufficiency causes a cycle in which growing urbanization increases water demand, aggravated by a poorly planned urban environment, as illustrated in Figure 5.

Figure 5. Urbanized area and urban water demand in Campina Grande



Source: Adapted from Mapbiomas (2021) and National Sanitation Information System - SNIS (2020).

With the substantial impacts of the multi-year drought between 2012 and 2018, agricultural production and human supply in the municipality were compromised. As a result of the water shortage, in critical periods, the municipality of Campina Grande began to suffer progressive rationing of water supply, where some localities began to suffer up to ten consecutive days without piped water (Miranda, 2017). Thus, studying water demand in a city like Campina Grande, which faces serious water scarcity problems, can contribute significantly to formulating public policies for sustainable urban development in semiarid regions.

4.2.2 Data collection

The LULC images from 2000, 2010 and 2020 were acquired from the Annual Mapping of Land Use and Cover in Brazil Project (Mapbiomas)[5], through the Google Earth Engine platform (Gorelick *et al.*, 2017). Mapbiomas represents an initiative involving a collaborative network of experts in biomes, land use, remote sensing, GIS, and computer specialists. These experts utilize images from Landsat satellites, each with a 30m resolution. The entire process relies on machine learning algorithms, resulting in highly reliable products that cover the entire territorial extent of the country, provided in a free and accessible manner (Souza Junior; Azevedo, 2017). Up until this study, Mapbiomas had been utilizing 34 LULC classes. However, they were grouped within a GIS environment for simplification purposes, as illustrated in Table 2.

Table 2. LULC classes used

LULC Type	Mapbiomas classes
Natural Formation	Forest, non-forest natural formation, beach, dune, other non-vegetated areas
Agriculture and Livestock*	Grazing, agriculture, forestry, mosaic of agriculture and grazing, mining
Water Body	River, lake, ocean, aquaculture
Urbanized Area	Urbanized area

**The study area has no record of mining and forestry activities.*

[5] The image of LULC of Campina Grande can be seen at this link.

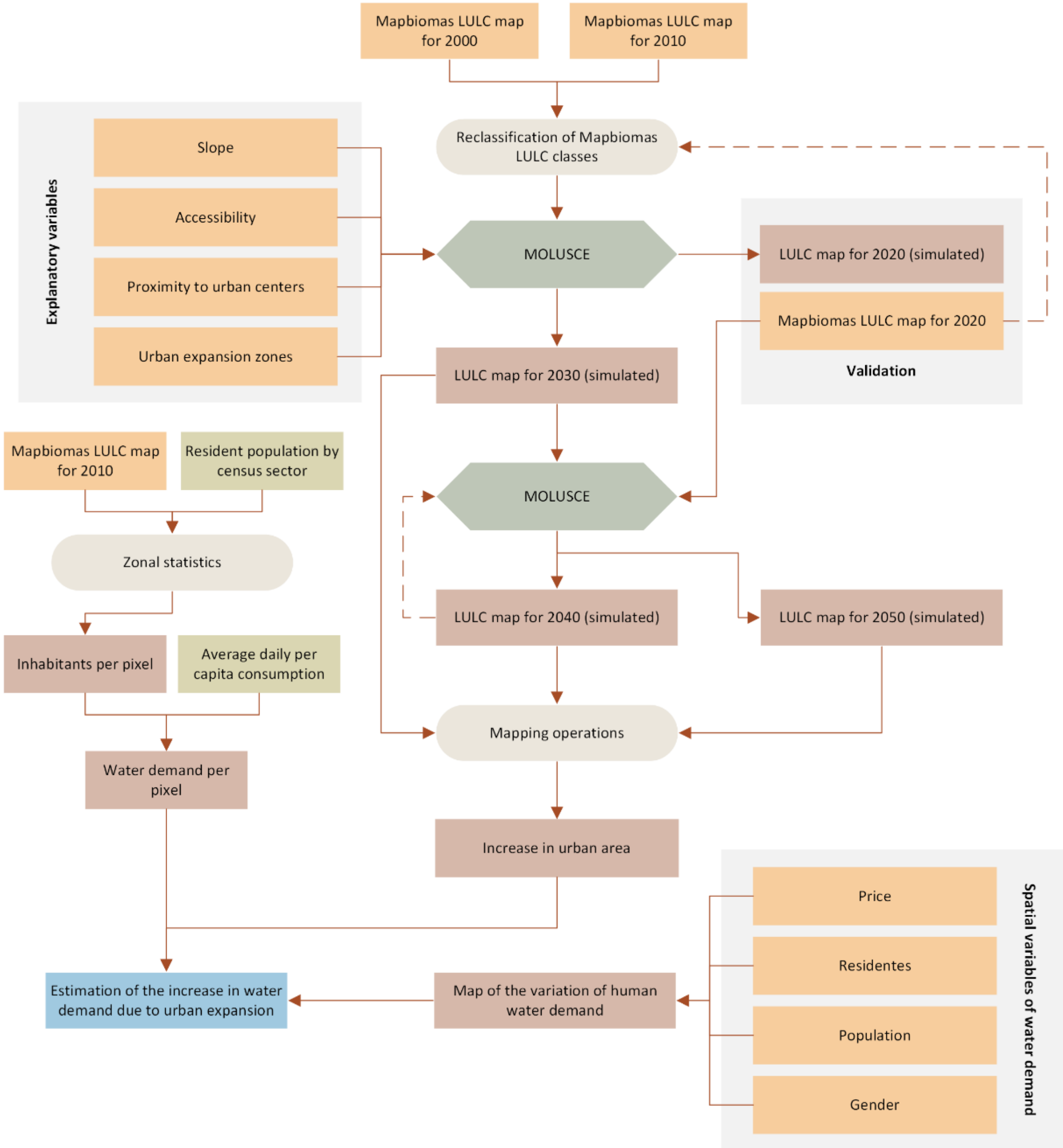
For the cellular automaton model simulation, the explanatory variables were chosen based on the research of (Brito; Rufino; Djordjević, 2021) for a similar region since the motivations for urban expansion in semiarid regions occur similarly in different cities. Table 3 describes the four explanatory variables of urban growth chosen within this study and the assumptions used for each. After data collection, the products were cropped and rescaled to the exact spatial resolution (30 meters) to serve as input data for the Modules for Land Use Change Evaluation (MOLUSCE) QGIS plugin and later assist in the future estimation of water demands.

Table 3. Explanatory variables and their assumptions.

Explanatory Variable	Abbreviation	Hypothesis
Slope	SLO	Low-slope surfaces are more attractive for human activities (crops, livestock, or settlements). Usually, flat surfaces allow for most activities without the need for high earth movement (cuts and embankments), which makes it more accessible for settlements or agricultural and livestock activities.
Accessibility	ACC	The more accessible an area is (for example, near roads and highways), the greater the chance that sites will become occupied.
Proximity to urban centers	PUC	Historically, urban centers attract human activities due to better access to infrastructure, services, and markets. The proximity to these centers facilitates land conversion for residential, industrial, and commercial purposes, making surrounding areas more susceptible to rapid LULC changes.
Urban Expansion Zones	UEZ	Throughout the urbanization process of cities, urban areas commonly redefine their boundaries. Thus, places, where urbanization processes are identified more pronouncedly attract real estate investments that contribute to the urbanization in the vicinity.

The slope variable was calculated within a GIS environment using the digital elevation model of the ALOS satellite. Similarly, accessibility, proximity to urban centers, and urban expansion areas were developed based on Euclidean distances. Accessibility relied on road data supplied by the National Department of Transport Infrastructure of Brazil (DNIT (Departamento Nacional de Infraestrutura de Transportes), 2013). Proximity to urban centers was determined by measuring the distance to the municipal headquarters, using information from the Brazilian Institute of Geography and Statistics (IBGE) (IBGE Cidades, 2020). Finally, the urban expansion zones correspond to the distances to the urban infrastructure classes of Mapbiomas for the year 2020 (the most current mapping available at the time of the research). All the variables were reclassified to a resolution of 30 meters to match the resolution of Mapbiomas. Figure 6 represents the methodological flow of the study.

Figure 6. Methodology overview



4.2.3 Model analysis, prediction, and validation

Spatiotemporal changes and the potential LULC transition between study intervals were obtained using the MOLUSCE plugin (Asia Air Survey; Next GIS, 2014), which integrates with the free software QGIS. A probability matrix for area change and transitions was derived using the LULC data and explanatory variables. This matrix includes rows and columns representing LULC categories in the initial and final years of the observed time interval.

This simulation aims to simplify the dynamics of composite urban structures and interpret them in an easily understandable way. The CA-ANN approach in the MOLUSCE plugin is considered more efficient than linear regression for potential transition modeling and future simulation (El-Tantawi *et al.*, 2019). The MOLUSCE plugin effectively calculates land use change analysis and is suitable for analyzing seasonal forest and land use change, potential transition modeling, and future scenario simulation.

The LULC for 2020 was projected using the MapBiomas LULC maps of 2000 and 2010, along with the explanatory variables. The MOLUSCE operates by first identifying land cover transitions that occurred between the two historical maps. These transitions serve as the basis for estimating change probabilities for each LULC class. Using statistical or machine learning algorithms—such as logistic regression, artificial neural networks, or weights of evidence—MOLUSCE models the relationship between these transitions and the explanatory variables.

Once the transition potential maps are generated, the plugin allocates future land use by identifying areas most likely to undergo change based on the calculated probabilities and historical trends. This spatial allocation respects both the intensity of past transitions and the influence of each variable, allowing the model to simulate where specific LULC classes are likely to expand, shrink, or remain stable.

To validate both the model and the accuracy of the prediction, the simulated 2020 LULC was compared with the MapBiomas LULC data for the same year. The MOLUSCE plugin offers a Kappa validation technique for comparing the projected and actual LULC images. This method assesses two types of similarity: quantitative similarity, which examines the number of pixels in each class (K_{Histo}), and spatial similarity, which checks their spatial distribution (K_{Loc}). The Kappa statistic was calculated by multiplying K_{Histo} and K_{Loc}.

Considering metrics that can provide a more informative and transparent approach for assessing the agreement between LULC classifications, cross-tabulation was employed, as recommended by Camacho Olmedo; García-Álvarez (2022), to validate the simulation. The tabulation was produced using the Semi-Automatic Classification Plugin within the QGIS environment, where two factors were analyzed: User's Accuracy (UA) and Producer's Accuracy (PA). How well different land cover types are correctly identified by the model is indicated by UA. On the other hand, PA shows how well it can notice reference pixels from specific classes.

Satisfactory model validation results were achieved after conducting numerous tests. Consequently, the LULC maps for 2010 and 2020 were employed to make predictions for the LULC in 2030. Subsequently, the 2020 and 2030 (simulated) LULC maps were utilized to generate the 2040 LULC map. Finally, the simulated 2030 and 2040 maps allowed the prediction of the 2050 LULC.

During the CA-ANN learning process, 5,000 random samples were utilized, 150 iterations were conducted, a neighborhood value of 3x3 pixels was set, a learning rate of 0.001 was implemented, 10 hidden layers were employed, and a momentum of 0.05 was applied. To summarize, the selection of these parameters during the CA-ANN learning process demonstrates an attempt to strike a balance between the speed of learning, the complexity of the model, and the stability of training. The learning rate is intentionally kept low to ensure weight adjustments while having 10 hidden layers, indicating a network capable of capturing intricate relationships — moreover, a momentum value of 0.05 aids in enabling the optimization process to discover solutions.

4.2.4 Estimating domestic water demand

Equations were used to estimate water consumption per pixel of urbanized areas, aiming to estimate the increased water demand resulting from urban expansion in Campina Grande. Initially, a correlation was performed between the census data of the resident population in each census sector and the LULC product of Mapbiomas. It is essential to highlight that the most recent demographic census for the Brazilian territory was available in 2010; therefore, the LULC of the same year was used for comparison purposes.

Using zonal statistics, estimating the number of inhabitants per pixel of an urbanized area was possible. Based on the sanitation indicators for the year 2010, made available by the National Information System on Water Resources (SNIS, 2020), it was found that the average daily per capita consumption for the municipality of Campina Grande was 117.49 liters per inhabitant per day. Thus, the water demand per pixel in each census sector could be estimated by associating water consumption with the number of inhabitants per pixel. To estimate the population increase in the region, the IBGE population growth projection for the state of Paraíba was used, based on the historical series of population growth, using a linear projection (IBGE, 2020). For the sake of simplification, it's important to note that this study does not address the increased water demand resulting from the region's socioeconomic development over the years.

Several factors can influence household water consumption and result in various patterns. In this perspective, da Veiga, Kalbusch and Henning (2022) developed a multiple linear regression model (Eq. 1), which demonstrated that household income, water tariff, number of residents per household, temperature, percentage of households with washing machines, total population, gender, percentage of households with piped water and municipality GDP influence urban water consumption in Brazil.

$$lnCONSUPTION = 1.3488 + 0.1775lnINCOME - 0.1456lnPRICE - 1.0298lnRESIDENTS + 0.5686lnTEMPERATURE + 0.0431lnWASHING_{MACHINE} + 0.0325lnPOPULATION + 0.4087lnGENDER + 0.2272lnPIPED + 0.0234lnGDP$$ Equation 1

Among the variables listed, based on demographic data made available for the entire Brazilian territory by IBGE (2010), it was possible to identify sectoral variations in a city, such as household income (PRICE), residents per household (RESIDENTS), total population (POPULATION) and gender (GENDER). Household income directly influences the ability to pay for water, while the number of residents per household and the total population impact the water demand per person. In addition, consumption differences between men and women can also influence the water consumption profile. Thus, from the analysis of the linear regression coefficients, it was possible to establish relationships between each variable's municipal average and each's influence on the percentage of water consumption in the census sector through Eq. 2.

$$CONSUPTION_{VAR} = e^{(\ln(A)+Cln(B))}$$ Equation 2

Where:

$CONSUPTION_{VAR}$ is the variation in water consumption resulting from the analyzed variable;

A is an arbitrary constant value, used as a reference value;

B is the percentage, in whole number, that represents the increase (or decrease) in relation to the municipal average;

C is the regression coefficient of the analyzed variable;

Therefore, from the LULC forecast (performed for the years 2030, 2040, and 2050) and the spatial variables that affect domestic water demand, it became possible to estimate the increase in demand arising from the increase in the urban area class. We used the R programming language (TEAM, 2013) to quantify the new urban areas and calculate the estimated future water demand.

To validate the results, water consumption data for the year 2020 was collected from the CAGEPA. This data corresponds to the total volume of water consumed by the municipality of Campina Grande, covering all uses such as irrigation, industry, and urban and rural supply. For comparison, it was assumed that urban supply constitutes 60.95% of the total consumption, based on information provided by the National Water Agency (ANA, 2019) regarding consumptive water uses. This data collection and analysis allowed the comparison of simulated results with the observed urban water consumption data for 2020.

4.3 RESULTS AND DISCUSSION

The dynamics of LULC for the next three decades in the municipality of Campina Grande were visualized utilizing the LULC classifications of Mapbiomas. The modeling satisfactorily represented the urban area for 2020, except in the southeast portion, where an additional expansion occurred in 2017 with the implementation of the Aluízio Campos Complex. This housing complex, which included over 4,100 units, marked Brazil's most significant housing complex under construction that year.

In this context, the explanatory variables used in the modeling are illustrated in Figure 7 and demonstrate the potential for urbanization caused by population increase and migration of the rural population to urban areas. Following the intensification of the migratory movement in the NEB, the urban area of Campina Grande, remains strategic for human development in the state's interior, presenting high growth rates, as discussed by Espindola, Carneiro and Façanha (2017).

The validation process performed in MOLUSCE, used the 2020 LULC maps from Mapbiomas and the simulated 2020 classification from the 2000 and 2010 LULC. The value of K_{Histo} was 0.81, while that of K_{Loc} was 0.71. Thus, the value of the overall Kappa index was 0.58. Based on the Kappa values, the results can be considered moderate.

Analysis of the error matrix (Table 4) highlights the simulation's performance, focusing especially on the urban area class, which represents the core of this classification. The results reveal an AP of 98.91% for this class, highlighting the model's remarkable ability to identify urban areas accurately. In addition, the UA of 92.25% strengthens the model's reliability in identifying urban areas in the simulated data. The overall accuracy (OA) reached 79.81%, reflecting the model's comprehensive effectiveness and confirming that the simulation is satisfactory and reliable for the application.

There are numerous challenges for predictive modeling in BSR; among them stands out the phenology of the vegetation of the Caatinga biome, where the photosynthetic material of the vegetation is strongly related to the rainfall regime and suffers direct impacts from climate change (Medeiros *et al.*, 2022). This region's climatic variability corroborates intra-annual variations in vegetation and agricultural management, hindering the remote classification of LULC by machine learning systems (Cunha *et al.*, 2019).

After obtaining satisfactory results in the model validation step, the spatial variables and the transition map were used to predict LULC for 2030, 2040, and 2050. Figure 8 presents the resulting maps from the simulations. At the urban edge, subsistence agriculture is common, carried out by the most vulnerable population; as urbanization advances over the territory, agriculture will make room for new construction. The simulations estimated an increase of more than 4 km² of the urban area between 2030 and 2050, while in the same period, the classes of natural formation and agriculture suffered reductions of 0.6 and 3.4 km², respectively.

Figure 7. LULC maps used in the validation step and explanatory variables. A) LULC Mapbiomas 2020 B) Simulated LULC for 2020 C) Slope, D) Urban expansion zones, E) Proximity to urban centers, F) Accessibility

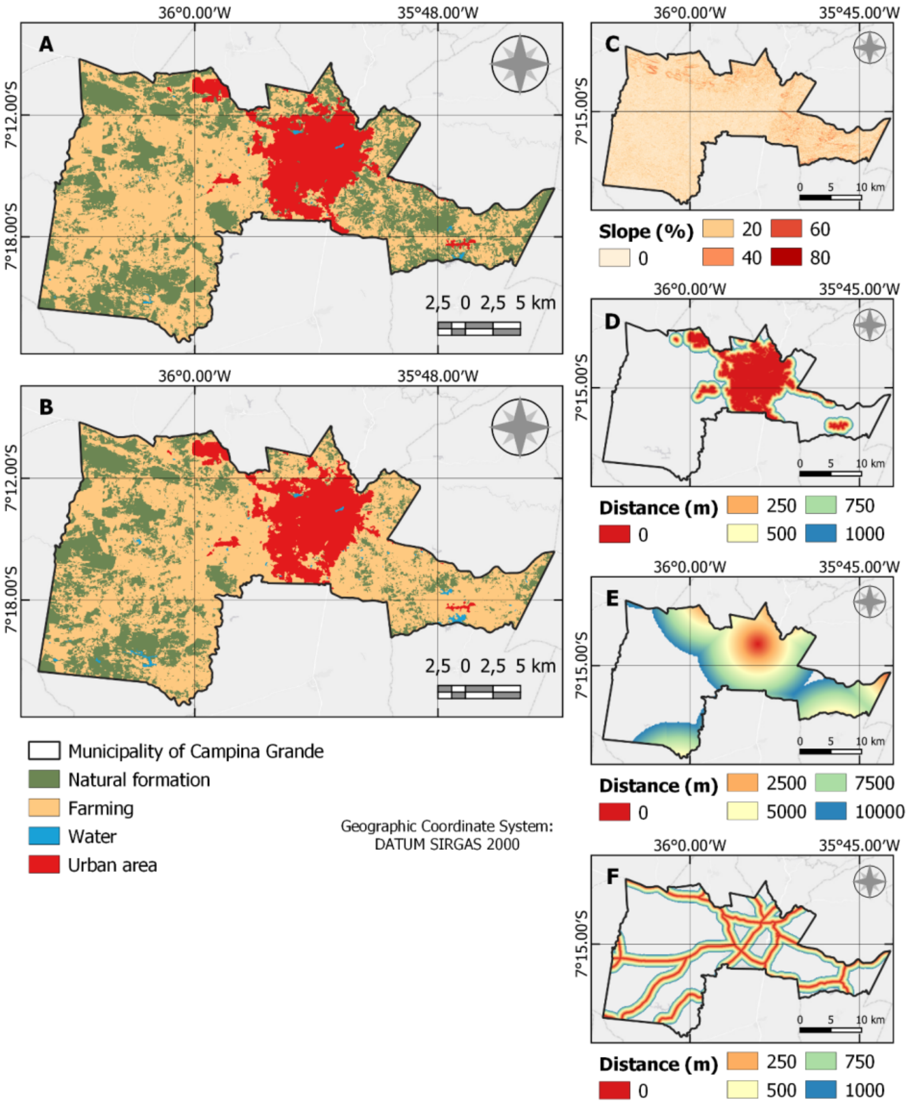
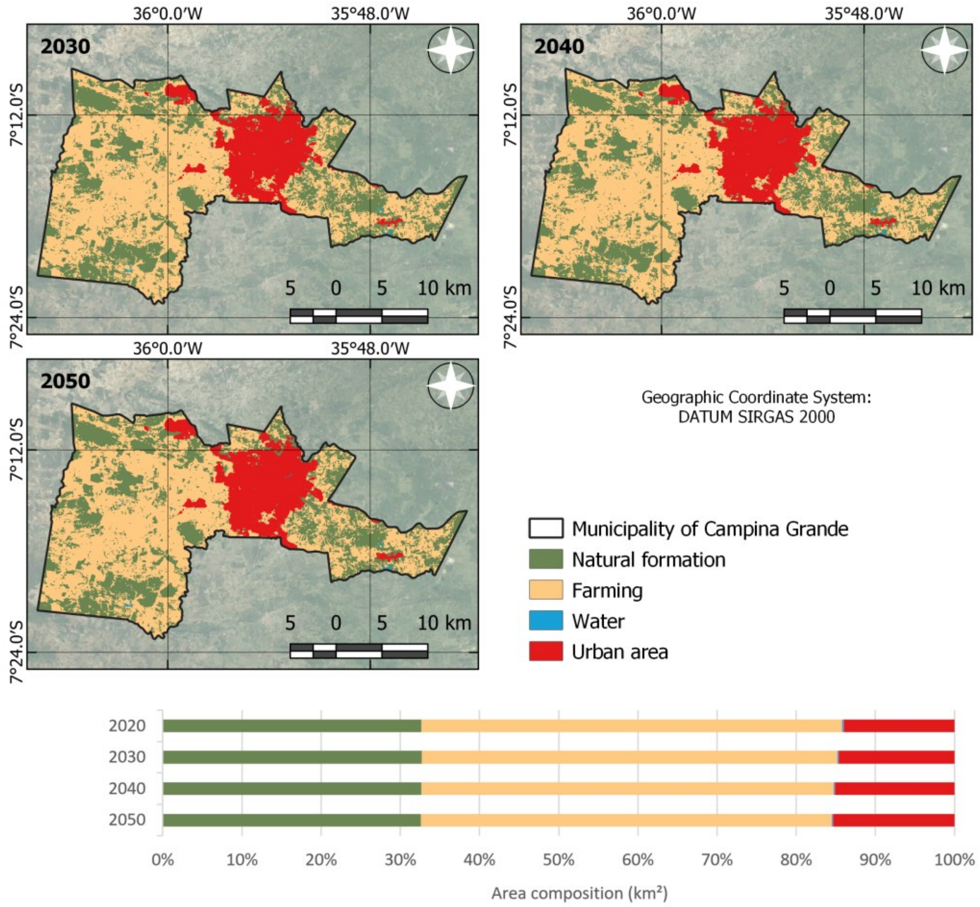


Table 4. Accuracy of the classes in the simulation

	Natural formation	Farming	Water	Urban area
PA (%)	75.85	77.82	37.51	98.91
UA (%)	61.78	87.58	91.53	92.25

Figure 8. Simulated LULC (2030, 2040, 2050) and area composition (km²) compared to that observed in 2020



	2050	2040	2030	2020
Natural formation	196.52	196.90	197.11	197.03
Farming	312.91	314.01	316.37	320.07
Water	1.06	1.07	1.08	1.43
Urban area	92.36	90.88	88.31	84.33

Although modest, the increase in urban areas accompanies changes in land use patterns, including the transition from agricultural areas and natural formations to urban areas. Supporting this observation, (Wang, 2020) emphasizes the complex interplay of urbanization, population concentration, and land use intensification, which can notably affect urban water demand. This transition often leads to increased water demand due to the rise in population density and the growth of industrial and commercial activities in urban areas.

The simulations reveal a potential slowdown in urban expansion over time, partially attributed to the declining association between population growth and urban sprawl. Based on the results, the urban area is expected to increase by 2.6 km² between 2030 and 2040 and 1.5

km² between 2040 and 2050. This trend is a result of the way MOLUSCE simulates land use changes, as the model calculates transition probabilities based on historical data and explanatory variables and as the simulation progresses, areas with a high probability of urban growth become increasingly saturated, reducing the availability of cells with strong transition potential. This phenomenon closely links the densification of cities and the more efficient use of available interior spaces (Teller, 2021). In this context, research conducted by Fan and Zhou (2019) highlights the significant influence of intergovernmental competition in promoting urban densification, ultimately leading to the vertical growth of cities.

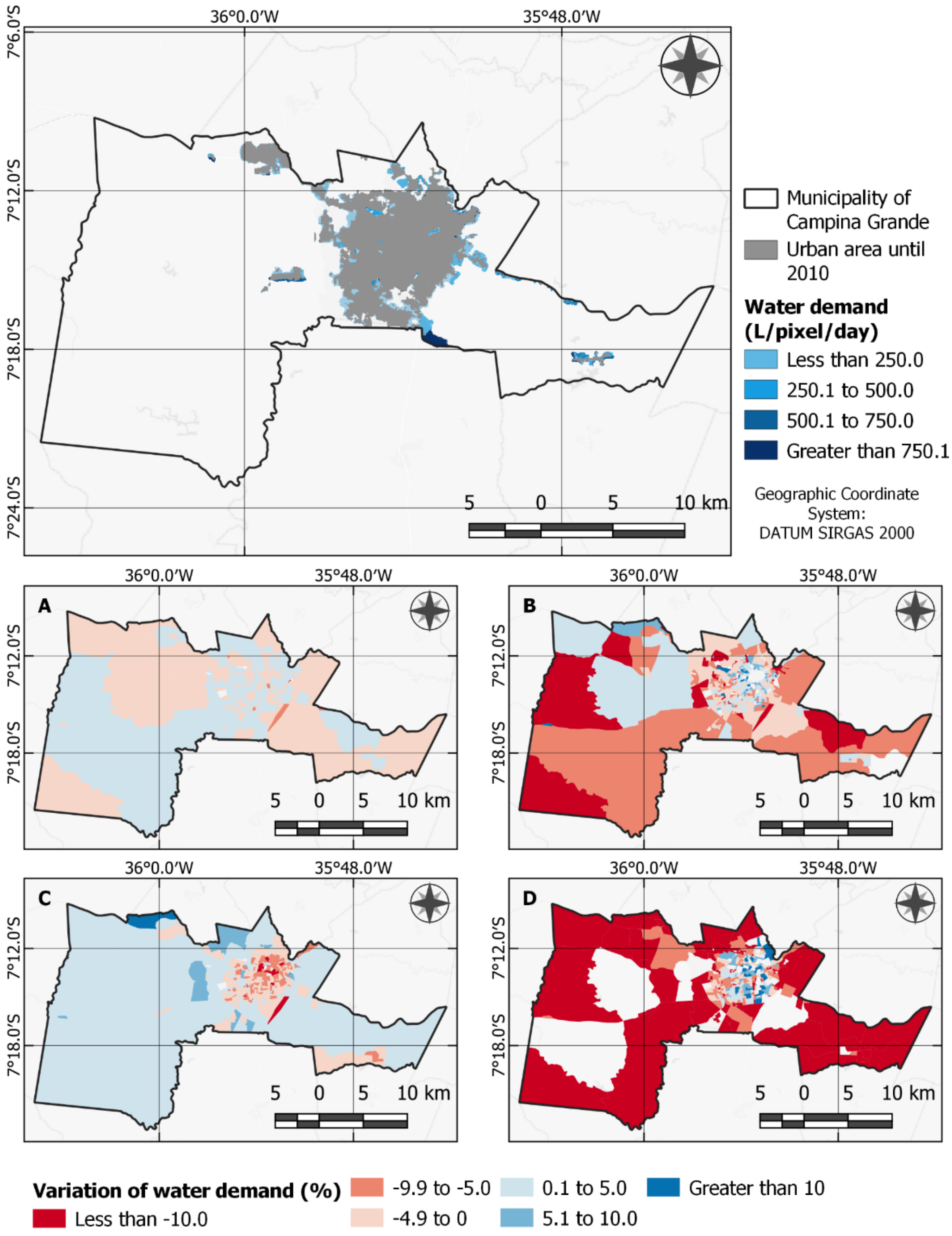
This observation aligns with national patterns observed by Iablonovski and Evers (2025), who found that while large Brazilian metropolises underwent vertical expansion, medium-sized cities such as Campina Grande predominantly experienced horizontal growth. This spatial pattern often reflects urban forms that are less efficient in absorbing population increases, generating challenges for infrastructure provision and sustainable land use planning.

After the second half of the twentieth century, Brazilian medium-sized cities (such as Campina Grande) began to present a quick urbanization process, accompanied by verticalization, attributed to economic interests aimed at diversification of investments (Casaril; Fresca, 2000). In this period, Campina Grande underwent urbanization plans driven by new development ideals; from this, the verticalization process intensified in the city (Souza, 2021). Significantly, this urban transformation underscores its relevance as it sheds light on the profound implications for water demand prediction based on LULC in the region.

In this context, the LULC results highlight the viability of predictive land use modeling, an achievement made possible by the accessibility of resources such as the Mapbiomas collection adapted for the various Brazilian biomes. This expanded horizon of resources opens up new perspectives for hydrological and urban modeling, improving the ability to understand and anticipate complex dynamics related to land use and water demand.

The urban environment is highly dynamic, and occupation varies spatially. Thus, the heterogeneous distribution of the city's population and social factors leads to different consumption profiles among residents of the same municipality. In most Brazilian cities, no water micro-measurement data is available. For domestic demand estimation purposes, government agencies use estimates of average consumption per inhabitant based on flow and total population (SNIS, 2020). Figure 9, prepared from the consumption variables proposed by da Veiga, Kalbusch and Henning (2022), seeks to refine the water demand estimates from LULC, considering spatial factors that alter the consumption profile of the inhabitants.

Figure 9. Household water demand from 2010 to 2050 and spatial variables of consumption: A) POPULATION, B) RESIDENTS, C) GENDER, D) PRICE



The spatial variables of consumption that most influenced water demand were RESIDENTS and PRICE, which are directly related to the population's purchasing power. The number of residents per household, generally higher in poorer areas, tends to increase water consumption, especially in daily activities such as bathing, washing clothes and dishes, and using the toilet. Household income directly influences water consumption since families with higher purchasing power have access to goods and services that require greater water use, such as swimming pools, gardens, and bathtubs. Thus, it was found that regions further away from the urban center and low-income neighborhoods exhibited a negative variation in water demand. Simultaneously, areas with a higher presence of high-income populations experienced an increase of more than 10% in consumption.

In a region marked by frequent droughts whose surrounding areas face a high risk of desertification triggered by climate change, as is the case of Campina Grande, a growing increase in domestic water demand puts even more pressure on surface reservoirs in the region, primarily responsible for human, industrial and agricultural supply. In this context, Table 5 presents the simulation results of the water demand required to supply the municipality's domestic consumption between 2020 and 2050 and compares the results with 2010, where daily consumption was 16,530,731.18 m³. Based on the results, it is estimated that in 2050, there will be an increase in domestic water consumption of 2,348,424.96 m³ compared to 2010, equivalent to a 14.21% increase. A modest value compared to Grouillet *et al.* (2015) estimates for Mediterranean cities in the same period.

Table 5. Simulated domestic water demand

Year	Domestic water consumption (m³/year)	Consumption growth compared to 2010 (%)
2020	17,773,950.83	7.52
2030	18,339,904.78	10.94
2040	18,681,267.76	13.01
2050	18,879,156.14	14.21

Unfortunately, no data in the region is available to validate all the results obtained. Consumption data for 2020 from CAGEPA was the only information obtained. According to the agency, the municipality of Campina Grande consumed 17,352,517.00 m³ of water for human and industrial consumption in 2020. Also, according to the agency, in the region, water consumption is classified into four categories: residential, commercial, industrial, and public, and each of them is assigned a specific tariff. Although there are distribution networks in some parts of the rural area, they are primarily for residential use. Agriculture, on the other hand, utilizes raw water directly abstracted from the spring. In certain regions, such as along the Paraíba River, regulatory agencies authorize farmers to use water in this manner. Therefore, it is crucial to emphasize that agriculture falls outside the consumption above categories. Furthermore, the commercial consumption category encompasses industries connected to the water distribution network. This category includes all industries that rely on water supplied by the public network for their production activities.

Thus, the data obtained from CAGEPA regarding water consumption in Campina Grande during 2020 are insufficient to validate the research results fully. This inadequacy arises because the regulatory agency does not provide figures by consumption category, making it impossible to directly compare the data obtained with the study results. However, it is essential to highlight that the simulated values obtained in the research presented a variation of only 2.43% concerning CAGEPA's data. However, the description of the consumption categories provided by the regulatory agency, the details about water distribution in rural areas, and the exclusion of agriculture as a consumption category support the consistency of the simulated values with reality.

Consequently, the water demand estimation elucidated within this study establishes a fundamental foundation for exploring the intricate relationship between land use and water demand, providing valuable insights that can shape government policies and strategies finely tailored to the nuanced requirements of urban and rural planning. These insights facilitate resource allocation and augment the efficacy of long-term sustainable development.

Hence, it is incumbent upon stakeholders to consider a holistic perspective, one that encompasses both physical and governance aspects, to ensure the continued availability of water resources for the current generation and safeguard the water needs of posterity. In this light, domestic water demand forecasting remains a dynamic research challenge, with significant opportunities for researchers to advance hybrid or specialized methodologies that account for the distinctive physical and socioeconomic characteristics of diverse regions across the globe, particularly those facing inadequate monitoring infrastructure.

4.4 FINAL CONSIDERATIONS

Based on the results obtained in this study, the research appears as a reasonable alternative, supported by its consistent ability to predict future domestic water consumption with the help of LULC data. This achievement is precious in regions where data regarding water consumption is notably scarce, a situation frequently observed in many BSR cities. Consequently, the implications of the findings provide a replicable methodology that can be applied across the country, offering preliminary insights into future water consumption using currently available datasets.

However, as expected, the lack of official data by consumption category limited the validation of the results. Consequently, advocacy is made for future studies to proactively establish institutional partnerships to galvanize regulatory bodies into intensifying their data collection and monitoring efforts, amassing a more comprehensive dataset capable of enhancing the precision of regulatory measures and modeling techniques. Additionally, the potential for forthcoming studies to integrate supplementary variables, such as climate change and economic factors, is acknowledged to develop more comprehensive water demand models. Another limitation observed was the transition of some pixels from rural to urban sectors over the analyzed years. This spatial reclassification may affect the consistency of demand estimates, particularly when based on fixed census sector boundaries.

Notwithstanding, water quantity and quality challenges necessitate multifaceted solutions, encompassing access, regulation, control, and demand reduction. These measures are pivotal in ensuring that all segments of society benefit sustainably from this invaluable resource. Governance strategies specific to this region should also integrate forward-looking aspects, addressing the perpetual surge in water demand and the repercussions of climate change on the region's rainfall patterns.

Given the scarcity of consumption data, the next chapter of this research will shift its focus to a more detailed examination of LULC dynamics. Understanding how these dynamics influence urban growth and resource allocation is essential to improving the accuracy and applicability of future simulations. By investigating the sensitivity of LULC explanatory variables and their interactions, the study aims to refine the predictive capacity of spatial models, paving the way for more effective urban planning and sustainable resource management in semi-arid environments. This progression contributes to a better understanding of the drivers of change and advances methodological approaches that can be adapted to address urban and environmental challenges.

5 DRIVERS OF LULC CHANGE AND THEIR IMPLICATIONS FOR THE URBANIZATION PROCESS IN CAMPINA GRANDE, BRAZIL

How do the explanatory variables used in LULC modeling influence the accuracy of spatial simulations, and what are their interactions in representing urban dynamics?

English

Extending the predictive modeling framework introduced in the previous chapter, Chapter 5 investigates which spatial factors most strongly drive LULCC in rapidly urbanizing contexts. Using sensitivity analysis within the simulation model, the chapter identifies urban expansion zones and proximity to infrastructure as the most influential variables shaping future patterns of imperviousness in Campina Grande. By clarifying the weight of each driver, this chapter enhances the interpretability and strategic utility of LULC forecasts—supporting more precise, data-informed planning interventions in cities facing development pressures and growing water vulnerabilities.

Portuguese

Ampliando a estrutura de modelagem preditiva apresentada no capítulo anterior, o Capítulo 5 investiga quais fatores espaciais impulsionam mais fortemente o LULC em contextos de rápida urbanização. Utilizando a análise de sensibilidade no modelo de simulação, o capítulo identifica as zonas de expansão urbana e a proximidade com a infraestrutura como as variáveis mais influentes na formação dos padrões futuros de impermeabilidade em Campina Grande. Ao esclarecer o peso de cada fator, este capítulo aprimora a interpretabilidade e a utilidade estratégica das previsões de LULC — apoiando intervenções de planejamento mais precisas e baseadas em dados em cidades que enfrentam pressões de desenvolvimento e crescentes vulnerabilidades hídricas.

5.1 BACKGROUND

LULC changes driven by urbanization are considered emerging challenges in the Brazilian semiarid region, an area already vulnerable due to natural climate variability, extreme climatic conditions, and increasing pressure on natural resources. The expansion of urban areas has reshaped regional landscapes, generating demands for infrastructure and urban services while intensifying environmental and social impacts (Barros Ramalho Alves *et al.*, 2020). These changes, driven by human activities such as socioeconomic development, are also influenced by biophysical conditions such as climate, topography, and soil quality (Xu, X. *et al.*, 2020).

In Brazil, land-use transformations over decades have reflected the interplay of environmental policies, financial incentives, and agricultural sector demands, resulting in changes in landscape composition and functionality (Gomes *et al.*, 2020). Between 2001 and 2015, the region experienced a significant increase in degraded areas, totaling over 200,000 km², which reflects declining land productivity (Paredes-Trejo *et al.*, 2023). This degradation is associated with reclassifying semiarid areas as arid and hyper-arid due to intensifying adverse climatic conditions (Batista *et al.*, 2022).

Urbanization in BSR has caused a reorganization of regional landscapes, leading to problems such as the loss of permeable surfaces, exacerbation of urban heat islands, and increased surface runoff, intensifying floods and environmental contamination (Lizárraga-Mendiola; Vázquez-Rodrígue; Bigurra-Alzati, 2021). Strategies such as expanding vegetation in urban areas and adopting resilient solutions like green infrastructure and water resource conservation can help address water scarcity and enhance cities' adaptive capacity in the face of climate change and anthropogenic pressures (Bigurra-Alzati *et al.*, 2020; T. A. *et al.*, 2023). These challenges highlight the importance of tools to understand territorial dynamics and guide more sustainable planning strategies.

In this context, models based on neural networks have stood out for their ability to capture the non-linearity and complexity of the interactions between explanatory variables, allowing for more accurate predictions. These models use information from remote sensors and Geographic Information Systems (GIS), which provide multi-temporal data on LULC, facilitating the identification of spatial and temporal patterns of change (Abujayyab; Karaş, 2020). Among the explanatory variables influencing LULC change are proximity to infrastructure (e.g., roads), population density, slope, accessibility to urban centers, and urban expansion zones. These drivers function as forces that guide the spatial trajectory of urban growth and environmental transformation—each with varying degrees of influence on how land transitions from rural or natural to urban or artificial uses (Kamaraj; Rangarajan, 2022; Vu; Shen, 2021).

Understanding the sensitivity of LULC models to these variables is critical: it reveals which drivers have the most significant impact on simulation outcomes, thereby influencing the reliability of projected urban scenarios (Gaur; Singh, 2023). For example, a high sensitivity to road proximity may indicate strong dependence on infrastructure development, while low sensitivity to topographic factors might suggest limited physical constraints on expansion (Karimi; Sultana, 2024). This knowledge enables urban planners and policymakers to better anticipate where land transformations are most likely to occur—and why.

By quantifying the relative influence of each driver, researchers can develop more precise and robust simulations, which are essential for the design of effective mitigation and adaptation strategies. These strategies, in turn, are foundational for managing urban growth under increasing climatic and demographic pressures, especially in regions where land and water resources are particularly vulnerable (Li; Chunyu; Huang, 2022). However, despite their importance, few studies explore the comparative sensitivity of these drivers in depth, representing a methodological and practical gap. Addressing this gap is essential for enhancing the predictive power of LULC models and ensuring that future urban scenarios are grounded in the realities of both environmental constraints and socioeconomic trends.

From this perspective, LULC change modeling should incorporate drivers that assist in planning decision-making for developing urban planning policies and strategies. Thus, this chapter addresses the following questions: (1) What are the main drivers of LULC change in the study area? (2) How do the explanatory variables interact with each other in the urban context? (3) Which classes of LULC are most impacted by the explanatory variables? Thus, the main objective of this study is to evaluate the influence of LULC drivers in the city of Campina Grande, focusing on their impact on urban sprawl, to provide information for formulating land use plans that promote the sustainable management of the landscape.

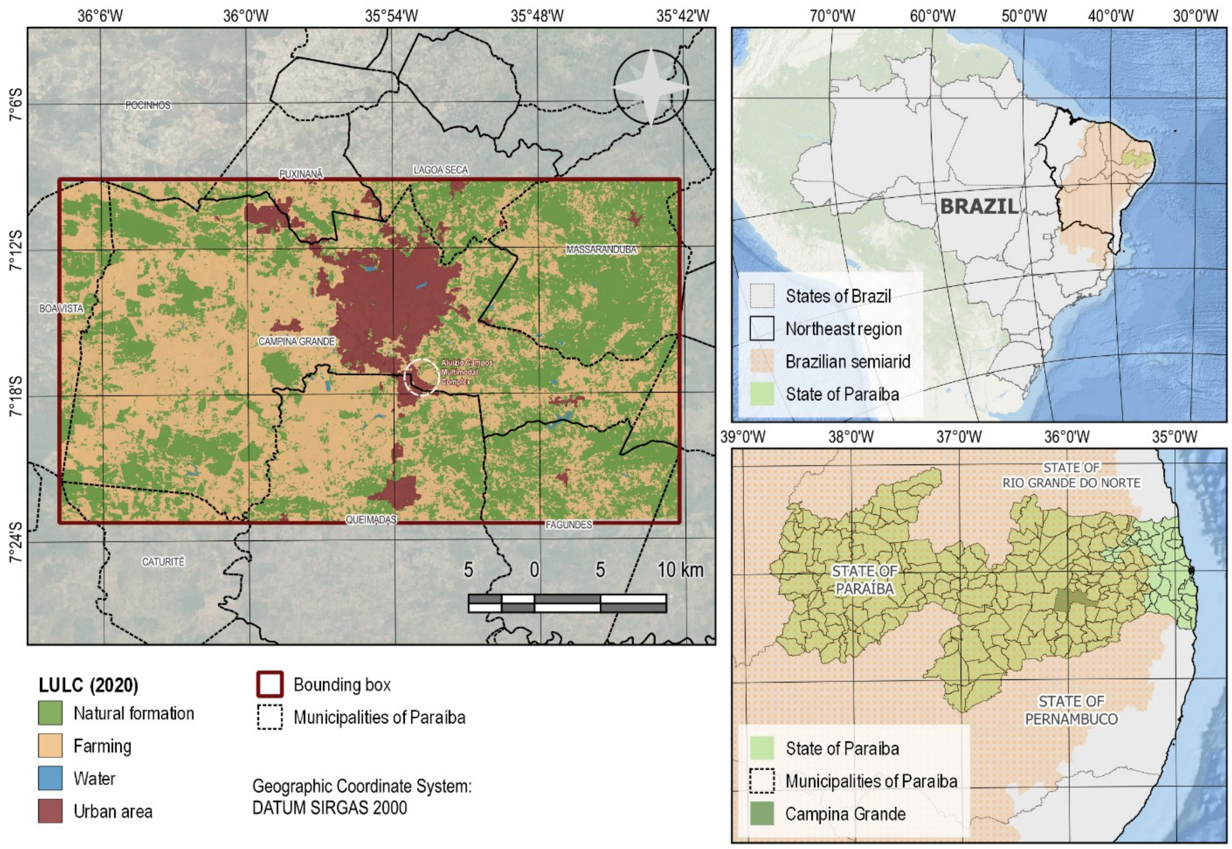
5.2 MATERIALS AND METHODS

This study adopted a multi-methods approach combining spatial simulation techniques with statistical analyses to analyze LULC changes in Campina Grande, Brazil. The methodology was designed to assess explanatory variables' influence and interactions on LULC simulation accuracy, employing the MOLUSCE plugin[6] and statistical analyses.

5.2.1 Delimitation of the study area

For this chapter, Campina Grande was delineated by a bounding box that encompasses the municipality's boundaries (Figure 10). This choice is justified because several bordering areas are fully occupied, especially in the northern and southern portions, and some residential condominiums are being constructed in neighboring municipalities, such as Lagoa Seca and Queimadas. This urban expansion beyond municipal boundaries requires an integrated approach to territorial planning, considering interactions between Campina Grande and its neighboring municipalities.

Figure 10. Bounding Box and LULC for Campina Grande (PB), Brazil.



Source: LULC 2020 adapted from Mapbiomas (MapBiomas Project, 2021).

[6] MOLUSCE is a QGIS plugin designed to analyze and model changes in LULC. Based on LULC data from two different time points, MOLUSCE applies statistical and machine learning algorithms (such as logistic regression, neural networks or decision trees) to estimate transition probabilities between land use classes. The plugin can also generate projections of future land use, helping in spatial planning and environmental scenario analysis.

5.2.2 LULC simulations

The LULC data for Campina Grande were obtained from the Google Earth Engine platform, using the Mapbiomas Collection 6. For this study, the 34 original LULC classes were aggregated into broader categories, as described in the previous chapter, to simplify the analysis and improve the applicability of the model in predicting urban expansion.

As in the previous chapter, the simulations were conducted using the MOLUSCE plugin within QGIS and the CA-ANN model was trained using the same methodological path presented previously. The parameters included 5,000 random samples, 150 iterations, a 3x3 neighborhood, a learning rate of 0.001, 10 hidden layers and a momentum coefficient of 0.05.

Fifteen LULC simulations were conducted, exploring all possible combinations of explanatory variables. Table 6 presents the simulations, indicating the inclusion or exclusion of each variable, where a value of 1 represents the presence and 0 the absence of the variable in the simulation. It is important to note that MOLUSCE does not allow simulations without including at least one explanatory variable, which makes it impossible to conduct a simulation without variables.

Table 6. LULC simulations conducted

Simulation	Explanatory variable[7]			
	SLO	ACC	PUC	UEZ
sim_0111	0	1	1	1
sim_1101	1	1	0	1
sim_0011	0	0	1	1
sim_1001	1	0	0	1
sim_1111	1	1	1	1
sim_0101	0	1	0	1
sim_1011	1	0	1	1
sim_0001	0	0	0	1
sim_0110	0	1	1	0
sim_1100	1	1	0	0
sim_1110	1	1	1	0
sim_0100	0	1	0	0
sim_1000	1	0	0	0
sim_0010	0	0	1	0
sim_1010	1	0	1	0

5.2.3 Sensitivity analysis

The analysis was divided into three main steps: (1) Calculation of area differences: the absolute difference between the simulated and observed areas for each land cover class was

[7] As mentioned in the previous chapter: Slope (SLO), Accessibility (ACC), Proximity to urban centers (PUC) and Urban Expansion Zones (UEZ).

calculated; (2) Accuracy assessment: spatial statistical metrics were computed to evaluate the accuracy of each simulation relative to the observed LULC; (3) Two-way Analysis of Variance (ANOVA): a two-way ANOVA was employed to assess the statistical significance of each variable, providing insight into the effects contributing to the observed variations across simulations.

For the calculation of area differences, the areas occupied by each LULC class for all simulations were computed, and the absolute differences from the observed raster were summed to obtain the total area difference for each simulation. The total difference is defined by Equation 3.

$$Total\ difference_i = \sum_{c} \left| Area_{i,c} - Area_{observed,c} \right|$$ Equation 3

where $Area_{i,c}$ represents the area of class c in simulation i and $Area_{observed,c}$ is the corresponding area in the scenario observed by Mapbiomas for 2020. The total difference captures the magnitude of variation for each simulation compared to the observed scenario, serving as a measure of the impact of the variables in each configuration.

LULC simulation accuracy was assessed by comparing the LULC classes predicted by the simulations with those observed by Mapbiomas. This evaluation used the Semi-Automatic Classification Plugin in QGIS (Congedo, 2021). The elements in the main diagonal of the confusion matrix indicate the number of correctly classified pixels, known as true positives (TP). In contrast, the off-diagonal elements represent incorrectly classified pixels: false positives (FP) and false negatives (FN). To quantify the accuracy of the LULC maps, spatial statistical metrics such as PA, UA, OA, and the Kappa coefficient were used, as described by (Indraja; Aashi; Vema, 2024).

PA reflects the proportion of correctly classified pixels, while UA is related to user interpretation, measuring the ability of the LULC map to represent real land conditions faithfully. OA indicates the total percentage of pixels correctly classified by the algorithm about the total number of pixels analyzed. The Kappa coefficient is a statistical measure that assesses the degree of agreement between the predicted and actual LULC classes in the confusion matrix. Equations 4, 5, 6, and 7 show the mathematical expressions for each of these metrics.

$$User's\ accuracy\ (UA) = \frac{TP}{TP + FN}$$ Equation 4

$$Producer's\ accurary\ (PA) = \frac{TP}{TP + FP} \quad \text{Equation 5}$$

$$Overall\ accurary\ (OA) = \frac{TP + TN}{TP + FP + TN + FN} \quad \text{Equation 6}$$

$$Kappa\ coefficient = \frac{P_o - P_e}{1 - P_e} \quad \text{Equation 7}$$

where *TN* is the true negative, *TP* is the true positive, *FP* is the false positive, *FN* is the false negative, P_o is the observed proportion of agreement, and P_e is the proportion of agreement expected by chance.

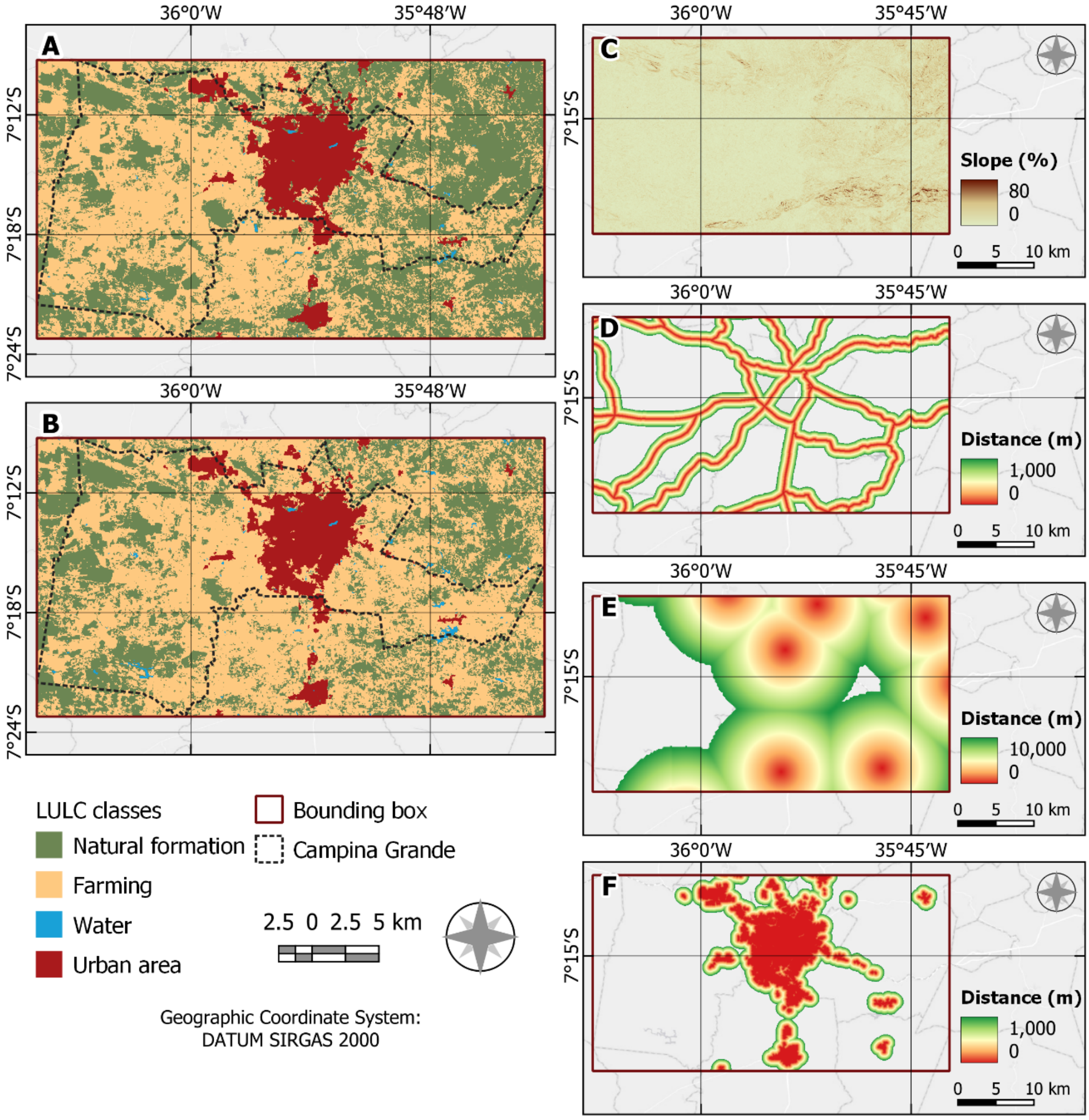
The statistical significance of each effect in the model was tested using a two-way ANOVA in Microsoft Excel[8] with the XLSTAT add-on version 2019.2.2 for MS Excel[9]. The analysis decomposes the total variability of the area difference into components attributable to each variable. ANOVA generates F-values for each effect, identifying which variables explain significant variation in the total difference, with *p-value* below the significance level ($\alpha = 0.05$) indicating statistical significance.

5.3 RESULTS

The results of this study highlight the relevance of explanatory variables in modeling LULC changes in Campina Grande. Figure 11 illustrates the comparison between the observed LULC and the simulated LULC using all explanatory variables (sim_1111) and the explanatory variables themselves. The area differences between the simulated maps and those observed by Mapbiomas for 2020 were calculated and synthesized in Figure 12.

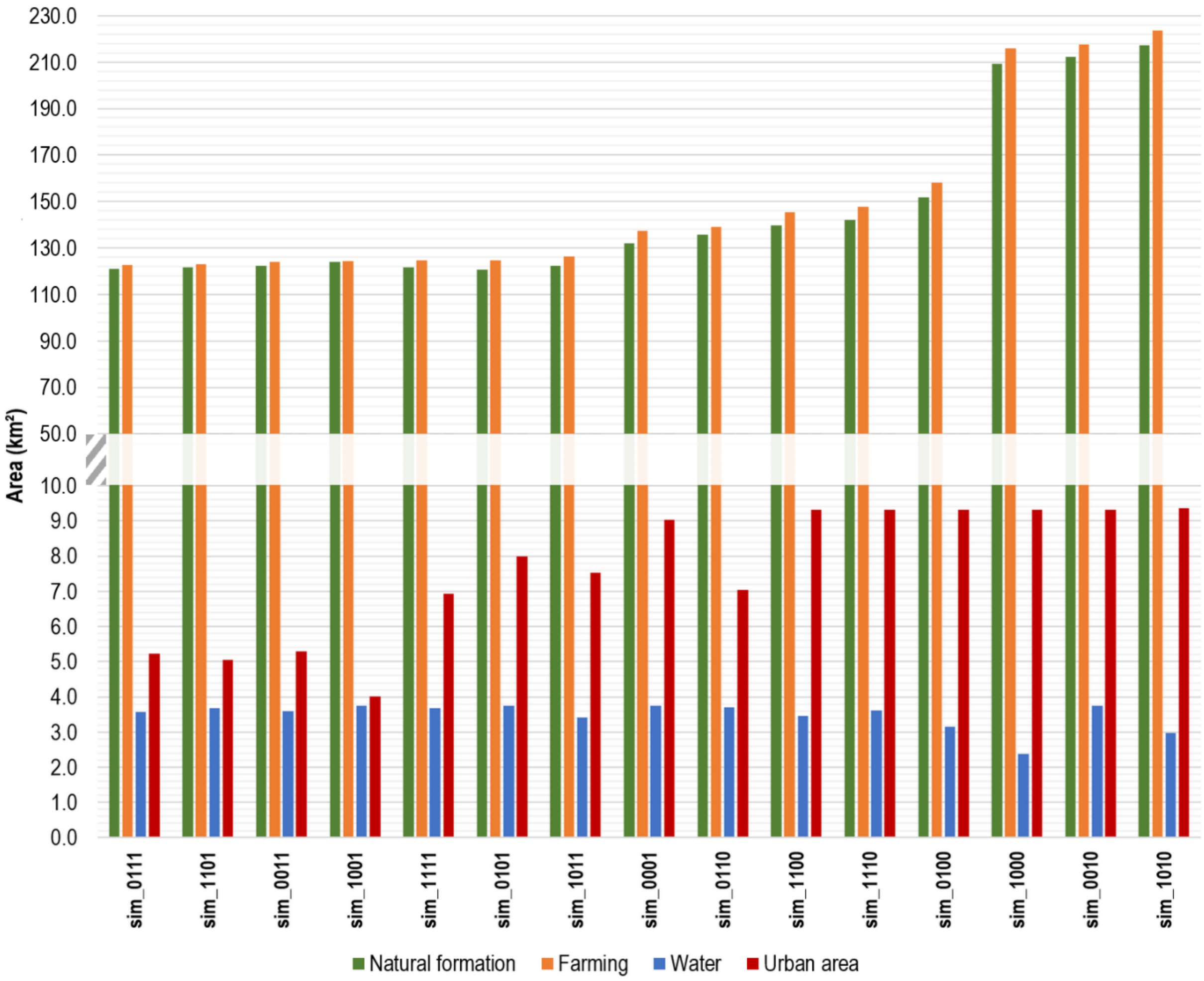
[8] Microsoft 365 version 2108, Microsoft Corp., Redmond, WA, USA.
[9] Addinsoft SARL, Paris, France

Figure 11. LULC maps and explanatory variables[10]. (A) LULC Mapbiomas 2020; (B) Simulated LULC for 2020 (sim_1111); (C) SLO; (D) ACC; (E) PUC; (F) UEZ



[10] As mentioned in the previous chapter: Slope (SLO), Accessibility (ACC), Proximity to urban centers (PUC) and Urban Expansion Zones (UEZ).

Figure 12. Area difference between LULC classes relative to observed LULC



The analysis of area differences between the simulations and the Mapbiomas observed data for 2020 underscores the importance of explanatory variables in the accuracy of LULC projections. The results indicate that simulations incorporating multiple drivers presented minor discrepancies, while those with fewer drivers presented pronounced divergences.

Specifically, the urban area class proved sensitive to including explanatory variables. Simulations incorporating all variables (e.g., sim_1111) presented moderate differences (6.93 km²) compared to observed data, whereas more restrictive simulations, such as sim_0001, reached differences of up to 9.03 km².

This trend indicates that explanatory variables such as ACC and UEZ play a decisive role in shaping the spatial allocation of urban growth in LULC simulations. ACC captures the ease of movement and connectivity to key infrastructure and services, often as a proxy for development potential. Areas with higher accessibility tend to attract more urban development due to reduced transportation costs and greater service availability (Poelmans; Van Rompaey, 2010). Likewise, UEZ delineates regions that are institutionally or strategically designated for future growth, embedding planning intentions into spatial modeling. Including these variables enhances the spatial realism of simulation outputs, as they guide land transition toward urban classes where development pressure is institutionally and functionally supported (Domingo; Palka; Hersperger, 2021).

Other LULC classes also showed variations in area differences across simulations. The natural formations class was the most affected by excluding explanatory variables. In simulations where variables were omitted—such as in sim_1010—the discrepancy reached 217.31 km², compared to 120.92 km² in models with more variables, like sim_0111. These results indicate that ACC and PUC highly influence the spatial distribution of natural areas. When these variables are not considered, the model tends to overestimate the extent of natural land, likely because it fails to account for development pressures that reduce such areas near urban zones.

Similarly, the farming class exhibited considerable variations, with differences ranging from 122.58 km² (sim_0111) to 223.70 km² (sim_1010), highlighting the influence of anthropogenic factors, such as urban expansion zones and accessibility, on the spatial distribution of agricultural activities. In contrast, the water bodies class showed the least minor differences among simulations, with variations ranging from 2.38 km² (sim_1000) to 3.75 km² (across various simulations), suggesting that the spatial configuration of these areas is less affected by the analyzed drivers, likely due to their more fixed and limited distribution. In the Brazilian semiarid region, most water bodies exhibit limited spatial and temporal variability over the long term, while displaying significant fluctuations during short rainy periods due to the intermittent nature of many watercourses.

When compared across simulations, the total differences reinforce explanatory variables' influence in modeling. For instance, sim_0111, which included ACC, PUC, and UEZ, showed a total difference of 252.30 km², while simulations with fewer variables, such as sim_1000 and sim_0100, reached total discrepancies of 436.80 km² and 322.42 km², respectively.

The PA, UA, OA, and the Kappa coefficient results emphasize the importance of including explanatory variables in simulation performance (Table 7). The simulation incorporating all variables (sim_1111) demonstrated balanced performance, with an OA of 76.06% and a Kappa coefficient of 0.577, indicating strong consistency between observed and predicted values. Notably, this simulation achieved high PA values for the urban class (91.89%) and the cropland class (86.38%), reflecting its robust ability to capture areas of intense anthropogenic activity.

Table 7. Spatial statistical metrics for the simulations

Simulation	PA (%)				UA (%)				OA (%)	Kappa
	Natural formation	Farming	Water	Urban area	Natural formation	Farming	Water	Urban area		
sim_1111	61.05	86.38	82.99	91.89	79.94	71.31	34.79	98.60	76.06	0.577
sim_0111	61.19	86.33	81.82	93.00	79.99	71.48	34.85	98.03	76.18	0.580
sim_1101	61.14	86.37	83.09	93.02	80.08	71.48	34.75	97.88	76.19	0.580
sim_0011	61.11	86.49	81.48	92.76	80.18	71.47	34.55	97.85	76.21	0.580
sim_1001	60.86	86.48	83.49	93.96	80.17	71.45	34.62	97.83	76.20	0.581
sim_0101	61.25	86.42	83.39	91.51	80.00	71.34	34.55	99.32	76.14	0.579
sim_1011	61.21	86.67	77.70	91.69	80.28	71.39	33.92	99.02	76.24	0.580
sim_0001	59.68	87.07	83.42	90.93	80.30	70.63	34.53	99.78	75.74	0.571
sim_0110	59.20	87.15	83.22	91.71	80.41	70.54	34.67	98.52	75.64	0.569
sim_1100	59.20	88.02	80.44	90.70	81.28	70.61	34.85	99.83	75.97	0.574
sim_1110	58.42	87.67	81.04	90.71	80.69	70.13	34.31	99.83	75.47	0.566
sim_0100	57.56	88.63	79.44	90.71	81.68	69.91	36.27	99.83	75.57	0.567
sim_1000	50.72	92.42	68.72	90.70	85.45	67.66	36.19	99.83	74.48	0.545
sim_0010	48.12	90.60	83.46	90.70	81.91	66.19	34.55	99.83	72.52	0.510
sim_1010	47.78	91.17	77.39	90.66	82.73	66.11	36.53	99.83	72.64	0.512

**The colors indicate an increase (green) or decrease (orange) in the spatial statistics compared to the simulation with all the explanatory variables (sim_1111).*

Comparatively, simulations excluding specific variables, such as sim_1000 and sim_1010, showed significant reductions in both OA (74.48% and 72.64%, respectively) and the Kappa coefficient (0.545 and 0.512, respectively). Although these simulations maintained high performance for the urban class regarding UA (99.83%), they exhibited lower PA values, particularly for the natural formations and cropland classes, indicating limitations in adequately representing areas less influenced by anthropogenic variables.

The water class emerged as the most challenging to model, with consistently low UA across all simulations, reaching only 36.53% in sim_1010. Conversely, the urban and cropland classes displayed high UA values, indicating that the models reliably represented areas with significant human interference. The inverse relationship observed between PA and UA in some simulations suggests that while the model effectively identifies large areas of these classes, it struggles with accurately representing transitions or boundaries between classes.

Overall, simulations incorporating multiple explanatory variables (sim_1111, sim_0111, and sim_1101) achieved the best balance among PA, UA, and the Kappa coefficient. This finding highlights the importance of an integrated approach in selecting drivers for LULC modeling, mainly to capture the dynamics of urban and cropland areas in highly complex contexts such as the Brazilian semiarid region.

The ANOVA results (Table 8) emphasize the differential influence of explanatory variables on LULC classes. The urban expansion zones (UEZ) variable showed the highest F-values and statistical significance for various classes, especially urban areas ($F = 10.981$; $p = 0.008$), cropland ($F = 24.310$; $p = 0.001$), and natural formations ($F = 22.691$; $p = 0.001$). These findings demonstrate that including UEZ is critical for accurately modeling transitions between classes, reflecting the dynamics of urbanization and agricultural expansion.

Table 8. ANOVA results for the influence of drivers on LULC classes

Class	**Driver**	**F**	***p* value**
Urban area	SLO	0.098	0.761
	ACC	0.264	0.618
	PUC	0.321	0.583
	UEZ	10.981	0.008
Water	SLO	1.179	0.303
	ACC	1.676	0.225
	PUC	0.712	0.418
	UEZ	4.438	0.061
Farming	SLO	0.012	0.914
	ACC	10.041	0.010
	PUC	0.000	0.991
	UEZ	24.310	0.001
Natural formation	SLO	0.014	0.908
	ACC	10.132	0.010
	PUC	0.002	0.966
	UEZ	22.691	0.001
All classes	SLO	0.009	0.927
	ACC	10.033	0.010
	PUC	0.000	0.999
	UEZ	24.276	0.001

The ACC variable also demonstrated statistical significance for classes such as cropland ($F = 10.041$; $p = 0.010$) and natural formations ($F = 10.132$; $p = 0.010$), suggesting that proximity to highways plays a central role in defining the spatial patterns of these classes. In contrast, the SLO and PUC variables exhibited low statistical significance for all classes, with F-values and p-values exceeding critical thresholds, indicating limited influence in the study area.

When analyzed collectively, the results for all classes reinforce the predominant role of UEZ ($F = 24.276$; $p = 0.001$) and ACC ($F = 10.033$; $p = 0.010$) as influential drivers in LULC change modeling. The low significance of SLO ($F = 0.009$; $p = 0.927$) and PUC ($F = 0.000$; $p = 0.999$) suggests that these variables may be less relevant in regions with low topographic variability and high urban infrastructure density.

These findings highlight the necessity of prioritizing specific drivers, such as UEZ and ACC, in modeling to accurately capture the anthropogenic and biophysical interactions shaping LULC patterns. While these results are particularly relevant to the urban dynamics of Campina Grande, they are also applicable to other cities that share similar characteristics. Proximity to transportation networks has been consistently associated with urban sprawl and the conversion of non-urban land to urban, as observed in other regions (Kasraian *et al.*, 2016).

5.4 DISCUSSION

The results highlight the significance of the UEZ and ACC variables and reflect the influence of socioeconomic dynamics and specific urban processes in Campina Grande. These factors are directly linked to the LULC patterns observed in the study area.

The high significance of UEZ ($F = 24.276$; $p = 0.001$) in the simulations is supported by developments such as the Aluízio Campos Multimodal Complex, which substantially impacted the urban expansion patterns of Campina Grande. With over 4,100 housing units delivered in 2019, this complex—considered Brazil's largest housing project—redefined urban distribution by incorporating approximately 800 hectares into the city's urban perimeter, representing 20% to 25% of the total urban area (Mota; Cavalcanti, 2020). This project integrates housing, industrial, and logistics zones, advanced services, and community facilities such as schools, daycare centers, parks, and a botanical garden designed to accommodate an estimated population of 25,000. The findings of this study demonstrate that including UEZ improved simulation accuracy, particularly for urban areas. The Aluízio Campos project exemplifies how planned expansion directly influences land occupation and configuration, fostering new development hubs that address regional housing and economic demands.

The ACC variable ($F = 10.033$; $p = 0.010$) also reflects the influence of local processes, particularly the connectivity provided by the road network and investments in urban infrastructure. Proximity to airports, highways such as BR-230 and BR-104, and other structural roads create favorable conditions for economic development and the expansion of urban and agricultural areas (Cerqueira; Albuquerque; Souza, 2017). Additionally, universities, as centers of education and technological innovation, play a crucial role in attracting investments and driving growth in previously peripheral areas (Bandeira; Casimiro; Lima, 2020). These impacts are evident in the simulations, where ACC enhances the spatial representation of urbanized and agricultural areas. Furthermore, the economic growth of Paraíba, with a projected GDP increase of 6.8% for 2024 (G1 PB, 2024), along with cultural events (Leão *et al.*, 2017), underscores the relevance of ACC in fostering economic development and territorial value.

The low significance of the slope variable (SLO) ($F = 0.009$; $p = 0.927$) aligns with the predominantly flat topography of the Campina Grande region, which imposes no significant physical barriers to urban development. This condition facilitates land occupation and territorial expansion, diminishing the influence of slope in modeling. Similarly, the limited relevance of the proximity to the urban center variable (PUC) ($F = 0.000$; $p = 0.999$) can be attributed to the diffuse urban expansion pattern observed in the city. Growth predominantly occurs along highway corridors and areas offering infrastructure and accessibility, even in peripheral regions.

The proliferation of planned housing developments in peripheral neighborhoods evidences this behavior. Although distant from the city's traditional center, these areas attract new residents due to the availability of infrastructure and connectivity to major structural roads, particularly in the southwestern region of the city (Mendes Agra, 2021). In this context, such characteristics demonstrate that ACC plays a more decisive role in the dynamics of urban occupation in Campina Grande than in physical proximity to the city center or other municipalities.

The simulations capture these dynamics, indicating that the absence of PUC did not significantly compromise simulation accuracy. Instead, integrated with road corridors, the decentralized growth pattern underscores the importance of variables like ACC in explaining the spatial distribution of urban areas. These factors reflect the unique urbanization processes of Campina Grande, where planning and infrastructure drive the expansion of peripheral regions, contributing to the spatial redistribution of urban growth.

Although these findings are rooted in the specific urban dynamics of Campina Grande, they hold broader applicability for LULC modeling in other mid-sized cities, especially in semiarid or rapidly urbanizing regions of the Global South. The strong influence of UEZ and ACC observed in this study reflects broader spatial patterns of planned peripheries and infrastructure-driven development. Similar dynamics have been documented in India; studies across multiple mid-sized cities demonstrate how proximity to highways and planned growth zones consistently influences urban sprawl and the loss of rural land cover (Chettry; Surawar, 2021; Verma; Jangra; Kaushik, 2024).

5.5 FINAL CONSIDERATIONS

The results of this study highlight the complexity of LULC dynamics in Campina Grande, emphasizing the predominant influence of variables such as UEZ and ACC in modeling these transformations. The high statistical significance of these variables reflects local realities, where planned developments and road infrastructure play central roles in shaping urban spatial configurations.

It is important to note that the assessment of influence was based on the results of ANOVA significance tests (p-values), which revealed that ACC and UEZ were the most statistically significant variables. This contrasts with the initial analysis of raw area differences between LULC classes, where SLO also appeared to be a major contributor. However, slope did not present statistically significant variation across classes based on ANOVA results, suggesting that its apparent influence in the spatial overlay was not consistent enough to be considered a robust driver.

The analysis revealed that SLO and PUC exhibited low significance, aligning with the region's predominantly flat topography and the diffuse urban expansion pattern that follows road axes. These findings suggest that, in similar contexts, variables related to accessibility and urban planning may be more critical for modeling land use changes than topographic or centrality factors.

Limitations of this study include the simplification of LULC classes, grouped from Mapbiomas categories, which may have reduced the accuracy of the analyses, while the exclusion of socioeconomic factors, such as population density and housing policies, limited the scope of the model. Furthermore, the spatial resolution of Landsat imagery (30 meters) may not capture more detailed urban transitions. The use of the MOLUSCE plugin proved effective for exploratory LULC modeling; however, it offers limited flexibility for incorporating complex variable interactions and handling temporally irregular datasets. Future studies could benefit from integrating additional drivers, such as planned development zones or fiscal incentives, to improve the realism and policy relevance of LULC projections.

Finally, this chapter reinforces the relevance of spatial modeling tools as decision-support instruments, enabling both the anticipation of impacts and the development of mitigation strategies. The applicability of this approach extends beyond Campina Grande, proving particularly valuable for developing cities seeking to balance urban growth with environmental preservation. In a context where sensors, remote data, and atirfitial intelligence increasingly drive the creation of future scenarios and digital twins, incorporating sensitivity analysis becomes essential. It allows for the refinement of model predictions by dentifying the most influential variables, thus enabling the design of more realistic and actionable simulations. This increases the robustness of planning tools and provides urban planners and policymakers with closer approximations of plausible futures, supporting more equitable and sustainable actions in diverse global contexts.

SECTION II

WASHINGTON, D.C.

a US case study

Credits: washington.org

6 GREEN INFRASTRUCTURE FOR WHOM? WHERE SUSTAINABLE SOLUTIONS (DON'T) ARRIVE: AN ANALYSIS OF BMPS IN WASHINGTON, D.C.

How can the integration between urban planning and water management promote a more equitable distribution of green infrastructure?

English

After examining the interplay between urban growth, water demand, and LULC dynamics in a semiarid context, Chapter 6 shifts the geographical lens to Washington, D.C., to explore how sustainability interventions—specifically green infrastructure—intersect with patterns of environmental inequality. Drawing on a dataset of nearly 100,000 management practices, the chapter uses spatial statistical techniques to reveal how green infrastructure is unevenly distributed across racial, economic, and educational lines. This transition from modeling future urban pressures to analyzing existing infrastructure underscores a broader insight of the thesis: that water-related vulnerabilities are not only technical or environmental, but also deeply shaped by governance, equity, and historical urban form. By reframing green infrastructure as a selective spatial process, the chapter invites a more critical and justice-oriented view of urban sustainability.

Portuguese

Após examinar a interação entre crescimento urbano, demanda por água e dinâmicas de LULC em um contexto semiárido, o Capítulo 6 desloca a lente geográfica para Washington, D.C., a fim de explorar como intervenções de sustentabilidade – especificamente infraestrutura verde – se cruzam com padrões de desigualdade ambiental. Com base em um conjunto de dados de quase 100.000 práticas de gestão, o capítulo utiliza técnicas estatísticas espaciais para revelar como a infraestrutura verde é distribuída de forma desigual entre linhas raciais, econômicas e educacionais. Essa transição da modelagem de pressões urbanas futuras para a análise da infraestrutura existente ressalta uma visão mais ampla da tese: a de que as vulnerabilidades relacionadas à água não são apenas técnicas ou ambientais, mas também profundamente moldadas pela governança, equidade e forma urbana histórica.

6.1 BACKGROUND

Best Management Practices (BMPs) refer to a set of strategies and technologies designed to control non-point source pollution and surface runoff, particularly in densely impervious urban environments. These practices range from structural solutions, such as detention basins, permeable pavements, rain gardens, and bioretention systems, to non-structural interventions, including awareness campaigns, land use management, and regulatory incentives (Jayakaran; Rhodes; Vogel, 2021). In practice, BMPs are often implemented through regionally adapted frameworks such as Green Infrastructure, Green Stormwater Infrastructure (GSI), LID in North America, and SUDS in Europe. These approaches promote the decentralization and naturalization of urban water management by enhancing infiltration, evapotranspiration, and stormwater reuse, thereby supporting more resilient and ecologically integrated urban environments.

Embedded within the broader context of SUDS, BMPs operate under the paradigm of green infrastructure. These solutions mimic natural hydrological processes, such as infiltration and evapotranspiration, contributing to flood mitigation, improved water quality, and enhanced urban biodiversity (Moazzem *et al.*, 2024). Moreover, several authors highlight the multifunctional nature of these solutions, which are capable of simultaneously addressing environmental, social, and urban planning aspects (Chandratreya, 2024). However, understanding the broader performance of BMPs also requires attention to the urban landscape in which they are embedded—particularly the dynamics of LULC, which shape runoff patterns, flood susceptibility, and the overall functioning of drainage systems.

Washington, D.C. exemplifies a paradigmatic case of urbanization marked by racial, economic, and spatial inequalities. According to Park (2023), the U.S. capital exhibits a persistent spatial pattern of social vulnerability in which racialized and low-income communities concentrate low levels of green infrastructure, even amid the growing adoption of sustainability-based strategies. As a result, these populations face physical vulnerabilities and a legacy of institutionalized exclusion in urban planning decisions (LeFevre *et al.*, 2023).

Studies have advocated for the potential of BMPs as corrective tools that, when strategically implemented, can help mitigate these spatial injustices. Garcia-Cuerva, Berglund and Rivers (2018) propose an integrated approach that prioritizes the installation of green infrastructure in historically marginalized communities, promoting both environmental and social benefits. In Washington, D.C., cases such as Hickey Run illustrate how urban hydrological reimagining can serve environmental justice by transforming neglected waterways into ecological and cultural assets for the local population (Kaku, 2023).

Furthermore, the literature emphasizes that SUDS should be integrated within a systemic perspective that accounts for the social, ecological, and decision-making complexity of contemporary cities (Adem Esmail; Suleiman, 2020; Kabisch *et al.*, 2017; Lähde *et al.*, 2019). The experience of D.C., in this regard, reinforces the importance of intersectional and participatory approaches to ensure that the benefits of green infrastructure are not confined to privileged enclaves, but instead contribute to addressing long-standing structural imbalances.

Thus, by recognizing the role of BMPs beyond their technical and environmental value, it becomes possible to envision their function as instruments of social repair and transformation, fundamental to the construction of more just and resilient cities. While this chapter centers on the spatial distribution and equity dimensions of BMPs, it also sets the stage for subsequent discussions on how urban form and LULC transformations influence hydrological outcomes and flood vulnerability. From this perspective, this chapter aims to analyze the spatial correlations between the distribution of BMPs and socioeconomic indicators in Washington, D.C., based on the principles of environmental justice. The goal is to understand whether and how the implementation of these sustainable solutions is associated with the reproduction or mitigation of historical inequalities, revealing patterns of inclusion or exclusion in access to green infrastructure.

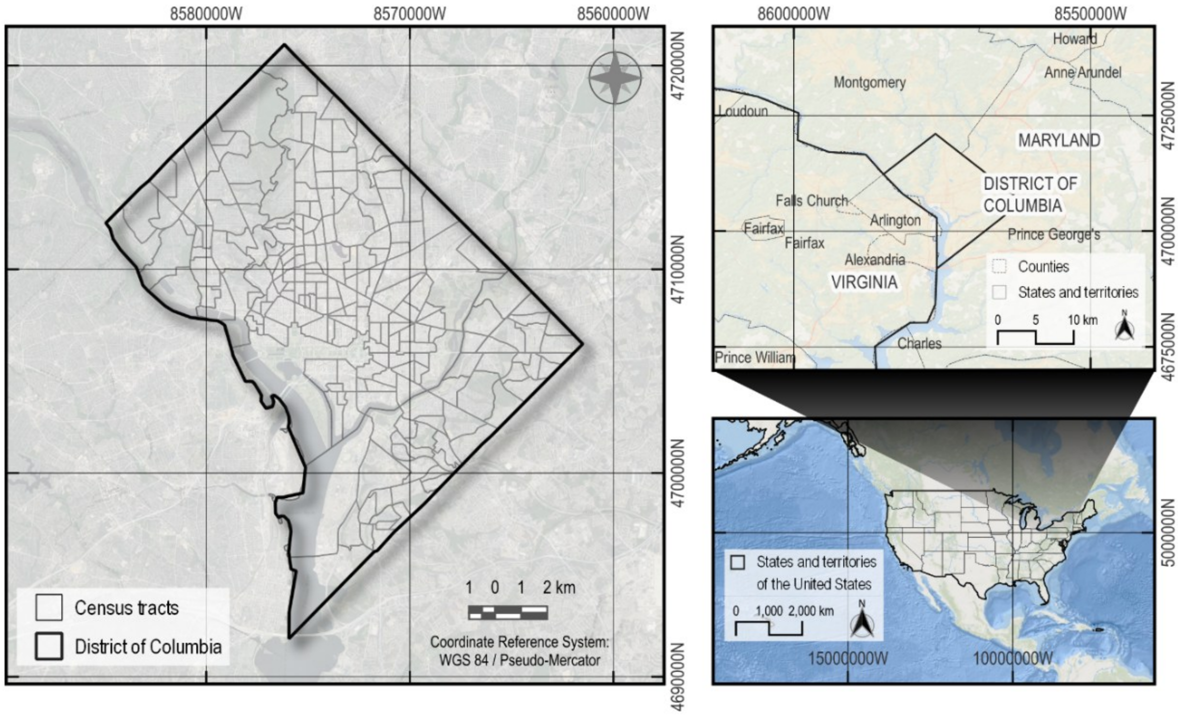
6.2 METHODOLOGY

The methodology employed in this chapter was structured into three main stages. First, an analysis of the spatial distribution of the selected variables was conducted in order to describe the geographic organization of socio-environmental indicators, such as the presence of green infrastructure, income levels, and racial composition. Next, spatial correlation patterns were identified through the calculation of the Global Moran's I Index, aiming to detect statistically significant spatial clusters. Finally, the Bivariate Local Moran's I Index was applied to examine spatial associations between distinct variables, allowing for the assessment of whether social disparities were spatially correlated with the distribution of environmental benefits across the urban territory.

6.2.1 Study area

Washington, D.C., the capital of the United States (Figure 13), is shaped by a historical legacy of spatial segregation that continues to influence its urban dynamics. Practices such as redlining—which throughout the 20th century systematically denied Black communities access to housing credit and infrastructure—have cemented patterns of exclusion whose effects persist in the city's environmental and social inequalities (Williams, 2001).

Figure 13. Location map of Washinton, D.C.



Historical spatial segregation is particularly evident in the southeastern region of Washington, D.C., where the majority of the population is Black and has, for decades, faced the consequences of exclusionary urban policies that have linked these territories to racial and economic marginalization. Reese (2019) argues that the geographic separation enforced by the Anacostia River is not only physical but also symbolic—reinforcing the devaluation of these communities in relation to the rest of the city and consistently limiting access to essential resources such as healthy food, infrastructure, and public investment.

These areas have some of the lowest levels of green infrastructure, making them more vulnerable to environmental risks such as flooding, urban heat islands, and water pollution (Fang *et al.*, 2023). In contrast, historically privileged neighborhoods have benefited from investments in sustainable infrastructure, contributing to what has been termed "green gentrification," which perpetuates socio-spatial inequalities under a new guise (Avni; Fischler, 2020).

As part of its environmental reconfiguration, Washington, D.C. implemented a transformation of the Clean Rivers Project, partially replacing traditional gray infrastructure solutions with nature-based interventions such as rain gardens, permeable pavements, and green roofs. This shift was accompanied by a financial innovation: the issuance of green bonds and, later, an Environmental Impact Bond (EIB), directly linking environmental performance to financial returns for investors. According to Christophers (2018), this "double greening"—of infrastructure and finance—has amplified both environmental and financial risks, particularly for city residents, who continue to bear the project's costs through rising service fees.

However, the distribution of these sustainable interventions has been uneven. Historically marginalized communities remain excluded from the benefits of BMPs, both in terms of infrastructure and participation in decision-making processes (Park, 2023). Sen (2008) argues that without a careful focus on environmental justice dynamics, such policies risk reproducing the very exclusions they aim to overcome.

6.2.2 Data sources

The analyses conducted in this study were based on geospatial and socioeconomic data referenced to the census tract level, which, according to the 2020 Census division, comprises a total of 206 tracts. Socioeconomic data were obtained from the American Community Survey (ACS) 5-Year Estimates (2019–2023), made available by the U.S. Census Bureau[11], specifically drawing from datasets related to demographics, economics, housing, and social characteristics.

From these sources, the following variables were extracted for analytical processing: (i) Percentage of the population aged 25 and over with a bachelor's degree or higher – VEDU; (ii) Percentage of population identifying as 'One race: Black or African American – VBLA; (iii) Percentage of population identifying as 'One race: White – VWHI; (iv) Percentage of individuals whose income in the past 12 months was below the poverty level – VPOV; (v) Median value of owner-occupied housing units (in U.S. dollars) – VVAL.

Information on green infrastructure was obtained from the Open Data DC[12] platform, based on data from the District Department of Energy and Environment (DOEE), which provides BMP records totaling 95,763 entries dated between November 17, 2015, and March 6, 2025. For typological analysis, records classified under the following BMP types were

[11] The U.S. Census Bureau (https://data.census.gov/) is the federal agency responsible for collecting, analyzing, and publishing statistical data about the population and economy of the United States. Its most well-known effort is the Decennial Census, conducted every 10 years, which gathers detailed information on all U.S. residents, including age, sex, race, housing, and household composition. In addition to the decennial census, the Bureau conducts ongoing surveys like the American Community Survey, which provides annual data on education, income, transportation, housing, and more, across various geographic levels (nation, state, county, city).

[12] Open Data DC is the official open data portal of the government of the District of Columbia, United States. It provides access to hundreds of publicly available datasets, enabling residents, researchers, and developers to explore and use information related to various aspects of Washington, D.C. (https://opendata.dc.gov/).

considered: bioretention, green roofs, infiltration, permeable pavements, and rainwater harvesting.

6.2.3 Spatial distribution analysis

Given the inherently geographic nature of the data, spatial models were used in this study. Spatially distributed variables tend to exhibit spatial dependence, meaning that observations in nearby locations are often more similar to each other than those further apart—an effect summarized by Tobler's First Law of Geography: "Everything is related to everything else, but near things are more related than distant things" (Tobler, 1970). Ignoring this spatial autocorrelation can lead to inflated beta coefficients and biased inferences in standard regression models, which assume independence among observations (Anselin, 1988).

The first stage of the analysis involved structuring and exploring the spatial distribution of the selected socioeconomic and environmental variables, based on the census tract as the geographic unit. The aim was to identify intra-urban variation in the indicators and recognize areas with relatively high or low concentrations of each variable. To this end, thematic maps were produced, enabling the visualization of the spatial heterogeneity of attributes such as educational attainment, proportion of the population living in poverty, median housing values, and racial composition (percentages of Black and White populations) across the District of Columbia.

Regarding BMPs, the records were spatially mapped to observe their distribution and frequency throughout the urban fabric. To identify areas with higher concentrations of these interventions, a heat map was created, visually highlighting hotspots—regions with a high density of BMPs—and providing an initial assessment of potential spatial patterns of concentration, dispersion, or absence of these practices in specific sectors of the city.

6.2.4 Spatial autocorrelation patterns

The analysis of spatial autocorrelation patterns was conducted using GeoDa software, following the framework proposed by Lopes *et al.* (2024), employing exploratory spatial data analysis techniques to identify spatial structures within the analyzed data. The objective was to determine whether the values of certain variables—such as BMP presence and socioeconomic characteristics—exhibited non-random spatial clustering across the census tracts of Washington, D.C.

A first-order Queen contiguity spatial weights matrix was defined, which considers as neighbors all tracts that share borders or vertices. This configuration enhances sensitivity in detecting spatial dependence, allowing for broader identification of relationships between adjacent territorial units. The resulting contiguity matrix is represented by a square matrix W of dimension $n \, x \, n$, where each element w_{ij} takes the value 1 if tracts i and j are neighbors, and 0 otherwise. This matrix served as the basis for subsequent tests.

Based on this structure, the Global Moran's I Index (Eq. 8) was calculated for all variables of interest: the total number of installed BMPs, the five specific BMP types (bioretention, green roofs, infiltration, permeable pavements, and rainwater harvesting), and five socioeconomic indicators (percentage of Black population, percentage of White population, higher educational attainment, median value of owner-occupied housing units, and population below the poverty line). The index quantifies the degree of global spatial autocorrelation, with values ranging from -1 (perfect dispersion), 0 (randomness), to +1 (perfect clustering). Statistical significance was assessed based on 999 random permutations, with a 5% significance threshold ($p < 0.05$).

$$I = \frac{n}{\sum_i \sum_j w_{ij}} \frac{\sum_i \sum_j w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_i (x_i - \bar{x})^2} \quad \text{Equation 8}$$

Where:

n is the number of spatial units (census tracts);

x_i and x_j are the values of the variable under analysis in tracts i and j;

$\bar{x}$ is the mean of the variable;

w_{ij} represents the spatial weights between tracts i and j;

Subsequently, the Local Moran's Index (Local Indicators of Spatial Association – LISA) was applied for the total number of installed BMPs and for each of the five specific types. The aim was to identify statistically significant local clusters and spatial outliers (Eq. 9). LISA enables the classification of census tracts into the following spatial patterns: High-High, Low-Low, High-Low, and Low-High. These patterns indicate, respectively, areas with high (or low) values surrounded by tracts with similar values, or tracts with values that deviate from those of their neighbors. These spatial patterns were visualized using thematic maps, allowing for the observation of the spatial configuration of environmental and social inequalities across the territory.

$$I_i = (x_i - \bar{x}) \sum_j w_{ij}(x_j - \bar{x})$$ Equation 9

Where:

I_i represents the local Moran's I value for spatial unit i, and the remaining terms follow the notation previously described.

6.2.5 Spatial associations between variables

Continuing the spatial analyses, the Bivariate Local Moran's I Index was applied to explore spatial associations between the presence of sustainable water management practices and socioeconomic characteristics. This approach allows for the assessment of whether the distribution of an environmental variable in one spatial unit is associated with the values of a socioeconomic variable in neighboring units, revealing potential patterns of socio-spatial inequality (Anselin, 2005).

A total of 30 bivariate combinations were analyzed, derived from the cross-tabulation of six variables representing the total number of BMPs and their five typologies (bioretention, green roofs, infiltration, permeable pavements, and rainwater harvesting) with five socioeconomic indicators (proportion of Black population, proportion of White population, higher educational attainment, population below the poverty line, and median value of owner-occupied housing). The statistic was calculated according to Eq. 10.

$$I_i = (x_i - \bar{x}) \sum_j w_{ij}(y_j - \bar{y})$$ Equation 10

Where x_i represents the value of the environmental variable in tract i, y_j the value of the socioeconomic variable in neighboring tracts j, $\bar{x}$ and $\bar{y}$ their respective means, and w_{ij} the spatial weights defined by the previously established Queen contiguity matrix. The statistical robustness of the results was tested using 999 random permutations, with a significance level of $p < 0.05$.

6.3 RESULTS AND DISCUSSION

The thematic maps presented in Figure 14 reveal distinct spatial patterns that indicate an unequal distribution of BMPs with socioeconomic and demographic variables across the city of Washington, D.C.

To begin with, the map illustrating the distribution of BMPs (Figure 14A) shows a marked concentration of these sustainable solutions in central areas, predominantly located in the northern and northwestern regions of the city—areas historically recognized as wealthier and with a higher proportion of White residents (Figure 14D).

This concentration highlights a clear pattern of spatial inequality, aligning with previous studies such as Park (2023) and Avni and Fischler (2020), which discuss "green gentrification" as a phenomenon wherein privileged areas receive greater investments in green infrastructure.

When comparing this pattern with the spatial distribution of the Black or African American population (Fig. 17C), a low incidence of BMPs is observed in regions where this population is predominant, particularly in the southern and southeastern parts of the city. This situation reinforces the historical and structural perspective of racial segregation and institutionalized exclusion, as described by Reese (2019), in which the legacy of redlining continues to create barriers to essential and sustainable infrastructure in these communities.

Analyzing the educational dimension (Fig. 17B), a strong visual correlation can be seen between census tracts with a high proportion of residents holding a higher education degree and those with a greater presence of BMPs. This alignment suggests that communities with higher educational attainment—likely possessing greater social and political capital—are more successful in attracting public and private investment in green infrastructure. This reflects inequalities that go beyond racial and economic dimensions, extending into the realms of political influence and civic participation.

The map depicting the proportion of the population below the poverty line (Fig. 17E) further underscores the spatial disparity, showing that economically disadvantaged census tracts have fewer BMPs. This finding reaffirms the arguments of Sen (2008) and Garcia-Cuerva et al. (2018) regarding the urgent need for an integrated approach that prioritizes marginalized communities in order to overcome environmental inequalities.

The median value of owner-occupied housing units (Fig. 17F) also clearly aligns with the presence of BMPs, highlighting that neighborhoods with higher-value properties—often inhabited by wealthier and predominantly White populations—are privileged in the distribution of these environmental resources. This finding is consistent with the discussions of Christophers (2018), who critiques how innovative financial mechanisms, such as Environmental Impact Bonds, while potentially beneficial in theory, often end up favoring areas that are already economically well-served.

Figure 14. Thematic maps of the spatial variables analyzed: A) BMPs; B) Educational Attainment; C) Black or African-American population; D) White population; E) Income Below Poverty Level; F) Value of owner-occupied units

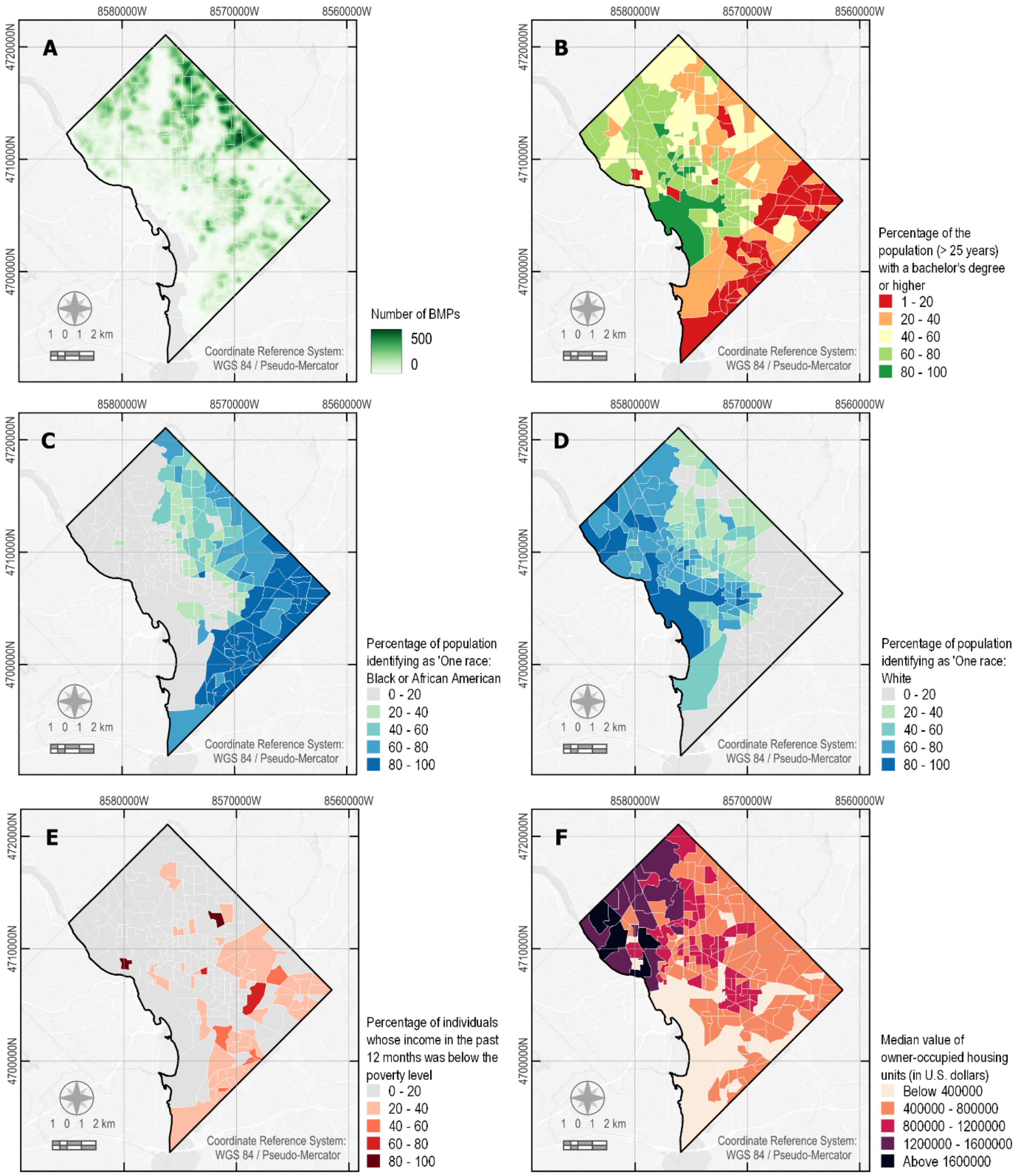


Table 9 presents the Global Moran's I values for socioeconomic variables and BMP typologies, indicating patterns of spatial autocorrelation. Notably, the highest indices are associated with racial composition: Black or African American population (0.859) and White population (0.839). These values quantitatively confirm the historical pattern of racial segregation in the city, demonstrating that racial groups are spatially clustered in specific regions.

Table 9. Global Moran's index for socioeconomic variables and BMP typologies

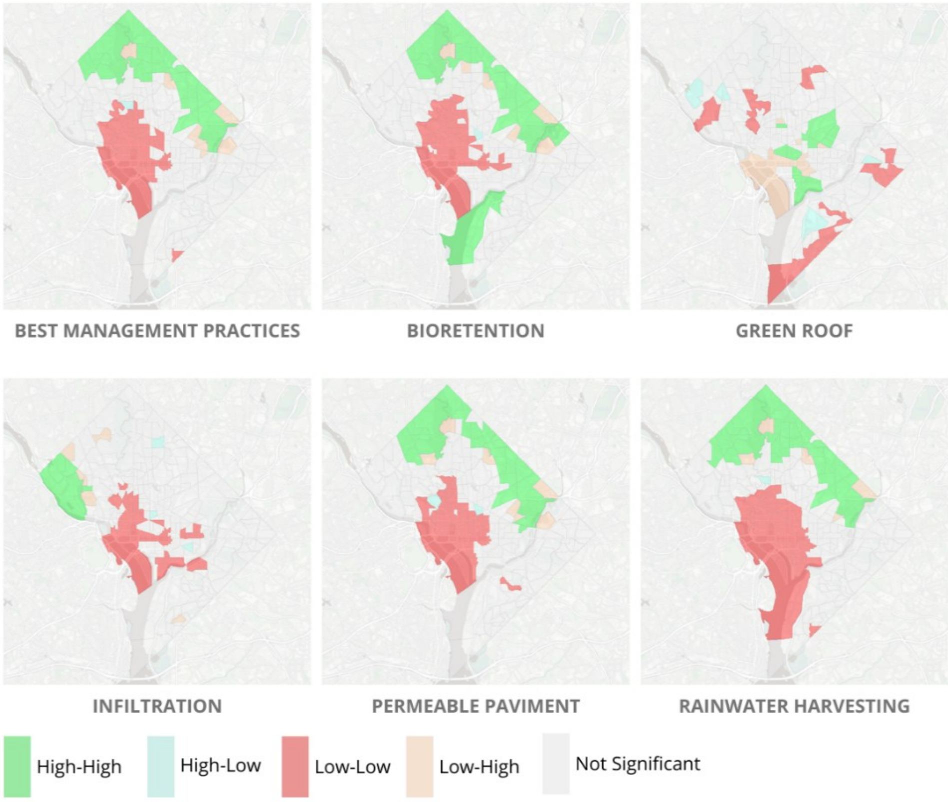
Variables	Global Moran's Index
Socio-economic variables	
Percentage of the population aged 25 and over with a bachelor's degree or higher	0.471
Percentage of population identifying as 'One race: Black or African American	0.859
Percentage of population identifying as 'One race: White	0.839
Percentage of individuals whose income in the past 12 months was below the poverty level	0.220
Median value of owner-occupied housing units (in U.S. dollars)	0.501
BMPs	
All BMPs	0.533
Bioretention	0.455
Green roofs	0.252
Infiltration	0.289
Permeable pavements	0.456
Rainwater harvesting	0.552

The educational attainment variable (0.471) also shows significant spatial autocorrelation, indicating that census tracts with higher education levels tend to cluster geographically. In contrast, the population below the poverty line shows the lowest Moran's I value among the socioeconomic indicators analyzed (0.220), suggesting a less concentrated spatial distribution, which may reflect the presence of dispersed areas with varying poverty levels.

Regarding specific BMP typologies, rainwater harvesting (0.552) and permeable pavements (0.456) show higher levels of spatial clustering. These results suggest that these infrastructures are concentrated in particular areas of the city. In contrast, green roofs (0.252) and infiltration practices (0.289) present lower spatial autocorrelation values, indicating a relatively more dispersed distribution of these sustainable solutions.

Figure 15 presents the univariate analysis of LISA for the distribution of BMPs in Washington, D.C., revealing specific local patterns of concentration or dispersion of these environmental practices. This analysis aims to identify statistically significant local clusters and isolated census tracts (outliers), which may indicate areas of environmental exclusion or privilege.

Figure 15. LISA for the univariate analysis of BMPs



The analysis reveals a well-defined spatial clustering of High-High areas in the northern and northwestern portions of the city, where census tracts with high concentrations of BMPs are surrounded by similarly performing neighbors. This spatial autocorrelation indicates the presence of established green infrastructure zones, likely supported by sustained environmental investments and planning efforts. These patterns reflect a territorial concentration of resources and infrastructure that align with the formation of ecological corridors. This spatial distribution reinforces previous findings discussed by Avni and Fischler (2020), and Park (2023).

In contrast, Low-Low clusters are observed in sectors located in the southern and southeastern regions of the city, indicating adjacent areas with low investment or a complete absence of BMPs. These sectors, already identified by Reese (2019) as historically marginalized regions, remain excluded from the benefits of green infrastructure, further reinforcing preexisting environmental inequalities.

Additionally, some spatial outliers are identified, classified as High-Low and Low-High tracts. These may represent isolated initiatives of BMP implementation in traditionally underserved regions or, conversely, pockets of exclusion within predominantly well-served areas. Such situations highlight specific opportunities and challenges for environmental urban planning, suggesting that isolated interventions—without an integrated spatial justice strategy—are insufficient to mitigate broader inequalities.

Figure 16 also presents the results of the bivariate LISA analysis. This analysis helps to understand how patterns of BMP implementation are spatially associated with social, racial, and economic conditions.

Figure 16. Bivariate analysis of LISA between BMPs (all types) and (A) VEDU; (B) VBLA; (C) VWHI; (D) VPOV; (E) VVAL[13]

In the association between BMPs and the percentage of the population with higher educational attainment, High-High clusters are predominant in the northern and northwestern regions of the city. This indicates that areas with a high proportion of residents holding a college

[13] As mentioned previously: VEDU: Percentage of the population aged 25 and over with a bachelor's degree or higher; VBLA: Percentage of population identifying as 'One race: Black or African American; VWHI: Percentage of population identifying as 'One race: White; VPOV: Percentage of individuals whose income in the past 12 months was below the poverty level; VVAL: Median value of owner-occupied housing units (in U.S. dollars).

degree also tend to have a greater presence of BMPs. This pattern suggests that educational capital functions as a factor in attracting environmental investments, likely linked to these communities' capacity to influence urban planning decisions—as noted by Zhang *et al.* (2022), who emphasize the role of educational composition in access to green infrastructure within U.S. school districts, and by Hendricks and Van Zandt (2021), who identify the overlap between educational attainment, vulnerability, and environmental protection. Conversely, Low-Low areas, particularly in the southeastern part of the city, reveal a dual disadvantage: lower levels of higher education and reduced access to sustainable infrastructure. This reinforces patterns of environmental injustice that, as demonstrated by Adorno, Pereira and Amaral (2025), can be effectively detected through spatial clustering analyses such as LISA.

Consequently, the analysis between BMPs and the Black or African American population reveals a predominance of Low-High classified tracts in the southeastern region, indicating areas with a high presence of this population but low incidence of BMPs in surrounding neighborhoods. This result suggests that Black residents live in areas spatially associated with a scarcity of green infrastructure investments—a dynamic also observed by Ferguson *et al.* (2018), who discuss how the distribution of green infrastructure is spatially unequal, even if not always explicitly linked to race.

In contrast, the analysis of the White population and BMPs reveals High-High clusters, primarily concentrated in the northern and northwestern regions. These census tracts indicate a positive spatial relationship between the presence of green infrastructure and a high concentration of White residents, exposing spatial patterns of environmental privilege correlated with race. This pattern is not exclusive to the U.S. capital; similar phenomena have been observed in other urban contexts, as demonstrated by Venter *et al.* (2020), who discuss the concept of "Green Apartheid" to describe the racially and economically uneven distribution of green infrastructure in South Africa.

The analysis of the relationship between BMPs and the population below the poverty line shows a predominance of Low-High clusters, particularly in the southeastern and eastern areas. These clusters represent tracts with high poverty concentrations and low BMP presence in surrounding neighborhoods. This pattern reveals how economically vulnerable populations face simultaneous social and environmental disadvantages, reflecting the spatial reproduction of existing socioeconomic inequalities in cities (Heckert; Rosan, 2016).

The relationship between BMPs and the median value of owner-occupied housing units shows High-High clusters in census tracts with higher property values, concentrated in the northwest. This finding suggests that areas with greater real estate value are being favored in the implementation of BMPs, potentially fueling property appreciation and environmental gentrification. Conversely, areas with lower property values remain spatially associated with limited access to green infrastructure.

The bivariate spatial analysis of bioretention BMPs (Figure 17) reveals nuances not as evident in the global analysis that considers all typologies collectively. While certain structural patterns—such as the concentration of interventions in the northwest and their systematic absence in the southeast—remain, the spatial behavior of bioretention suggests an even more selective logic of implementation. These findings reinforce the critique raised by Hendricks and Van Zandt (2021), who argue that the deployment of green infrastructure often overlooks the specific vulnerabilities of racialized and low-income communities, thereby perpetuating environmental injustices in new forms.

The results also reveal a presence of Low-High clusters in sectors with a low incidence of bioretention systems located near areas with a high proportion of black residents (Figure 17B) and individuals living below the poverty line (Figure 17D). This pattern indicates the selective nature of this green infrastructure typology, whose implementation is often structured around racialized dynamics that perpetuate environmental inequalities under the guise of sustainability (Lewartowska *et al.*, 2024).

Reading these patterns reveals that even in neighborhoods with strong indicators of social vulnerability, the presence of bioretention practices remains limited or absent, underscoring their selective deployment. Some spatial outliers (such as High-Low tracts) are also noted, deviating from regional patterns and possibly indicating isolated implementation efforts that did not extend to the surrounding areas.

Figure 17. Bivariate analysis of LISA between bioretention BMPs and (A) VEDU; (B) VBLA; (C) VWHI; (D) VPOV; (E) VVAL[14]

Figure 18, which presents the bivariate analysis between green roofs and socioeconomic and demographic variables, shows more dispersed and fragmented spatial patterns compared to those observed for other typologies, such as bioretention. Although High-High tracts are still identified in the northwestern region—especially in association with higher educational attainment and greater housing value—the extent of these clusters is notably smaller. The presence of green roofs appears to be more concentrated in specific locations, suggesting an implementation logic tied more to isolated initiatives or particular architectural opportunities than to city-wide planning strategies.

[14] As mentioned previously: VEDU: Percentage of the population aged 25 and over with a bachelor's degree or higher; VBLA: Percentage of population identifying as 'One race: Black or African American; VWHI: Percentage of population identifying as 'One race: White ; VPOV: Percentage of individuals whose income in the past 12 months was below the poverty level; VVAL: Median value of owner-occupied housing units (in U.S. dollars).

Figure 18. Bivariate analysis of LISA between green roof BMPs and (A) VEDU; (B) VBLA; (C) VWHI; (D) VPOV; (E) VVAL[15]

This selectivity may reflect a broader process of urban exclusion, in which, as argued by Shi (2020), sustainable infrastructures can contribute to the exclusion of vulnerable populations through dynamics of spatial valorization and indirect displacement.

The distribution of Low-High clusters in the cross-analysis with the Black population and the population below the poverty line shows a less systematic occurrence compared to other practices analyzed, yet still visible in sectors located in the southern and southeastern areas of the city. In these cases, it is evident that areas with high levels of vulnerability exhibit low concentrations of green roofs, even when surrounded by neighborhoods with similar demographic or economic profiles. This configuration suggests that the implementation of

[15] As mentioned previously: VEDU: Percentage of the population aged 25 and over with a bachelor's degree or higher; VBLA: Percentage of population identifying as 'One race: Black or African American; VWHI: Percentage of population identifying as 'One race: White; VPOV: Percentage of individuals whose income in the past 12 months was below the poverty level; VVAL: Median value of owner-occupied housing units (in U.S. dollars).

green roofs, although less aligned with continuous patterns of privilege, has not meaningfully reached the most socially disadvantaged sectors.

Figure 19 presents the bivariate LISA analysis for infiltration practices and reveals a relatively more dispersed distribution compared to other BMP typologies. While some High-High clusters are still observed—particularly in the northwestern areas, where census tracts with higher educational attainment and elevated property values predominate—the degree of clustering is less pronounced. This pattern suggests that the adoption of infiltration practices may have occurred more opportunistically, potentially taking advantage of specific soil and space conditions, rather than following a deployment logic clearly associated with socioeconomic indicators.

When analyzing the relationship with racial composition (Black and White populations) and income (particularly the percentage of individuals below the poverty line), the presence of dispersed Low-High and High-Low tracts can be observed across various parts of the city, without forming large homogeneous blocks. This diffuse mapping indicates that, although some regions rich in infiltration infrastructure may align with favorable socioeconomic attributes, there are also locations that deviate from the dominant pattern—either due to the absence of BMPs in tracts neighboring higher-income areas, or the unexpected presence of such practices near more vulnerable populations.

These spatial outliers support the hypothesis that technical, geological, or structural factors related to urban morphology may have influenced the placement of this BMP typology. Recent studies confirm that variables such as soil type, availability of urban space, and land prices play a decisive role in the allocation of green infrastructure, producing non-linear distribution patterns often characterized by local exceptions and spatial discontinuities (Rodriguez *et al.*, 2021; Zhou *et al.*, 2024).

Figure 19. Bivariate analysis of LISA between infiltration-type BMPs and (A) VEDU; (B) VBLA; (C) VWHI; (D) VPOV; (E) VVAL[16]

Figure 20 reveals varied spatial patterns in the association between permeable pavements and socioeconomic and demographic indicators. Figure 20A, which analyzes the relationship with the percentage of the population holding higher education degrees, predominantly shows Low-High tracts—indicating a reduced presence of this BMP typology in areas whose neighboring sectors have a high concentration of highly educated residents.

The low occurrence of High-High clusters suggests that, in this case, permeable pavement does not follow the typical pattern of concentration in more educated regions. This deviates from trends observed in cities like Philadelphia, where surface permeability has been positively correlated with socioeconomic indicators such as education and income levels,

[16] As mentioned previously: VEDU: Percentage of the population aged 25 and over with a bachelor's degree or higher; VBLA: Percentage of population identifying as 'One race: Black or African American; VWHI: Percentage of population identifying as 'One race: White ; VPOV: Percentage of individuals whose income in the past 12 months was below the poverty level; VVAL: Median value of owner-occupied housing units (in U.S. dollars).

indicating that green infrastructure tends to be more prevalent in areas with higher educational capital (Zhu, 2022). In the context analyzed here, this atypical distribution may be associated with technical constraints, specific urban morphology, or even a lower prioritization of permeable pavement in planning agendas despite the presence of greater educational resources.

Figure 20. Bivariate analysis of LISA between permeable pavements BMPs and (A) VEDU; (B) VBLA; (C) VWHI; (D) VPOV; (E) VVAL[17]

Figures 20B and 20D, which present the bivariate analysis with the Black population and the population below the poverty line, respectively, reveal a distinct pattern. In both cases, High-High clusters stand out in the northwest quadrant of Washington, D.C., indicating that census tracts with a high percentage of Black residents and individuals experiencing poverty

[17] As mentioned previously: VEDU: Percentage of the population aged 25 and over with a bachelor's degree or higher; VBLA: Percentage of population identifying as 'One race: Black or African American; VWHI: Percentage of population identifying as 'One race: White ; VPOV: Percentage of individuals whose income in the past 12 months was below the poverty level; VVAL: Median value of owner-occupied housing units (in U.S. dollars).

are spatially associated with areas showing a greater presence of permeable pavements. This pattern diverges from the trends observed in other typologies—such as green roofs or bioretention systems—and may reflect targeted initiatives or context-specific strategies aimed at mitigating environmental vulnerabilities in historically underserved areas (Park *et al.*, 2024).

The distribution observed in Figures 20C and 20E—which correspond to the White population and the median housing value—returns to previously identified patterns, with High-High clusters concentrated in northwestern neighborhoods, known for their higher socioeconomic capital. These clusters suggest that the presence of permeable pavements continues to partially align with the broader logic of investment in privileged areas.

However, the simultaneous presence of High-High clusters in both vulnerable (Figures 20B and 20D) and privileged (Figures 20C and 20E) sectors points to a more balanced spatial dispersion of this BMP typology when compared to others. The interpretation of Figure 20, therefore, reveals a mixed pattern in which permeable pavements appear both in historically advantaged contexts and in vulnerable areas—potentially indicating a typology with greater territorial reach and more flexible implementation in diverse urban scenarios.

Figure 21 highlights the spatial patterns of association between rainwater harvesting systems and socioeconomic and demographic variables, revealing both alignments with patterns of urban privilege and possible indications of interventions in vulnerable areas.

In Figure 21A, which refers to the proportion of the population with higher education, Low-High and High-Low sectors predominate, indicating a weak spatial correspondence between the presence of this BMP typology and the educational capital of the surrounding area. The near absence of High-High sectors suggests that the implementation of rainwater harvesting systems has not systematically prioritized areas with higher education levels, unlike what is observed for other BMPs.

This finding aligns with the analysis by Bitterman *et al.* (2016), who argue that water security through rainwater harvesting must also be understood in light of social inequalities, going beyond strictly technical criteria. For example, in the Brazilian context, several studies echo this perspective by emphasizing how access to rainwater harvesting systems is often mediated by structural inequalities and the legacy of territorial exclusion (Alves; Djordjević; Javadi, 2022; Del Grande *et al.*, 2016).

Figure 21B, which examines the Black population, reveals a distinct pattern, with several High-High clusters located primarily in the southeastern part of the city. This configuration indicates a significant spatial association between rainwater harvesting systems and racialized areas, contrasting with the distribution of other BMPs, which are often limited to historically privileged sectors. The presence of these clusters in areas with a high concentration of Black residents may reflect targeted actions aimed at mitigating historical inequalities in access to environmental infrastructure. Such a pattern may reflect intentional inclusion initiatives, as discussed by Radonic and Zuniga-Teran (2023), who analyze rainwater harvesting incentive programs designed with racial and income equity criteria, promoting greater socio-environmental justice in segregated urban contexts.

In contrast, Figure 21C, which considers the White population, shows a concentration of High-High clusters in the northwestern part of the city. This indicates that, despite its presence in racialized sectors, this typology also maintains a footprint in areas traditionally associated with socioeconomic privilege, suggesting a mixed distribution pattern.

Figure 21D, related to the population below the poverty line, reveals a more limited pattern. Although a few High-High sectors are present, Low-Low and Low-High classifications predominate, particularly in the southern and southeastern regions. This suggests that, while this typology is associated with the Black population, it remains less common in sectors with a higher proportion of individuals in poverty. These findings align with those of Moses *et al.* (2022), who show how sociodemographic variables—including race and income—influence not only the distribution but also the perception and adoption of environmental technologies, such as rainwater harvesting infrastructure.

Finally, Figure 21E, which relates this typology to the median housing value, shows a concentrated High-High pattern in the city's northwest, signaling a coincidence between the presence of rainwater harvesting systems and areas with higher real estate value.

Figure 21. Bivariate analysis of LISA between rainwater harvesting BMPs and (A) VEDU; (B) VBLA; (C) VWHI; (D) VPOV; (E) VVAL[18]

6.4 FINAL CONSIDERATIONS

This study examined the spatial distribution of BMPs in relation to socioeconomic and demographic variables in Washington, D.C., highlighting key aspects related to environmental justice. The spatial analyses conducted—particularly through LISA—revealed spatial association patterns between different types of green infrastructure and indicators such as educational attainment, race, income, and housing value, partially confirming the socio-spatial inequalities already documented in the literature.

[18] As mentioned previously: VEDU: Percentage of the population aged 25 and over with a bachelor's degree or higher; VBLA: Percentage of population identifying as 'One race: Black or African American; VWHI: Percentage of population identifying as 'One race: White ; VPOV: Percentage of individuals whose income in the past 12 months was below the poverty level; VVAL: Median value of owner-occupied housing units (in U.S. dollars).

The results showed that, at a global level, there is a tendency for BMPs to concentrate in the northwestern and central areas of the city, where more favorable socioeconomic conditions prevail. These areas, characterized by higher education levels, greater property values, and a significant presence of White residents, are consistently associated with a higher incidence of sustainable practices, indicating the historical continuity of unequal access to environmental infrastructure. In this respect, bioretention and green roof typologies seem to reflect both technical and economic criteria and socio-spatial dynamics of historical exclusion.

However, typology-specific analyses revealed important nuances. Practices such as permeable pavements and rainwater harvesting displayed heterogeneous spatial patterns, with the presence of High-High clusters in areas of high racial vulnerability, particularly in the southeastern portion of the city. These results suggest evidence of targeted initiatives aimed at mitigating historical socio-environmental inequalities through these BMPs. Still, rainwater harvesting—despite reaching racialized areas—remains absent or underrepresented in zones marked by extreme economic vulnerability, indicating that socioeconomic barriers persist even when efforts are made toward racial inclusion.

Nonetheless, understanding inequality in the provision of green infrastructure is only part of the challenge in building more resilient cities. Urban sustainability also requires an understanding of how LULC changes influence hydrological dynamics and flood risks. While this chapter focused on the spatial distribution and correlations of BMPs, the next will delve deeper into the relationships between LULC and flood events. This analysis will offer a broader perspective on the processes that exacerbate Washington, D.C.'s flood vulnerability and underscore the importance of integrated strategies, in which both the implementation of BMPs and proper land use management become drivers of environmental justice and urban resilience.

7 HOW CHANGES IN LULC SHAPE FLOOD HAZARD IN WASHINGTON, D.C.: A SPATIAL ASSESSMENT

How are LULC changes shaping urban flood hazards and patterns, and what urban planning and stormwater management strategies can mitigate these hazards supported by future scenarios?

English

Building on the spatial diagnosis of infrastructural inequality in the previous chapter, Chapter 7 investigates how projected land use changes may intensify flood hazards in Washington, D.C.—linking urban form, hydrological vulnerability, and planning foresight. Using flood modeling combined with LULC simulations for the Hickey Run watershed, the chapter evaluates how different urban growth scenarios reshape the spatial distribution and severity of flood risks. The analysis reveals that even moderate increases in impervious surfaces can expand the area exposed to flooding, particularly in already vulnerable areas. This chapter reinforces the idea that urban resilience depends not only on existing infrastructure, but also on anticipating how development trajectories alter the city's relationship with water.

Portuguese

Com base no diagnóstico espacial da desigualdade infraestrutural do capítulo anterior, o Capítulo 7 investiga como as mudanças projetadas no uso do solo podem intensificar os riscos de inundações em Washington, D.C. — relacionando a forma urbana, a vulnerabilidade hidrológica e a previsão do planejamento. Utilizando modelagem de inundações combinada com simulações de LULC para a bacia hidrográfica de Hickey Run, o capítulo avalia como diferentes cenários de crescimento urbano remodelam a distribuição espacial e a gravidade dos riscos de inundação. A análise revela que mesmo aumentos moderados em superfícies impermeáveis podem expandir a área exposta a inundações, particularmente em áreas já vulneráveis. Este capítulo reforça a ideia de que a resiliência urbana depende não apenas da infraestrutura existente, mas também da antecipação de como as trajetórias de desenvolvimento alteram a relação da cidade com a água.

7.1 BACKGROUND

Throughout the urbanization process, the transformation in the LULC improves human living conditions and modifies the land surface environment. This increases the likelihood of urban flooding and modifies the natural hydrological cycle (Shrestha *et al.*, 2018). The problem of LULC changes and their impact on flooding events in urban watersheds is becoming increasingly relevant in light of climate change and accelerated urban expansion (Kabeja *et al.*, 2020). The relationship between LULC dynamics and extreme hydrological events requires research to develop effective strategies to mitigate negative impacts (Sertel *et al.*, 2019; Talib; Randhir, 2023).

Despite the historical tendency to treat urban flooding as an exclusively infrastructural challenge, solvable through engineering interventions, this approach is insufficient as it ignores the dynamics of LULC (Sahu; Bose; Samal, 2021). The need for effective land use planning that incorporates socio-economic and environmental considerations is therefore recognized, aiming to not only meet current needs but also prevent future disaster risks, thus fostering greater urban resilience and long-term sustainability (Burby *et al.*, 2000).

It has, therefore, become crucial to anticipate changes in LULC and assess their consequent effects on hydrology in the context of disaster risk management in urban areas and urban planning (Wagner *et al.*, 2019). Thanks to its efficiency, time-saving capacity, and flexibility, the InfoWorks Integrated Catchment Model (ICM)[19] has gained prominence in flood modeling and estimating hazards related to urban flooding (Ferguson; Fenner, 2020).

Cities, are global centers of socio-economic, financial, and industrial development, and with high population density, face hydrological changes resulting from urban land use, which makes them vulnerable to flooding (Pabi; Egyir; Attua, 2021; Puzyreva; de Vries, 2021). With climate change, the frequency of flood events and the number of communities at risk will likely increase. This leads to a deeper understanding that it is impossible to eliminate flooding completely and that traditional structural protection measures are insufficient to ensure the resilience of communities against these disasters (Puzyreva; de Vries, 2021).

Washington, DC, the capital of the United States, stands out as an emblematic case of the environmental problems faced by global urban centers due to its geographical location and urban development. Situated along the Potomac River, near its confluence with the Anacostia

[19] InfoWorks ICM is an advanced hydrological and hydraulic modeling software developed by Innovyze. InfoWorks ICM combines precipitation, topography, land use and infrastructure data to simulate stormwater and wastewater runoff, predict urban flooding, evaluate the performance of drainage systems and test solutions based on gray and green infrastructure.

River, the city is susceptible to various flood risks, including river flooding and sea level rise (Brandes, 2007). In this way, the city's vulnerability to flooding is exacerbated by extensive urbanization and the high rate of soil sealing. Therefore, understanding the risks associated with changes in land use in urban areas requires looking not only at the immediate impacts on surface runoff but also at the broader implications of these changes for sustainability and urban resilience (Ghalehteimouri; Ros; Rambat, 2023; Meyer *et al.*, 2013).

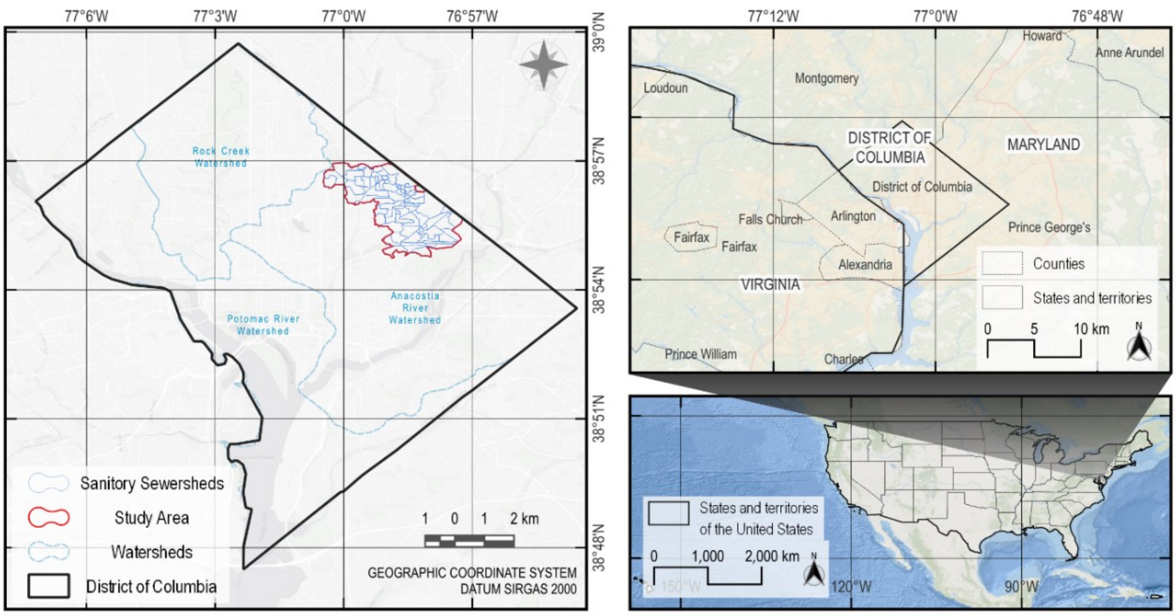
In this context, this study aims to analyze the hazards associated with urban waterlogging in an area located in Washington, DC, focusing on the influence of impervious, resulting from changes in the LULC, on the frequency and severity of these events. This analysis aims to identify current hazards and project future scenarios that are capable of contributing to the development of urban planning strategies that prioritize the mitigation of these disasters, thus promoting urban resilience and sustainability.

7.2 MATERIALS AND METHODS

7.2.1 Study area

The study area, Hickey Run, is a region in the Anacostia River basin in Washington D.C., encompassing 73 sanitary sewersheds (Figure 22). This region has a history of exposure to residential and commercial effluents, which results in a distinct aquatic microbiota (Cagle *et al.*, 2019; Wilson, 2020).

Figure 22. Hickey Run area in Washington D.C.



The study area is within the Anacostia River watershed, which has undergone several phases of transformation, from ecological degradation due to agriculture and industrialization to the current stage focused on restoration and green infrastructures. In this context, Arnold *et al.* (2018) address how current restoration activities are still influenced by the legacies of past regimes and the ongoing pressures of urban development.

The Hickey Run area can therefore be seen as an example of how urban development and human practices can influence the aquatic ecosystem from a biological, hydrological, and economic point of view (Raffensperger; Voronin; Dieter, 2021). The restoration and green infrastructure initiatives currently underway in the region aim to mitigate environmental impacts and promote the recovery of this area.

7.2.2 Overall workflow

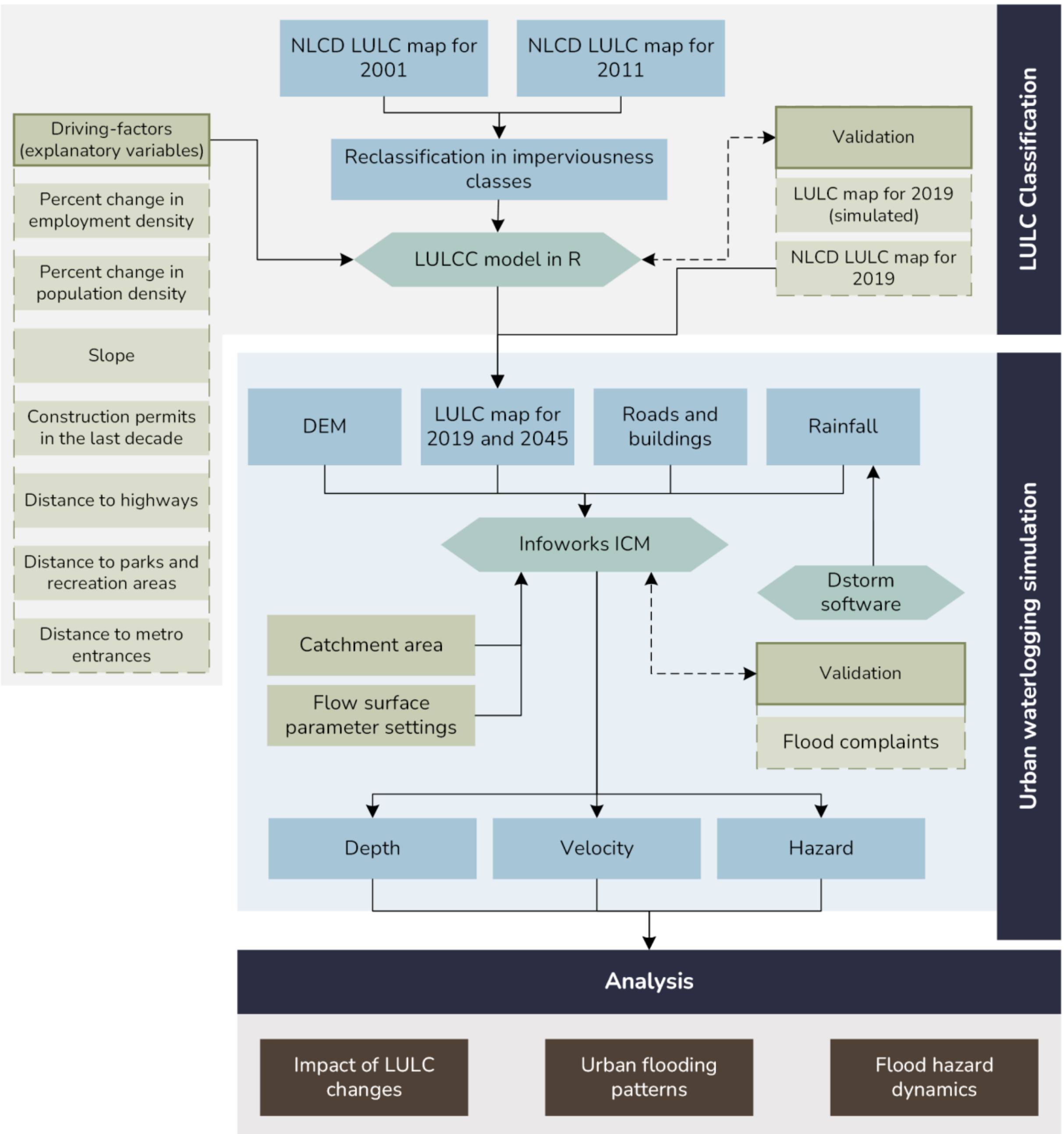
The methodological process (Figure 23) consisted of three main phases: Firstly, the LULC classification stage, in which impermeability images from the National Land Cover Database (NLCD)[20] were collected and reclassified. These images were then used to simulate future scenarios, integrating explanatory variables and LULC data into the LULCC model to project LULC for 2045.

The second phase involved simulating urban flood events, incorporating the LULC data for the years 2019 and 2045, information on precipitation, road infrastructure, buildings, and DEM data into the InfoWorks ICM software, in order to evaluate urban flood scenarios.

Finally, the third phase consisted of carrying out spatial analyses, drawing up flow diagrams, and quantifying the results acquired to examine the impacts of changes in the LULC, the changes in flood patterns caused by these variations, and the evolution of the flood hazard in the area studied.

[20] The National Land Cover Database (NLCD) is a standardized land cover dataset for the United States, developed by the U.S. Geological Survey. It provides wall-to-wall coverage of the country at a 30-meter resolution and was first released in 1992. The database includes a consistent classification of land cover types into categories such as developed land, forest, agriculture, wetlands, and water.

Figure 23. Overall workflow for the study



7.2.3 LULC classification

This study adopted an integrated methodological approach to assess the impacts of flood events in Washington, D.C., under different LULC scenarios. Initially, a survey was conducted on the Open Data DC platform to identify relevant explanatory variables for future LULC modeling. The selection was guided both by prior knowledge of the region's urban dynamics—particularly factors known to influence impervious surface expansion—and by the availability and consistency of spatial datasets. As a result, seven explanatory variables were chosen:

1. Percent change in employment density: calculated based on the variation between the density forecast for 2045 and the observed density for 2020;
2. Percent change in population density: calculated based on the variation between the population projection for 2045 and the observed population for 2020;
3. Slope: derived by DEM;
4. Construction permits in the last decade: prepared using a Geohash Density Map based on the sum of all permissions granted for construction between 2013 and 2023.
5. Distance to highways: calculated using Euclidean distance to highways;
6. Distance to parks and recreation areas: calculated using Euclidean distance from the union of data from national parks and recreation areas;
7. Distance to metro station entrances: calculated using Euclidean distance to metro entry points.

To improve the efficiency of processing time and ensure direct ranked between the data, the values of the explanatory variables were readjusted according to Table 10, as well as the minimum and maximum values identified for each variable. The slope variable was based on the USDA classification (Tsuchiya *et al.*, 2021). The other explanatory variables were ranked according to their assumed influence on the likelihood of impervious surface occurrence. In this scheme, lower scores represent a higher probability of imperviousness, while higher scores indicate lower likelihood.

It is important to acknowledge that this ranking process is not based on ground-truth measurements or empirical calibration, but rather on a conceptual framework that draws from prior research, urban planning logic, expert judgment, and policy guidelines. For example, proximity to roads or high concentrations of construction permits are typically associated with greater urban development pressure, justifying their lower ranks. Conversely, higher slopes or greater distances from infrastructure tend to constrain urbanization, thus receiving higher ranks. While this approach enhances the model’s interpretability and computational performance, it inherently involves subjective assumptions about urban growth dynamics and must be understood as a heuristic, not an absolute classification.

Unlike the previous chapter, the MOLUSCE plugin was not used in this stage due to limitations identified during preliminary tests. In a highly urbanized setting like Washington, DC, MOLUSCE struggled to adequately capture temporal variations in LULC transitions, particularly because available land for conversion is minimal and spatial dynamics are more constrained. Additionally, the LULC data used (NLCD) does not offer equal time intervals like Mapbiomas, with uneven year gaps (e.g., 2001, 2006, 2011, 2016, 2019), which made it impractical to define reliable past trends and simulate future scenarios within the MOLUSCE framework.

Table 10. Ranking of explanatory variables

Percent change in employment density and percent change in population density	
Percent	*Value*
≤ 25	5
25 to 50	4
50 to 75	3
75 to 100	2
> 100	1
Slope	
Degree	*Value*
≤ 2	1
2 to 5	2
5 to 8	3
8 to 17	4
17 to 24	5
24 to 33	6
> 33	7
Construction permits in the last decade	
Density	*Value*
≤ 40	5
40 to 80	4
80 to 120	3
120 to 160	2
> 160	1
Distance to highways, distance to parks and recreation areas, distance to metro entrances	
Distance (m)	*Value*
≤ 100	1
100 to 500	2
500 to 1000	3
1000 to 1500	4
> 1500	5

For the LULC classification, the "NLCD Imperviousness" product was used, considering that the study area was a consolidated urban environment with stable land use classes. The LULCC package[21] for modeling land use change in R follows a workflow in four main stages: preparation of raster data, generation of probability surfaces, allocation, and validation. The steps involve preparing observed land use data, modeling probability surfaces, and allocating land use changes based on projected demands. Specific tools and methods are used at each stage to facilitate the analysis and prediction of land use changes.

In addition, LULCC is a package that facilitates the analysis of land use change scenarios based on historical data and future projections without the need for identical time steps. To calibrate and validate the model, imperviousness data from the NLCD for 2001, 2011, and 2019 was used, and the percentages of imperviousness were divided into five classes, as

[21] The LULCC package was selected for simulating LULC changes instead of the MOLUSCE plugin in QGIS due to its methodological flexibility and compatibility with the data structure. A key factor in this choice was the LULCC package's ability to handle LULC datasets with unequal temporal intervals between classification years, a feature particularly relevant for the NLCD, which does not follow regular time steps across its editions.

shown in Table 11. Calibration was carried out with the 2001 and 2011 products, and validation with the 2019 product.

Table 11. Imperviousness classes

Imperviousness rate (%)	Class
0 to 20.00	1
20.01 to 40.00	2
40.01 to 60.00	3
60.01 to 80.00	4
80.01 to 100	5

The model's accuracy was assessed using the Producer and User accuracies (PA and UA, respectively) in the QGIS software. These are efficient indicators for assessing the accuracy of the model's classifications and the reliability of the information generated. Producer accuracy refers to the proportion of real observations of a class that the model correctly identifies, while consumer accuracy indicates the proportion of observations classified into a class that correctly represents that class in reality (Congalton; Green, 2019). Pontius and Millones (2011), for instance, argue for abandoning Kappa altogether in favor of more intuitive and informative measures such as PA and UA, which better support model refinement and transparency in landscape classification. These measures help to understand how simulations can be trusted to represent reality, allowing adjustments and improvements to classification models.

7.2.4 Urban waterlogging simulation

The next stage involved flood modeling using Infoworks ICM software, a modeling application for drainage systems developed by Innovyze ®, recognized for its effectiveness in analyzing and managing urban drainage systems and predicting urban flooding (Sidek *et al.*, 2021). This software can create detailed hydrology and hydraulics models for drainage networks, allowing accurate simulations of sewage systems, storm drains, combined drainage systems, and diffuse surface flows (Yang *et al.*, 2020). InfoWorks ICM enables surface flood simulations by integrating one-dimensional (1D) hydraulic models with two-dimensional (2D) flood models, where the 1D model details aspects such as the extent and depth of the water. In contrast, the 2D models use complex terrain geometry and dynamic calculations to enhance the analysis (Yang *et al.*, 2022).

For this study, the Chicago Rainfall type was used, calculated from NOAA data (2023) in the DStorm software (Rossman, 2022), the 2022 Digital Surface Model (DSM) generated with LiDAR, available on OpenDC, as well as LULC data. Due to computational limitations, the MDS, with an original resolution of 1 meter, was subjected to spatial aggregation to a resolution of 5 meters. At the same time, the LULC data was kept at its resolution of 30 meters.

The procedure adopted in InfoWorks ICM for simulating urban flooding involved several steps. Initially, the DSM was input in the software. Subsequently, urban structures and other physical barriers were incorporated into the model using geographical information. The next stage consisted of automatically generating a network of triangles to make estimating the depth and flow of water in each triangular element easier. As a result, the process made it possible to determine flood levels, overflow paths, and flow rates.

For a comprehensive analysis, 12 (twelve) flood scenarios were developed, incorporating current and future floodproofing under three rainfall events with different durations, as illustrated in Table 12. Thus, the scenarios explored the LULC for 2019 and 2045 and rainfall events with return times of 5, 25 and 100 years, with durations of 1 and 3 hours.

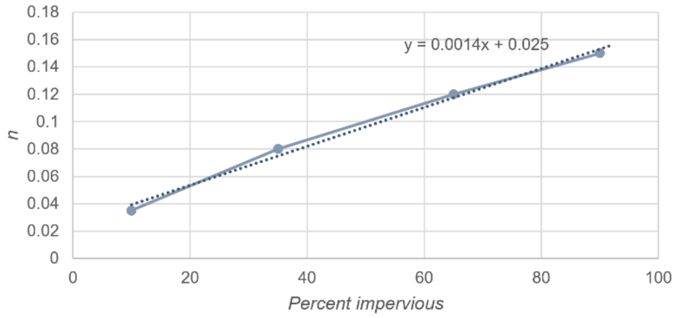
Table 12. Simulated flood scenarios

Return period (years)	Duration of rainfall (min)	Precipitation (mm)	Scenarios	
			Imperviousness data	
			2019	2045
5	60	47	1	2
	180	60	3	4
25	60	65	5	6
	180	84	7	8
100	60	81	9	10
	180	108	11	12

Also, in Infoworks ICM, Manning's roughness coefficient (n) was adapted according to the NLCD waterproofing classes based on the HEC-RAS 2D Manual (Brunner, 2021) and the USDA NRCS guidelines (Janssen, 2016), which present estimates for the coefficient for various LULC categories according to the NLCD classification. In addition, the HEC-RAS[22] 2D Manual and its associated examples provide recommended values for percent imperviousness for various NLCD land cover classifications. It was, therefore, possible to estimate the coefficient based on the percentage of waterproofing from a linear trend line, as illustrated in Figure 24.

[22] HEC-RAS, developed by the US Army Corps of Engineers, is software for hydraulic modeling of water flows in canals. Widely used in the US, it facilitates runoff analysis and flood simulations, supporting water resources planning and flood risk management. Its importance comes from its robustness and ability to integrate geospatial data, essential for hydraulic and environmental engineering.

Figure 24. Estimation of Manning's coefficient based on suggestions for NLCD land cover



Suggested Manning's n and Percent Impervious for NLCD Land Cover

Impervious (%)	*n*
10	0.035
35	0.08
65	0.12
90	0.15

The flood simulation process in InfoWorks ICM, after setting up the 2D simulation zone, involves applying hydrological and hydraulic data to model the behavior of water in rainfall scenarios. Initially, rainfall data is entered, specifying the rain's intensity, duration, and spatial distribution. The software uses this information to calculate the volume of water entering the system. Next, based on the topographical and physical characteristics of the modeled area, InfoWorks ICM simulates the movement of water over the surface, including infiltration processes, surface runoff, and interaction with urban structures. The modeling takes into account the resistance to flow offered by these obstacles, as well as the connections with existing drainage systems. The result is the generation of flood maps showing potentially affected areas, water depths, and flow velocities, thus providing a valuable tool for planning flood risk mitigation and management measures.

Due to the absence of detailed data, this study was unable to incorporate existing drainage infrastructure into the analysis. Specifically, the lack of precise information on drainage elements and pipes limited the ability to simulate the hydraulic behavior of the system accurately. However, it is essential to note that for the specific objectives of this research, which aim to analyze the behavior of flooding patterns resulting from LULC alterations, the integrity of the analysis was not compromised.

7.2.5 Hazard analysis

The methodology used to analyze the hazards associated with flooding adopted an integrated approach, mixing geoprocessing techniques and data obtained through hydrological flood modeling. Initially, the results of the flood simulations were compared using the map algebra technique to quantify two-dimensional differences between the areas analyzed.

The assessment of direct risks to the population exposed to flooding was measured using the DEFRA Index (HR Wallingford, 2006), shown in Equation 11, which was calculated for each scenario in Infoworks ICM. The index is a consolidated tool for assessing direct risks to people exposed to flood waters, considering both the physical conditions (depth and speed of the water) and the presence of debris, which can significantly increase the danger.

$$HR = d\ x\ (v + 0.5) + DF \qquad \text{Equation 11}$$

Where:

HR[23] = hazard rating (flood);

d = depth of flooding (m);

v = velocity of floodwaters (m/s);

DF = Debris Factor;

Where Debris Factor is assumed to be:

0.5 for depths < 0.25m

1.0 for depths > 0.25m

Once the HR is calculated for each pixel or area, the values are then classified into hazard bands (Low, Moderate, Significant or Extreme) using predefined thresholds. These classes follow this convention based on DEFRA guidance:

- Low (HR < 0.75): Caution;
- Moderate (0.75 ≤ HR < 1.25): Dangerous for some;
- Significant (1.25 ≤ HR < 2.5): Dangerous for most people;
- Extreme (HR ≥ 2.5): Dangerous for all;

The assessment of buildings located in flood hazard areas was done by applying zonal statistics in QGIS, using the shapefile of buildings made available by Open Data DC for 2022. To determine the number of health and education facilities in risk zones, a 50-meter buffer was established around the central point of each facility, followed by the execution of zonal statistics. Data on health and education facilities was compiled from a variety of sources, including Homeland Infrastructure Foundation-Level Data (HIFLD), Federal Emergency Management Agency (FEMA), Urgent Care Association of America, Healthcare Ready, Private School Survey, Common Core Data, Integrated Post Secondary Education System, and IMSL U.S. Public Library Administration Entities, through the HILFDL catalog (HIFLD, 2023).

[23] The Hazard Rating does not represent the probability of flooding, but rather the severity of danger to people once a flood occurs. It reflects physical hazard based on depth, velocity, and debris, and is used to classify the intensity of flood impacts.

7.2.6 Validation for the flood model

The flood model validation in this study adopted claims data to evaluate the accuracy of model predictions compared to actual flood observations. This method is particularly useful for a location where conventional flood data, such as satellite imagery or detailed mapping of flood events, is scarce or non-existent. Zischg *et al.* (2018) argue that conventional validation data (such as observed flooded areas) may not fully capture the complexity and specific impacts of flood events in urban environments, although complaints tend to provide a conservative view of flood impacts.

Therefore, to validate the flood model in this study, an approach was adopted that evaluates the accuracy of the results. Data was collected from flood complaints provided by DC Water between 2006 and 2024, totaling 585 records. These records were classified into six distinct groups:

- Group I (22 complaints): complaints about flooding without specifying exact causes;
- Group II (88 complaints): problems with urban drainage that contribute to flooding;
- Group III (209 complaints): contains a broader mix of complaints related to clogged culverts and flooding conditions;
- Group IV (24 complaints): Similar to Group I, these complaints also focus on clogged culverts, but with descriptions that may be a little more precise in terms of specificity or location;
- Group V (148 complaints): Includes requests to plumbers for assistance with water shut-offs or problems related to technical assistance and maintenance;
- Group VI (94 complaints): Emergency issues such as burst pipes that require water to be turned off;

Based on the characteristics of each group, groups V and VI were excluded from the analysis as they were not directly related to flooding due to rainfall events, resulting in 343 complaints. Scenario 5, which has characteristics more similar to the provided database, was used for validation, with a TR of 25 years, a duration of 1 hour, and LULC of 2019. It is worth noting that only flood areas with water depths equal to or greater than 0.15 meters were considered for analysis; this value was established based on Rentshler, Salhab and Jafino (2022) and Russo, Gómez and Macchione (2013).

For the performance analysis, the distances between the complaint locations and the centroids of the flood polygons were calculated using the Distance to nearest hub tool in QGIS. This measure aims to establish a geographical correlation between the floods reported and those predicted by the model in Scenario 5. In addition, the Jaccard Similarity Index (JSI) was calculated according to Equation 12, considering a buffer of 20 meters around the location of the complaint, to assess the overlap between the simulated flooding and observed complaints, providing a metric of how well the model can predict flooding compared to the reported flooding problems.

$$JSI = \frac{S_{sim} \cap S_{obs}}{S_{sim} \cup S_{obs}} \qquad \text{Equation 12}$$

Where S_{sim} corresponds to simulated flooding and S_{obs} to observed complaints.

7.3 RESULTS

Validation of the LULC simulation for 2019 revealed an overall accuracy of 95.81%, demonstrating the robustness and accuracy of the model despite the challenges inherent in working with inputs of different time scales and in predicting waterproofing in already consolidated urban areas, such as the Hickey Run region. This context adds a layer of complexity, given the subtlety and unpredictability of changes in land use classes, especially in the face of current government initiatives aimed at implementing SUDS, which reduce soil sealing (DDOT, 2020; DOEE, 2023; EPA, 2023). The details on PA and UA presented in Table 13 highlight the model's ability to navigate these complexities and produce consistent projections, reiterating the importance of this type of approach in anticipating and adapting to such environmental and political dynamics.

Table 13. LULC simulation accuracy metrics for 2019

Accuracy Metrics	**Imperviousness classes**				
	1	2	3	4	5
PA (%)	87.26	97.64	94.88	99.11	100.00
UA (%)	85.88	99.68	98.31	94.46	95.86

Analysis of the LULC simulations reveals patterns of variation in imperviousness throughout the region studied, as illustrated in Figure 25. There is a predominance of impermeable areas in the south, contrasting with a greater presence of permeable areas in the north, a phenomenon directly associated with the distribution of parks and recreational areas, shown in Figure 25F. The explanatory variables used in the simulation highlight the heterogeneity in the distribution of regional factors. Specifically, employment and population densities (Figures 25A and 25B) vary significantly, with the southern portion showing the greatest changes, influenced by the increased accessibility due to the proximity of highways and subway entrances (Figures 25E and 25G). Additionally, the area's terrain is characterized by a relief that varies from flat to moderately sloping, with only a few areas exhibiting steep slopes. In the last decade, most of the region's registered building permits are below 40, although there are contrasting areas where the number exceeds 160, reflecting the complexity and dynamism of urban development.

The flow diagram illustrating the evolution of the imperviousness classes between 2011 and 2045 captures the land-use transitions based on the NLCD data for 2011 and 2019 and the simulation for 2045. There is a notable decrease in the classes with the lowest levels of waterproofing, which saw a reduction of more than 50% over the period analyzed. At the same time, the classes with intermediate levels of imperviousness (between 20.01% and 80%) experienced an increase of more than 11% over the same period. On the other hand, the category with the highest levels of imperviousness (above 80.01%) saw a drop of more than 6%, an expected development given government policies to promote green infrastructure in the area. These patterns suggest a significant reconfiguration of the urban fabric, influenced by sustainability and urban planning initiatives that prioritize soil permeability and the integration of green spaces.

The performance analysis of the flooding model resulted in a JSI of 0.71, indicating significant agreement between the areas predicted by the model and the population's complaints. Additionally, the analysis of the distances between the complaints and the flooding events revealed that 88.4% of the complaints were located within 40 meters of the flooded areas, with an average distance of 20.37 meters and a maximum distance of 164.32 meters. Table 14 shows the results of the proximity analysis.

Figure 25. LULC data, simulation results, variation in imperviousness classes (Sankey diagram) and explanatory variables: A) Percent change in employment density; B) Percent change in population density; C) Slope; D) Construction permits in the last decade; E) Distance to highways; F) Distance to parks and recreation areas; G) Distance to metro entrances

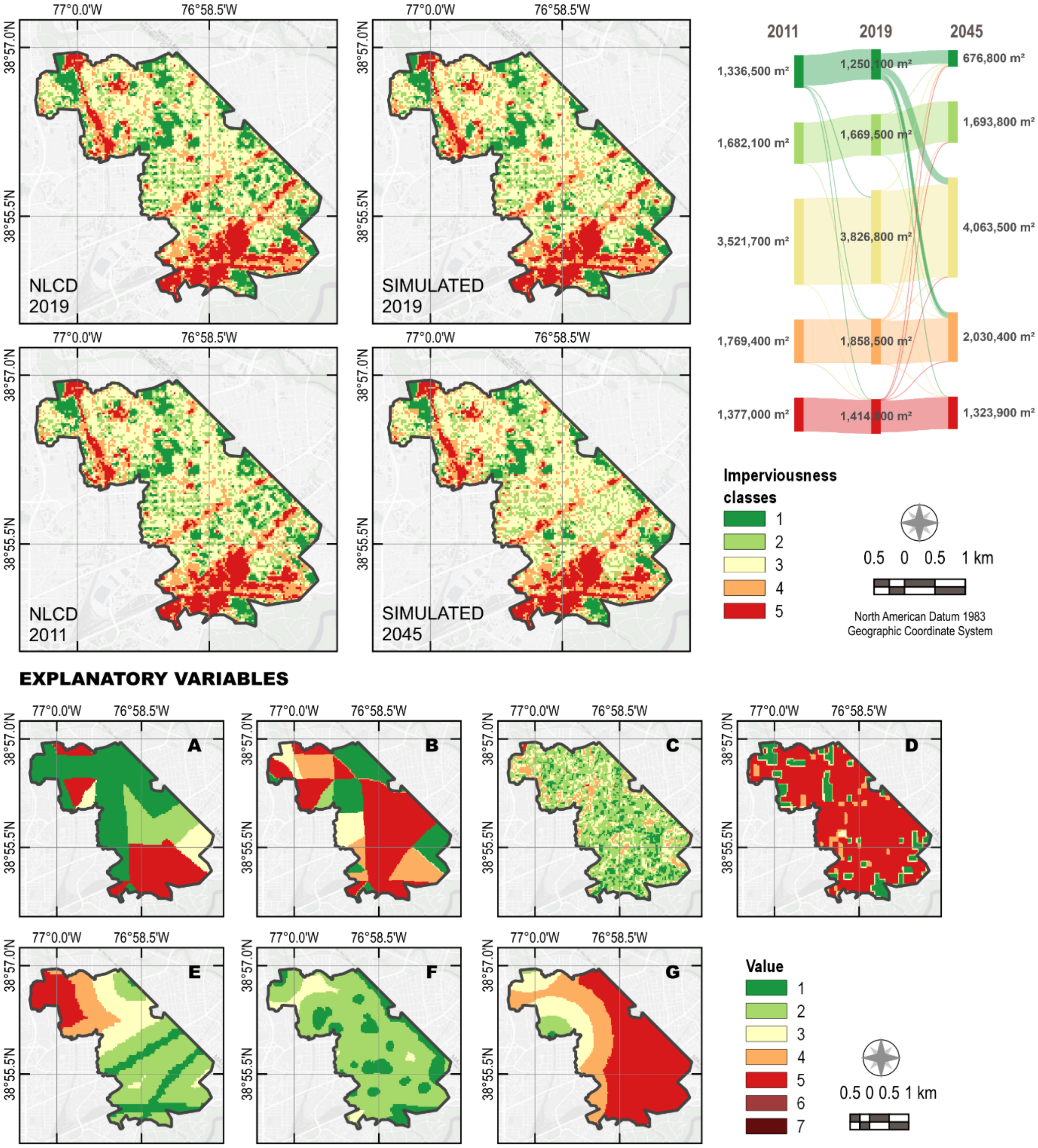


Table 14. Analysis of distance between flooding and complaints

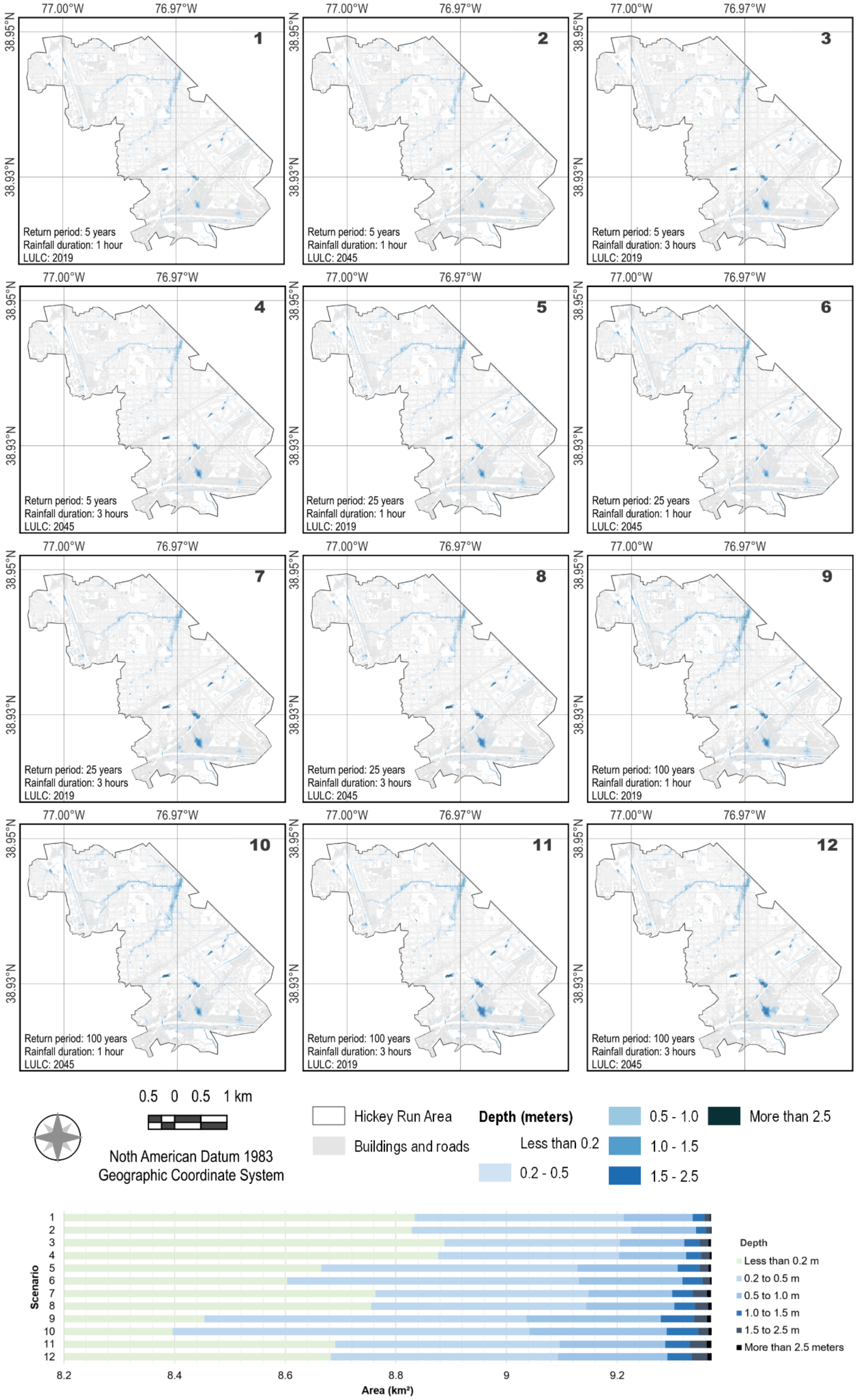
Distance to flooding (meters)	Number of complaints	Percentage
Less than 20	214	62.7%
20 to 40	88	25.7%
40 to 60	31	9.0%
60 to 80	3	1.2%
Greater than 80	7	1.7%

In the analysis of the 12 flooding scenarios derived from hydrological simulations (Figure 26), the results show variability in the consequences of rainfall events on flooding dynamics at different return times (5, 25, and 100 years) and rainfall durations (60 and 180 minutes), considering the different LULC configurations. Notably, scenarios 9 and 10, which correspond to 60-minute rainfalls with a return time of 100 years for both LULC scenarios, prove to be the most critical, manifesting the greatest water depths. This situation indicates increased vulnerability in the areas analyzed, especially under extreme rainfall conditions. The transition to the 2045 LULC scenario is projected to result in a slight reduction in flood depths. However, this reduction in severity is counterbalanced by the expansion of areas susceptible to flooding, a spatial transformation evidenced by Table 15. This phenomenon suggests that, although changes in the LULC may offer some relief in the intensity of floods, the expansion of the area of exposure to these events increases the hazard in previously unaffected areas.

Table 15. Statistical table with depth results

Year	Scenario	Return period (years)	Rainfall duration (min)	Max water depth (m)	Average water depth (m)	Area of water accumulation (km²)
2019	1	5	60	3.229	0.010	0.982
	5	25	60	3.514	0.010	1.232
	9	100	60	3.859	0.010	1.574
	3	5	180	3.537	0.012	0.822
	7	25	180	3.806	0.012	0.997
	11	100	180	3.897	0.013	1.105
2045	2	5	60	3.272	0.013	1.059
	6	25	60	3.326	0.013	1.482
	10	100	60	3.727	0.012	1.869
	4	5	180	3.536	0.011	0.837
	8	25	180	3.806	0.012	1.012
	12	100	180	3.896	0.012	1.117
2045 -2019	-	5	60	0.043	0.003	0.077
	-	25	60	-0.188	0.002	0.250
	-	100	60	-0.132	0.002	0.295
	-	5	180	-0.001	0.000	0.016
	-	25	180	0.000	0.000	0.015
	-	100	180	-0.001	0.000	0.013

Figure 26. Urban flooding scenarios for 2019 and 2045



Analysis of the spatial distribution of flooding in the region under study reveals a predisposition to more severe events in the north and southeast, outlining a geography of vulnerability. Specifically, in the north, the regions surrounding Upshur St NE, Michigan Ave NE, and 20th St NE, and in the southeast, areas adjacent to New York Ave NE, 25th Pl NE, and Evarts St NE emerge as critical zones. Observing the simulated scenarios indicates that scenario 11 shows the greatest recorded water depth. In contrast, scenario 10 shows the greatest extent of surface water accumulation, highlighting the variability of hydrological responses to modeled rainfall conditions.

A turning point in this study is the comparison between scenarios 9 and 10, which differ exclusively in LULC parameters, revealing a 18.7% increase in the extent of areas susceptible to water accumulation under the 2045 scenario. This data reinforces the narrative that changes in the landscape, including urbanization and vegetation, can exacerbate the risks of flooding, increasing the severity and scope of flood events. This analysis is in line with previous studies, such as those by Zhou *et al.* (2012), which demonstrates the significant influence of LULC modifications on surface runoff and water accumulation volumes, as well as the research by Smith *et al.* (2017), which underlines the importance of considering LULC transformations in flood hazard modeling.

The DEFRA index, which considers the depth of the water table and the flow speed, shows that the areas most susceptible to hazards are often located where the accumulation of water is most significant. Thus, by organizing the results of the flood hazard analyses according to different return times, one can observe distinct patterns in the spatial distribution of the associated risks.

Specifically, for the 5-year return period, Figure 27 highlights the zones of greatest hazard to the population, revealing important nuances in flooding dynamics. For rainfall events lasting 60 minutes, there is a noticeable upward trend in the “low”, “moderate” and “significant” hazard categories. In contrast, the “extreme” category shows a marked reduction, exceeding 57% when analyzing the LULC between 2019 and 2045. This decrease in the highest hazard class suggests a possible change in characteristics in the region. On the other hand, for 180-minute rainfall, there is a decrease in the “low” and “extreme” hazard categories, while the “moderate” and “significant” categories show an increase. This behavior indicates a redistribution of hazard levels, reflecting how different durations of rainfall events impact the severity and extent of flooding.

Figure 27. Flood hazard degrees with a 5-year return period

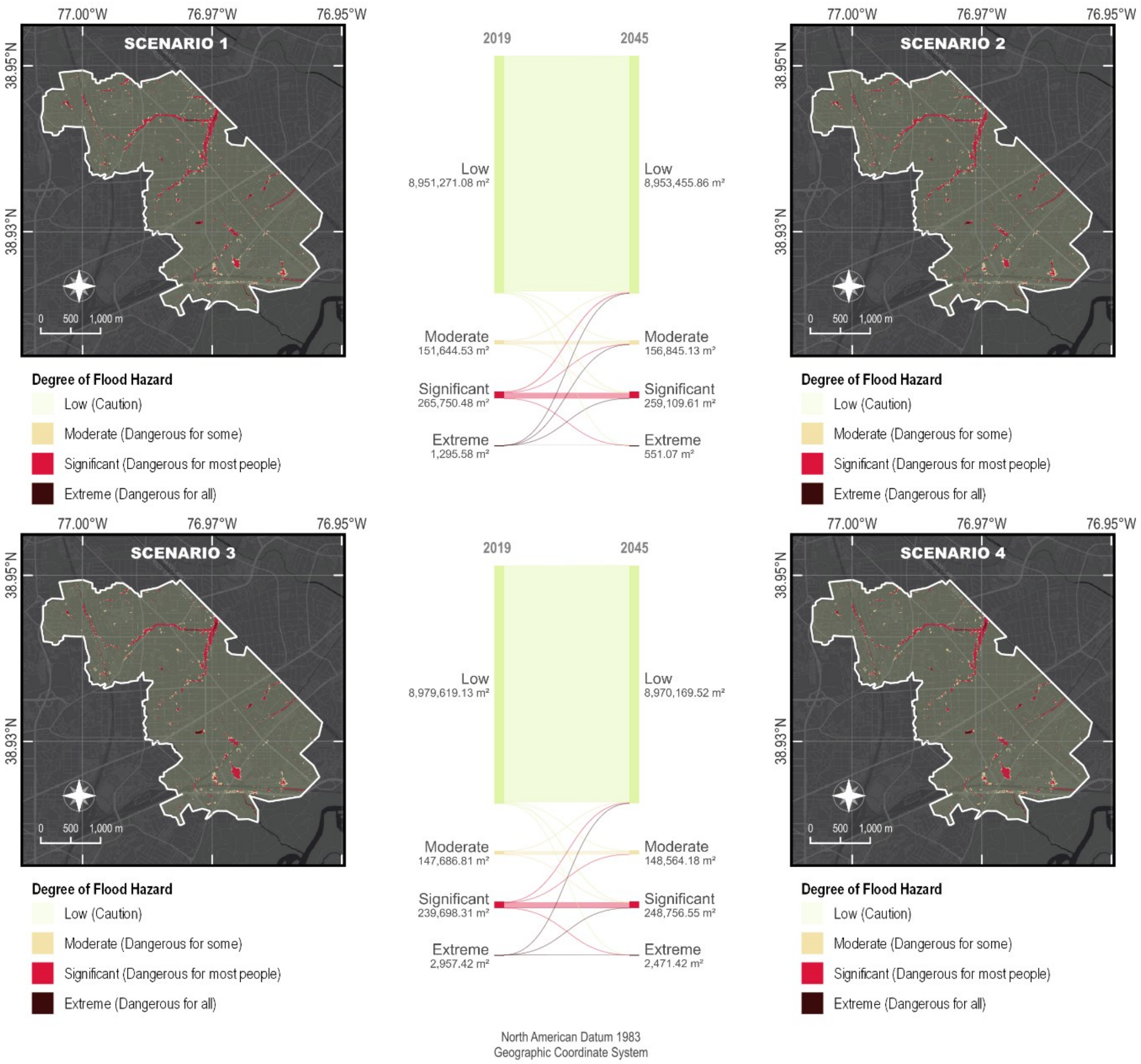
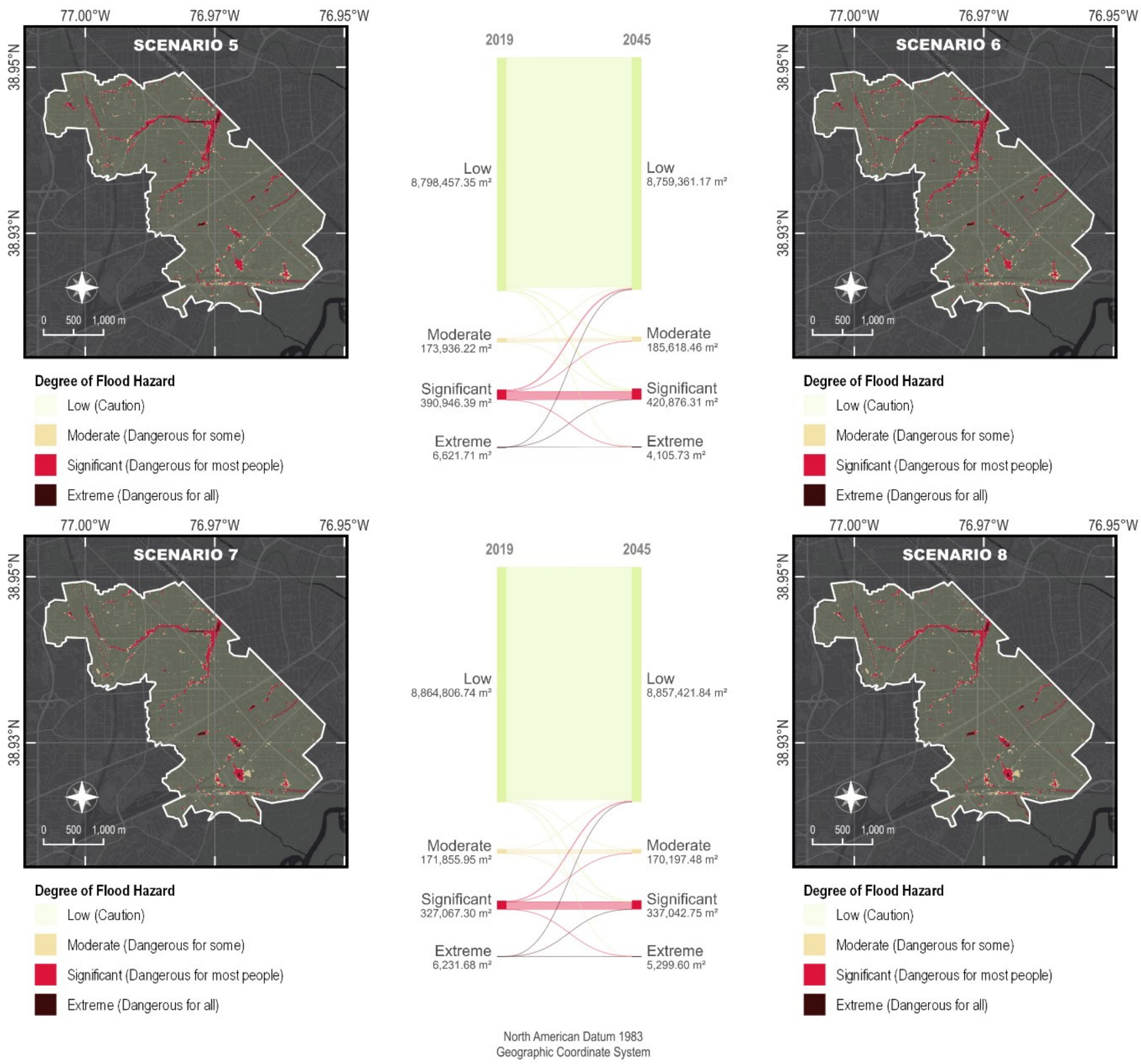


Figure 28 shows the projected scenarios for rainfall events with a return time of 25 years. These scenarios reveal a significant increase in the areas categorized as "moderate", "significant" and "extreme" hazard, with an approximate increase of 95,000 m² compared to the scenarios corresponding to rainfall events with a return time of 5 years. This increase in the highest risk classes suggests an escalation in vulnerability and exposure to hydrological risks in regions previously identified as susceptible. Notably, the northwest and southeast areas show an intensification in the degree of risk, pointing to a more pronounced and expanded spatial distribution of risk areas compared to previous scenarios.

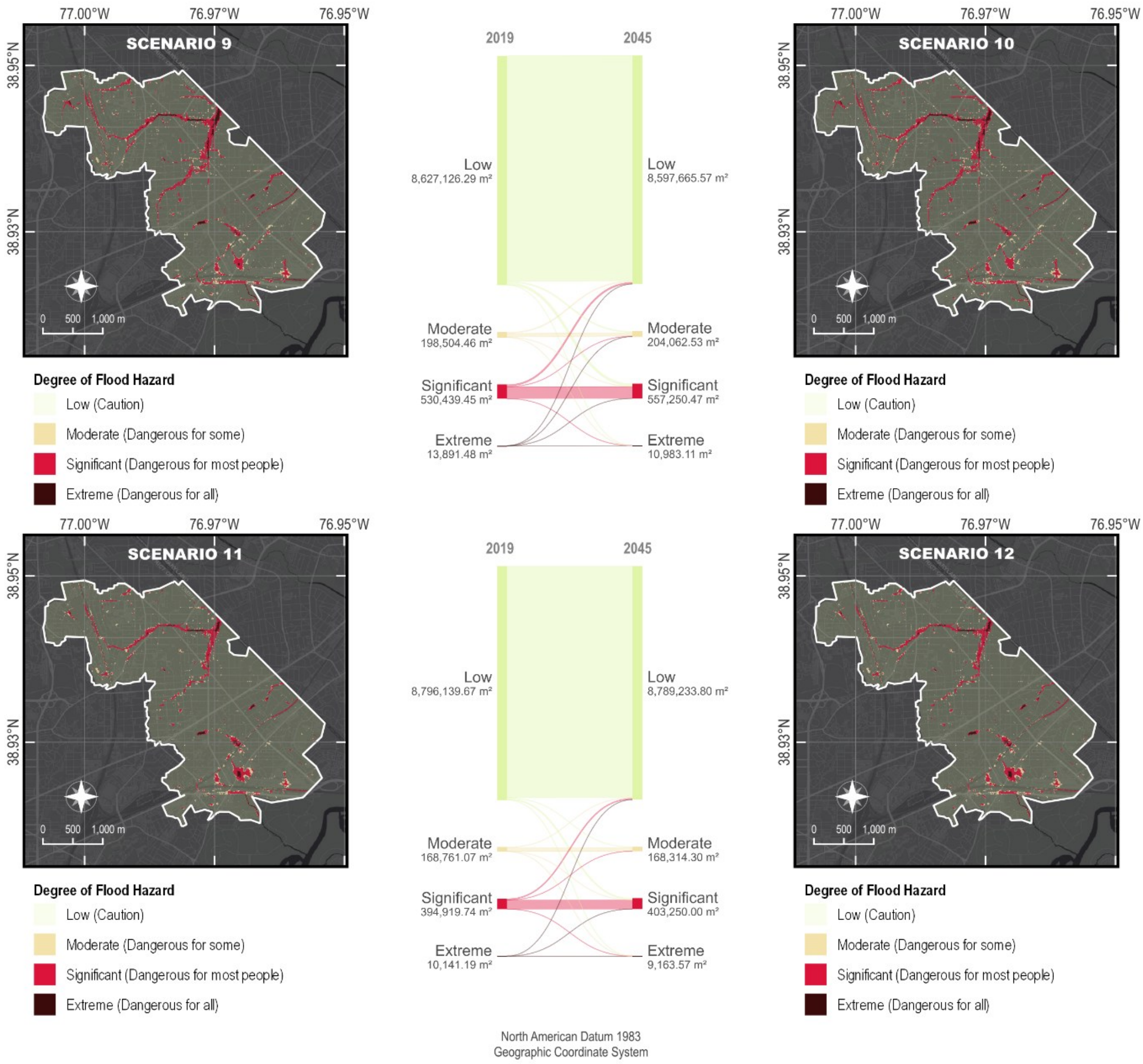
An analysis of the distribution of risk categories in each scenario indicates a reduction in the "low" and "extreme" classes, while there is a notable increase in the "significant" classification. This phenomenon can be interpreted as a transition from lower and extreme risk areas to more moderate but still significant risk categories. This dynamic shows a redistribution of risk levels in response to urban development.

Figure 28. Flood hazard degrees with a 25-year return period



The analysis of the scenarios focused on flood events with a return time of 100 years (Figure 29) sheds light on the issue of the increase in the danger of flooding under the direct influence of soil sealing. Specifically, the comparison between the scenarios that contemplate 1-hour rainfall shows a notable increase in the areas exposed to flood hazards, especially under the sealing projections for the year 2045. There is a significant reduction in the areas categorized as low danger, decreasing by around 30,000 m² between scenarios 3 and 9, and a worrying increase of more than 26,000 km² in the zones classified as significant danger. The spatial distribution of the data suggests not only an expansion of areas previously recognized as vulnerable but also the emergence of new territories at risk, extending the boundaries of susceptibility to flooding.

Figure 29. Flood hazard degrees with a 100-year return period



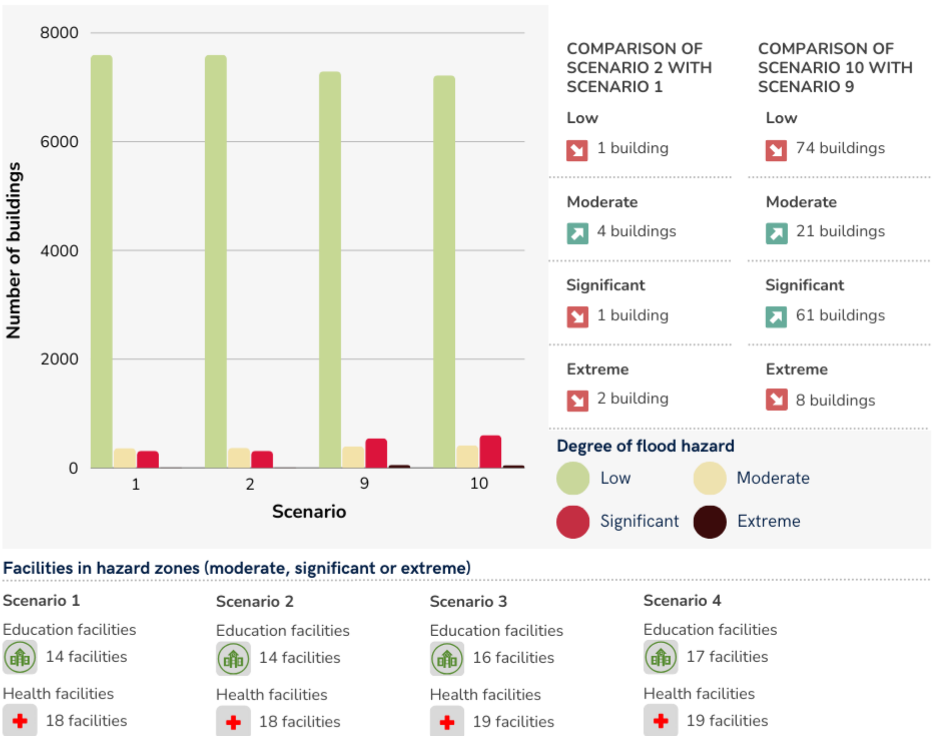
7.4 DISCUSSION

Incorporating the spatiality of LULC into hydrological models represents an important step towards increasing the accuracy and relevance of flood forecasts and water management. Unlike many models based only on general proportions of different LULC classes, ignoring their spatial distribution, this simplification can result in significant inaccuracies when simulating complex hydrological processes, especially in urban contexts. The spatial arrangement of LULC classes directly influences hydrological connections in the area, establishing corridors and barriers that modify the course of water and the spread of pollutants.

Thus, models that take into account the spatial distribution of LULC classes provide a more solid foundation for modeling water dynamics in the landscape, offering more accurate predictions about the impact of LULC changes on water resources (Hasanuzzaman *et al.*, 2022; Yang *et al.*, 2022).

Figure 30 highlights the quantitative changes resulting from the alteration of the LULC in the area studied. The comparative analysis between different scenarios exposed to the same rainfall event and duration clearly illustrates the impact of changes in the LULC on the risk of flooding. Between scenarios 2 and 1, there is an increase in the "moderate" hazard degree. At the same time, the other classes show a reduction. In this comparison, there is no change in the number of educational and health facilities in the most vulnerable areas. In the comparison between scenarios 10 and 9, there is a noticeable decrease in the number of buildings in low-hazard areas and an increase in the "significant" hazard degree, highlighting a scenario where an educational institution is now located in an area of greater hazard. These findings align with research by Zope; Eldho and Jothiprakash (2016), where the considerable increase in built-up area and a reduction in open spaces resulted in an increase in the flood area and the danger associated with flood events.

Figure 30. Degree of flood hazard of buildings located in the study area



The results of the flooding scenarios, considering LULC variations between 2019 and 2045, open a window to understanding the environmental and urban dynamics that influence water resource management and flood risk. The forecast decrease in areas with a high degree of waterproofing (greater than 80%) suggests a positive trend in mitigating extreme flood hazard classes. This phenomenon can be interpreted as the result of urban planning and environmental management policies that favor soil permeability, such as implementing urban green areas and promoting nature-based solutions.

In the context of urban development and stormwater management practices in this region, it is important to consider the influence of government initiatives and sustainability policies on land use dynamics and flood risk mitigation. Initiatives such as green infrastructure and programs like RiverSmart Homes represent a significant step in reducing soil sealing, which is essential for improving water quality in the Hickey Run watershed (DOEE, 2004). These measures promote water infiltration, reduce surface runoff, and improve the capacity of urban ecosystems to respond to extreme rainfall events, thus contributing to urban resilience to flooding (Fletcher *et al.*, 2015).

However, the trend towards a general increase in waterproofing in the study area brings up the debate about the consequences of urban planning that can lead to one-off measures that do not benefit the entire population. Thus, the possible decrease in the classification of low-hazard areas results in higher runoff rates, accelerating peak runoff, and increasing discharge during heavy rainfall events, contributing to worsening floods (Brooks; Ffolliott; Magner, 2012).

Therefore, integrating nature-based solutions into urban planning, such as creating green areas, preserving natural ecosystems, and implementing green infrastructure, is key to increasing urban resilience to climate change and flood risks (Meerow; Newell, 2019; Zevenbergen *et al.*, 2008). On the other hand, energy and sustainability policies, as outlined in the "Clean Energy DC" plan, which promote renewable energy and energy efficiency practices, can have a significant impact on reducing the carbon footprint of cities and, indirectly, on sustainable land use management and mitigating flood risks by promoting more compact developments integrated with green infrastructure (DOEE, 2018; Pamukcu-Albers *et al.*, 2021; Ramyar; Ackerman; Johnston, 2021).

7.5 FINAL CONSIDERATIONS

Based on the results obtained through the analysis of the scenarios resulting from the study's hydrological simulation, the research highlights the interaction between changes in

LULC and the increase in urban flood hazards. It was shown that the increase in sealing resulting from urban expansion significantly influences urban hydrodynamics, increasing the vulnerability of urban areas to extreme precipitation events.

The LULC simulation model used demonstrated high forecast accuracy for the region, reflecting the robustness and reliability of the model despite the complexities inherent in working with inputs from different time scales and in predicting imperviousness in consolidated urban areas, such as Hickey Run. The overall classification accuracy reached 95.81%, reiterating the importance of this approach in anticipating and adapting to environmental and political dynamics.

Analyzing flooded areas and risk zones in Washington D.C. revealed a trend towards greater distribution in areas with intense urbanization and high imperviousness. The study predicts that, with the continuation of current LULC trends, urban flooding in 2045 could be more widespread, affecting previously unimpacted areas due to the expansion of the exposure area. Future research should also explore how projected changes in precipitation patterns driven by climate change could affect urban flood hazards, particularly when combined with land use transformations.

In this context, implementing nature-based solutions and green infrastructure emerge as a promising strategy to mitigate flood hazards and promote urban resilience and sustainability. Thus, it becomes imperative that government initiatives and public policies adopt a proactive and equitable stance, adhering to green infrastructure measures and fostering urban governance that balances spatial planning, disaster risk management, and sustainability. Initiatives such as "RiverSmart Homes" illustrate the potential of integrated policies in promoting sustainable practices and mitigating flood risks, serving as a model for future initiatives.

In view of the challenges identified in this study, it is clear that there is a need to integrate more detailed analysis of drainage infrastructure and dynamic climate models to assess urban flood risks under various climate scenarios. This gap in current research serves as a starting point for the next chapter, which will focus on exploring stormwater management and green infrastructure strategies not only for risk mitigation, but also for promoting environmental justice by exploring how such practices can be implemented equitably in different urban communities.

8 INTEGRATING SUDS AND FLOOD HAZARD ASSESSMENT IN WASHINGTON, D.C.: IMPLICATIONS FOR ENVIRONMENTAL JUSTICE IN URBAN SCENARIOS

How do SUDS contribute to mitigating flooding impacts while promoting environmental justice and providing social and environmental benefits?

English

Following the projection of future flood hazards in the previous chapter, Chapter 8 evaluates whether nature-based solutions—specifically SUDS—can mitigate these hazards under varying urban development conditions. By incorporating real SUDS infrastructure into the existing hydrodynamic models for the Hickey Run watershed, the chapter assesses how these interventions influence flood volume and hazard distribution in both present (2019) and projected (2045) LULC scenarios. The results indicate that while SUDS offer meaningful reductions in localized flooding under current conditions, their effectiveness diminishes in highly impervious future landscapes. More critically, the simulations reveal that without equity-centered planning, SUDS may unintentionally shift flood risk to other areas—raising important questions about justice, scale, and long-term resilience in climate adaptation strategies.

Portuguese

Após a projeção de riscos futuros de inundações no capítulo anterior, o Capítulo 8 avalia se soluções baseadas na natureza – especificamente SUDS – podem mitigar esses riscos em diferentes condições de desenvolvimento urbano. Ao incorporar a infraestrutura real de SUDS aos modelos hidrodinâmicos existentes para a bacia hidrográfica de Hickey Run, o capítulo avalia como essas intervenções influenciam o volume de inundações e a distribuição de riscos nos cenários de LULC atuais (2019) e projetados (2045). Os resultados indicam que, embora os SUDS ofereçam reduções significativas em inundações localizadas nas condições atuais, sua eficácia diminui em paisagens futuras altamente impermeáveis. Mais criticamente, as simulações revelam que, sem um planejamento centrado na equidade, os SUDS podem transferir involuntariamente o risco de inundações para outras áreas — levantando questões importantes sobre justiça, escala e resiliência a longo prazo em estratégias de adaptação climática.

8.1 BACKGROUND

Flooding represents one of the most significant challenges associated with managing urban areas, often exacerbated by LULC changes accompanying urbanization (Das; Esraz-Ul-Zannat, 2022). In this scenario, SUDS emerge as a viable alternative to mitigate these impacts by promoting rainwater infiltration, storage, evaporation and beneficial use (Chapman; Hall, 2021). By integrating stormwater management strategies that represent natural processes, SUDS can reduce the likelihood of flooding events and contribute to the creation of greener, more resilient, and sustainable urban spaces.

Over the past decade, Washington D.C. has integrated SUDS such as rain gardens, permeable sidewalks, green roofs, and bioretention to mitigate runoff and improve urban water management (DDOT, 2020; DOEE, 2023; EPA, 2023). These measures seek not only to reduce the volume and speed of surface runoff but also to promote biodiversity and the aesthetics of the urban landscape.

In this context, SUDS transcend stormwater management, entering the territory of environmental justice, especially in consolidated and developed urban regions such as Washington D.C. (Nóblega Carriquiry; Sauri; March, 2020). By integrating SUDS into the urban fabric, cities can address socio-environmental inequalities by creating accessible green spaces and improving the quality of life in historically marginalized neighborhoods (Ferrans *et al.*, 2022). These water management practices mitigate the risks of urban flooding and offer collateral benefits such as reducing the heat island effect, increasing biodiversity, and promoting recreational spaces essential for community well-being (La Rosa; Pappalardo, 2020).

However, implementing SUDS in urban areas faces challenges related to existing infrastructure and socio-economic dynamics. In regions like Washington D.C., where space for new development is limited, the integration of SUDS requires solutions that integrate these measures with an already built environment, such as green roofs on existing buildings or permeable sidewalks in public areas (Oladunjoye; Proverbs; Xiao, 2022). These solutions require significant investment and a collaborative approach between governments, the community, and the private sector. Furthermore, such initiatives must be distributed fairly across the city, ensuring that low-income communities and disadvantaged areas also benefit from SUDS's environmental and social improvements.

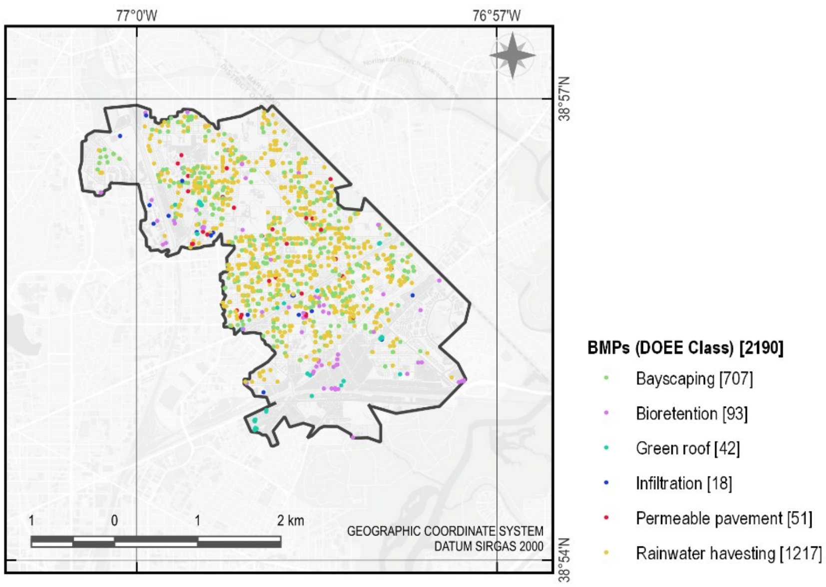
Therefore, in order to effectively contribute to environmental justice, the implementation of SUDS must transcend the technical aspects of water management, also encompassing the social and economic context through participatory planning that includes local communities (Chen *et al.*, 2021; Cotterill; Bracken, 2020). This approach makes it possible to redefine the relationship between consolidated urban areas, such as Washington D.C., and their water resources, promoting more equitable and sustainable water management and strengthening urban resilience in the face of climate change. Thus, this chapter aims to investigate, how SUDS can mitigate the impacts of flooding in Washington D.C., and equitably provide social and environmental benefits.

8.2 MATERIALS AND METHODS

This study extends the methodological framework of the previous analysis by integrating SUDS into the flood simulations conducted with Infoworks ICM for the Hickey Run area in Washington, D.C. The objective was to evaluate how SUDS practices influence urban flood dynamics and promote environmental justice by potentially reducing flood hazards in vulnerable communities.

Initially, the BMP data used in Chapter 6 were used to identify existing SUDS structures in the study area. Among the 95,763 BMPs cataloged for Washington D.C (Figure 31), only those supported for inclusion in Infoworks ICM were evaluated. Thus, the following typologies were included in the simulation: bioretention, bayscaping, green roof, infiltration, permeable pavement and rainwater collection, totaling 2,190 elements. These structures were associated with specific DOEE classes and mapped to corresponding Infoworks classes.

Figure 31. Types and quantities of BMPs present in the Hickey Run region



8.2.1 Data preparation and parameterization

Since the original SUDS dataset provided by DOEE was point-based, circular buffers were generated to approximate each element's actual surface area, based on the attribute table. To calculate the storage depth, the available storage volume was divided by the corresponding surface area. When the surface area was not explicitly available, it was estimated from the buffer geometry. For berm height estimation, was used the retention volume, assuming it encompasses the storage volume. Thus, berm height was derived by subtracting the storage volume from the retention volume and dividing the resulting surface retention by the surface area. In cases where this calculation produced negative values—suggesting inconsistencies or oversights in the data—those values were standardized to zero to ensure coherence in the modeling inputs.

Manning roughness coefficients (n) were assigned according to standard values referenced in previous research and technical guidelines, as presented in Table 16. Specifically, bioretention cells, rain gardens, infiltration swales, and rain barrels were assigned a coefficient of 0.1, permeable pavement was set at 0.015, and green roofs were assigned a value of 0.06, based on previous studies validated in similar urban contexts (Understanding the NEEDS for ACTING: An integrated framework for applying nature-based solutions in BrazilAlves; Djordjević; Javadi, 2022). Parameters for Infoworks not explicitly provided in the BMP attributes were estimated based on the constructive indications provided by the DOEE Stormwater Management Guidebook (DOEE, 2020).

Table 16. Associations and Manning coefficient for different types of BMP analyzed

Infoworks ICM Class	DOEE Class	Manning roughness coefficients
Bio-retention cell	Bioretention	0.1
Rain garden	Bayscaping	0.1
Green roof	Green Roof	0.06
Infiltration trench	Infiltration	0.1
Permeable pavement	Permeable Pavement	0.015
Rain barrel	Rainwater Harvesting	0.1

8.2.2 Implementation of SUDS in Infoworks ICM

The prepared spatial dataset of SUDS was then integrated into Infoworks ICM to simulate the potential impacts of these systems under various rainfall scenarios and urban configurations. Each SUDS feature was parameterized based on the specific hydraulic properties outlined above, ensuring accurate simulation of infiltration, storage, and flow attenuation processes. Additional attributes, such as the vegetation volume fraction and impervious fraction, were calculated to refine the representation of land cover change due to the implementation of SUDS. The vegetation fraction was determined by summing compacted, designed, and natural areas divided by the total impermeable area (available by DOEE). The impervious fraction was derived from dividing the impermeable area by the total contributing area. Fractions initially calculated as zero were revised to either one minus the impervious fraction or assigned a default value of 0.5 to represent realistic conditions.

The scenarios modeled in this study expanded 6 of the 12 previous urban flooding scenarios by including SUDS installations, allowing a direct comparison of flood risk mitigation before and after SUDS implementation. The simulations considered rainfall events with return periods of 5, 25 and 100 years, lasting 180 minutes, using the Chicago rainfall distribution type previously defined based on NOAA data. This longer duration was selected because extended rainfall events are more likely to saturate soils and overwhelm drainage systems, representing critical conditions under which SUDS performance is most relevant for flood attenuation (Archer *et al.*, 2020; Funke; Kleidorfer, 2024). One limitation of this approach is that the future scenarios did not account for the installation of new SUDS in the region, potentially underestimating the long-term benefits of expanded green infrastructure.

8.2.3 Evaluation metrics

The flood scenario assessment was carried out using the R programming environment, leveraging the *sf*[24], *data.table*[25], and *openxlsx*[26] libraries. The initial step involved reading two shapefiles representing the scenarios with and without SUDS. After correcting potential geometry inconsistencies, the layers were transformed into the same geographic coordinate reference system (CRS), when necessary, to standardize the analysis.

The next step involved performing an intersection operation to ensure an exact spatial overlay of the polygons from both scenarios. This stage aimed to prevent inconsistencies in the delineation of areas where flood overlap effectively occurred. Based on the intersection results, it was possible to calculate the water volume by multiplying the flood depth by the corresponding geometric area. In this way, each resulting polygon was assigned a volume corresponding to the without-SUDS and with-SUDS scenarios.

Based on the volume difference, the polygons were categorized into three classes: increase, reduction, or no change in flood volume, applying a numerical tolerance to disregard

[24] This package provides support for handling and analyzing spatial vector data in R.
[25] A high-performance package for fast and memory-efficient manipulation of large data sets. It's especially useful for big data analysis and reproducible workflows.
[26] This package is used to read, write, and format Excel .xlsx files without requiring external dependencies like Java.

minimal irrelevant variations. To enable the processing of a large number of polygons (approximately 239,000), the data were converted into a table, allowing for more efficient operations in R.

To quantify the impact of each class, the total volumes and areas were summed for polygons showing increase, reduction, or no change, resulting in global comparison metrics between the scenarios. Additionally, a hazard assessment was incorporated using the DEFRA Index classification (Low, Moderate, Significant and Extreme), according to each polygon's attribute values. This criterion allowed the measurement of area transitions to higher or lower risk classes when comparing the without-SUDS to the with-SUDS scenario. For this purpose, a numerical index was assigned to each hazard class, and the difference between the indices of the two scenarios indicated the direction of change (reduction, increase, or stability).

Given the large number of polygons, detailed visual representation in maps was not prioritized, as displaying 239 thousand elements simultaneously would result in excessive overlap and hinder cartographic interpretation. Instead, the approach focused on compiling consolidated statistics into tables. Finally, the results were organized into a single Excel spreadsheet, including total volume metrics, total area, and changes in hazard classes, with dedicated tabs to ensure better accessibility and documentation.

8.3 RESULTS AND DISCUSSION

The results obtained present the main findings of the hydrological simulations with and without the implementation of SUDS in the Hickey Run watershed, in Washington, D.C. The analyses encompass variations in flood area and volume, changes in hazard classes associated with different scenarios, and projections for the years 2019 and 2045. By integrating quantitative and spatial aspects, the results allow for an assessment of the effectiveness of the interventions in flood mitigation and their socio-environmental implications.

8.3.1 Flood scenarios

Table 17 below presents the consolidated results of the flood areas and volumes that increased or decreased as a result of the adoption of SUDS, under the 2019 and 2045 scenarios, considering different return periods.

Table 17. Comparison of flood areas and volumes with SUDS considering the LULC of 2019 and 2045

LULC Year	Return period (years)	Rainfall duration (min)	Total area that decreased water depth (m^2)	Total area that increased water depth (m^2)	Total area difference (m^2)	Reduced volume (m^3)	Increased volume (m^3)	Volume difference (m^3)
2019	5	180	41815.8	48775.8	-6960.1	231.0	197.8	33.2
	25	180	58027.5	58013.8	13.7	290.5	221.5	69.0
	100	180	67739.8	59459.4	8280.4	325.3	233.8	91.6
2045	5	180	0	0	0	0	0	0
	25	180	0	0	0	0	0	0
	100	180	0	0	0	0	0	0

In the comparison between scenarios with and without SUDS for 2019, both areas where the flood depth decreased and areas where it increased after the adoption of sustainable solutions can be observed. However, the volume columns show that, in all listed cases (5-, 25-, and 100-year return periods with 180-minute duration), the final volume balance (difference between increased and decreased volume) is positive, indicating that when summing all computational polygons where water depth decreased, the reduced volume exceeds the increased volume.

For example, in the 5-year, 180-minute event, there are approximately 41,816 m^2 where the flood depth decreased and 48,776 m^2 where it increased, resulting in a negative area difference (-6,960 m^2). Still, the total reduced volume with SUDS (231.0 m^3) exceeds the increased volume (197.8 m^3), yielding a net reduction of about 33.2 m^3. This behavior suggests that although there are more polygons (or a larger area) with increased water depth, the depth increment in each is generally shallow, whereas the depth reduction in other zones is sufficient to yield a favorable net volumetric gain from the use of SUDS.

A similar trend is observed in the 25- and 100-year events, both with 180-minute durations: the total area with decreased depth is nearly equal to or slightly greater than the area with increased depth, and in all cases, the reduced volume exceeded the increased volume (differences of 69.0 m^3 and 91.6 m^3, respectively). In other words, even when the areas with increased water depth are comparable to or greater than those with reductions, the depth increases tend to be minor, resulting in a positive volume balance in favor of SUDS adoption.

In the 2045 scenarios, all values were null, which may indicate that under the projected land use and land cover conditions for that year, there was no detectable variation in flood depth between the SUDS and non-SUDS scenarios within the analysis's detection limits.

A plausible explanation for the 2045 results is the high degree of projected imperviousness associated with LULC. The elevated level of impervious surfaces may drive surface runoff to such high levels that the simulated sustainable interventions are unable to significantly alter the watershed's hydrological behavior—at least as represented in the computational simulations used. In this context, Liu, Chen and Peng (2014) observed that while SUDS reduce runoff volume and peak flow, their mitigation capacity is limited in extreme events or areas with a high density of impervious surfaces. Similarly, Ortega Sandoval *et al.* (2023) reinforce this finding by showing that SUDS only marginally reduce flood extent in highly urbanized basins.

Practically speaking, the level of urbanization projected for 2045 implies an increase in impervious surface area. This reduction in infiltration promotes an increase in surface runoff volume and accelerates the watershed's hydrological response, concentrating flows over a shorter time and elevating the risk of urban flooding. Several studies confirm that this rise in imperviousness tends to intensify flood events by altering the natural hydrological cycle, making urban areas more vulnerable to intense rainfall (D'Ambrosio; Longobardi, 2023; Patil; Thakare; Nag, 2024). When SUDS are not adequately designed to compensate for this urban intensification, their mitigating effects become limited or even imperceptible in hydrological models, which may explain the absence of detectable differences in simulated flood volumes or areas for 2045.

Thus, the absence of polygons with measurable differences in the 2045 scenario may be associated with the limitations of the adopted hydrological model itself. The way the parameters were defined, as well as the location, scale, and density of the implemented SUDS devices, directly influences the model's ability to capture significant spatial variations. In highly urbanized contexts where impervious surface predominates, a phenomenon known as the "saturation effect" may occur: the watershed is so densely sealed that the contribution of green infrastructure becomes marginal or imperceptible in simulations (Liu *et al.*, 2020; Ortega Sandoval *et al.*, 2023).

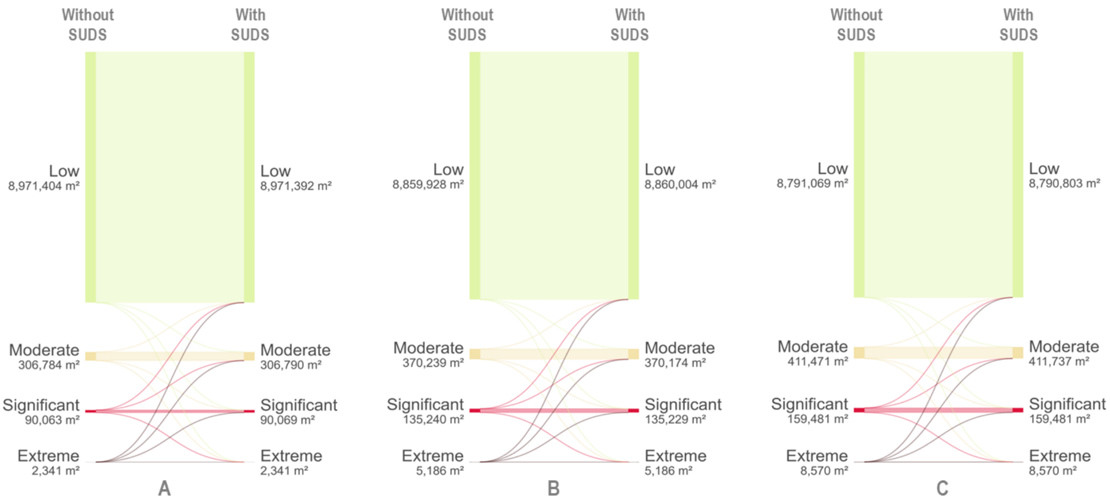
Therefore, the null values do not necessarily indicate a failure in the script or data, but may reflect the reality of a future scenario in which the growth of impervious surfaces, combined with the prolonged duration of rainfall events used in the simulations (180 minutes), surpasses the capacity of sustainable drainage systems to reverse—or even mitigate—the volume of accumulated water. In this sense, the results underscore the importance of planning and implementing sustainable drainage solutions at an adequate scale during the urban expansion phase, under the risk of not observing any effective difference in flood levels, as the 2045 data appear to indicate.

8.3.2 Hazard scenarios

Figure 32 presents three diagrams illustrating the changes in flood risk classification between scenarios without and with SUDS, corresponding to return periods of 5, 25, and 100 years. In the diagram associated with the 5-year return period (Figure 32A), changes in risk classes are observed in relatively small areas; however, these are sufficient to highlight a reallocation of hazard levels across the watershed. Although most polygons remain in the Low or Moderate categories, some areas shifted from Low to Moderate, while others moved from higher classes to lower ones, indicating that the adoption of SUDS led to changes in flood depth.

In summary, the total area that shifted to different risk classes remains moderate in relation to the watershed as a whole, but it nonetheless suggests that the hydrological behavior was altered—reducing risk in some locations while increasing it in others.

Figure 32. Transition of hazard classes (with and without SUDS) for return period of 5 years (A); 25 years (B) and 100 years (C)



In the diagram corresponding to the 25-year return period (Figure 32B), the changes are also moderate in absolute terms, but there is a slight increase in the lower risk classes, such as Low and Moderate, while areas previously classified as Significant become less representative after the implementation of SUDS. This redistribution suggests that, for intermediate rainfall intensities, sustainable drainage interventions are able to reduce water depth in parts of the watershed, reallocating some areas that would have been classified as Significant into less critical categories.

Even so, some transitions in the opposite direction still occur, indicating that, despite the overall positive effect, there are locations within the watershed where flood depth may increase due to the spatial redistribution of runoff.

In the diagram associated with the 100-year event (Figure 32C), the overall pattern partially resembles that of the first diagram, with minor shifts between the Low and Moderate classes. This suggests that the total area transitioning between these two hazard levels is not substantial compared to the size of the watershed. On the other hand, there is also a slight increase in the extent of areas shifting to the Significant or Extreme classes, although these changes do not reach high values.

8.3.3 Implications for environmental justice

The results presented have direct implications for issues related to environmental justice. By quantifying changes in flooded area and volume, as well as shifts in hazard classifications, the findings explicitly reveal how interventions affect different sectors of the watershed. Although the implementation of SUDS is globally positive in reducing total flood volumes in certain scenarios, it also triggered a spatial reallocation of risk: some areas experienced reductions, while others saw increases—representing a dynamic that may lead to the redistribution of vulnerabilities within the watershed. This phenomenon is recognized as both an ethical and technical challenge, as discussed by Liao, Chan and Huang (2019) in their examination of the “moral costs” of stormwater redistribution.

Even when small in absolute magnitude, this spatial redistribution of flooded areas becomes highly relevant from an environmental justice perspective—particularly considering that vulnerable urban areas often have a reduced capacity to respond and adapt to extreme hydrological events. As argued by Thaler *et al.* (2018) , poorly distributed climate adaptation policies can inadvertently intensify existing inequalities by protecting certain urban sectors at the expense of others.

The reallocation of risk, as revealed by the Sankey diagrams presented, reinforces the need for spatial analyses that clarify exactly who benefits and who may potentially be harmed by the implementation of these sustainable infrastructures. La Rosa and Pappalardo (2020) emphasize that the effectiveness of SUDS should also be evaluated based on their contribution to territorial equity, not solely through technical metrics. Without this consideration, there is a risk that interventions which are globally beneficial—but locally uneven—may exacerbate existing inequalities, transferring risks from communities with greater political or economic power to those historically marginalized or underrepresented in decision-making processes—an issue also raised by Nóblega-Carriquiry (2022) in their analysis of ecological transitions in consolidated urban areas.

The findings, particularly the absence of differences in the 2045 scenario, also suggest that without a significant and equitably distributed expansion of SUDS, increasing imperviousness and urbanization may nullify the localized benefits of such solutions, further deepening existing environmental and socioeconomic inequalities. This implies that public policies and urban planning strategies must consider not only the total volume and area of flood reduction, but also the spatial distribution of these reductions—prioritizing interventions in socially and environmentally vulnerable areas.

8.4 FINAL CONSIDERATIONS

The analyses conducted in this study demonstrated that the implementation of SUDS can yield benefits in reducing flooded areas and volumes, particularly under scenarios involving more frequent and lower-magnitude rainfall events, as observed in the 5-year return period. However, the interventions also revealed a spatial reallocation of hazards, indicating that while flood depth decreased in several regions, certain specific areas experienced an increase in water depth. This underscores the need for more detailed spatial analysis within the framework of environmental justice policies.

The transition diagrams of flood hazard classes confirmed this dynamic, showing that despite overall benefits, the impact of sustainable solutions is not uniform across the watershed. The spatial variability observed suggests that urban planning decisions and SUDS implementation should be guided not only by technical and environmental goals but also by principles of socio-spatial equity, ensuring that more vulnerable communities are not inadvertently harmed or overlooked by these systems. From a governance perspective, this transfer of flood hazard reinforces the importance of transparency and distributive justice in decision-making, as interventions that benefit the system as a whole may unintentionally intensify risks for specific areas.

For the future 2045 scenario, characterized by increased imperviousness associated with urban growth, the results indicated no differences between the scenarios with and without SUDS. This suggests a need to revise and expand the proposed interventions. Such a limitation may stem from both the modeling approach and the limited scope of the currently designed

SUDS, highlighting the importance of broadening the reach and scale of these interventions for future scenarios.

As a recommendation, future studies should explore a wider range of implementation scenarios, testing different SUDS typologies, within areas identified as critical from both hydrological and social vulnerability standpoints. Additionally, it is essential to investigate key operational questions: Which types of SUDS are most effective under specific urban conditions? Where should they be placed for maximum impact? How much surface area must be covered to meaningfully reduce runoff or mitigate flooding? Addressing these questions through spatial simulations and sensitivity analyses will contribute to a more refined and actionable understanding of the role of SUDS in urban resilience strategies.

9 CONCLUSIONS: A GEOSPATIAL ANALYSIS BETWEEN CAMPINA GRANDE AND WASHINGTON D.C.

How LULC changes, driven by urbanization, affect water resources in different geographical contexts, as growing cities and developed urban areas, and what integrated water resources management strategies can be implemented to mitigate these impacts and promote urban resilience and water sustainability?

English

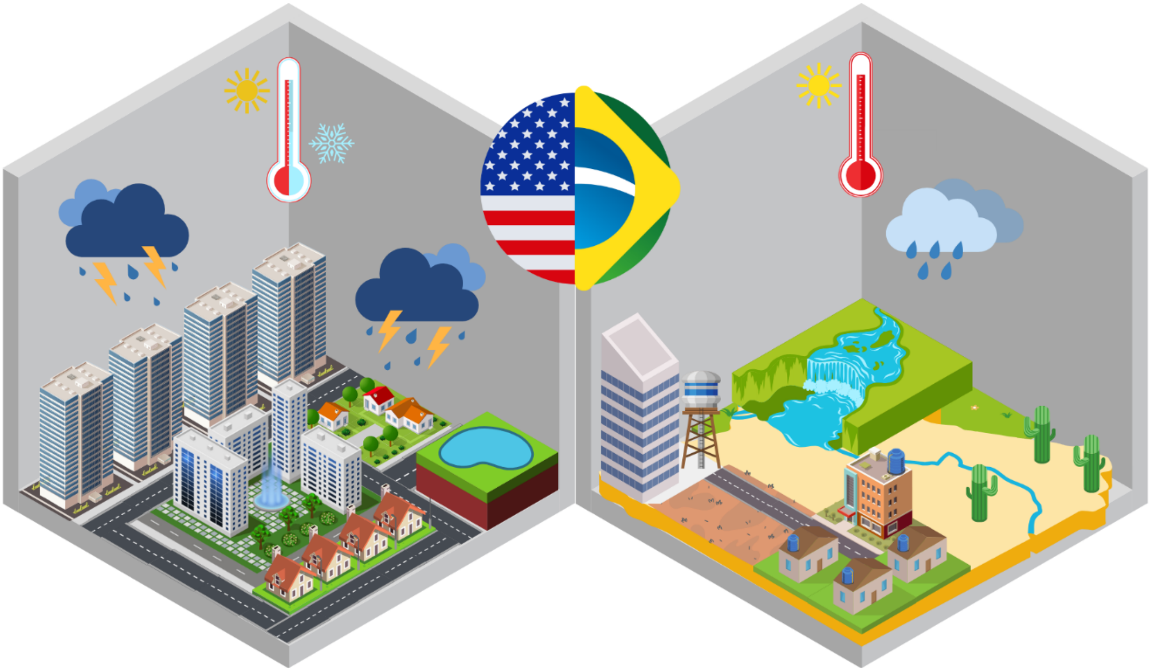
This concluding chapter synthesizes the analyses between two seemingly opposite urban realities: the context of rapid growth and water constraints in Campina Grande, Brazil, and the dynamics of advanced infrastructure, yet marked by socio-spatial inequalities, in Washington, D.C., United States. Through geospatial approaches and land use and land cover projections, it was identified that both the limited availability of data in highly vulnerable scenarios and the unequal distribution of infrastructure in developed urban centers can exacerbate water-related risks. By highlighting the influence of socioeconomic factors in water management, the chapter underscores the importance of interdisciplinary analyses and proposes pathways for developing public policies that integrate urban planning, environmental justice, and water resilience across diverse urban contexts.

Portuguese

Este capítulo de conclusão sintetiza as análises entre duas realidades urbanas aparentemente opostas: o contexto de crescimento acelerado e restrições hídricas de Campina Grande, no Brasil, e as dinâmicas de infraestrutura consolidada, porém marcadas por desigualdades socioespaciais, de Washington, D.C., nos Estados Unidos. Por meio de abordagens geoespaciais e projeções de uso e cobertura do solo, identificou-se que tanto a disponibilidade de dados em cenários de maior vulnerabilidade quanto a desigual distribuição de infraestrutura em centros desenvolvidos podem agravar riscos hídricos. Ao destacar a influência de fatores socioeconômicos no manejo da água, o capítulo valida a importância de análises interdisciplinares e propõe caminhos para se pensar em políticas públicas que aliem planejamento urbano, justiça ambiental e resiliência hídrica em distintos contextos urbanos.

The research presented in this dissertation has examined the complex spatial interrelations between LULC changes and water resource management, emphasizing urban hydrological challenges through a geospatial analysis of Campina Grande, Brazil, and Washington, D.C., USA. By exploring varied urban contexts — one characterized by rapid urban growth within a developing country and another representing a well-established urban center in a developed country — this study has highlighted distinct yet interconnected patterns of urban hydrological vulnerability and resilience (Figure 33).

Figure 33. Conceptual illustration between urban contexts in Brazil and the USA



9.1 PRINCIPAL FINDINGS

In Campina Grande, the detailed analyses conducted in Chapters 3, 4, and 5 yielded insights into the consequences of rapid urban expansion on water resources. The predictive spatial simulations clearly highlighted that urban growth substantially increases domestic water demand, exacerbating the city's vulnerability to persistent drought conditions and water scarcity. Notably, model forecasts revealed scenarios of intensified water shortages by the year 2050 under ongoing urbanization trends, emphasizing the urgent need for integrated water management and sustainable urban development practices. Sensitivity analyses underscored critical drivers influencing urban sprawl, particularly emphasizing accessibility, proximity to urban centers, infrastructure availability, and officially designated urban expansion zones. These factors collectively illustrate the necessity for urban planning interventions to control urban growth and promote efficient water resource utilization, thereby reducing environmental degradation and preserving hydrological balance.

Additionally, sentiment analysis from Chapter 3 demonstrated public perception strongly linked to water scarcity, underlining a high level of community concern regarding water resource availability and emphasizing the importance of involving stakeholders and local communities in decision-making processes to enhance water governance effectiveness. This integrative approach would enable more responsive and inclusive policies, better reflecting local needs and priorities.

In Washington, D.C., Chapters 6, 7, and 8 presented a comprehensive spatial analysis focusing on urban flooding and disparities in the distribution of green infrastructure. Despite the city's significant investment in BMPs, spatial autocorrelation analyses exposed socio-environmental inequities. These analyses specifically highlighted a clear pattern of inadequate flood mitigation infrastructure in economically disadvantaged. Consequently, these communities remain disproportionately vulnerable to urban flooding risks, perpetuating systemic inequalities and environmental injustice. Further, predictive flood hazard modeling demonstrated potential increases in flood risks associated with projected changes in LULC and impervious surfaces, emphasizing that future urban development without targeted interventions will likely exacerbate existing vulnerabilities.

Moreover, an integrated evaluation of the effectiveness of SUDS implemented in Chapter 8 provided compelling evidence that equitable placement and distribution of infrastructure significantly mitigate flooding risks. However, it also underscored the importance of ensuring that these infrastructure solutions are not only technically effective but also socially equitable, fostering resilience in vulnerable communities.

The geospatial analysis between Campina Grande and Washington, D.C., identified similarities and differences rooted primarily in socio-spatial inequalities. Both cities clearly demonstrated that disparities in infrastructure availability, influenced heavily by socioeconomic status, exacerbate vulnerabilities to their respective water-related challenges. However, the nature of these challenges differs distinctly between the two urban contexts. Campina Grande primarily faces water scarcity caused by inadequate management, exacerbated by rapid urbanization. In contrast, Washington, D.C., predominantly faces flood risks exacerbated by the uneven distribution and deployment of flood mitigation infrastructure and uneven urban development practices.

These findings collectively emphasize the importance of context-sensitive and flexible water management strategies tailored to specific local socio-economic and environmental conditions. Prioritizing equity, inclusive stakeholder engagement, and sustainable growth strategies emerges as fundamental in addressing urban hydrological vulnerabilities effectively. Thus, adopting an interdisciplinary approach to urban water management, informed by geospatial data and participatory processes, is essential to build resilient, equitable, and sustainable urban environments in diverse global contexts.

9.2 LIMITATIONS AND RECOMMENDATIONS

Despite its methodological rigor, this study encountered several limitations. In Campina Grande, the limited availability of temporal water consumption data and high-resolution imagery restricted the accuracy of predictions. Recommendations to address this may involve enhanced data integration strategies, incorporating multispectral and multitemporal remote sensing datasets, which could potentially refine model outputs, in addition to initiatives for systematic monitoring by managing agencies.

For Washington, D.C., although the quality of spatial data was high, the dynamic nature of urban policy interventions and inconsistencies in drainage infrastructure records posed challenges to accurately capturing real-world conditions. Future studies should employ longitudinal data collection strategies, along with participatory GIS methods, to better capture adaptive measures at the community level.

Furthermore, generalizing the results requires cautious interpretation. Urban hydrological dynamics vary due to local governance structures, socioeconomic contexts, and specific environmental conditions. Thus, while the study provides insights and replicable methodologies, contextual adaptation remains essential for practical application.

9.3 CONTRIBUTIONS TO SOCIETY

The findings of this dissertation offer tools for practical, spatially informed guidelines derived from analyses of LULC transformations and their impacts on urban water resources. By examining case studies in Campina Grande and Washington D.C., this research provides insights into urban planning, water resource management, and environmental justice.

Urban planners and policymakers may consider integrating SUDS, especially in areas identified as vulnerable through spatial autocorrelation and sensitivity analyses. Results indicated that SUDS mitigate flood risks under current urbanization scenarios but become less effective as imperviousness grows, suggesting zoning regulations and increased permeable surface requirements as beneficial measures in rapidly urbanizing areas.

The research highlights the importance of community engagement and participatory governance in managing water scarcity and flood vulnerabilities. Findings from sentiment analysis in Campina Grande underscore social and emotional impacts of water shortages, suggesting municipalities establish communication channels and stakeholder participation frameworks aligned with local perceptions and needs.

Another contribution is the identification of socio-spatial disparities in infrastructure distribution, revealing environmental justice implications. Policymakers may use spatial methodologies presented to identify underserved communities and promote equitable water-related investments, addressing historical inequalities and reducing vulnerability among disadvantaged populations.

Additionally, this research supports interdisciplinary approaches in urban hydrological management by integrating geospatial data, demographic analyses, and predictive modeling. Authorities may adopt these methodologies to proactively anticipate urban water risks and strategically address demographic shifts and urban growth pressures.

Lastly, the research provides practical tools for scenario analysis and urban planning by delineating influential variables through sensitivity analyses, enabling urban planners to efficiently allocate resources toward impactful factors affecting urban expansion and water resource dynamics.

Overall, by fostering greater understanding of how urban expansion impacts water resources differently across global contexts, this research reinforces the need for adaptive, integrated, and equitable urban water management strategies, supporting sustainable urban futures resilient to emerging hydrological challenges.

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