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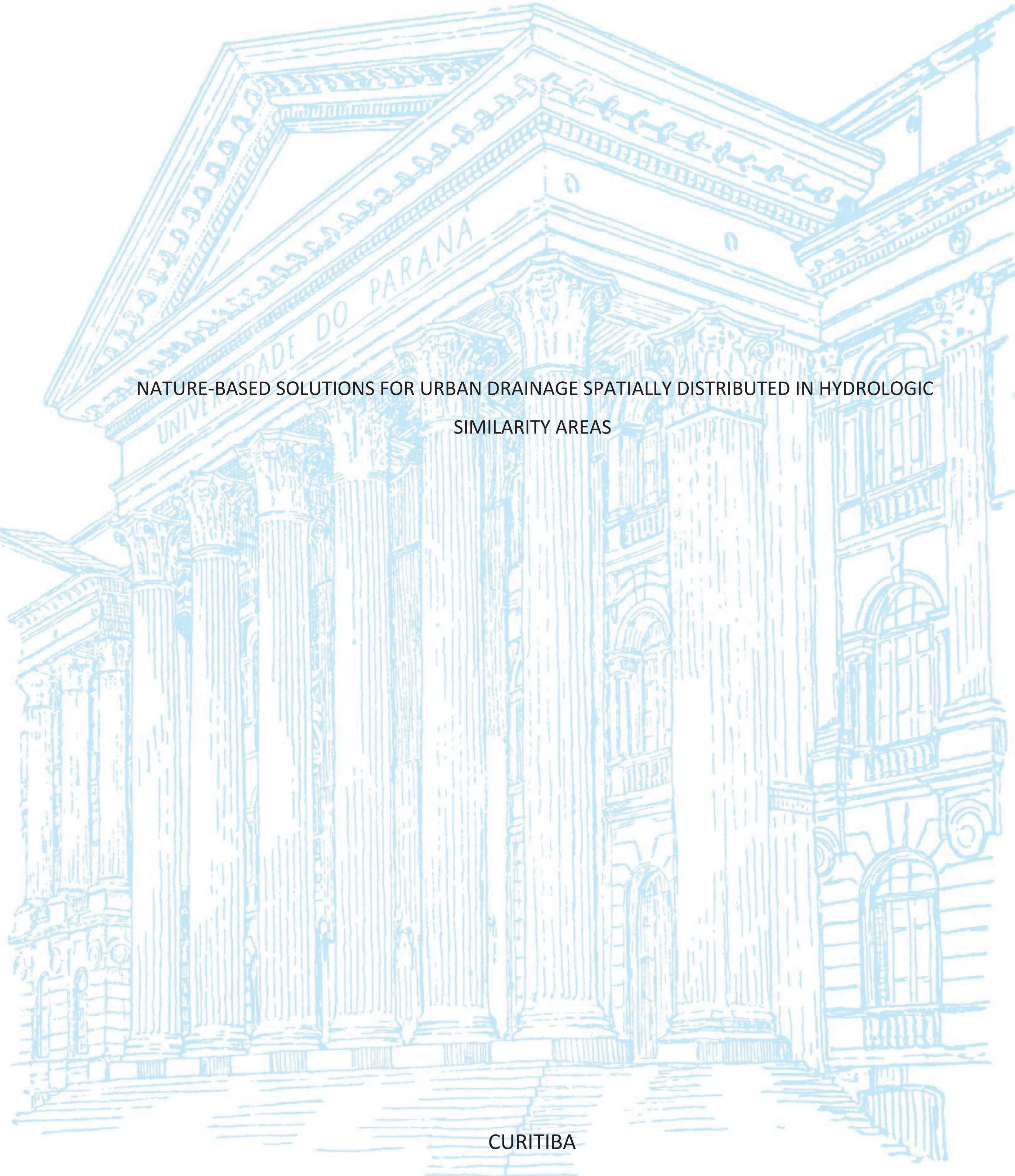

NATURE-BASED SOLUTIONS FOR URBAN DRAINAGE SPATIALLY DISTRIBUTED IN HYDROLOGIC SIMILARITY AREAS

CURITIBA

2023

JULIANA WILSE LANDOLFI TEIXEIRA DE CARVALHO

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Tese apresentada ao Programa de Pós-Graduação em Geografia, no Setor de Ciências da Terra, na Universidade Federal do Paraná, como requisito parcial à obtenção do título de Doutora em Geografia.

Orientador: Prof. Dr. Irani dos Santos

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TERMO DE APROVAÇÃO

Os membros da Banca Examinadora designada pelo Colegiado do Programa de Pós-Graduação GEOGRAFIA da Universidade Federal do Paraná foram convocados para realizar a arguição da tese de Doutorado de **JULIANA WILSE LANDOLFI TEIXEIRA DE CARVALHO** intitulada: **NATURE-BASED SOLUTIONS FOR URBAN DRAINAGE SPATIALLY DISTRIBUTED IN HYDROLOGIC SIMILARITY AREAS.**, sob orientação do Prof. Dr. IRANI DOS SANTOS, que após terem inquirido a aluna e realizada a avaliação do trabalho, são de parecer pela sua APROVAÇÃO no rito de defesa.
A outorga do título de doutora está sujeita à homologação pelo colegiado, ao atendimento de todas as indicações e correções solicitadas pela banca e ao pleno atendimento das demandas regimentais do Programa de Pós-Graduação.

CURITIBA, 15 de Fevereiro de 2023.

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In the hopes that this work may in some way contribute to building a sustainable future and resilient cities, I dedicate this thesis to the populations affected by urban floods.

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Eu pus os meus pés no riacho

E acho que nunca os tirei

(CAETANO VELOSO, 1978)

RESUMO

Soluções baseadas na Natureza (SbN) é um conceito guarda-chuva para conceitos relacionados à produção de serviços ecossistêmicos, incluindo os conceitos de drenagem sustentável. Na Hidrologia Urbana, SbN mostra-se como uma alternativa sustentável para redução dos efeitos adversos da urbanização no balanço hídrico e para mitigação de inundações. Há, no entanto, carência de estudos acerca de metodologias e do desempenho da implementação múltipla e descentralizada de SbN. Há também uma carência de estudos sobre a implementação de cenários realistas, que considerem a configuração espacial intraurbana pré-existente, haja visto que desconstruir cidades consolidadas é espacialmente e economicamente inviável, e que nem todas as SbN são viáveis para todas os espaços. A partir da delimitação de Áreas de Similaridade Hidrológica (ASH) resultantes de diferentes características espaciais intraurbanas, esta pesquisa tem por objetivo identificar como a implementação de SbN distribuídas em ASH pode reduzir os impactos da urbanização no balanço hídrico e nas inundações da bacia hidrográfica do rio Belém, considerando as limitações do espaço urbano pré-existente. Esta tese está escrita no formato de coletânea de artigos, sendo composta por quatro manuscritos que se associam de modo a atingir o objetivo geral. No primeiro artigo, uma análise teórica e uma revisão sistemática estruturada foram realizadas com o objetivo de identificar as interfaces existentes entre SbN e conceitos de drenagem sustentável. No segundo artigo, AHS foram delimitadas na bacia hidrográfica do rio Belém com base na configuração espacial intraurbana e o balanço hídrico anual e diário foi avaliado através de modelagem hidrológica com aplicação do modelo Aquacycle. No terceiro artigo, a dinâmica de inundações da bacia foi avaliada com base nos resultados obtidos no artigo 2 e na modelagem hidráulica com o modelo HEC RAS. A extensão e a profundidade das inundações foram identificadas para diferentes tempos de retorno (TR), bem como a contribuição da vazão por ASH, todos sob condições de chuvas intensas. Com base nos resultados obtidos nos três capítulos anteriores, foram definidos, no quarto artigo, cenários com implementação de SbN múltiplas e descentralizadas, estabelecidas de acordo com as condições espaciais das ASH. Também foram simulados os efeitos dos cenários no balanço hídrico e nas inundações urbanas. Os resultados obtidos no artigo 1 revelam que, apesar de existirem alguns contrapontos, os conceitos analisados convergem para os princípios de SbN e podem ser abarcados por seu guarda-chuva conceitual. A revisão sistemática revelou que a associação entre os conceitos se dá de diferentes formas na literatura científica, podendo resultar em confusões conceituais. No entanto, SbN demonstra potencial para alcançar relevância global na área dos recursos hídricos. No artigo 2, o método de delimitação de ASH se mostrou eficiente em agrupar áreas com características semelhantes. Seis ASH foram delimitadas na bacia do rio Belém, cujo percentual de áreas impermeáveis variou de 18% a 89%. Os resultados da modelagem mostram que a heterogeneidade espacial intraurbana se reflete no balanço hídrico anual e diário. No artigo 3, mapas de inundação foram obtidos para os TR 2, 5, 25 e 100 anos. Áreas susceptíveis a inundações foram identificadas em todos os trechos modelados, especialmente nas áreas mais a jusante. Os resultados mostraram uma grande variação no volume de vazão entre as ASH em todos os eventos simulados. Mostraram também que as áreas mais susceptíveis a inundações não são necessariamente as principais geradoras de vazão. Por fim, os resultados do artigo 4 demonstraram que os cenários com SbN podem aumentar a evapotranspiração em até 8% e a infiltração em até 19%, bem como reduzir o escoamento em até 20% e a vazão em até 8% na escala anual. No balanço hídrico diário foram observados aumentos entre 7% e 41% nas taxas de infiltração e reduções entre 3,6% e 29% no escoamento superficial, a depender do cenário simulado, volume de precipitação e condições de umidade antecedente. Com relação à dinâmica das inundações, foram obtidas reduções de até 16,3% nas vazões de pico e de até 22% na extensão das áreas inundadas. Por fim, a hipótese desta pesquisa foi validada, concluindo-se que a implementação de SbN para drenagem urbana é limitada de múltiplas formas pela configuração espacial pré-existente. Entretanto, cenários compostos por medidas múltiplas e combinadas em ASH, coalescentes às condições herdadas, podem apresentar respostas significativas no balanço hídrico, com diminuição dos picos de vazão máxima e das áreas suscetíveis à inundação.

Palavras-chave: Balanço Hídrico Urbano. Inundações Urbanas. Configuração Espacial Intraurbana. Drenagem Urbana Sustentável.

ABSTRACT

Nature-based Solutions (NbS) is an umbrella concept for ecosystem-related approaches, including sustainable drainage concepts. In Urban Hydrology, NbS reveals to be a sustainable alternative to reduce the adverse effects of urbanization on the water balance and mitigate floods. However, there is a lack of studies about methodologies and performance of implementing decentralized and multiple NbS. There is also a lack of studies about realistic scenarios considering the pre-existing intraurban spatial configuration since deconstructing consolidated cities is spatially and economically unfeasible, and not all NbS are suitable for all conditions. From the delimitation of Hydrologic Similarity Areas (HSA) resulting from different intraurban spatial features, this research aims to identify how the implementation of NbS distributed in HSA can reduce the impacts of urbanization on water balance and flood dynamics in the Belém catchment, considering the limitations of the pre-existing intraurban spatial configuration. This thesis is written in the format of articles collection, composed of four articles that associate with one another to achieve the main objective. In the first article, a theoretical analysis and a structured systematic review were conducted to identify the existing interfaces among NbS and sustainable drainage concepts. In the second article, Hydrologic Similarity Areas (HSA) were delimited in the Belém catchment based on intraurban spatial configuration patterns and their responses on annual and daily water balance were evaluated with hydrological modeling with Aquacycle. The third article described the catchment flood dynamic based on the results obtained in article 2 and on hydraulic modeling with HEC RAS. Flood extent and depth were identified at different return periods (RP), as well as the streamflow contribution per HSA under intense rainfall conditions. In the fourth article, based on the results obtained in the three previous chapters, scenarios with decentralized and multiple NbS according to the HSA spatial preconditions were set and its effects on water balance and urban floods were simulated. The results obtained in article 1 reveal that, despite a few counterpoints, the analyzed concepts converge to NbS principles and can be covered by its conceptual umbrella. The systematic review demonstrates that the association among concepts has taken place in different ways, which may result in conceptual confusion. Nevertheless, NbS has the potential to seek paths to achieve global relevance in the water resources field. In article 2, the method to delimit HSA has shown efficiency in grouping areas of similar features. Six HSA were delimited in the Belém catchment, whose percentage of impervious areas ranges from 18% to 89%. The modeling results show that the intraurban spatial heterogeneity is reflected in the annual and daily water balance. In article 3, flood maps were obtained for 2, 5, 25, and 100-year RP. Areas susceptible to flooding were identified in all modeled reaches, emphasizing downstream areas. The results showed a wide variation in streamflow volume among the HSA in all the simulated events and that the most susceptible to flooding areas are not necessarily the main contributors to streamflow. Finally, the results from article 4 showed that NbS scenarios can increase evapotranspiration by up to 8% and infiltration by 19%, reduce runoff by up to 20%, and streamflow by up to 8% in annual scale. In the daily water balance, increases ranging from 7% to 41% for infiltration rates and reductions ranging from 3.6% to 29% for runoff were observed, depending on the scenario, precipitation volume, and antecedent humidity conditions. Regarding the flood dynamics, reductions of up to 16.3% in peak flows and up to 22% in flood extent were obtained. Finally, the hypothesis is validated, concluding that the pre-existing urban spatial configuration limits the implementation of NbS for urban drainage. However, scenarios composed of multiple and combined measures into the HSA, accordant to preconditions, may present significant responses in the water balance, reducing the stormwater peak flows and the areas susceptible to flooding.

Keywords: Urban Water Balance. Urban Floods. Intraurban Spatial Configuration. Sustainable Urban Drainage.

LIST OF FIGURES

LIST OF ABBREVIATIONS OR ACRONYMS

A	- Area
A1	- Percentage Area of Pervious Store 1
*α*1	- Velocity Weighting Coefficients at Cross Section One
*α*2	- Velocity Weighting Coefficients at Cross Section Two
AH	- Antecedent Humidity
B	- Blue Band
BF	- Baseflow
BFLOW	- Baseflow Filter Program
BGCs	- Blue-Green Cities
BI	- Baseflow Index
BMP	- Best Management Practices
BRC	- Baseflow Recession Constant
C	- Expansion or Contraction Loss Coefficient
DRWM	- Decentralized Rainwater/Stormwater Management
DTM	- Digital Terrain Model
Ea	- Evapotranspiration
EbA	- Ecosystem-based Adaptation
EIA	- Effective Impervious Area
Eimp	- Evaporation
EMP	- Ecological Management Practices
EP	- Equivalent Population
EPA	- Effective Paved Area
Epc	- Plant Controlled Maximum Evapotranspiration
ERA	- Effective Roof Area
ERDA	- Effective Road Area
ETo	- Actual Evapotranspiration
EXC	- Rainfall Excess
g	- Gravitational Acceleration
G	- Green Band

GBI	- Green/Blue Infrastructure
GI	- Green Infrastructure
GWR	- Groundwater Recharge
GWS	- Groundwater Storage Level
he	- Energy Head Loss
HSA	- Hydrologic Similarity Areas
I	- Imported Water
II	- Infiltration Index
INF	- Infiltration of Stormwater into the Wastewater System
INFS	- Infiltration Store Level
IR	- Irrigation
IRC	- Infiltration Recession Constant
IRUN	- Impervious Surface Runoff
ISI	- Inflow
IUCN	- International Union for Conservation of Nature
IUWM	- Integrated Urban Water Management
IWD	- Illegal Wastewater Discharge
IWU	- Indoor Water Use
L	- Discharge Weighted Reach Length
LD	- Leakage Depth
LID	- Low Impact Development
LIDUD	- Low Impact Developments Urban Design
LIUDD	- Low Impact Urban Design and Development
LUE	- Light Use Efficiency
NAH	- No Antecedent Humidity
NbS	- Nature-based Solutions
NDVI	- Normalized Difference Vegetation Index
NDWI	- Normalized Difference Water Index
NEAR	- Non Effective Area Runoff
NIR	- Near Infrared Band
NSH	- Nash–Sutcliffe Efficiency Coefficient

$\overline{OBS}$	- Mean of Observed Discharges
OBS_i	- Observed Discharge at Time i
P	- Precipitation
PET	- Potential Evapotranspiration
PF	- Simulated Water Profiles
PS1	- Pervious Storage 1 Level
PS1C	- Pervious Storage 1 Capacity
PS2	- Pervious Storage 2 Level
PS2C	- Pervious Storage 2 Capacity
PST	- Paved Area Surface Storage Level
Qm	- Mean Daily Streamflow
Qmax	- Peak Flow
R	- Red Band
R^2	- Determination Coefficient
RDIL	- Road Area Maximum Initial Loss
RDST	- Road Surface Storage Level
REC	- Measured Flow
RIL	- Roof Area Maximum Initial Loss
RIS	- Infiltration Storage Recharge
RP	- Return Period
Rs	- Stormwater Runoff
RST	- Roof Surface Storage Level
Rw	- Wastewater Discharge
s	- Standard Deviation
Sc	- Scenario
SCM	- Stormwater Control Measure
SDS	- Sustainable Drainage Systems
$\bar{S}f$	- Representative Friction Slope Between Two Sections
SIM	- Simulated Flow
SIM_i	- Modeled Discharge
SPRI	- Scaled Photochemical Reflectance Index

SQUID - Stormwater Quality Improvement Devices

SRUN - Pervious Surface Runoff

SuDS - Sustainable Drainage Systems

TG - Garden Trigger to Irrigate

TIN - Triangulated Irregular Network

V1 - Average Velocities at Cross Section One

V2 - Average Velocities at Cross Section Two

WSUD - Water Sensitive Urban Design

x - Precipitation Corresponding to the Return Period

$\bar{x}$ - Mean of the Sample Values

Y1 - Depth of Water at Cross Section One

Y2 - Depth of Water at Cross Section Two

$Z1$ - Elevation of the Main Channel in the Section One

$Z2$ - Elevation of the Main Channel in the Section Two

SUMMARY

1. GENERAL INTRODUCTION

The urban water cycle is composed of a complex set of constructed and natural water pathways (MITCHELL, 2005; CARVALHO and SANTOS, 2021) and suffers several impacts from increasing urbanization. Scientific studies have demonstrated that changes in land use with the increasing impervious surfaces may result in severe distortion of water balance, reducing evapotranspiration and groundwater recharge, and increasing runoff, peak flows, and flood risk (LEE *et al*., 2010. MEJÍA *et al*., 2014; MITCHELL *et al*., 2008; HAASE, 2019; WANG *et al*., 2021; MACDONALD *et al*., 2022). It has also been demonstrated that the floods frequency and magnitude are intensifying due to the synergistic effects of urban expansion and densification, river channeling works (ASSUMPÇÃO and MARÇAL, 2012; CUNHA; 2012; SARTÓRIO, 2018), occupation of riverside areas (MIGUEZ, *et al*., 2015; TUCCI and VILLANUEVA, 2018), and the intensification of climate extreme events (PBMC, 2014; DEVI, SRIDHARAN and KUIRY, 2019).

In addition, climate change prospects the intensification of extreme events, which will demand greater resilience of the urban environments (ASADIEH and KRAKAUER, 2017; WATER, 2020; SANTOS *et al*., 2020). For southern Brazil, for example, an increase of 30% is expected by 2100 in annual precipitation, as well as intensified extreme events, which increase susceptibility to droughts and floods (PBMC, 2014; MARENGO *et al*., 2021; CARVALHO, IENSEN and SANTOS, 2021). Nevertheless, beyond the changes in water dynamics, the denaturalization of rivers and hydrological processes can also affect microclimate, water security, production of ecosystem services, air and water quality, and reduce biodiversity, human health, and human well-being (COHEN-SHACHAM *et al*., 2016; WATER, 2018; WATER, 2020).

The International Union for Conservation of Nature (IUCN) lists climate change, water security, disaster risk, human health, and economic and social development as the leading global societal challenges in the 21st century (COHEN-SHACHAM *et al*., 2016). They are all related to water resource management in some way and to the potential to provide ecosystem services. Such challenges are representative in urban environments, which currently concentrate around 55% of the world's population, possibly reaching 70% by 2050 (UN-HABITAT, 2016). In Brazil, the urban population is around 84% (IBGE, 2012).

Faced with such challenges and impacts, approaches and concepts related to sustainable urban drainage emerged in the scientific literature after the second half of the 20st century, such as Low Impact Development (LID), Sustainable Drainage Systems (SuDS), Water Sensitive Urban Design (WSUD), Re-naturing cities, Sponge Cities and Green/Blue Infrastructure (GBI) (FLETCHER *et al*., 2015). Differently from the traditional urban water management approaches, which aim to reduce the water residence time in watersheds, the concepts linked to sustainable drainage aim to reintroduce water into the urban landscape, reconstructing or mimicking the hydrological processes previously impacted (LARSEN *et al*., 2016; ECKART *et al*., 2017). Some examples of sustainable urban drainage practices are green roofs, green walls, rainwater tanks, rain gardens, infiltration trenches, and permeable pavements (FLETCHER *et al*., 2015).

With a greater profusion of concepts related to sustainability at the beginning of the 21st century, the concept of Nature-Based Solutions (NbS) emerged, but not only addressed to urban environments and water resources. According to the IUCN, NbS are defined actions to protect, sustainably manage and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits (COHEN-SHACHAM *et al*., 2016). They tend to provide a set of ecosystem services, contributing to build resilient systems and reduce risks through the combined implementation of green, blue, and gray infrastructures. It is an umbrella concept for ecosystem-related approaches.

One of the main characteristics of NbS is that it was presented as an umbrella concept for ecosystem-related approaches (COHEN-SHACHAM *et al*., 2016). Hereupon, the Urban Hydrology has a range of concepts related to sustainable drainage (FLETCHER *et al*., 2015), which converge to the NbS principles. The association of green concepts and NbS has been carried out in different ways (NESSHÖVER *et al*., 2017; HANSON, WICKENBERG and OLSSON, 2020; HUANG *et al*., 2020; RUANGPAN *et al*., 2020; BRASIL *et al*., 2022), but no research has specifically explored the relationships between sustainable urban drainage concepts and NbS so far.

According to Cohen-Shacham *et al*. (2016), the NbS applied to urban drainage can improve air quality, support wastewater treatment, reduce stormwater runoff and water pollution, and improve quality of life. In 2018, the NbS concept was the theme of The United Nations World Water Development Report, consolidating its role and significance regarding the challenges on water resources. The report discusses water resource demands, including availability, quality, and water-related risks (WATER, 2018).

Understanding the impacts of urbanization on the water dynamics of urban watersheds, as well as identifying alternatives for building more sustainable and resilient cities, are among the research questions to be explored by the hydrological community in this decade (MCMILLAN *et al*., 2016). Developing efficient tools to model urban water and flood dynamics is one of the main challenges. This is because the coexistence and interaction of natural and built drainage systems (public supply, sanitary sewage, and artificial drainage) (MITCHELL *et al*., 2008; MCMILLAN *et al*., 2016) makes complex the mathematical representation of the urban hydrological cycle.

A range of models has been developed to encompass the most significant number of systems, interactions, and structures necessary for modeling urban water dynamics. Some examples are the hydrological models Aquacycle (MITCHELL, 2005), IUWM (SHARMA *et al*., 2008), UQV (MITCHELL and DIAPER, 2005), SWITCH (LAST and MACKAY, 2007), and the hydraulic model HEC-RAS (BRUNNER, 2016).

Another challenge is the understanding and modelling the different responses in water dynamics arising from intra-urban spatial heterogeneity. Understanding urban areas as homogeneous spaces and identifying their standard dynamics in the different fields of geographical analysis are widespread practices in the scientific literature, including Urban Hydrology. Studies relating intraurban spatial configuration to other variables, such as air temperature (LEMOINE-RODRÍGUEZ, INOSTROZA and ZEPP, 2022), relative humidity, wind speed, global radiation, thermal comfort (TOP *et al*., 2020), and concentrations of fine particulate (ASHAYERI *et al*., 2021) have been developed in the field of Environmental Sciences. However, few studies on Urban Hydrology investigate spatial heterogeneity's role in the water balance.

Homogeneity conditions are ordinarily assumed, applying average values for an entire urban system (LEE *et al*., 2010; HAASE, 2009; WANG *et al*., 2021; MACDONALD *et al*., 2022). Nevertheless, studying the intraurban spaces' diversity can be crucial to understand the urban water dynamics, serving as a subsidy for managing drainage interventions (FENDRICH, 2002; DONIA, MANOLI and ASSIMACOPOULOS, 2013). Furthermore, different spaces in the same city are expected to generate different hydrological responses, and contribute to floods on different proportions, given the heterogeneity of intraurban spaces.

Herein, the Hydrologic Similarity Area (HSA) concept is employed to propose a systematic and statistically based method to define intraurban clusters and evaluate their hydrological responses. The objective of classifying urban space in HSA is to identify areas with the same spatial configuration patterns and, therefore, similar water dynamics (CARVALHO and SANTOS, 2021). Such patterns of urban configuration denote the highly dependent relationship between the percentage of impervious surfaces and the hydrological processes' denaturalization (CARVALHO, MARANGON and SANTOS, 2020) that are reflected in the water balance (MEJÍA *et al*., 2014). Thereby, it is argued whether these same HSA present different limitations and potentialities in implementing NbS for urban drainage.

Despite NbS have demonstrated to be a promising approach in Urban Hydrology, many gaps still need to be addressed, mainly due to its recent insertion in the scientific literature. In a systematic review, Stroud, Peacock and Hassall (2022) verify that few studies reported on the use of NbS in ecosystem service provision by urban blue and green space, and of these, 80%

focused on a single NbS. Majidi *et al*. (2019), Ferreira *et al*. (2020), and Vojinovic *et al*. (2021), however, identify that the most effective performance of NbS in terms of flood mitigation and ecosystem services providing is achieved by applying different measures in different locations, in a decentralized way. In this sense, studies on strategies and performance of hybrid and decentralized measures are necessary to understand how NbS can result in significant responses in reducing impacts on urban water dynamics.

Another gap concerns developing realistic implementation strategies considering pre-existing urban spatial conditions, especially in the Global South context (CHEN *et al*., 2021). Considering that deconstructing consolidated cities is spatially and economically unfeasible, it must be understood that there are areas with greater potential for adapting to specific measures than others and that there are more effective and adaptable measures for each type of urban spatial configuration. In this sense, Zölch *et al*. (2017) argue that not all NbS are suitable for all conditions. However, many studies simulate the implementation of NbS where they are not applicable or unfeasible scenarios.

Based on the abovementioned issues, it is questioned "whether" and "how" the pre-existing spatial conditions can limit the implementation of SbN and which types of SbN can better adapt to different types of intra-urban spatial configuration. In this sense, this study aims to answer the following question: How the intraurban spatial configuration and NbS for drainage can be related to set scenarios that result in significant responses in the water balance, decreasing peak flows and the areas susceptible to flooding?

The hypothesis here proposed is that the implementation of NbS for urban drainage is limited by the pre-existing urban spatial configuration. However, scenarios composed of multiple and combined measures into the HSA, accordant to preconditions, may present significant responses in the water balance, reducing the stormwater peak flows and the areas susceptible to flooding.

To answer the research question and validate the hypothesis, hydrological and hydraulic modeling were applied at Belém catchment, southern Brazil. Belém is a headwater catchment of the Iguaçu basin. With 87.8 km² of drainage area, it encompasses the most urbanized area of Curitiba, the capital of Paraná. It is representative of urban watersheds in Brazil in several aspects, including its diversity of spatial configuration patterns originated by the spontaneous urbanization and urban planning matchup, the complex dynamics of water pathways in the urban drainage system (CARVALHO and SANTOS, 2021), and the frequent occurrence flash floods (IBGE, 2008).

Before the modeling-based studies, theoretical analysis and a structured systematic review were also carried out to explore the relationships between sustainable urban drainage concepts and NbS, serving as a subsidy for the research discussions involving NbS and urban drainage.

1.1 RESEARCH OBJECTIVES

Based on the abovementioned issues, on the research question and on the proposed hypothesis, this study aims to identify how the implementation of NbS distributed in HSA can reduce the impacts of urbanization on water balance and flood dynamics in the Belém catchment, considering the limitations of the pre-existing intraurban spatial configuration.

The specific aims are:

1) To identify the existing interfaces among NbS and the Urban Hydrology concepts linked to sustainable drainage.
2) To delimit Hydrologic Similarity Areas in the Belém catchment based on intraurban spatial configuration patterns and evaluate their responses on the water balance, with an emphasis on runoff rates.
3) To describe flood dynamics in the Belém catchment (Curitiba/PR), identifying flood extent and depth at different return periods and the streamflow contribution of HSA under intense rainfall conditions.
4) To set scenarios with NbS implementation in the Belém catchment´s HSA and simulate its effects on water balance and urban flood dynamics.

1.2 RESEARCH STRUCTURE

This doctoral thesis is written in the format of articles collection, composed of one review article and three research articles. Each specific aim gives rise to a scientific manuscript corresponding to a thesis chapter. Therefore, the specific aims associate with one another and build a knowledge pathway to achieve the main objective and validate the research hypothesis.

A general introduction at the beginning of the document presents the research problem, hypothesis, and objectives. A general conclusion at the end discusses the conclusions considering all articles and their correlations. Due to the choice of scientific journals to submit the manuscripts, the entire document is written in English.

Note that, due to the format chosen to organize the thesis, some results obtained in the first chapters are a subsidy for later chapters. In this document, references to such results were made by referencing the chapters themselves.

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2. A REVIEW OF NATURE-BASED SOLUTIONS FOR URBAN HYDROLOGY: CONCEPTS AND INTERFACES

Abstract: Nature-based Solutions (NbS) is an umbrella concept for ecosystem-related approaches. Urban Hydrology has a range of sustainable drainage concepts that can converge to NbS principles, but no research has explored such relation so far. Herein we aim to identify the existing interfaces among NbS and sustainable drainage concepts. To do so, we conducted a theoretical analysis to verify how Low Impact Development (LID), Sustainable Drainage Systems (SuDS), Water Sensitive Urban Design (WSUD), Re-naturing Cities, Sponge Cities, and Green/Glue Infrastructures (GBI) can be covered by the NbS conceptual umbrella, and a structured systematic review to analyze how the scientific community relates such concepts. The results reveal that, despite a few counterpoints, the concepts converge to NbS principles and can therefore be covered by its conceptual umbrella. The systematic review demonstrates that the association among concepts has taken place in different ways. The different positions are even contradictory and may result in conceptual confusion. Thus, 45% consider drainage concepts as part of the NbS umbrella, 20% as synonyms, 3% as associated concepts, and 1% as different concepts. Notably, 32% of the manuscripts do not establish any relations, indicating a significant number of publications where the relationship between concepts may be operationally empty. Nevertheless, the set of analyzes from our systematic review shows that NbS has the potential to seek paths to achieve global relevance in the water resources field.

Keywords: Low Impact Development; Sustainable Drainage Systems; Water Sensitive Urban Design; Re-naturing Cities; Sponge Cities; Green/Blue Infrastructures.

2.1 INTRODUCTION

Many are the challenges that face society worldwide due to population growth, the increasing demand for natural and energy resources, and its consequences in the social and environmental spheres. The International Union for Conservation of Nature (IUCN) describes that climate change, water and food security, disaster risk, human health, and economic and social development are the main societal challenges in the 21st century (COHEN-SHACHAM *et al*., 2016). Such challenges are closely related to urban environments, as they concentrate 55% of the world's population (HABITAT, 2016). According to Habitat (2016), it is estimated that by 2050 the world's population must reach ten billion, with around 70% of the world's population living in cities.

Since the beginning of the 70s, such challenges have emerged in scientific literature together with concepts and approaches aimed at practices that produce less environmental impact. In the 90s, driven by forums and world meetings, such as Eco-92 and the 1st World Water Forum, a systematic approach was required to investigate the connections between people and nature (COHEN-SHACHAM *et al*., 2016). However, it was just in the 21st century that a greater profusion of sustainable-related concepts took place in scientific research. In this context, concepts like Nature-based Solutions (NbS) emerge.

Despite being recent in the scientific literature, and latest contribution to the green concept family (HANSON, WICKENBERG and OLSSON, 2020), the NbS concept achieves global relevance due to its potential when facing current and future societal challenges. When the International Union for Conservation of Nature (IUCN) published the "Nature-based solutions to address global societal challenges Report" (COHEN-SHACHAM *et al*., 2016), its concept was consolidated, establishing its objectives and principles.

Cohen-Shacham *et al*. (2016) defines NbS as actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits. A set of NbS principles must be considered to provide a conceptual understanding. Among them, the authors highlight that NbS actions can be implemented with or without grey and technological infrastructures, must be applied at the landscape scale, and should be part of the overall design of policies. Such actions do not include interventions that are inspired by nature but those that are built with nature.

Nature-based Solutions is an umbrella concept for ecosystem-related approaches (COHEN-SHACHAM *et al*., 2016). The terminology is recent, but its principles have been applied in practice for much longer through other concepts. In this sense, concepts from different origins converge to a standard and current conceptual need. Urban Hydrology has a range of drainage concepts with a sustainable urban water management approach (FLETCHER *et al*., 2015), which converge to NbS principles. According to Cohen-Shacham *et al*. (2016), NbS actions applied for urban drainage can enhance air quality, support wastewater treatment, reduce stormwater runoff and water pollution, and improve life quality through thermal comfort, visual amenity, and risk reduction.

Urban water dynamics suffer several impacts from increasing urbanization, mainly due to land use changes (CLEUGH *et al*., 2005; SHARMA *et al*., 2008; MITCHELL *et al*., 2008; LEE *et al*., 2010; MEJÍA, 2014, CARVALHO and SANTOS, 2021), river denaturalization (ASSUMPÇÃO and MARÇAL, 2012; CUNHA, 2012), and the intensification of extreme events arising from climate change (ASADIEH and KRAKAUER, 2017; WATER, 2020). Among the main effects on urban water dynamics, the shifts in water balance stand out, with surface runoff increase and evapotranspiration and infiltration decrease (CLEUGH *et al*., 2005; SHARMA *et al*., 2008; MITCHELL *et al*., 2008; LEE *et al*., 2010; MEJÍA, 2014, and CARVALHO and SANTOS, 2021). Hence, peak flows and flood risk are higher during precipitation events. Microclimates and groundwater recharge are also affected, decreasing thermal comfort and water availability.

In 2018, the NbS concept was the theme of The United Nations World Water Development Report, consolidating its role and significance regarding the challenges to water resources. The report discusses water resource demands, including availability, quality, and water-related risks (floods and droughts) (WATER, 2018).

Urban Hydrology has used concepts linked to sustainable water management when seeking solutions to mitigate the adverse effects of urbanization on the water balance by reintroducing natural elements in urban watersheds and reducing risks (FLETCHER *et al*., 2015; ECKART *et al*., 2017). Among such concepts, Low Impact Development (LID), Sustainable Drainage System (SuDS), Water Sensitive Urban Design (WSUD), Re-naturing Cities, Sponge Cities, Green Infrastructure (GI), and Green and Blue Infrastructure (GBI) stand out (FLETCHER *et al*., 2015). As previously mentioned, NbS can gather all these concepts under its conceptual umbrella. According to Fletcher *et al*. (2015), adopting universal terms linked to urban drainage facilitates multidisciplinary dialogue and knowledge profusion.

The association of green concepts and NbS has been carried out in different ways, but no research has specifically explored the relationships between sustainable urban drainage concepts and NbS so far. Hanson, Wickenberg and Olsson (2020) investigate how scientists have used the NbS concept in the scientific literature, driving temporal, ontological and epistemological analysis. They identify links between NbS, green infrastructure, and ecosystem service concepts. They also verify that more than half of the analyzed publications discuss urban environments, and that flood mitigation is the most related sustainability goal.

Ruangpan *et al*. (2020) provide a critical literature review on NbS to reduce hydro-meteorological risks, including floods, droughts, storm surges, and landslides. They identify current knowledge gaps and future research perspectives, pointing out that the number of scientific studies focused on NbS to reduce hydro-meteorological risk continuously increases worldwide. Huang *et al*. (2020) review NbS applied to urban flood control, its benefits and limitations. The authors briefly discuss the concepts that can be covered by NbS but do not establish relations among the concepts' principles and how they have been associated with to NbS. The literature also discusses associations between NbS and GI-BGI concepts in Nesshöver *et al*. (2017) and between NbS and LID in Brasil *et al*. (2022).

Based on the abovementioned issues, this research aims to identify the existing interfaces among Nature-Based Solutions and the Urban Hydrology concepts linked to sustainable drainage. In this sense, we aim to build a review of the different approaches that can be considered NbS related to urban drainage.

2.2 METODOLOGY

Two main steps were employed to identify the existing interfaces among Nature-Based Solutions and the Urban Hydrology concepts linked to sustainable drainage. Firstly, we conducted a theoretical analysis of the six main concepts linked to sustainable urban drainage, analyzing their main characteristics and scope, and establishing their conceptual relationships with the NbS principles. Then, we performed a structured systematic review to identify how NbS and selected concepts have been addressed in the scientific literature. Details of each of the two steps are described below.

2.2.1 Step 01: Selected drainage concepts and NbS principles

The six main sustainable drainage concepts in Urban Hydrology were selected for our study: Low Impact Development (LID), Sustainable Drainage Systems (SuDS), Water Sensitive Urban Design (WSUD), Re-naturing Cities, Sponge Cities, Green Infrastructure (GI), and Green and Blue Infrastructure (GBI). They were selected because they are the most cited terms in peer-reviewed scientific publications in the last decade (FLETCHER *et al*., 2015; RUANGPAN *et al*., 2020; RODRIGUEZ-ROJAS and MORENO, 2022), except Re-naturing Cities. Such term was chosen due to its holistic and integrative character in the river/basin relation.

In this step, we explore the concepts´ history, ontology and epistemology, aiming to understand how interrelated concepts are defined and how the NbS conceptual umbrella can encompass them. To do so, we used the eight principles of NbS established by Cohen-Shacham *et al*. (2016) as a reference and established the relationships based on an interpretative analysis. The results were organized in a Sankey diagram.

The eight principles of NbS are: embrace nature conservation norms (and principles); can be implemented alone or in an integrated manner with other solutions to societal challenges (e.g. technological and engineering solutions); are determined by site-specific natural and cultural contexts that include traditional, local and scientific knowledge; produce societal benefits fairly and equitably, promoting transparency and broad participation; maintain biological and cultural diversity and the ability of ecosystems to evolve over time; are applied at the landscape scale; recognize and address the trade-offs between the production of a few immediate economic benefits for development, and future options for the production of the full range of ecosystems services; are an integral part of the overall design of policies, and measures or actions, to address a specific challenge.

2.2.2 Step 02: Literature search and selection of publications

To analyze how the NbS concept is used and interpreted in peer-reviewed scientific publications, we conducted a domain-based and structured systematic review (PAUL and CRIADO, 2020) based on Tranfield, Danyer and Smart (2003) methodology. After identifying the literature gap and defining the review proposal, we established the protocols for searching the peer-reviewed articles. Web of Science was the chosen platform to collect data from relevant international peer-reviewed journals. The study was carried out by searching for keywords combinations by topic, that is, in the article title, keywords, or abstract. The search was performed only with articles written in English.

The combination of keywords for search are: ‘Nature-based Solutions’ AND ‘urban’ AND ‘drainage’, ‘Nature-based Solutions’ AND ‘urban’ AND ‘Low Impact Development’, ‘Nature-based solutions’ AND ‘Sponge Cities’, ‘Nature-based solutions’ AND ‘Sponge City’, ‘Nature-based Solutions’ AND ‘urban’ AND ‘Green and Blue Infrastructure’, ‘Nature-based Solutions" AND ‘urban’ AND ‘Green Infrastructure’ AND ‘drainage’, ‘Nature-based Solutions’ AND ‘urban’ AND ‘Sustainable Drainage Systems’, ‘Nature-based Solutions’ AND ‘Water Sensitive Urban Design’, ‘Nature-based Solutions’ AND ‘urban’ AND ‘renaturalization’, ‘Nature-based Solutions’ AND ‘urban’ AND ‘renaturing’, ‘Nature-based Solutions’ AND ‘urban’ AND ‘flood’, ‘Nature-based solutions’ AND urban AND ‘best management practices’.

The search was finished in October 2022 and resulted in 319 peer-reviewed manuscripts. After removing duplicates resulting from the use of multiple search strings, 204 manuscripts remained for the abstract screening stage. In this step, we used the following criteria for abstracts selection: (1) research or review articles, excluding editorials and comments (2) manuscripts from high impact journals (impact factor higher than 1.5) and with good quality (3) urban approach (4) sustainable drainage system approach (5) articles that only addressed topics related to management and governance were not selected.

After the abstract screening was completed, 112 articles were discarded. The remaining 92 articles were read in full and used to build up the current research investigation. Full text documents were downloaded by Web of Science using the Federal University of Parana license.

2.2.2.1 Data extraction and analysis

For each one of the 92 selected manuscripts, eleven of questions were systematically applied to extract quantitative and qualitative information for the current analyzes: (1) year of publication (2) scientific journal (3) study type (theoretical, review, modelling, empirical, perception) (4) geographical scope (5) which are the sustainable drainage concepts mentioned in the text? (6) is the NBS concept explicitly defined? (7) how many times is the concept mentioned in the text? (8) in which sections of the manuscript is NbS mentioned? (9) what are the sustainable urban drainage solutions discussed or cited in the text? (10) what are the NbS benefits verified in the research? (11) how the authors relate GI/GBI, LID, SuDS, WSUD, Sponge City, Re-naturing concepts to NbS?

The data extracted from the articles were synthesized in text, tables and graphics for further analysis, report, and recommendations for specific knowledge.

2.3 RESULTS AND DISCUSSION

2.3.1 Nature-based Solutions and urban drainage concepts

2.3.1.1 Low Impact Development (LID)

Among the concepts analyzed in this research, Low Impact Development (LID) was the first to emerge in the scientific literature. It was first mentioned in a land-use planning report in Vermont, USA (BARLOW, BURRILL and NOLFIL, 1977, cited by HUANG *et al*., 2020). Currently, it is part of many urban water management policies in different cities in the United States, Canada, and New Zealand (FLETCHER *et al*., 2015). Through a design-with-nature approach, LID actions attempt to minimize the adverse effects of urbanization on the hydrological dynamic.

Low Impact Development can be defined as micro-scale management practices and impact-minimization measures that control stormwater at the source, changing conventional site design and creating a hydrologically functional landscape that mimics natural watershed hydrology (volume, frequency, recharge, and discharge) (COFFMAN, 2000). Its main objective is to conduct the urban hydrology dynamics closer to pre-development conditions. The small-scale stormwater action function is to evenly distribute slight infiltrations, storage, retention, and detention measures throughout the landscape, where each item in the landscape is designed to provide some beneficial hydrological function (COFFMAN, 2000).

The LID actions include infiltration-based or stormwater-retention techniques. Infiltration-based techniques include swales, infiltration trenches, bioretention systems, sand filters, and porous pavements. Stormwater-retention techniques are wetlands, ponds, green roofs, and rainwater harvesting (cisterns, storage basins) (ECKART, MCPHEE, and BOLISETTI, 2017).

Since the term developed in the 70s, the concept was designed for a growth and expansion context of urban centers. Coffman (2000) and Fletcher *et al*. (2015) point out that the way to apply both concept and actions in an urban density context can be different and challenging. When analyzing peer-reviewed articles with LID application in different contexts over time, Ahiablame, Engel, and Chaubey (2012) and Eckart, Mcphee and Bolisetti (2017) found out that such experiences have come to be successful in many cases, showing great potential for mitigating the effects of urbanization and land development on hydrology, mainly when continued and integrated planning is carried out.

2.3.1.2 Sustainable Drainage Systems (SuDS)

The Sustainable Drainage Systems (SuDS) concept was initially set out by D'Arcy (1998) in the United Kingdom (FLETCHER *et al*., 2015). Butler and Parkinson (1997) developed its principles in the same period. *Sustainable Drainage Systems* are defined as drainage solutions designed to manage environmental risks and improve the built urban environment while simultaneously reducing the problems related to water quantity and quality, maximizing amenities and opportunities for biodiversity (MIGUEZ, VERÓL and CARNEIRO, 2012). In this sense, the effects of implementing a drainage system should not transfer impacts over time and space.

Its objectives, defined by Butler and Parkinson (1997), are: to maintain adequate public health barriers and provide sufficient protection from flooding; avoid local and more distant pollution of the environment; minimize the use of natural resources; be operable in the long-term and adaptable to future requirements. Butler and Parkinson (1997) emphasize the importance of multidisciplinary approaches linked to environmental education. SuDS practical measures include green roofs, porous pavements, swales, dry basins, ponds, infiltration trenches, rain barrels, wetlands, and soakaways (GIMENEZ-MARANGES, BREUSTE and HOF, 2020).

2.3.1.3 Water Sensitive Urban Design (WSDU)

Water Sensitive Urban Design (WSUD) concept originated in Australia in the 1990s. According to Fletcher *et al*. (2015), the concept was first discussed by Mouritz (1992) and later incorporated into stormwater planning and management reports and policies in Australia, New Zealand, and the United Kingdom.

Lloyd, Wong, and Chesterfield (2002) understand the concept as a philosophical approach to urban planning and design that promotes sustainable and integrated urban water cycle management, including water supply, sewage network, and stormwater management. On the other hand, Eckart *et al*. (2017) argue that the term corresponds to a methodology to manage the water balance and quality, maintaining environmental opportunities.

Ashley *et al*. (2018) explain that WSUD is a broad stormwater management strategy that comprises LID and SuDS measures, among others. WSUD actions include pervious or porous pavers, rainwater tanks, harvesting, and reuse, raingardens, buffer strips, bioswales, bioretention systems, constructed wetlands, and tree pits (DONOFRIO *et al.* 2009). Therefore, these are strategies adopted in urban infrastructure planning, aiming to minimize the hydrological impacts caused by urban development on the environment. In general, WSUD assists in flood control, flow regulation, improvements in the quantity and quality of water, and provides reuse of water for non-potable purposes (LLOYD, WONG and CHESTERFIELD 2002; CLEUGH *et al*., 2005). According to Mouritz, Evangelisti and McAlister (2006), this approach represents a significant change in how the hydrological cycle and water infrastructure are considered in the cities and neighborhoods planning at different scales and densities.

The WSUD concept served as an inspiration to develop several Australian urban water balance models for simulating the urban hydrological cycle as an integrated whole, such as Aquacycle (MITCHELL, 2005), IUWM (SHARMA *et al*. 2008), UQV (MITCHELL and DIAPER, 2005), SWITCH (LAST and MACKAY, 2007). Such models are essential tools for both research and planning. Its structures analyze the built drainage systems (stormwater, water supply, and sewage network), the natural drainage systems, and their interactions.

2.3.1.4 Re-naturing cities

Renaturalization was first employed in the hydrological sciences literature around the 2000s, referring to one of the rivers´ recovery approaches. Binder (2001) defines *renaturalization* as a complex process of returning to the sustainable condition of a river, initiated by revitalization principles, preceded by substrates and banks recomposition, humid areas recovery, aquatic fauna and flora recovery, and conservation of natural flooding areas. Binder (2001) highlights that renaturalization does not mean the return to the original landscape unmodified by man but the restoration of the sustainable development of the river.

Recently, the concept has also developed a more systemic approach, considering not only the river conditions but its watershed too (GULSRUD *et al.*, 2018; RAFAEL *et al.*, 2020). This approach considers that rivers result from watershed conditions (CARVALHO, MARANGON, and SANTOS, 2020). In this sense, re-naturing cities through NbS became the theme of the European Union Research and Innovation policy agenda in 2015. The four main goals were enhancing sustainable urbanization, restoring degraded ecosystems, developing climate change adaptation and mitigation, and improving risk management and resilience (EU, 2015).

Based on this modern perspective of renaturalization, De Oliveira (2019) defines the re-naturing cities term as a theoretical framework to orient the integration of the multiple benefits we derive from nature into urban areas based on a holistic appreciation of the interplay of the manifold challenges and opportunities for a systemic integration of grey, green and blue spaces. Its principles include the connectivity network among green and blue spaces, proximity between nature and population, distribution, and accessibility of natural elements in cities, and a multi-scale and multi-functionality approach.

2.3.1.5 Sponge Cities

The Sponge City concept was first proposed in 2012 at the Urban Development and Low Carbon Technology Forum. In 2013, the Government of China adopted the concept to promote its wide adoption to achieve a new model of urbanization for Chinese cities (XIA *et al*., 2017). According to Li *et al*. (2017), a Sponge City refers to sustainable urban development, including flood control, water conservation, quality improvement, and natural ecosystem protection. Thus, cities with a water system that operates like a sponge to absorb, store, infiltrate and purify rainwater and release it for reuse. Such an approach takes inspiration from other sustainable drainage concepts, such as LID, SuDS, and WSUD (LI *et al*., 2017).

Furthermore, Sponge City must adopt the integration of source control measures (such as LID and GI), grey infrastructure (such as the built drainage system, sewage, and water supply networks), and natural elements (such as rivers, lakes, and forests) (XIA *et al*. 2017). The main objectives are to adopt practices to improve control of urban peak runoff, temporarily storing, recycling, and purifying stormwater; to upgrade the traditional drainage systems using more flood-resilient infrastructure and to increase current drainage protection standards using sustainable practices; encourage multifunctional objectives, integrating natural and artificial solutions (CHAN *et al*., 2018). Some of the Sponge City practices are bio-swales, artificial ponds, artificial wetlands, concave green land, cisterns, rain garden system, tree planter system, green/blue roof systems, infiltration planter systems, pervious pavement, underground infiltration, and underground detention (CHAN *et al*., 2018; LI *et al*., 2017, DU *et al*. 2018).

2.3.1.6 Green and Blue Infrastructure (GBI)

Green Infrastructure (GI) concept emerged in the USA in the mid-1990s (FLETCHER *et al*., 2015). Unlike the other concepts analyzed here (LID, SuDS, WSUD, Sponge Cities, and Re-naturing), the GI purpose goes beyond stormwater management. The European Commission (2013) defines GI as a strategically planned network of natural and semi-natural green areas designed to provide a wide range of ecosystem services. Green and Blue Infrastructure (GBI), a concept variation, refers to the network of green (e.g., parks, forests, trees, green roofs) and blue structures (e.g., ponds, rivers, and wetlands) for the same purpose.

When related to stormwater management, especially in urban areas, GI is considered the network of decentralized stormwater management practices that can capture and infiltrate rain where it falls, thus reducing stormwater runoff and improving the health of surrounding waterways (FOSTER, LOWE and WINKELMAN, 2011). GI and GBI make a counterpoint to grey drainage infrastructures. Grey infrastructure is part of a traditional urban water management approach. The aim is to drain stormwater quickly out of the urban environment, reducing the residence time of water in the watershed.

The benefits of replacing grey infrastructures with GI or GBI are widely addressed in the scientific literature, as in Liquete *et al*. (2016), Zimmermann *et al*. (2016), Blau, Luz and Panagopoulos (2018), Castonguay *et al*. (2018), McFarland *et al*. (2019), Radinja *et al*. (2019), Sahani *et al*. (2019), Stefanakis (2019), Alves *et al*. (2019), and Kozak *et al*. (2020). Some verified benefits are flood risk reduction due to the infiltration and water residence time increase, evapotranspiration index increase, thermal comfort enhancement, and the creation of leisure spaces.

According to Shade and Kremer (2019), GI describes the interdependence of land conservation and land development. One of its main characteristics is its multifunctionality, simultaneously providing environmental, social, and economic ecosystem service benefits (CONNOP *et al.*, 2016). GBI actions include green corridors, parks, nature reserves, rivers, streams, lakes, lagoons, open green reservoirs, bioretention basins and floodable parks (KOZAK *et al.*, 2020).

2.3.1.7 Nature-based Solutions: an umbrella concept

Based on the concepts´ analysis, we elaborated Figure 2.1. The image illustrates in a Sankey diagram how drainage concepts are linked to NbS principles and can, therefore, be covered in its conceptual umbrella. On the left side of the diagram are the NbS principles. On the right side are the urban drainage concepts discussed in this research (LID, SuDS, WSUD, Re-naturing Cities, Sponge City, and GI/GBI). The lines link the concepts to each one of the associations made with NbS principles.

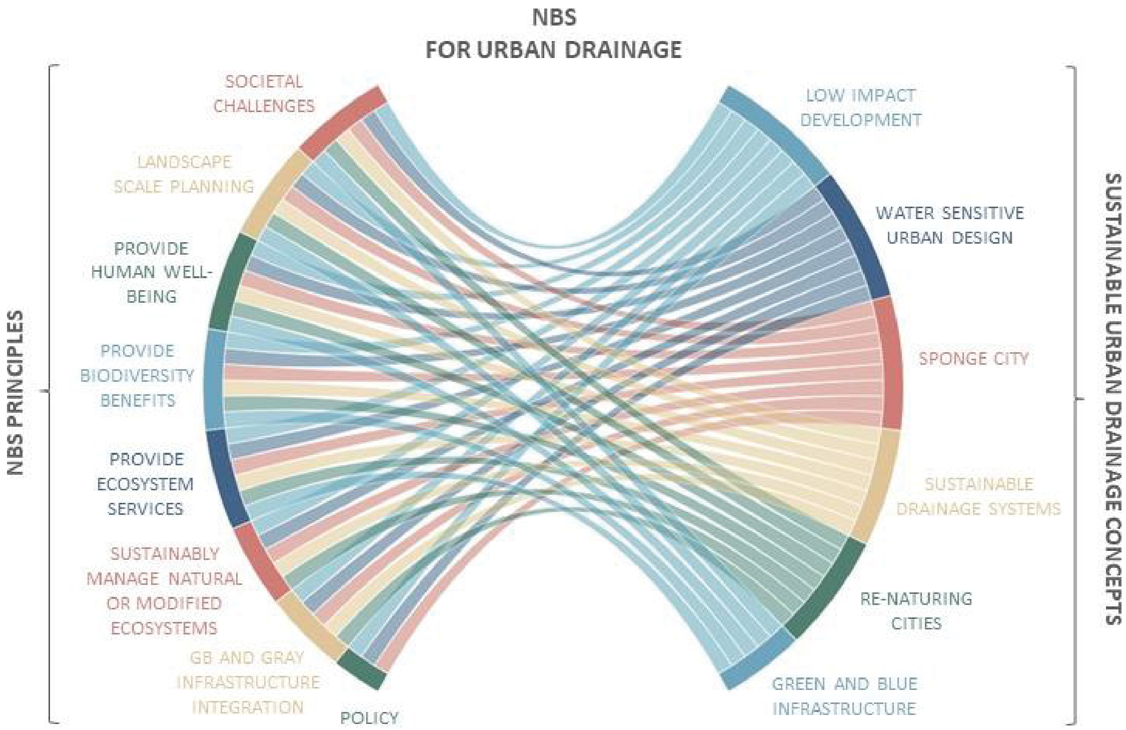

Figure 2.1 - Sankey diagram with the NbS umbrella conceptual model associated with urban drainage concepts.

The integrated analysis shows that most of the NbS principles can be found in the concepts here explored. The results reveal that all concepts can be addressed in some way to the challenges of society listed by IUCN, especially disaster risk, water security, and climate change resilience. Thus, despite having different origins, all they converge to a current conceptual need of society, which becomes visible in the Urban Hydrology field. We highlight that all the concepts attempt to minimize the negative effects of urbanization on the hydrological dynamic, reducing flood risk, improving water quality, air quality, and water harvesting.

Also, all the concepts bring up solutions for sustainably managing natural or modified ecosystems, and all of them aim to provide ecosystem services, human well-being, and biodiversity benefits. Another characteristic common to all concepts is the planning of measures at the landscape scale. Even LID, defined as micro-scale management practices designed to control stormwater at the source, must be implemented throughout the landscape (COFFMAN, 2000).

The NbS principles that are not covered by all the concepts are green/blue/grey infrastructure interactions and policy planning. GI/GBI is the concept that did not cover the joint use of green/blue/grey infrastructures in the analyzed literature. In contrast, most of the authors that discuss GI/GBI understand it as a grey infrastructure opposite and simulate the replacement of one infrastructure to another.

As for Policy planning, the concepts that showed direct relations with policies were LID, WSUD, Re-naturing cities, and Sponge City. LID emerged from applying sustainable urban drainage in land-use planning reports, first in Vermont, then in different cities in the United States, Canada, and New Zealand (BARLOW, BURRILL and NOLFIL, 1977, cited by HUANG *et al*., 2020). WSUD was incorporated into stormwater planning and management reports and policies in Australia, New Zealand, and the United Kingdom (FLETCHER *et al*., 2015). Re-naturing cities through NbS became the theme of the European Union Research and Innovation policy agenda in 2015 (EU, 2015). Finally, the Government of China adopted the Sponge Cities concept in 2013, aiming to achieve a new model of urbanization for Chinese cities (XIA *et al*., 2017).

Despite a few counterpoints among the main characteristics of the analyzed concepts, it is evident that there are more convergences than divergences among them and that, as previously mentioned, they share the same principles and solutions. Our analysis reveals that sustainable urban drainage concepts converge to NbS principles and can be covered by its conceptual umbrella. Thus, a possible path for NbS in Urban Hydrology could be its consolidation as a universal term, able to link urban drainage terms, facilitating multidisciplinary dialogue and knowledge profusion.

2.3.2 Literature synthesis and analysis

The Figures 2.2, 2.3, and 2.4 show infographics composed by the results obtained in the systematic review. Each graph or table is numbered according to the question applied to the manuscripts, as previously described in the methodology. Figure 2.2 shows the results obtained from questions 1 to 4.

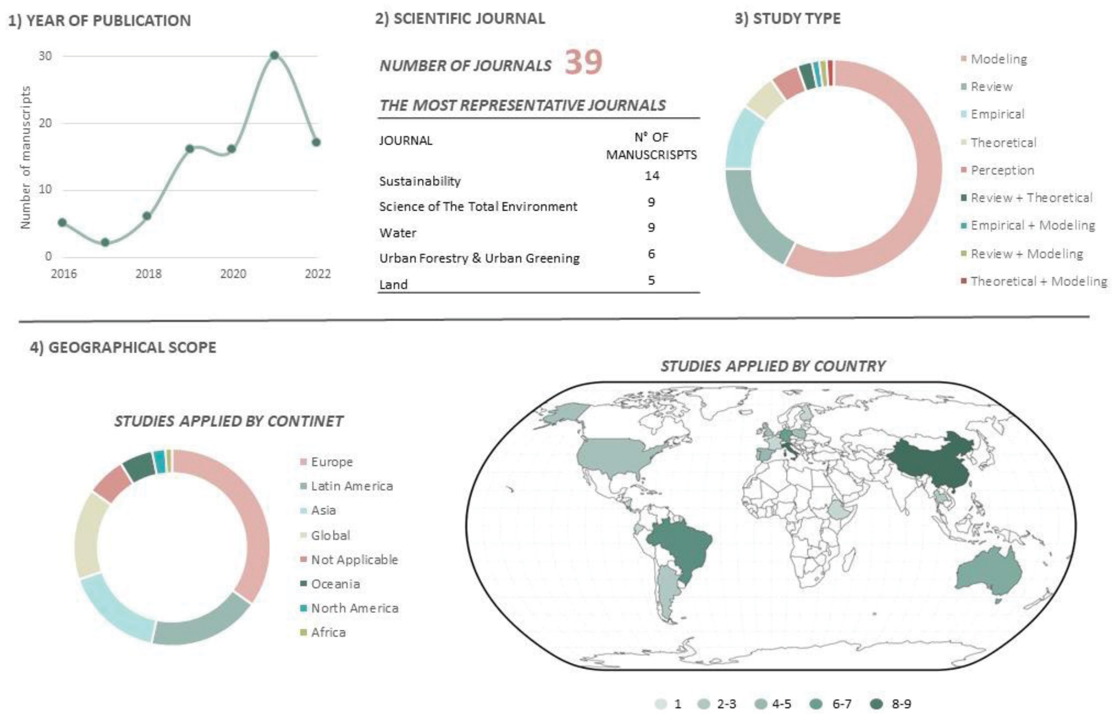

Figure 2.2 - Systematic review results synthesis – questions 1, 2, 3 and 4

The results reveal that the publications that discuss the concepts LID, SuDS, WSUD Re-naturing, Sponge Cities, and GI/GBI associated with NbS are recent in the scientific literature. There have been publications since 2016, the same year that IUCN published the Nature-based Solutions to Address Global Societal Challenges report, proposing NbS definition and suggesting its goals and principles. The increase in the number of publications from 2019 is noteworthy, reaching the highest number (30) in 2021. It happened after NbS was addressed in The United Nations World Water Development Report (Nature-based Solutions for Water) in 2018. Such publication increased the concept's visibility, primarily when related to water management, fostering its approach in scientific research since then. We point out that this systematic review was carried out in October 2022, thus resulting in a lower number of publications in 2022 when comparing to 2021. A new search could be performed after December to verify the actual number of publications, possibly resulting in a growing outcome.

The 92 analyzed manuscripts were published in 39 different scientific journals, showing a spread and decentralized content. *Sustainability* (14) and *Science of the Total Environment* (9) stand out with the higher number of publications. These journals have a systemic and multidisciplinary scope and present high-impact factors. *Water*, a hydrological sciences journal, also stands out with 09 manuscripts. With 06 publications, *Urban Forestry & Urban Greening* is specifically focused on urban green infrastructure use, planning, design, establishment, and management. Finally, within the most representative journals in the sample, *Land* has 05 publications.

The other journals hold from 01 to 04 manuscripts. The scopes focus mainly on Urban Hydrology, ecosystem services, environmental research, and sustainability in urban environments. It is noteworthy that many journals emphasize multidisciplinary and systemic research, such as *Sustainability, Science of the Total Environment, Land, Ecosystem Services, Environmental Management, Environmental process - An International Journal, Environmental Research, Global Environmental Change, International Journal of Environmental Research and Public Health, Journal of Environmental Management* and *Nature Sustainability*, in line with the NbS holistic character (COHEN-SHACHAM *et al*., 2016). Otherwise, a large number of journals from Hydrological Sciences, such as *Environmental Science -Water Research & Technology, Hydrology Research, Journal of Flood Risk Management, Journal of Hydrology, Journal of Hydrology-Regional Studies, Water, Water Research, Water Resources Management* and *Water Science and Technology*, points to the concept deepening and consolidation in the water resources field.

Regarding the types of study, 58% of the sample are modeling type, 17% are review, 10% are empirical, 5% theoretical, and 2% merge review and theoretical approach. With 1% each on, the sample also includes one article that merges empirical and modeling approaches (REY-MAHIA *et al*., 2022), one with review and modeling (CHIA, WANG and CHEN, 2021), and one with theoretical and modeling (BASU *et al*., 2021).

Most of the modeling articles simulate scenarios with NbS implementation and its effects on urban flood mitigation in hydraulic-hydrological models, such as the implementation of green roofs in Sicily/Italy (LA ROSA and PAPPALARDO, 2020), in Cagliari/Italy (CRISTIANO *et al*. 2020) and in Helsinki/Finland (TWOHIG, CASALI and AYDIN, 2022), rain gardens in Shanghai/China (DU *et al*., 2018; SHEN *et al*., 2019), or even combined alternatives such as detention basins, rainwater tanks, permeable pavements in Saint-Martin (ALVES *et al*., 2019) and green roofs, permeable pavements, rainwater tanks and urban agriculture in Rio de Janeiro/Brazil (Ronchi, ARCIDIACONO and ANDREA, 2019). Moreover, others simulate improvements in water quality (SILVA *et al*., 2019; RUBI and HACK, 2021), flood mitigation and thermal comfort (MAJIDI *et al*., 2019), flood mitigation and water harvesting (MACEDO *et al*., 2021). Among the types of modeling, the sample also contains climate change modeling (ZHANG *et al*., 2019; FITOBOR *et al*., 2022), multi-criteria analysis (RADINJA *et al*., 2019; PACETTI *et al*., 2022), and models to identify priority areas for the NbS implementation (VAN OORSCHOT *et al*., 2021; JESSUP *et al*., 2021).

Empirical studies include the implementation of lakes (JURCZAK *et al*., 2017), constructed wetlands (KOTSIA *et al*., 2020), swales (BOOGAARD, 2022), green spaces (GALLI *et al*., 2021), rain gardens (KASPRZYK *et al*., 2022), blue-green roofs (CRISTIANO *et al*., 2022) or combined multiple alternatives (CONNOP, 2016; DUSHKOVA *et al*., 2020; SANCHEZ-ALMODOVAR, OLCINA-CANTOS and MARTI-TALAVERA, 2022). It is noteworthy that all the empirical studies were carried out in European countries, except for Kotsia *et al*. (2020), which does not identify the experiment location, evidencing the continent's leading role when discussing NbS for urban drainage.

Among the sixteen review articles, only eight are specifically directed to the NbS concept. Sahani *et al*. (2019) and Ruangpan *et al*. (2020) review NbS for hydro-meteorological risk management. Huang *et al*. (2020) discuss the benefits and limitations of NbS applied to urban flood control. Brasil *et al*. (2021) evaluate the opportunities in applying real-time control techniques related to NbS for urban drainage. Brasil *et al*. (2022) explore Digital Twins application of NbS for stormwater and water security projects. Qi *et al*. (2020), Bouzouidja *et al*. (2021), and Cui *et al*. (2021), in turn, employ geographically targeted NbS reviews for Chinese Sponge Cities, European experiences from Nature4Cities and Singapore and Lisbon, respectively.

The other review articles (BRINK *et al.*, 2016; VENKATARAMANAN, 2020; AERTS, 2018; RODRIGUEZ-ROJAs and MORENO, 2022; VEERKAMP *et al.*, 2021; LEHMANN, 2021; MATSLER *et al.*, 2021; HAMEL and TAN, 2022) have other central themes linked to urban water management and do not bring NbS as the discussion focus. In Brink *et al*. (2016), Venkataramanan (2020), and Veerkamp *et al*. (2021), for example, the term NbS is cited in the text from one to three times only as a keyword, without necessarily exploring the concept usage in the literature. However, the existence of eight review articles addressing such a recent concept indicates the growing interest of the scientific community concerning this topic, specifically concerning to urban water management.

The same occurs with theoretical articles. Chan *et al*. (2018), Fu *et al*. (2022), and Stefanakis (2019) do not address NbS as a central theme and only mention the concept in the abstract, keywords, or introduction. Fernandes and Guiomar (2018) conduct a conceptual discussion of NbS, emphasizing the need to increase knowledge of their potentialities and limits. Oral *et al*. (2021) discuss urban water management with NbS in circular cities. Basu *et al*. (2021) elaborated a theoretical framework specific to green roofs NbS to assess its performance in mitigating urban floods.

Among the perception studies, we highlight Moosavi, Browne, and Bush (2022) and Bernello, Mondino and Bortolini (2022). Moosavi, Browne, and Bush (2022) investigate the Australian researchers and practitioners' perceptions about NbS for urban water challenges.

Bernello, Mondino and Bortolini (2022) conducted a study on people's perception of NbS for flood mitigation in Veneto/Italy.

Regarding the number of studies applied by continent, Europe has the greater representativeness with thirty-two, followed by Latin America (seventeen), Asia (fifteen), Oceania (five), North America (three), and Africa (one). Fourteen studies have a global approach, and in six manuscripts, the geographic scope is not applicable. Once again, European representativeness is evident, with a spread geographical distribution through ten countries. China stands out in Asia (nine manuscripts), and Brazil in Latin America (five manuscripts).

The Figure 2.3 shows the results obtained from questions 5 to 8.

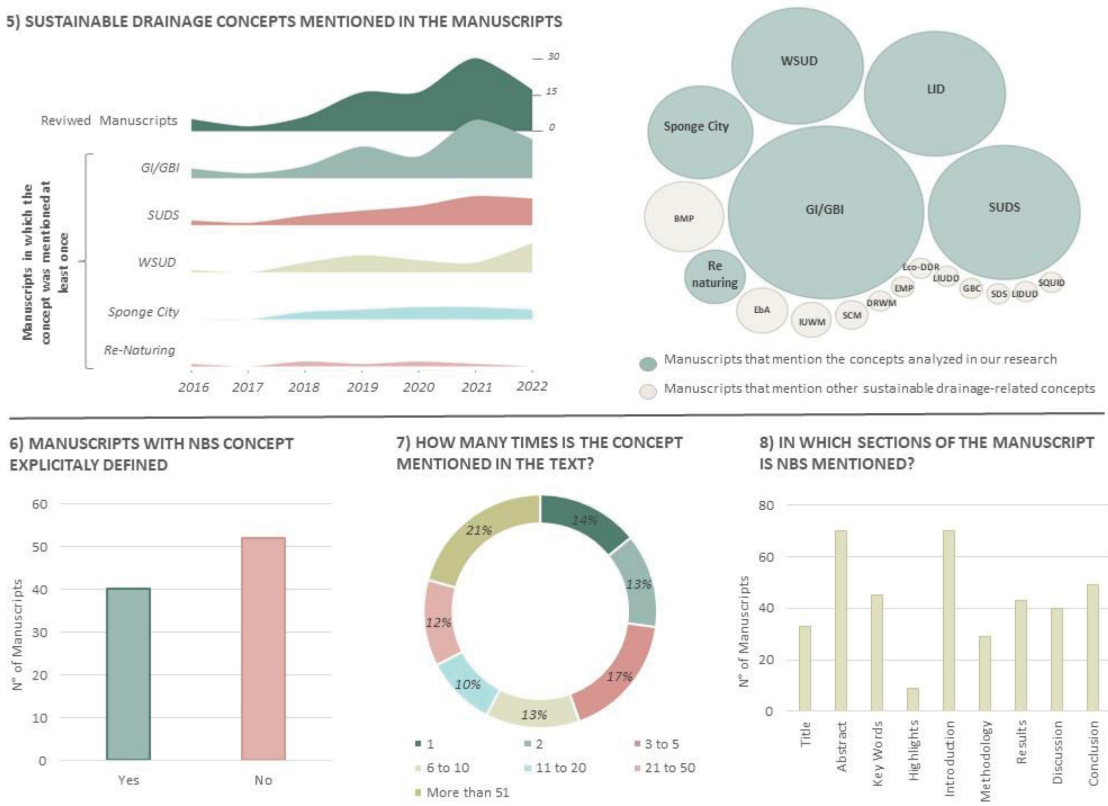

Figure 2.3 - Systematic review results synthesis – questions 5, 6, 7 and 8

We observed an increase in the use of all concepts over time. Among the concepts covered in this systematic literature review, Green Infrastructure (GI) and Green and Blue Infrastructure (GBI) achieved greater prominence, having been addressed in seventy-three of the ninety-two reviewed articles. Subsequently, SuDS is mentioned in forty-four manuscripts, LID in thirty-eight, WSUD in thirty-three, Sponge Cities in twenty-one, and Re-naturing in seven. Twenty-two articles still mention sustainable urban drainage concepts that are not addressed in this research, which indicates a possibility of expanding the current review.

Among such concepts, Best Management Practices (BMP) is the most recurrent with twelve mentions. The other concepts are mentioned from one to five times, with a predominance of only one mention. They are Ecosystem-based Adaptation (EbA) (BRINK *et al*., 2016; ALVES *et al*., 2019; MAJIDI *et al*., 2019; RUANGPAN *et al*., 2020), Integrated Urban Water Management (IUWM) (KOZAK *et al*., 2020; MOOSAVI, BROWNE and BUSH, 2021; SENES *et al*., 2021), Stormwater Control Measure (SCM) (HUANG *et al*., 2020; KOZAK *et al*., 2020), Decentralized Rainwater/Stormwater Management (DRWM) (HUANG *et al*., 2020), Ecological Management Practices (EMP) (SINGH *et al*., 2020), Eco-DRR (RUANGPAN *et al*., 2020), Low Impact Urban Design and Development (LIUDD) (QI *et al*., 2021), Blue-Green Cities (BGCs) (QI *et al*., 2021), Sustainable Drainage Systems (SDS) (BERNELLO, MONDINO and BORTOLINI, 2022), Low Impact Developments Urban Design (LIDUD) (CHAN *et al*., 2018) and Stormwater Quality Improvement Devices (SQUID) (KOZAK *et al*., 2020).

Notably, less than half of the research define the NbS concept. In line with Hanson, Wickenberg and Olsson (2020), if, on the one hand, familiarity with older green concepts facilitates the NbS concept acceptance, on the other hand, the concept is operationally empty in a significant number of publications. Our results reveal that 14% of the articles mention NbS only once in the text, 13% mention it twice, 17% from 3 to 5 times, and 13% from 6 to 10 times. Among them, there is a predominance of using the term in the keyword, abstract, or introduction sections without necessarily defining the concept or its relationship with other urban drainage concepts.

In general, it is in the manuscripts that most mention NbS (10% from 11 to 20 times, 12% from 21 to 50, and 21% more than 51) that the authors discuss the concept in more depth. In these same manuscripts, we note the use of the term in all sections, including the title (thirty-three manuscripts), showing the centrality of NbS in the research discussion.

Finally, Figure 2.4 shows the results obtained from questions 9 to 11.

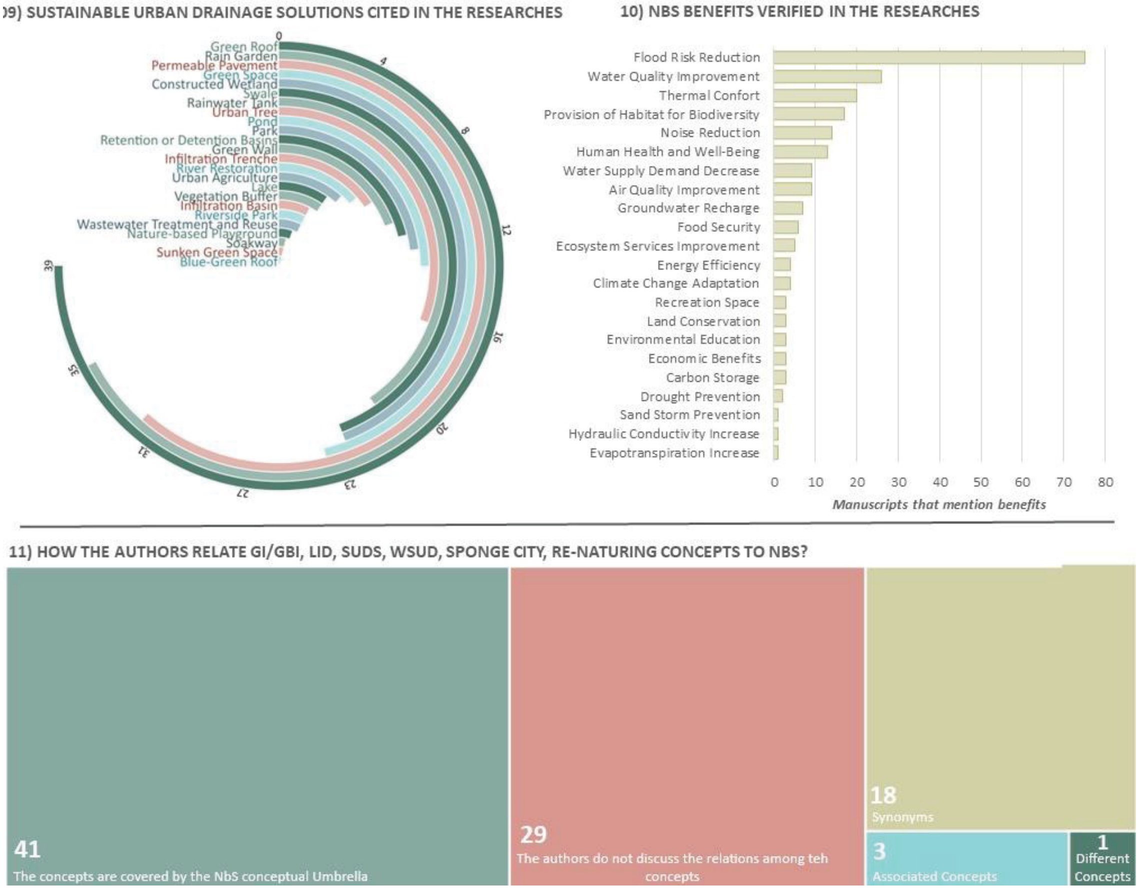

Figure 2.4 - Systematic review results synthesis– questions 9, 10, and 11

We identified twenty-four different sustainable drainage solutions in the manuscripts. Among the most addressed green roofs are in thirty-nine articles, rain gardens in thirty-five, and permeable pavements in thirty-two. Green spaces, swales, rainwater tanks, and urban trees are also mentioned in more than twenty articles.

Among the twenty-two NbS benefits verified in the researches, flood risk reduction is notably the most cited, being in seventy-five articles of the sample, corroborating the findings of Hanson, Wickenberg and Olsson (2020). Then, but with less representation, are water quality improvement (in twenty-six manuscripts), thermal comfort (in twenty manuscripts), and provision of habitat for biodiversity (seventeen manuscripts).

Although the Urban Hydrology research approach, the analyzed studies evidence that, in addition to the benefits verified in the hydrological dynamics, such as the increase in groundwater recharge (ALVES *et al*., 2019; GALLI *et al*., 2021) and evapotranspiration (ZÖLCH, 2017), decrease in runoff (SAMELA *et al.*, 2020; XU *et al.*, 2020; LO *et al*., 2021), peak flow (ZIMMERMANN *et al*., 2016; CHAN *et al*., 2018; QUICHIMBO-MIGUITAMA *et al*., 2022) and water supply demand (KOTSIA *et al*., 2020; MORAVEJ *et al*., 2022), NbS for urban drainage can provide benefits in multiple spheres. Alves *et al*. (2019) identify thermal comfort, recreation space, environmental education, and space for biodiversity as co-benefits of implementing green-blue-gray measures in Saint-Martin. In Derkzen, Astrid, and Verburg (2016), recreation space, noise reduction, carbon storage, thermal comfort, and improved air quality are the identified co-benefits of implementing GI in Rotterdam, Netherlands. Human health and well-being (CONNOP *et al*., 2016; BLAU *et al*., 2018; KEELER *et al*., 2019; RUANGPAN *et al*., 2020; ALVES, DJORDJEVIC and JAVADI, 2022), food security (DUSHKOVA *et al*., 2020), ecosystem services improvement (NCUBE and ARTHUR, 2021; LEHMANN, 2021), energy efficiency (MACEDO *et al*., 2021; REY-MAHIA *et al*., 2022), climate change adaptation (QI *et al*., 2020; SANCHEZ-ALMODOVAR, 2020; SÁNCHEZ-ALMODÓVAR, OLCINA-CANTOS and MARTI-TALAVERA, 2022), land conservation (FERNANDES and GUIOMAR, 2018; STEFANAKIS, 2019; JU *et al*., 2020), economic benefits (HUANG *et al.*, 2020), drought prevention (CUI *et al*., 2021) and sand storm prevention (JU *et al*., 2020) are some examples of other benefits identified in our review. Such results corroborate once again to the NbS holistic characteristic proposed by Cohen-Shacham *et al*. (2016).

Finally, the results obtained from the last question reveal that the way that each author understand the relations among the urban drainage concepts (LID, SuDS, WSUD, re-naturing, Sponge City, and GI / GBI) and NbS are diverse. The different positions are even contradictory and may result in conceptual misunderstandings.

Less than half of the sample (forty-one articles) consider that the NbS conceptual umbrella covers sustainable urban drainage concepts somehow. In some manuscripts, such relationship is clearly given, such as in Fernandes and Guiomar (2018), Keeler *et al*. (2019), Qi *et al*. (2020), Huang *et al*. (2020), Moosavi, Browne and Bush (2021), Qiu, Schertzer and Tchiguirinskaia (2021), and Ruangpan *et al*. (2021). In others, however, the term “umbrella” was not employed, but we comprehend, through text interpretation, that the authors considered it so.

Liquete *et al*. (2016), Connop *et al.* (2016), Zölch (2017), Aerts (2018), Beissler and Hack (2019), Shade *et al*. (2019), McClymont *et al*. (2020), Chen *et al*. (2021), Rosenberger *et al*. (2021), Seyedashraf, Bottacin-Busolin and Harou (2021), Shrestha *et al*. (2021), Talebzadeh *et al*. (2021), Quichimbo-Miguitama *et al*. (2022), for example, consider that the different concepts of sustainable urban drainage are Nature-based Solutions. Yu *et al*. (2019), when investigating the Shanghai residents' willingness to participate in the GI implementation in public and private spaces, argue that NbS are represented by GI. Hysa (2021) comments that BGI can provide multiple ecosystem services and inspire NbS. Pradilla, Lamberty and Hamhaber (2021) affirm that BGI and urban river restoration contribute to a comprehensive NbS framework. Lehmann *et al*. (2021) argue that NbS include several sustainable drainage systems. Dushkova *et al*. (2020), in turn, argue that NbS include the main ideas of GBI, ecosystem services, and biomimicry concepts. The authors highlight that the term GBI is embedded in one of the four objectives of NbS, which is to develop aspects of climate change adaptation and mitigation, including the redesign of human-made infrastructure and the integration of gray with green and blue infrastructure.

With an interpretation of the concept different from the previous ones, eighteen manuscripts consider that NbS and sustainable drainage concepts are synonymous. Kuller *et al*. (2019), when developing the Spatial Suitability ANalysis TOol (SSANTO) to simulate strategic WSUD positions in Darebin/Australia urban area, consider NbS a kind of distributed green stormwater management infrastructure, able to minimize negative impacts of climate change and urbanization in the hydrological cycle and provide ecosystem services. The authors understand NbS, WSUD, LID, and Sponge Cities terms as synonyms. For them, its use varies according to the study location: NbS in Europe, WSUD in Australia, LID in the United States, and Sponge Cities in China. The same understanding of different nomenclatures for different regions of the world is found in Castonguay *et al*. (2018), Du *et al*. (2018), Shen *et al*. (2019), Ju *et al*. (2020), Acosta and Haroon (2021), Bouzouidja *et al*. (2021), and Senes *et al*. (2021).

Among the similarities shared between the concepts, the authors list to mimic natural hydrological processes removed by urbanization (ZHANG *et al*., 2019), local actions for urban water management (JU *et al*., 2020), regulate stormwater in urban areas (PACETTI *et al*., 2022), reduce runoff and provide co-benefits (RADINJA *et al*., 2019), offer solutions based on nature to achieve urban challenges and enhance resilience and ecosystem services (ALVES *et al*., 2019), and promote urban livability (McFARLAND *et al*., 2019).

Three studies in the sample consider that NbS and sustainable drainage concepts are just associated. Such a relationship is discussed between GI and NbS in Zimmermann *et al*. (2016), between Sponge Cities and NbS in (ZHAI *et al*., 2021), and among GI, LID, and NbS in Brasil *et al*. (2021). One article evaluates them as different terms. According to Alves, Djordjevic and Javadi (2022), the main difference is that the NbS focus on providing benefits and co-benefits for society at a broader scale and beyond water-related hazards, while the other concepts are specifically linked to urban water management.

The number of manuscripts that mention NbS and sustainable urban drainage concepts but do not make clear their conceptual relations is noteworthy. There are twenty-two in such condition. In some cases, we note that the relationship is not established because NbS is cited only once as a keyword, making only a small reference to the topic, as is the case of Derkzen, Astrid and Verburg (2016), Chan *et al*. (2018), Macedo *et al*. (2021), Veerkamp *et al*. (2021), Arthur and Hack (2022) and Uribe, Brenes, and Hack (2022). In others, however, such as Shih and Chen (2021), Jessup *et al*. (2021), and Bernello, Mondino and Bortolini (2022), terms are mentioned several times, but the relationship between the concepts is not evident. As it is a recent concept and proposes to encompass ecosystem-related concepts, it seems to be fundamental that the relationships are clearly established so that their use is appropriately applied and operationally valid.

Among the analyzed papers, there is also a set of articles that discuss NbS, urban drainage, and flood risk reduction, but do not mentioning any of the other concepts related to sustainable urban drainage. They are Cristiano *et al*. (2020), Ferreira *et al*. (2020), Kostia *et al*. (2020), Young and Papini (2020), Gali *et al*. (2021), Vojinovic *et al*. (2021), and Cristiano *et al*. (2022). Such a condition can indicate that NbS has started to set up its field on urban water drainage as a base concept for building resilient cities without necessarily referring to the oldest green concepts.

Our results reveal that, despite being recent in the scientific literature, the NbS concept seeks paths to achieve global relevance in the water resources field. It is clear that its principles have been applied in practice for much longer through other sustainable drainage concepts when seeking solutions to mitigate the adverse effects of urbanization on the water balance and that NbS can conceptually gather all those.

In this sense, we recommend that, when linking NbS to sustainable drainage concepts, consider them part of the NbS conceptual umbrella, as Cohen-Shacham *et al*. (2016) proposed in the IUCN report. Furthermore, comprehending its definition and clarifying the relations is essential when merging such concepts. Thus, conceptual confusion, misunderstandings, and ambiguities can be avoided. Finally, NbS reveals itself as a path for consolidating a universal term, able to facilitate multidisciplinary dialogue and contribute to Urban Hydrology knowledge.

2.4 CONCLUSION

Our research investigated the existing interfaces among Nature-Based Solutions and the Urban Hydrology concepts linked to sustainable drainage through theoretical analysis and structured systematic review. Our first contribution refers to the theoretical analysis results, where we attest to the ontological and epistemological coherence of classifying sustainable urban drainage concepts as part of the NbS conceptual umbrella. Despite a few counterpoints among the concepts' main characteristics, it is evident that there are more convergences than divergences among them, that they share the same solutions and converge to NbS principles.

Our second contribution refers to the systematic review results, which detail how the scientific community relates NbS to Low Impact Development (LID), Sustainable Drainage

Systems (SuDS), Water Sensitive Urban Design (WSUD), Re-naturing Cities, Sponge Cities, and Green/Glue Infrastructures (GBI) concepts. The questions applied to each selected manuscript provided a comprehensive view of the strengths and weaknesses in associating the concepts. It also revealed that NbS builds tangible paths to achieve global relevance in the water resources field.

We highlight the predominance of European researches, reflected in the higher number of manuscripts, modeling studies, and the exclusivity in empirical studies. On the other hand, Africa and North America present a reduced number of studies, revealing a significant gap to be filled by the scientific community. Our results also show that, despite the centrality on Hydrological Sciences, the multidisciplinary character is inherent to NbS for urban drainage, mainly reflected in the diversity of environmental, economic, and social co-benefits mentioned in the analyzed manuscripts.

Our results also point to multiple interpretations of the sustainable urban drainage concepts and NbS relation. The different positions are even contradictory and may result in conceptual confusion and ambiguity. The results also show many manuscripts that do not explicitly define NbS and do not explain how it relates to other sustainable drainage concepts.

Based on the results obtained in the two main steps of this research, we conclude that the sustainable drainage concepts here analyzed present all the necessary requirements to be considered as part of the NbS conceptual umbrella. Understanding their definition is essential to avoid conceptual confusion when merging such concepts. As NbS is a recent concept and proposes to encompass ecosystem-related concepts, it seems to be fundamental that the relationships are clearly established so that their use is appropriately applied and operationally valid.

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3. INTRAURBAN SPATIAL CONFIGURATION, HYDROLOGIC SIMILARITY AREAS AND THEIR ROLES IN URBAN DRAINAGE DYNAMICS

Abstract: Hydrologic Similarity Areas (HSA) were delimited in the Belém catchment, and their responses on the water balance were evaluated. For this purpose, a cluster analysis of intraurban spatial configuration patterns was conducted to delimit the HSA, and the urban water balance was performed in the Aquacycle model. We delimited six HSA, whose percentage of impervious areas ranges from 18% to 89%. The method proved to be efficient in grouping areas of similar features. The model calibration resulted in satisfactory adherence of the simulated data to the measured streamflow, with R^2 0.88/NSH 0.86 at the weekly time step, and R^2 0.95/NSH 0.94 at the monthly time step. Indeed, the modeling results show that the intraurban spatial heterogeneity is reflected in the annual and daily water balance. The evapotranspiration rates can represent 25% to 50% precipitation in the different HSA. Moreover, infiltration can be five times higher, and runoff is about 3.5 times lower in HSA I compared to HSA VI. In analyzing the daily events, we identified the areas that most contributed to runoff and those with higher infiltration capacity during flood events. Such results may support future studies on understanding flood dynamics and guide the implementation of sustainable urban drainage solutions that aim to reduce runoff and control flood risk.

Keywords: Urban Water Balance; Aquacycle; Headwater Catchments.

3.1 INTRODUCTION

Understanding urban areas as homogeneous spaces and identifying their standard dynamics in the different fields of geographical analysis are widespread practices in the scientific literature, including Urban Hydrology. Studies relating intraurban spatial configuration to other variables, such as air temperature (LEMOINE-RODRÍGUEZ, INOSTROZA and ZEPP, 2022), relative humidity, wind speed, global radiation, thermal comfort (TOP *et al*., 2020), and concentrations of fine particulate (ASHAYERI *et al*., 2021) have been developed in the field of Environmental Sciences. However, few studies on Urban Hydrology investigate spatial heterogeneity's role in the water balance. Homogeneity conditions are ordinarily assumed, applying average values for an entire urban system. Nevertheless, studying the intraurban spaces' diversity can be crucial to understanding the urban water dynamics, serving as a subsidy for planning and managing the territory.

Urbanization affects the water cycle dynamics, making it more complex and denaturalizing the hydrological processes. Lee *et al*. (2010) identified that the increase of impervious surfaces in the Goonja drainage basin, Seoul, decreased evapotranspiration by 29%, groundwater recharge by 74%, and increased surface runoff by 41% in thirty years, indicating a severe distortion of the water balance. Mejía *et al*. (2014) verified from the application of a stochastic streamflow model in urban basins located in the Baltimore-Washington region that the greater the percentage of impervious areas, the greater the conversion of green water (evapotranspiration) in blue water (streamflow). Wang *et al*. (2021) conclude that the percent imperviousness of urban catchments has a crucial impact on water balances, increasing runoff rates and decreasing groundwater recharge. Haase (2009) verified that the advancing urbanization in Leipzig city caused disturbances in runoff, evapotranspiration, and infiltration patterns. Macdonald *et al*. (2022), in turn, identify a strong correlation between the layout of the built environment and peak flows in a study carried out in residential areas of southern England, which increases the risk of flooding.

Such abovementioned results are, in general, related to entire urban systems. Furthermore, different spaces in the same city are expected to generate different hydrological responses, given the heterogeneity of intraurban spaces. Downtown areas, for example, tend to present more buildings, higher population density, lower vegetation cover, and more impervious areas. In hydrological terms, these characteristics can result in a greater demand for water supply, more wastewater production, lower evapotranspiration and groundwater recharge rates, and higher runoff. Residential neighborhoods, in turn, may present a higher number of gardens and parks and lower population density than downtown, resulting in higher infiltration and evapotranspiration rates and lower runoff. Peripheral residential neighborhoods, however, tend to present a higher density of roofs, less green areas, and greater population density. Different patterns can be found in service, industry, single-family housing, collective housing areas, and many other existing cities' land use, each with different possible hydrological responses.

Notably, the diversity of intraurban spaces can result from spontaneous urbanization or planning actions, and in most cases, both processes simultaneously. Unplanned urbanization is the most common process of expansion in Brazilian cities. The 70s and '80s experienced intense rural exodus, which resulted in the accelerated growth of urban areas. However, some cities, such as Brasilia, planned to have Zoning Laws regulating land use and occupation since their conception. It is noteworthy that, even in planned cities, characteristics resulting from both processes are observed.

Given the watersheds' spatial heterogeneity, Fendrich (2002) argues that for more rigorous assessments of the cities' flood dynamics, it is necessary to quantify the efficiency of runoff in a distributed way, considering the watershed spatial heterogeneity. Donia, Manoli and Assimacopoulos (2013) discuss the importance of identifying the sub-systems areas where decentralized solutions could be promising for water saving.

Some experiences of compartmentalizing urban spaces to understand water dynamics are observed in the scientific literature. However, few studies have specifically addressed such topic, employing systematic and statistically based methodologies.

Lekkas, Manoli and Assimacopoulos (2008) classified the Athens area into five clusters based on the satellite image analysis to simulate the water balance with sustainable water use scenarios. The characteristics analyzed for clusters' delimitation were the number of buildings per block, and residential building characteristics, such as garden area and building height. Lee *et al*. (2010) and Duong *et al*. (2011) carried out analyzes of the urban water balance in the Goonja drainage basin (Seoul) and Tel Aviv (Israel), respectively, fragmenting the study area into sub-catchments. Donia, Manoli and Assimacopoulos (2013) delimited seven clusters in the city of Alexandria, Egypt, to model the urban water system using rainwater and reuse of wastewater. Clusters were also defined based on satellite images. The characteristics analyzed were the type of buildings, open spaces distribution, and population seasonality. Mitchell *et al*. (2008) analyzed the effects of urban design on the water balance dividing Canberra (Australia) per neighborhood. Macdonald *et al*. (2022), in turn, identified different characteristics of land use patterns in residential neighborhoods.

Herein, the Hydrologic Similarity Area (HSA) concept is employed to propose a systematic and statistically based method to define intraurban clusters and evaluate their hydrological responses. The objective of classifying urban space in HSA is to identify areas with the same spatial configuration patterns and, therefore, similar water dynamics. Such patterns of urban configuration denote the highly dependent relationship between the percentage of impervious surfaces and the hydrological processes' denaturalization (CARVALHO, MARANGON and SANTOS, 2020) that are reflected in the water balance (MEJÍA *et al*., 2014).

The particularities of each city's historical processes may result in an infinity of elements available for analyzing the diversity of intraurban spaces. However, regardless of the historical process of city formation, the urban environment presents heterogeneity in the spatial configuration, allowing its compartmentalization into HSA.

Based on the abovementioned issues, this research aims to delimit Hydrologic Similarity Areas in the Belém catchment based on intraurban spatial configuration patterns and evaluate their responses on the water balance, with an emphasis on runoff rates. To do so, we performed hydrological modeling in Aquacycle, a specific model for urban environments capable of representing the complexity of urban water pathways and the responses of different intraurban spaces in the water balance.

In our previous study (CARVALHO and SANTOS, 2021), we started to develop a methodology to compartmentalize urban spaces into HSA. Such a methodology was based on an integrated analysis of Zoning and Land Use Law, demography data, and satellite images. Since we had not used any statistical method, herein we seek to enhance the methodology once initiated, incorporating cluster analysis in identifying and grouping similar areas. Thus, we may statistically ensure that we are gathering the ideal zones into the same group. Previously, we also conducted the Aquacycle model calibration in the Belém catchment. The recent access to detailed streamflow, land use, and water use data also made it possible to enhance the study area's model calibration results.

3.2 STUDY AREA

Located in Southern Brazil, the Belém catchment is the most densely urbanized area of Curitiba. Figure 3.1 provides its location details, the Zoning and Land Use Law distribution, and the area used to calibrate the hydrological model. The catchment has 87.8 km² of drainage area, with an estimated population of five hundred thousand people (IBGE, 2012). The main river is about 17km long and flows into the Iguaçu River, close to the Belém wastewater treatment station (FIGURE 3.1). The Belém catchment encompasses 47 neighborhoods, including downtown. The diversity of spatial configuration patterns is notary, comprising downtown, park, residential, institutional, and service areas.

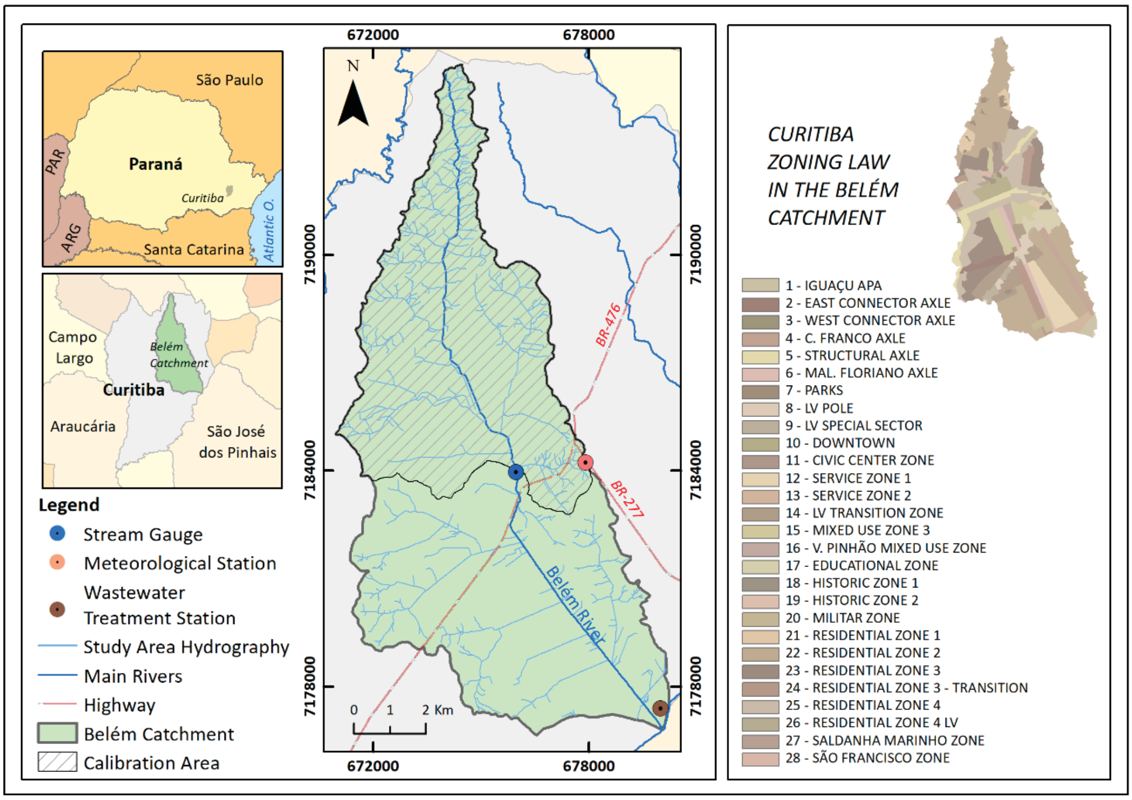


Figure 3.1 - Location map

Despite not being planned since its beginning, Curitiba underwent an urban restructuring between the 1970s and 1990s. Currently, the Zoning and Land Use Law (n° 15.511/2019) makes the city have several spatial patterns arising from planning. Other characteristics, however, result from past or current spontaneous urbanization processes, especially in peripheral neighborhoods. In the Belém catchment, both processes set the intraurban spatial configuration.

The climate in the study area is subtropical, with very distinct seasons, absence of dry months, and well-distributed rainfall, being more expressive during the summer. Based on the climatic data series observed in this research (2003-2017) at station 83842, located in the study area (FIGURE 3.1), the average annual rainfall is 1619mm, and the average number of rainy days is 184 per year. The mean maximum, average, and mean minimum temperatures are 24°C, 19°C, and 14°C, respectively.

Floods are frequent throughout the catchment, especially in downstream areas. Short-term intense rainfall episodes are the primary triggers of urban floods in Curitiba (GOUDARD and MENDONÇA, 2020). They are associated with heavy convective rains during the summer and advancing cold fronts throughout the year. The study area's water dynamic is particularly complex because, in addition to the complexity inherent to the diversity of water pathways in an urban context, the residence time is low. Fortin *et al*. (2020) estimate residence time of 144 minutes in the Belém catchment.

3.3 METODOLOGY

3.3.1 Land use map

The land use map is a crucial data source for two different steps of this research: the HSA delimitation method and the hydrological modeling input data. In HSA delimitation, the percentage of impervious area per zone is one of the four variables that integrate the cluster analysis. In hydrological modeling, land use data is one of the five input data sets required for calibration and modeling. The mapped classes are Garden and Public Open Space (pervious surfaces), Roof, Road, and Paved Area (impervious surfaces).

We mapped based on remote sensing techniques, using the CBERS4A-L4 satellite free image obtained on 05/25/2021. Its WPM camera provides panchromatic and multispectral images with a 2m and 8m spatial resolution, respectively. After concatenating the Blue (B), Green (G), Red (R), and Near Infrared (NIR) bands, we merged them with the panchromatic band through the Pansharpening tool, resulting in an image with a resolution of 2m, which is satisfactorily detailed to map intraurban objects. The algorithm used for fusion was “rcs”.

Then, we segmented and classified the image with the *eCognition 64* object-oriented classification software. We opted for object-oriented classification because identifying intraurban targets is complex and challenging. When using automatic or supervised pixel-by-pixel classification, models tend to mix and confuse classes, given the variety of objects with similar spectral responses (CHEN *et al*., 2009; BHASKARAN, PARAMANANDA and RAMNARAYAN, 2010). Object-oriented classification has been used to identify intraurban targets (CHEN *et al*., 2009; BHASKARAN, PARAMANANDA and RAMNARAYAN, 2010). It can segment the image into objects according to the spectral response of a set of pixels and characteristics such as shape, compactness, or pre-existing vector files.

To perform object-oriented classification, we structured and implemented object segmentation rules and a semantic network (FIGURE 3.2) for classifying intraurban objects in the Belém catchment. Semantic networks are graphs built to represent knowledge, where nodes and arcs are connected, forming groups and subgroups in a hierarchical structure.

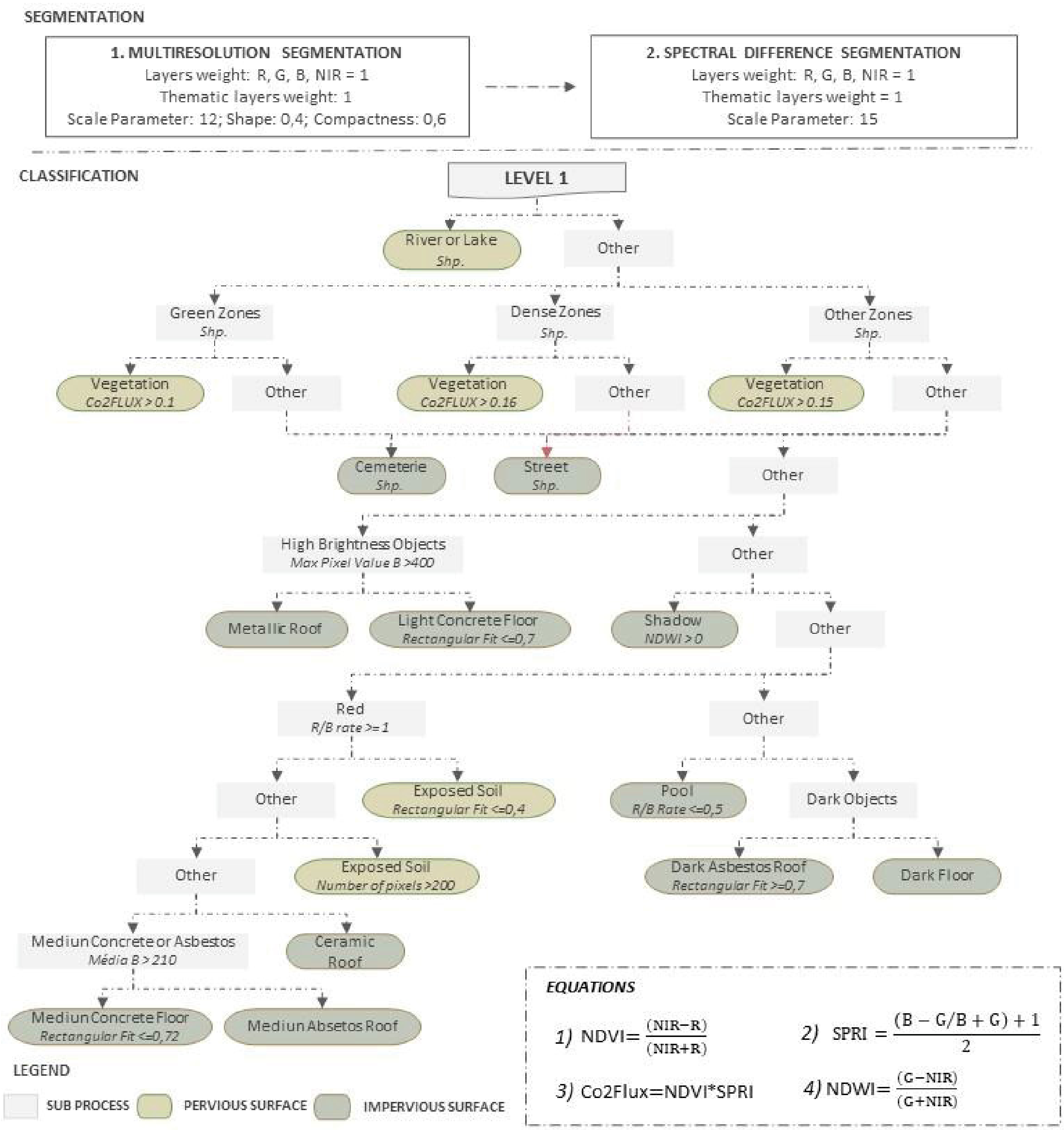


Figure 3.2 - Object-oriented classification semantic network and segmentation rules

Segmentation was performed in multiresolution and spectral difference segmentation steps. For both, all available bands were used, as well as vector files of rivers, lakes, streets, and cemeteries, made available by IPPUC (2022).

Rivers and lakes were the first objects to be classified. Based on the city's zoning, the remaining area was separated into green (areas with vegetated parks), dense (densely urbanized areas, such as the downtown), and other zones. Vegetation was extracted from each of these areas using the Co2Flux index, which integrates two other vegetation indexes: the Normalized Difference Vegetation Index (NDVI) and the Scaled Photochemical Reflectance Index (SPRI) (SILVA and BAPTISTA, 2015). NDVI is often used to measure the object's green intensity (SILVA and BAPTISTA, 2015). SPRI, in turn, indicates the Light Use Efficiency (LUE) (GAMON, SERRANO, and SURFUS, 1997). Integrating NDVI and SPRI indexes enable photosynthetically active targets to be identified, eliminating conflicts with shadow and other green objects (SILVA and BAPTISTA, 2015).

From the remaining area, we firstly separated street and cemetery vectors. Afterward, we identified objects with high brightness by selecting the maximum pixel value (> 400) in the B band, classifying the metallic roofs. Light concrete floors were separated by the rectangular fit (<=0.7). Shadows were classified by using the Normalized Difference Water Index (NDWI). The NDWI index is often used to classify water bodies (McFEETERS, 1996), but as the water had been previously separated, all objects with NDWI < 0 could be classified as shadow. Thereafter, we split the red objects from the remaining area with the R/B band's quotient. Then, a sequence of rules (FIGURE 3.2) divided them into exposed soil, ceramic roof, medium concrete floor, and medium asbestos roof. We classified pool and dark objects from non-red areas, later separated into dark asbestos roof and dark floor.

We emphasize that the classification with the abovementioned objects was conducted to further the distinction among intraurban targets. To adjust classes to Aquacycle model input data, we grouped them into Public Open Space (Rivers, Lakes, Vegetation, and Exposed soil in public spaces), Garden (Lakes, Vegetation, and Exposed soil in non-public spaces), Paved Area (Pool, floor, cemetery, and shadow), Roof (all roof classes) and Road (streets).

3.3.2 The Hydrologic Similarity Areas

To evaluate the intraurban spatial configuration and delimitate the HSA, we conducted a cluster analysis using parameters that could represent zoning and spontaneous urbanization. We also performed a variance analysis to verify the parameter's non-homoscedasticity.

The zoning parameters were obtained from Curitiba Zoning Law (2020), which divides Curitiba's territory establishing criteria for land use and occupation in each zone, such as allowed activities, the maximum number of floors per building, and occupancy rate per lot. The construction pattern in each zone can directly influence current and future urban water dynamics, such as demand for imported water, wastewater production, infiltration, evapotranspiration, and surface runoff. There are 28 zones in the study area (FIGURE 3.1).

The variables selected for analysis after applying non-homoscedasticity test are occupancy rate per lot in collective housing or non-housing buildings, the maximum number of floors allowed in collective housing, the maximum number of floors allowed in buildings for non-residential use, and projected occupancy density. The occupancy rate per lot can directly influence the percentage of impervious areas in each zone. The maximum number of floors per building indicates urban densification. The occupancy density, in turn, directly affects the volume of imported water and wastewater. It can also mean verticalization or soil impermeabilization. As there were no statistically significant differences compared to the other variables, we did not consider the occupancy rate and the number of floors in single-family dwellings for analysis.

The percentage of impervious area was extracted from the previously mentioned land use map and used as a complementary variable in the HSA delimitation. In addition to portraying the effectiveness of planning, the variable also collects information about spontaneous urbanization.

We performed the HSA delimitation with hierarchical cluster analysis, using Ward's method to assemble similar zones. Hierarchical clustering analyzes are used to divide elements of a given sample into groups so that aspects of the same group are similar, based on measured variables. Finally, we generated a dendrogram cut at Euclidean distance 3, resulting in the grouping of zones and the HSA delimitation.

3.3.3 Hydrological modeling

The urban water balance of each HSA in Belém catchment was simulated in the Aquacycle model. Aquacycle is a hydrological model that simulates the urban water cycle as an integrated whole, encompassing natural and built drainage systems in the same modeling framework (MITCHELL, 2005). Its mathematical structure includes the complex dynamics of water pathways in an urban environment. It has been shown to be an effective tool to perform the urban water balance under different conditions (MITCHELL *et al.*, 2008; LEE *et al.*, 2010; ZHANG *et al.*, 2010; DUONG *et al.*, 2011; DONIA, MANOLI and ASSIMACOPOULOS, 2013; CARVALHO and SANTOS, 2021). The conceptual model of the urban water balance in Aquacycle, its main algorithms and some adaptions that we made for Brazilian context are represented in Figure 3.3.

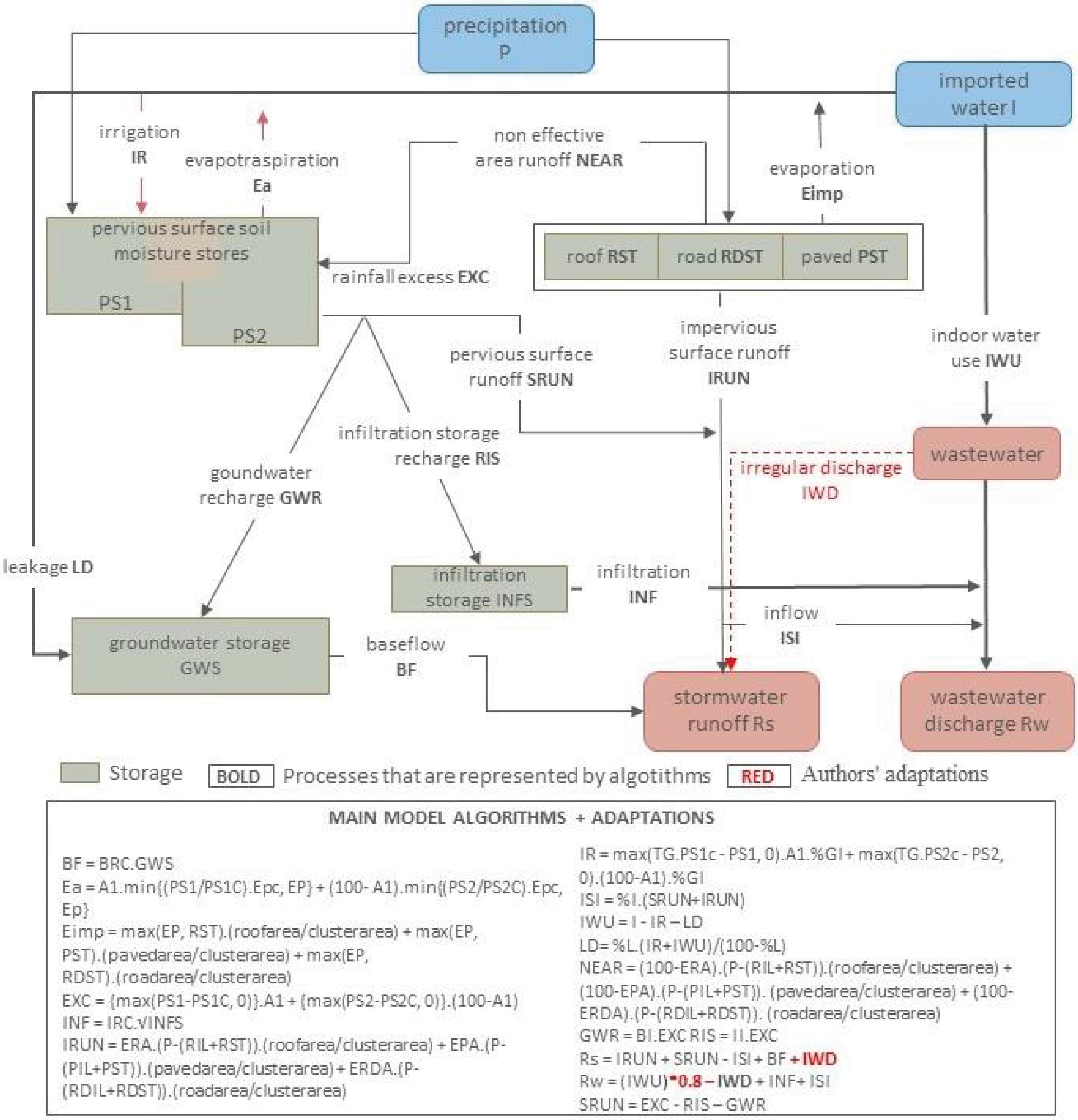


Figure 3.3 - Conceptual representation of the urban water cycle in the Aquacycle model, main model algorithms and our mathematical adaptations (adapted from MITCHELL, 2005).

The model operates with block, cluster, and watershed spatial scales. It allows understanding the effect of individual or sets of elements such as roofs, streets, sidewalks, gardens, or sustainable drainage systems (MITCHELL, 2005). Herein, the clusters were defined as HSA. The model's data output occurs in daily, monthly and annual time scales.

The required input files are climate data, water use, spatial, and calibration parameters (MITCHELL, MEIN and MCMAHON, 2001). Climate data include daily precipitation and potential evapotranspiration (PET). Precipitation and other variables used to calculate PET were obtained from the Curitiba meteorological station (83842) (FIGURE 3.1). We used a 15-year data series (2003-2017) to simulate annual averages, a period with a higher quality of data series and the possibility to fill gaps with nearby station data. Periods from 1999 and 2019 were also modeled separately to simulate specific flood events. We calculated PET by the Penman-Monteith method (PENMAN *et al*., 1948).

Water use data were determined at the watershed scale in daily per capita consumption, which varies from 102 to 291 $L.day^{-1}$ among the neighborhoods in Belém catchment (BREMBATTI, 2014). The average value obtained for the catchment, proportional to the number of residents in each area, was 168 $L.day^{-1}$. The obtained average is lower than that used in Carvalho and Santos (2021) once we simulate the water balance in the whole catchment, including neighborhoods with lower consumption rates.

The spatial parameters include land use data, number of inhabitants per household (average), number of blocks per cluster, and the reticulation system leakage rate. Land use data were obtained from the previously mentioned land use map. The model uses the average household occupancy to determine the water consumption volume in each cluster. Given the large number of non-residential establishments that consume significant volumes of water, we proportionally raised the average occupancy per household to represent the micro measured volumes per pressure zone (SANEPAR, 2010). Finally, the adopted reticulation system leakage rate was 32%, according to estimates by CURITIBA, 2017.

To better portray the water balance in the study area, we made two mathematical adaptations, as illustrated in Figure 3.3. The first one was to include illegal wastewater discharge (IWD) into the drainage system since part of sewage in Brazil is directly dumped into the rivers (IBGE, 2012). The mathematical solution was to add this volume to the reticulated system leakage so that it could be added to the baseflow and, consequently, to the streamflow. We adopted 0.46, the same rate used in Carvalho and Santos (2021). We also adapted the wastewater discharge calculation, including IWD subtraction and multiplying IWU per 0.8, the quotient obtained by wastewater production per water consumption in Brazil (ANA, 2019).

Aquacycle calibration parameters include stormwater, wastewater, and water use variables. The parameters were defined according to the current literature and adjusted based on the simulated and measured hydrograph comparison. The Effective Impervious Area (EIA) was estimated with the Sutherland EIA equation for average basins (SUTHERLAND, 2000). Soil pervious store parameters were selected based on the area lithological characteristics (GIUTSI, 1989; FENDRICH, 2002). The baseflow index and baseflow recession constant were obtained through the Baseflow Filter Program (BFLOW) (ARNOLD *et al.*, 1995).

The fluviometric data, recorded by a limnigraph every 15 minutes, were obtained at the stream gauge 65011400 (FIGURE 3.1). Such time-scale detailing allowed an accurate daily average streamflow calculation, able to consider the complex dynamic of an urban catchment with short residence time. After analyzing data consistency, the years 2010-2013 were selected for calibration and 2007-2009 for validation. We highlight that the calibration is a manual process in Aquacycle.

For calibration, we used the 42.6km² drainage area up to the stream gauge (FIGURE 3.1). The good replication of the quantity (SIM/REC), Nash–Sutcliffe efficiency coefficient (NSE), and determination coefficient (R^2) were used to compare simulated and measured streamflow. The SIM/REC parameter is the sum of simulated flow (SIM) divided by the sum of measured flow (REC). YES/REC = 1 means that the flows are equal over time, although they do not necessarily have the same temporal pattern (MITCHELL, 2005). The NSE coefficient, in turn, evaluates the predictive ability of hydrological models, dividing the variance of the modeled time series error by the observed series variance (NASH and SUTCLIFFE, 1970) (EQUATION 3.1):

$$NSE = 1 - \sum_{i=1}^{n}(OBS_i - SIM_i)^2 \div \sum_{i=1}^{n}(OBS_{i-} - \overline{OBS})^2 \quad (3.1)$$

Where $\overline{OBS}$ is the mean of observed discharges, SIM_i is the modeled discharge, and OBS_i is the observed discharge at time i. Finally, R^2 is a simple linear regression fit measure to the observed values of a random variable.

We calculated the average annual water balance of a 15-year data series (2003-2017), a period with a higher quality of data series, and the possibility of filling gaps with nearby station data. Data were compiled for the Belém catchment and each HSA. We spatialized the data on maps to identify the areas with the highest production of surface runoff as well as the other urban water balance components' behavior. The analyzed parameters are actual evapotranspiration, infiltration, baseflow, runoff, and streamflow.

We also conducted a daily scale analysis on five specific events that occurred in the study area and triggered floods. We selected events that could represent the study area's reality, ranging from regular rainfall (45mm/day: return period < 1 year) to rare extreme events (146mm/day: return period = 100 years). Flood events on the selected dates were confirmed by surveying local newspaper reports. For daily time step evaluation, the analyzed parameters are infiltration and runoff. We calculated the return period (RP) for each rainfall episode using the Gumbel method (GUMBEL, 1941), based on a 30-year rainfall series. The results of each event were organized per HSA into web graphs.

3.4 RESULTS AND DISCUSSION

3.4.1 Hydrologic Similarity Areas

Applying the hierarchical cluster analysis in the study area land use zones resulted in the dendrogram illustrated in Figure 3.4. Cut at Euclidean distance 3, the dendrogram resulted in seven clusters. However, zones 1, 8, 11, and 14 were grouped into a single set, given the reduced area of such zones. Thereby, we obtained the delimitation of six HSA in the study area.

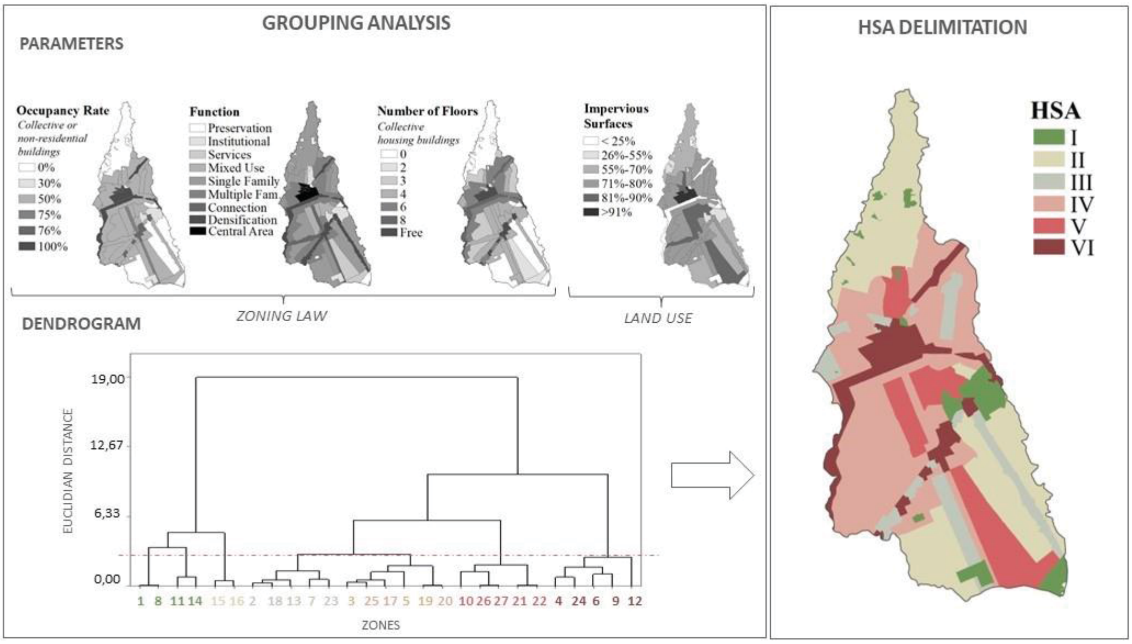


Figure 3.4 - Parameters used in cluster analysis; dendrogram resulting from the grouping of zones; and delimitation of HSA in Belém catchment

The main characteristics identified in the grouped zones are:

- HSA I - With only 4.75km², this cluster comprises two main types of zones: Parks, characterized by preservation and leisure areas, and educational and military institutional zones. In this second type of use, the occupancy rate is 30%, and the number of floors in collective housing and non-residential buildings is four. In general, the occupancy density is low. Impervious surfaces represent 18% of the HSA.
- HSA II: With 26.18km², the HSA II comprises single-family housing areas. The occupancy rate is 50%, collective housing buildings are not allowed, and the number of floors in non-residential buildings is 2. The occupancy density is low, and the impervious surfaces represent 66% of the HSA.
- HSA III: With 7.44km², the HSA III is composed of densification, transition, and historic zones. The occupancy rate allowed is 50%, and the number of floors in collective housing and

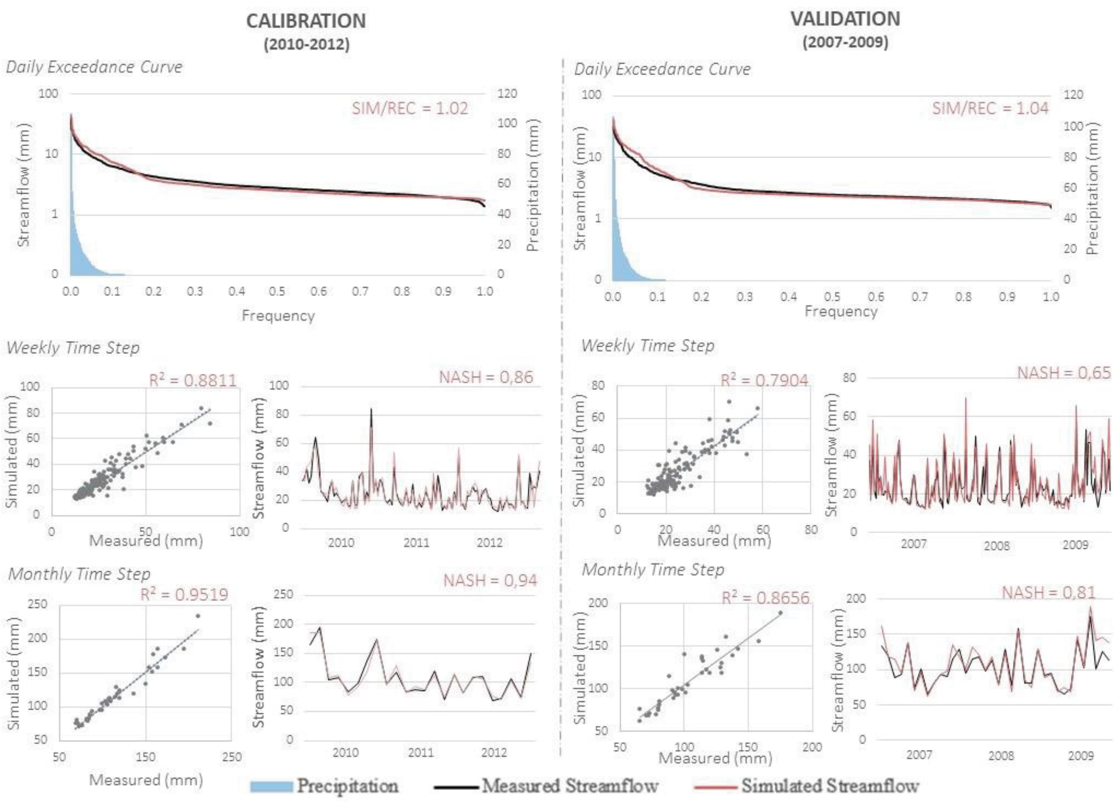
non-residential buildings varies from 4 to 6. The occupancy density is medium, and the impervious surfaces represent 76% of the HSA.

- HSA IV: With 30.4km², the HSA IV comprises connection zones and medium to high density housing areas. The occupancy rate varies from 50 to 75%, the number of floors allowed in collective housing buildings varies from 2 to 6, and the number of floors in non-residential buildings from 3 to 4. The impervious surfaces represent 78% of the HSA.
- HSA V: With 10.87km², the HSA V is composed of service, mixed-use, and public institutional zones. The occupancy rate is 50%, the number of floors in collective housing buildings varies from 2 to 6, and the number of floors in non-residential buildings from 2 to 4. The occupancy density ranges from medium to high surfaces, and the impervious represent 83% of the HSA.
- HSA VI: With only 7.95km², the HSA VI comprises downtown, densification, and connection zones. The occupancy rate varies from 76% to 100%, the number of floors in collective housing and non-residential buildings from 3 to free. The occupancy density is high, and the impervious surfaces represent 89% of the HSA.

The analysis of the main characteristics gathered in the HSA, both those linked to the zoning law and percentage of impervious area, shows that the method is efficient in grouping areas of similar features. We notice an increase in urbanization, densification and soil impermeabilization rates as we proceed with the analysis from HSA I to HSA VI.

3.4.2 Calibration and validation

The access to some data once unavailable during our previous research (CARVALHO and SANTOS, 2021), such as the gauge height recorded every 15 minutes and updated Curitiba´s water use data, enhanced calibration and validation performance. In an urban watershed with low residence time, the mean daily streamflow obtained through the gauge height measured at 7 am, and 5 pm often does not represent the natural water dynamics. The mean daily streamflow obtained by registering gauge heights every 15 minutes, in turn, can better represent streamflow variations concentrated at specific times of the day. Figure 3.5 shows the results obtained in Aquacycle calibration and validation processes on weekly and monthly scales, as well as the adopted parameters. The figure also contains daily exceedance curves comparing measured and simulated streamflow data.



CALIBRATION PARAMETER	UNIT	ADOPTED VALUE
Per cent area of pervious store 1	%	40
Capacity of pervious store 1	mm	15_40
Capacity of pervious store 2	mm	90
Roof area maximum initial loss	mm	4
Effective roof area	%	Sutherland Equation per HSA
Paved area maximum initial loss	mm	4
Effective paved area	%	Sutherland Equation per HSA

CALIBRATION PARAMETER	UNIT	ADOPTED VALUE
Road area maximum initial loss	mm	4
Effective road area	%	Sutherland Equation per HSA
Base flow index	ratio	0.72
Base flow recession constant	ratio	0.0163
Per cent of surface runoff as inflow	%	45
Garden tigger-to-irrigate	ratio	0
Public open space tigger-to-irrigate	ratio	0

Figure 3.5 - Calibration parameters adopted for Belém catchment and calibration and validation results: daily exceedance curves; SIM/REC results; linear regression, R^2, discharge hydrograph and NSE at weekly and monthly time steps

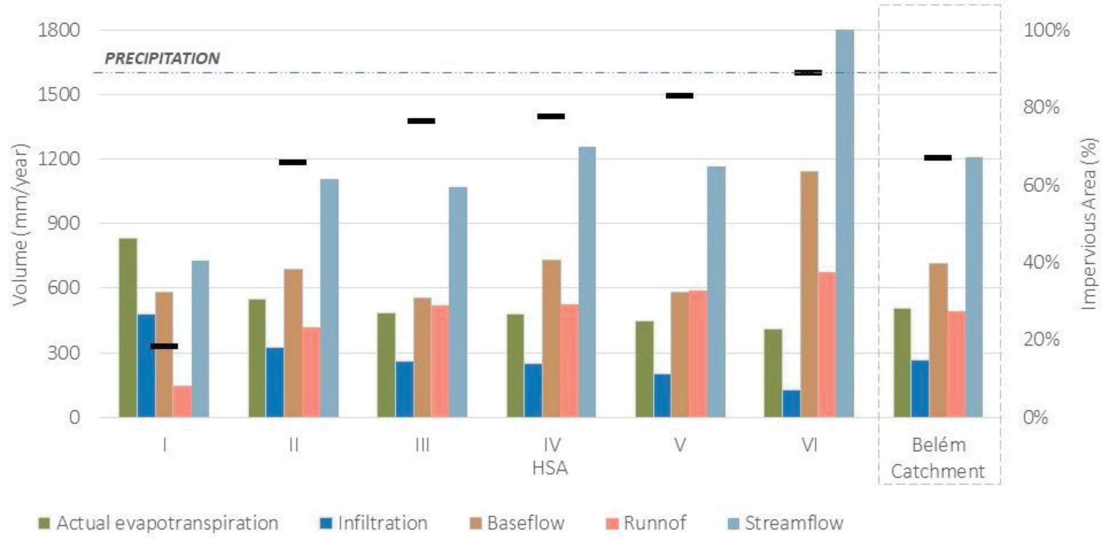
The results obtained on the calibration demonstrate satisfactory adherence of the simulated data to the measured streamflow. An improvement in the calibration fit is observed when compared to Carvalho and Santos (2021). In the 2010-2012 period, the SIM/REC resulted in 1.02, a value considered perfect in terms of adequacy performance (MITCHELL, 2005). At the weekly time step, R^2 resulted in 0.88 and NSH in 0.86. The values are also considered good, according to Mitchell (2005). Furthermore, the calibration results enhance at the monthly time step, where R^2 is 0.95, and NSH is 0.94.

We observe a good fit of simulated streamflow in the exceedance curve, with minor negative variations among 0.2 and 0.4 frequencies. Moreover, there are slight positive deviations among 0.05 and 0.15 frequencies, characterized by rainfall days. Such deviations result from the characteristics of this urban catchment, which present sub-daily behavior of data. However, we used sub-daily data to calculate the mean daily streamflow, some limitations are inherent to the modeling process in Aquacycle (MITCHELL, 2005). Such limitations make the model unable to accurately replicate all the variations in the rainfall-streamflow ratio that occurs during the day, especially in an area with such a low residence time.

The validation, carried out in the 2007-2009 period, SIM/REC resulted in a good performance of 1.04. At the weekly time step, R^2 obtained is 0.79, and NSH is 0.65. The results were also enhanced at the monthly time step, such as in the calibration process, with R^2 resulting in 0.86 and NSH in 0.81. The graphs reveal that the model could reproduce the hydrograph behavior satisfactorily over time in the adopted temporal analysis scales.

3.4.3 The HSA´s water balance

With the simulation performed in the Aquacycle model, we assessed the results in annual and daily time scales for each HSA and for the whole catchment. Figure 3.6 synthesizes the results obtained on a yearly scale for the 2003-2017 period. The graph displays the Eto, infiltration, baseflow, runoff, and streamflow results per HSA and for Belém catchment, with their respective values described below. The percentage of impervious areas is illustrated on the secondary axis. Note that the numbering of the HSAs is on a scale of increasing impermeability, where HSA I is the most pervious (18%), and HSA VI is the most impervious (89%). The figure also shows the variables´ spatial distribution on the study area.



Actual evapotranspiration	Infiltration	Baseflow	Runnof	Streamflow	
832	480	580	146	726	HSA I
548	322	686	420	1106	HSA II
483	258	552	519	1071	HSA III
477	250	728	526	1254	HSA IV
446	200	582	586	1168	HSA V
411	128	1139	676	1815	HSA VI
508	268	712	495	1207	Belém Catchment

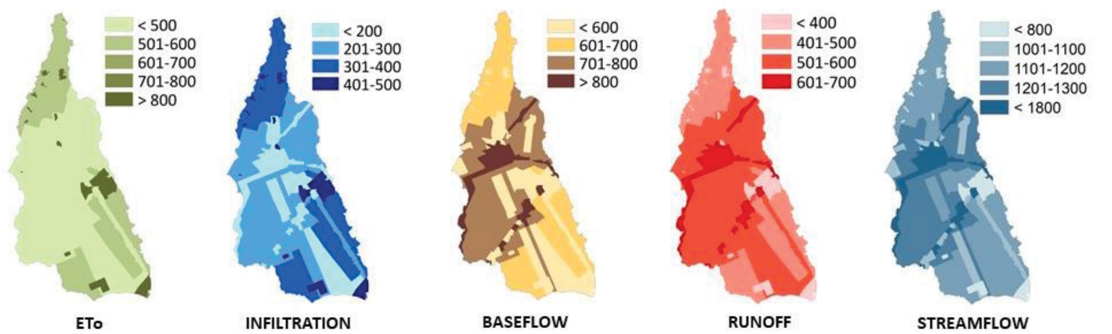


Figure 3.6 - Annual water balance per HSA and annual ETo, infiltration baseflow, runoff and streamflow spatial distribution

As observed by Mejia *et al*. (2007), Carvalho and Santos (2021) and Wang *et al*. (2021), the runoff is directly proportional to the rate of impervious area. Eto and infiltration parameters, in turn, are inversely proportional to the percentage of impervious area.

With 832mm/year, Eto fits 51% of the rainfall volume in the HSA I. From HSA II, Eto substantially decreases, resulting in 548mm/year. As the percentage of impervious areas increases, such a reduction proceeds, reaching 411 mm/year in HSA VI, representing only 25% of the precipitation. The average for the catchment is 508mm/year, resulting in 31% of the rainfall volume.

The role of vegetated areas in increasing Eto in urban areas is evident when we remove HSA I from Eto calculation in the Belém catchment. Even representing only 5% of the total catchment area, its absence can reduce the Eto volume to 463mm/year, that is, a 9% reduction in the annual Eto volume. Thereby, we verify that small urban green spaces distributed throughout the Belém catchment can contribute to control urban microclimate functions related to evapotranspiration, such as air temperature and humidity regulation.

The infiltration parameter rate also decreases as the percentage of impervious areas increases. At HSA I, the groundwater recharge volume (480mm/year) is about three times higher than the runoff volume (146mm/year) and represents 30% of rainfall. From HSA II onwards, we verify that the infiltration is always smaller than the runoff. The difference grows until the HSA VI, where the infiltration (128mm/year) is about five times smaller than the runoff (676 mm/year), representing only 8% of rainfall. In the study area, infiltration (268 mm/year) represents 17% of precipitation and is less than twice as low as runoff (495 mm/year).

Runoff, a parameter deeply related to the risk of flooding in urban headwater catchments, reveals to be susceptible to the increase of impervious areas. Its volume varies from 146 mm/year on HSA I to 676 mm/year on HSA VI. In the Belém catchment, the average value is 495 mm/year. Converting the produced volume from mm to m^3, we notice that, despite the HSA V and VI, which have an impervious surface greater than 80%, even though they represent 21% of the catchment area, together, they produce 27% of the total runoff. HSA I and II, in turn, which represent 35% of the total area, produce the same 27% runoff. Such results point to the areas with the most significant relative weight in the contribution of water volume to flood events. They may support future studies related to understanding the flood dynamics and guide the implementation of sustainable urban drainage solutions that aim to reduce runoff and control flood risk.

As expected for urban catchments, Eto, infiltration, and runoff depend on precipitation and the percentage of impervious areas. However, the results suggest that baseflow and streamflow do not present such a dependence relation. For the Belém catchment, the contribution of IWU and IWD to the baseflow and streamflow makes such parameters influenced by population density and water use. In these cases, the population density will display an essential role in annual baseflow and streamflow composition.

The streamflow in the HSA VI is about 650mm larger than the precipitation. Further, HSA´s II, III, IV, and V streamflows are lower than rainfall, but they have almost the same value, again evidencing IWU and IWD contribution. We highlight that IWU and UWD values are practically constant over time and not significant contributors to flooding events. Among the analyzed parameters, infiltration and runoff reveal to be the most relevant parameters for understanding flood dynamics.

Beyond yearly study, we also conducted a specific daily time scale analysis on five events that occurred in the study area and triggered floods. Figure 3.7 illustrates the five events with the rainfall volume, RP calculated with the Gumbel method, and runoff and infiltration results generated in the Aquacycle model, organized by HSA into web graphs. There are also distribution graphs with the percentage proportion of the HSA´s area, runoff production, and groundwater recharge.

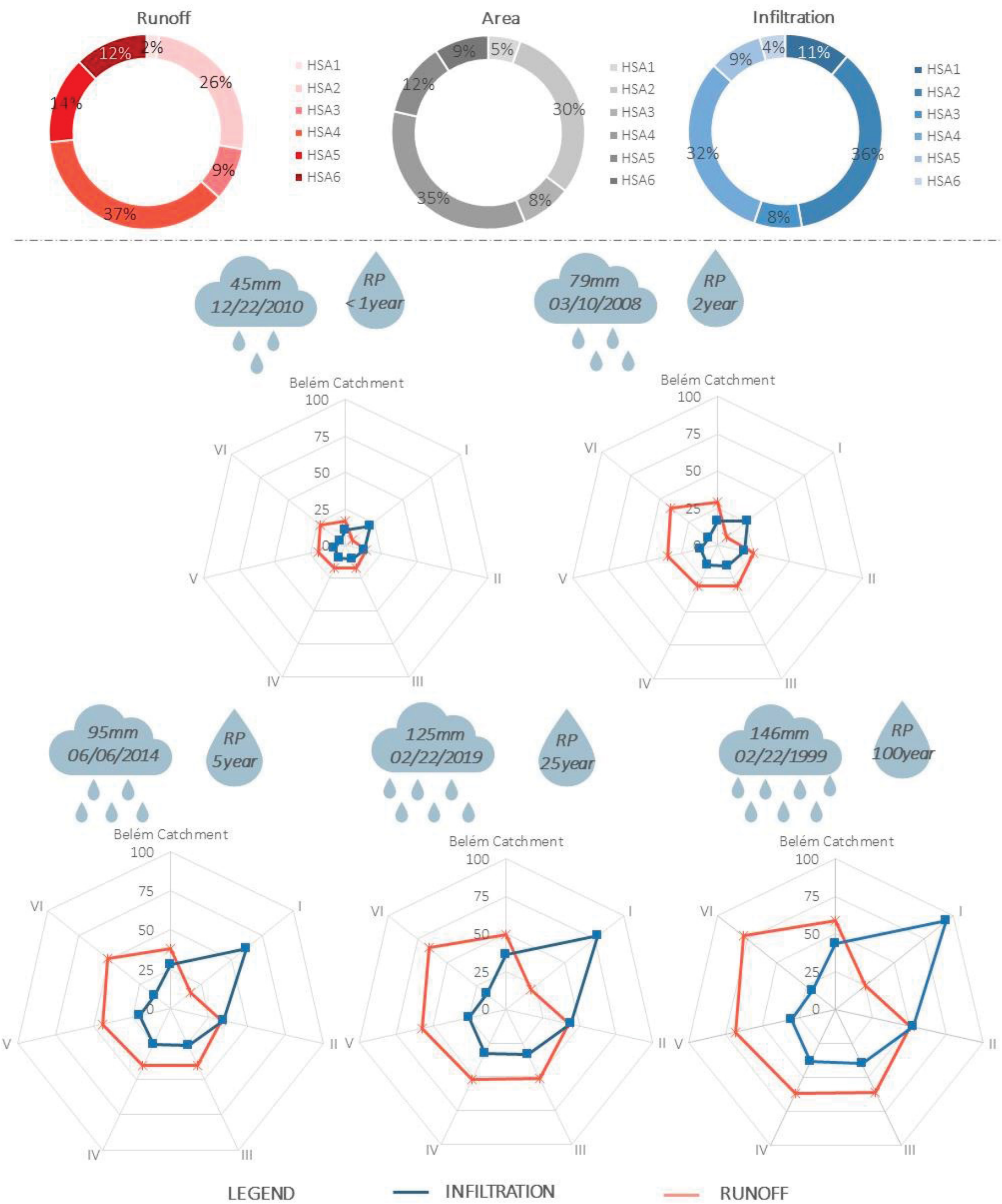


Figure 3.7 - Daily runoff and infiltration results for specific flood events in Belém catchment

As previously mentioned, we selected events that could represent the study area's reality, ranging from regular rainfall to rare extreme events. They are 22/02/1999, 10/03/2008, 22/12/2010, 06/06/2014, and 22/02/2019. All the selected events are intense short-term rainfall. Some are associated with heavy convective rains during the summer under higher antecedent humidity conditions. Others are associated with advancing cold fronts with lower antecedent humidity conditions during the winter. The results show that the proportions of runoff and infiltration parameters are always similar between the HSA.

In the HSA I, characterized predominantly by vegetated areas, we observe a high capacity for rainwater infiltration, even during extreme events (RP 25 or 100 years). The simulation results show that the HSA can absorb up to 65% of the precipitation through groundwater recharge. Figure 3.7 illustrates an increase in runoff as the precipitation rises. Even so, such an increment is much smaller than the increment in infiltration in absolute values.

Encompassing only 5% of the catchment area, HSA I contributes 2% of the total runoff and 11% of the water infiltrated in the study area during the analyzed events. Therefore, HSA I reveals to be an essential area for groundwater recharge and for urban floods amortization in the Belém catchment.

The HSA II, composed of residential areas with lower population density, also proves to be resilient in the analysis of simulated events. Infiltration and runoff values are almost always similar among them, respectively, 13mm and 14mm on 22/12/2010, 34mm and 33mm on 06/06/2014, and 44 and 43 on 22/22/2019. Encompassing 30% of the study area, HSA I contributes 26% of the runoff and 36% of the infiltration.

From the HSA III, gradual gaps among the resulting values for infiltration and runoff are observed, characterized by the growth in the runoff volume to the detriment of infiltration. The behavior of HSA III and HSA IV are similar in all rainfall events, resulting in 31mm of runoff and 15mm of infiltration in a 2-year RP rainfall and 52mm of runoff and 32mm of infiltration in a 25-year RP rainfall. Representing 8% of the study area, HSA III contributes 9% of the runoff and 8% of the infiltration. HSA IV, in turn, represents 35% of the study area, contributing 32% of the infiltration and 37% of the runoff. On average, 41% of precipitation is converted to runoff.

With higher percentages of impervious areas, the HSA V and HSA VI present the most significant absolute difference between the analyzed parameters, being the major contributors to runoff. In HSA V, runoff is about 2.5 times greater than infiltration. In HSA VI, the difference is about four times. Encompassing 9% of the study area, HSA V contributes 14% of the runoff and 9% of the infiltration. The HSA VI, in turn, represents 5% of the study area, contributes 12% of the runoff generation, and only 4% with the infiltration. In the 25-year RP event, HSA VI generates 66mm of runoff, while in a 100-year RP event, such value rises to 78mm. Thus, about 45% of precipitation is converted to runoff in HSA V, whereas this percentage reaches 52% in HSA IV.

Finally, our modeling results show that the intraurban spatial heterogeneity is reflected in the HSAs' annual and daily water balance. Severe distortion could be observed in infiltration, evapotranspiration, runoff, and baseflow rates in the Belém Catchment due to urbanization, corroborating Lee *et al*. (2010). Nevertheless, such distortions are verified in different proportions depending on the intraurban spatial configuration, specially related to the percentage of impervious surfaces. Given the watersheds' spatial heterogeneity and the variability of their responses on the water balance, studying the intraurban spaces' diversity reveals to be crucial to comprehend the urban water dynamics, serving as a subsidy for planning and managing the territory.

3.5 CONCLUSIONS

In this research, we delimited Hydrologic Similarity Areas (HSA) in the Belém catchment and evaluated their responses on the water balance respectively through cluster analysis of intraurban spatial configuration patterns and hydrological modeling. Firstly, our research contributes to investigating spatial heterogeneity's role in the water balance. Homogeneity conditions are ordinarily assumed in the literature, applying average values for an entire urban system. Nevertheless, studying the diversity of intraurban spaces in the Belém catchment reveals the variability of responses in the annual and daily water balance verified among the HSA.

In this research we also enhanced the methodology to delimitate HSA proposed in our previous work, employing systematic and statistically based methods. The insertion of cluster analysis using parameters that could represent zoning and spontaneous urbanization proved to be effective in identifying areas with the same spatial configuration patterns and, therefore, similar water dynamics. We emphasize that the particularities of each city's historical processes may result in an infinity of elements available for analyzing the diversity of intraurban spaces. However, regardless of the historical process of city formation, the urban environment presents heterogeneity in the spatial configuration, allowing its compartmentalization into HSA.

Concerning the hydrological modeling process, improvements are observed in the quality of input data and in the Aquacycle model calibration compared to our previous study. The modeling results show significant variability in the responses of the water balance parameters in the HSA, linked primarily to the percentage of impervious areas. The evapotranspiration rates can represent 25% to 50% precipitation in the different HSA. Moreover, infiltration can vary up to 5 times, and runoff up to 3.5 times among the HSA.

The role of vegetated areas in increasing evapotranspiration and infiltration rates, consequently contributing to microclimate and flood regulation, was evidenced. Even representing only 5% of the catchment area, small urban green spaces distributed throughout the Belém catchment, represented by the HSA I, can contribute with 11% of the groundwater recharge volume and 9% of the evapotranspiration of the study area. On the other hand, the HSA with a higher percentage of impervious surfaces revealed to be the major contributor to runoff, with lower rates of infiltration and evapotranspiration.

Such results point to the areas with the most significant relative weight in the contribution of water volume to flood events. Thus, they may support future studies related to understanding flood dynamics and guide the implementation of sustainable urban drainage solutions that aim to reduce runoff and control flood risk.

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4. ASSESSING URBAN FLOOD DYNAMICS AT DIFFERENT RETURN PERIODS WITH AQUACYCLE AND HEC RAS MODELS

Abstract: This research describes flood dynamics in the Belém catchment (Curitiba/PR), identifying flood extent and depth at different return periods (RP) and the streamflow contribution of Hydrologic Similarity Areas (HSA) under intense rainfall conditions. To do so, we conducted hydrological modeling in Aquacycle to elaborate the streamflow map and to support steady flow calculation. The hydraulic modeling, in turn, was set and calibrated in HEC RAS to simulate areas susceptible to floods at 2, 5, 25, and 100 RP. Our results show an increase of 50% in the extent of flooded areas from a 2-year RP to a 5-year RP event, 40% from a 5-year RP to a 25-year RP event, and 20% from a 25year RP to a 100-year RP event. Areas susceptible to flooding were identified in all modeled reaches, emphasizing downstream areas. The results also reveal a wide variation in streamflow volume among the HSA in all the simulated events and that the most susceptible to flooding areas are not necessarily the main contributors to streamflow. Thus, the intensification of soil sealing in upstream areas results in outstanding runoff production. In association with rectification works that increase the streamflow speed in those areas, impacts are transferred downstream, affecting the areas that least contribute to the streamflow in the Belém catchment. Furthermore, the higher the percentage of impervious areas, the sooner intense rainfall episodes are converted into higher and faster peak flows, intensifying flash floods.

Keywords: Flash Floods; Peak Flow; Hydrologic Similarity Areas; Short-term Intense Rainfall

4.1 INTRODUCTION

Urban floods are one of the most frequent and representative water resources-related disasters affecting human society (UNESCO, 2021). Therefore, studies have deepened discussions on floods´ causes, effects, dynamics, mitigation alternatives, and increasing urban resilience (TENG *et al*., 2017). According to UN-Habitat (2016), 1.2 billion people live in areas susceptible to flooding, most of whom live in urban areas. Farther, it is expected that this number will reach 1.6 billion by 2050. In Brazil, the urban population is around 84% (IBGE, 2012). Intense rainfall events and floods are frequent in almost half of Brazilian cities and practically in all the capitals (IBGE, 2008).

Flooding are natural phenomena, defined as the watercourse overflowing, when the water level exceeds the riverbank until reaching not usually submerged areas (CHRISTOFOLETTI, 1980; LEOPOLD, 1996). In cities, however, flood frequency and magnitude have been intensifying due to the synergistic effects of urban expansion and densification, the use of urban drainage traditional approaches, changes in land use, increase of impervious areas, occupation of riverside areas, and the intensification of climate extreme events.

Assumpção and Marçal (2012), Cunha (2012), and Sartório (2018) demonstrate how traditional river engineering techniques, such as river channeling, can make environments more susceptible to flooding. Changes in sedimentological, water, hydraulic, and biotic watercourses dynamics are also observed.

When analyzing the water dynamics in urban watersheds trough hydrological modelling, Cleugh *et al*. (2005), Sharma *et al*. (2008), Mitchell *et al*. (2008), Lee *et al*. (2010), Mejía (2014) and Carvalho and Santos (2021) demonstrate that the increase of impervious areas significantly increases surface runoff and peak flows during rainfall events. Carvalho, Marangon and Santos (2020), in turn, discuss the interdependence and synchronicity of the denaturalization processes that occur among the river reaches and their respective drainage areas, which are also reflected in the increase of flooding susceptible areas.

In addition, climate change prospects the intensification of extreme events (ASADIEH and KRAKAUER, 2017; WATER, 2020; SANTOS *et al*., 2020). For Southern Brazil, PBMC (2014) observed trends in increased precipitation since the mid-20th century and projects scenarios with an increase of up to 25% in average temperature and 30% in precipitation by 2100. Santos *et al*. (2020) also performed climate modeling that projects an increase in extreme rainfall events in the Southern region. Marengo *et al*. (2021) verify that Southern Brazil is the most exposed and vulnerable to climate-related disasters triggered by extreme rainfall faced to climate change. Further, Carvalho, Iensen and Santos (2021) modeled scenarios with a perspective of an increase in the annual volume of rainfall and a decrease of rainy days in Curitiba/PR until 2100, indicating the intensification of drought and extreme precipitation events.

Faced with the complexity of the factors that influence urban flood dynamics and occurrence and the need to identify floodable areas, many modeling tools and techniques have been developed to map areas susceptible to flooding (TENG *et al*., 2017). Flood mapping is one of the non-structural solutions for flood mitigation and management, being crucial for risk reduction (HAFNAOUI *et al*., 2020).

HEC-RAS is a hydrodynamic model commonly used to elaborate flood maps in natural, rural, and urban areas. Developed by the U.S. Hydrologic Engineering Center Army Corps of Engineers, the mathematical model uses a computational environment to simulate the movement of water in rivers and floodplains (TENG *et al.*, 2017), with the possibility of modeling steady (1 dimension) and unsteady (1 dimension and 2 dimension) flow (BRUNNER, 2016).

The HEC-RAS model has been widely applied in urban spaces. Zope, Eldho and Jothiprakash (2016), Devi, Sridharan and Kuiry (2019), Abdulrazzak *et al*. (2019), and Hafnaoui *et al*. (2020) are examples of its application in mapping flood areas at different return period (RP) or specific episodes under current conditions. It has also been applied to simulate the effects of urban expansion, climate change, and sustainable drainage systems on flooding dynamics (DEVI, SRIDHARAN and KUIRY, 2019; CALIXTO, WENDLAND and MELO, 2020; AKTER, TANIM and ISLAM, 2020).

Hydrological models are used in association with the HEC HAS model due to the need for input flow data. The HEC-HMS model is further applied in the literature (KELLER et al, 2022) as it belongs to the same group of models developed by the U.S. Hydrologic Engineering Center Army Corps of Engineers. However, some hydrological models developed to specifically urban spaces can better simulate the complexity of urban water dynamics and can be used instead of HEC-HMS.

Aquacycle is an urban water balance model capable of simulating urban water dynamics as an integrated whole, encompassing natural and built drainage in a single modeling framework (MITCHELL, 2005). The model quantifies the different sources that compose the streamflow in urban environments. In addition to baseflow and runoff, the water supply system leakage (MITCHELL, 2005), the illegal wastewater inflow into the drainage system (CARVALHO and SANTOS, 2021), and the rainwater inflow into the wastewater system (MITCHELL, 2005) can also be considered.

The spatial scales used in the model (block, cluster, and catchment) allow accessing the effect of each existing structure, such as roofs, streets, sidewalks, and gardens, or of a set of structures in the same cluster (CLEUGH *et al*., 2005; MITCHELL *et al*., 2008). The Aquacycle model efficiently evaluates the water performance of different configurations of urban space in the same catchment (MITCHELL, 2005). The results are given in daily, monthly, and annual time scales.

In our previous manuscript (CHAPTER 02), we discussed and employed the Hydrologic Similarity Area (HSA) concept to compartmentalize the Belém catchment intraurban space into areas with similar spatial configurations and, therefore, similar water dynamics. We applied a systematic and statistically based method to define intraurban clusters based on Curitiba's Zoning Law (CURITIBA, 2019) and on the percentage of impervious areas. Thereafter, the water balance of these HSA was simulated in the Aquacycle model.

When comparing the water balance results on the six delimited HSA, we found that the responses are heterogeneous and may reveal a highly dependent relationship among the percentage of impervious areas, the land use, and runoff, infiltration, and evapotranspiration rates. Such variability of responses suggests that the HSA contribute to urban flooding in different proportions, becoming an essential concept in understanding the urban water dynamics and managing drainage interventions.

Based on the abovementioned issues, this research aims to describe flood dynamics in the Belém catchment (Curitiba/PR), identifying flood extent and depth at different return periods (RP) and the streamflow contribution of Hydrologic Similarity Areas (HSA) under intense rainfall conditions. To do so, we employed hydrological and hydraulic modelling, respectively with the Aquacycle and the HEC RAS model.

No studies have joined the Aquacycle and HEC RAS models to investigate urban floods in the scientific literature at all. Nevertheless, there is significant potential to use Aquacycle outputs to estimate peak flows and assess flood extent and depth in HEC RAS, mainly because the model performs the complexity of urban water dynamics, considering the diversity of water pathways in intraurban spaces.

4.2 STUDY AREA

Within in the Alto Iguaçu basin context, the Belém catchment has 87.8km² and covers 20% of Curitiba´s territory. Entirely urban, the catchment has a wide diversity of spatial configuration patterns, comprising downtown, park, residential, institutional, and service areas, being representative of urban watersheds in Brazil. Its main geomorphological, climatic, and hydrological features are described in Figure 4.1.

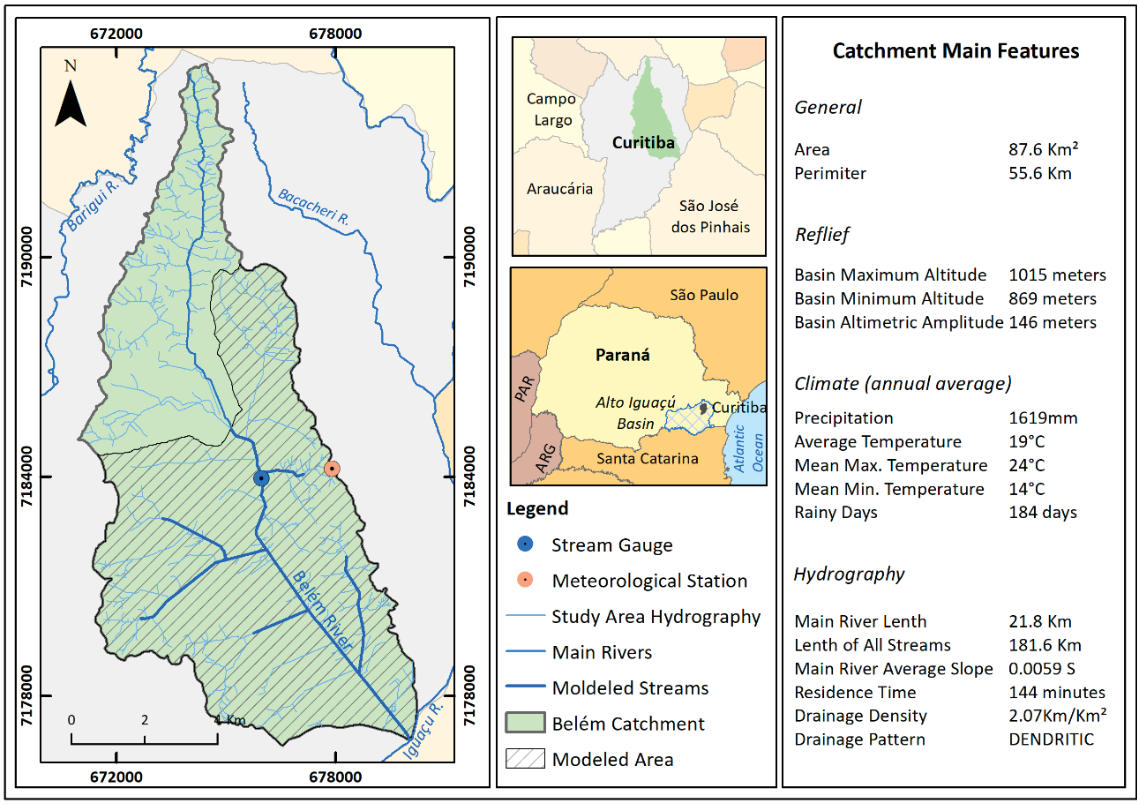


Figure 4.1 - Location map

Once meandering, many segments of the main river and its tributaries were channeled and rectified over time to provide space for urbanization and lessen floods. Historically, many channeling works were carried out on the rivers, but few successfully reduced susceptibility to flooding.

Due to the association of climatic characteristics, low natural soils permeability (Guabirotuba geological formation) (BIGARELLA and SALAMUNI, 1962), an increase in the percentage of impervious areas, and bad dimensioning of urban drainage systems, Curitiba suffered more than 200 flooding episodes in the last 30 years (GOUDARD, 2019). Among the most significant and recent events in terms of impacts, 02/21/2019 stands out (FIGURE 4.2), with 119.6 mm/day of registered rainfall, equivalent to a 25y RP episode. Many streets, houses, institutions, and commercial establishments were affected. The civil defense of Paraná recorded the occurrence of floods in 18 neighborhoods, including downtown.

Floods are frequent throughout the catchment, especially in downstream areas. In this research, we mapped floodable areas in the hatched region of Figure 4.1, which corresponds to the unchanneled reaches of the Belém River and its main tributaries. Such areas are the most affected by floods.

Short-term intense rainfall episodes are the primary triggers of urban floods in Curitiba (GOUDARD and MENDONÇA, 2020). They are associated with heavy convective rains during the summer and advancing cold fronts throughout the year. Fortin *et al*. (2020), Goudard (2019), and Goudard and Mendonça (2020) note that floods are triggered by precipitation at intensities of 20 to 30 mm/hour.

In addition to the complexity inherent to the diversity of water pathways in an urban context, the study area´s water dynamics is particularly complex due to a low residence time (*rt*). The RP is the time required for the entire watershed area to contribute to surface runoff at the outfall. As the RP is low in Belém catchment, intense rainfall episodes are soon converted into higher and faster peak flows, causing flash floods.

Figure 4.2 - Flood of 02/19/2019 recorded in the Boqueirão region

4.3 METODOLOGY

To achieve flood dynamics in Belém catchment we conducted hydrological and hydraulic modeling. The models used were, respectively, Aquacycle and HEC RAS. Figure 4.3 summarizes the methodology steps in a flowchart.

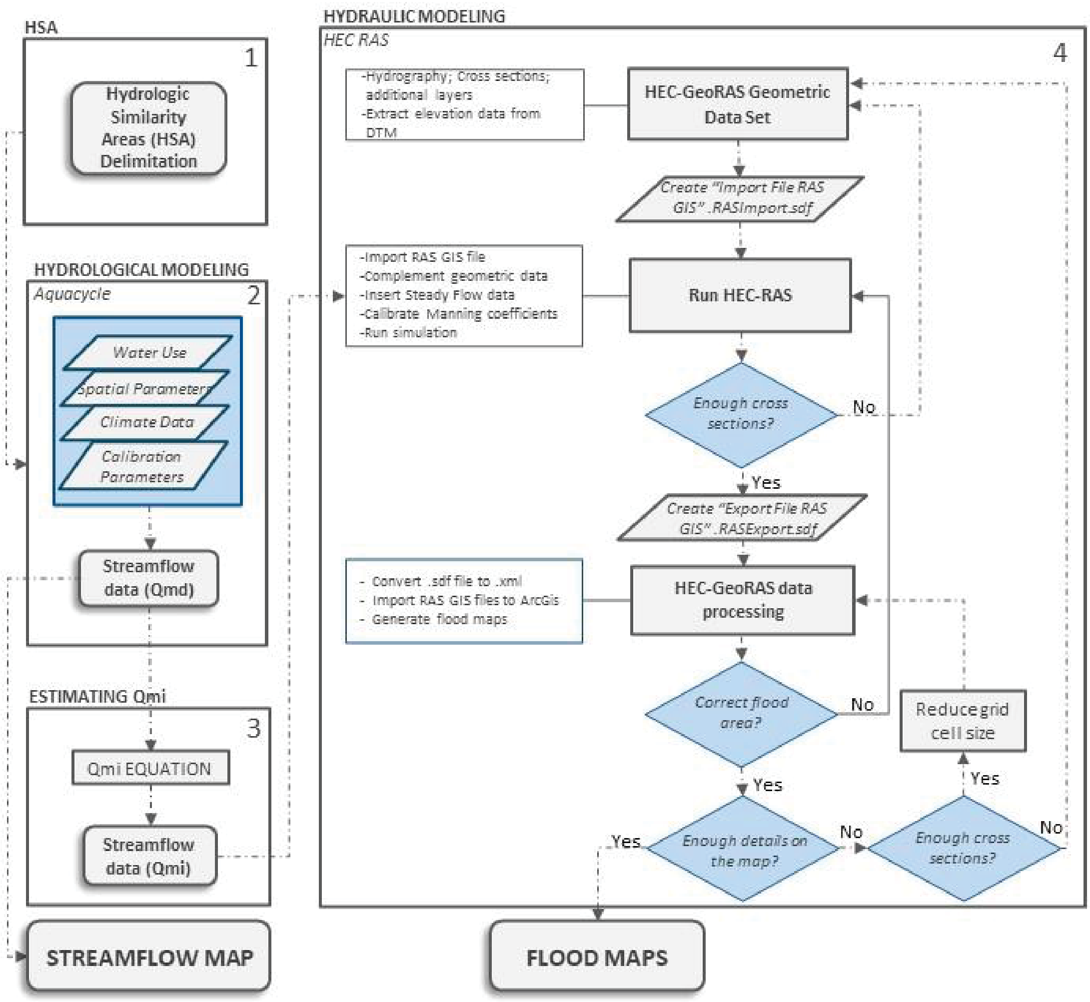


Figure 4.3 - Methodology flowchart

4.3.1 Hydrologic and hydraulic modelling

To access streamflow data on a daily time scale, we used Aquacycle, a water balance model developed to simulate the complexity of water pathways in urban spaces. In our previous manuscript (CHAPTER 2) we delimited six Hydrologic Similarity Areas (HSA) and calibrated the Aquacycle model for the Belém catchment. Herein we use the same HSA delimitation, input data, and calibration as previously applied. The required input files are climate data, water use, spatial, and calibration parameters (MITCHELL, MEIN and MCMAHON, 2001). The results obtained in the hydrological modeling were a crucial data source for two different steps of this research: calculating steady flow input data for HEC RAS model and elaborating the streamflow map. For more details on the input data and calibration process in the Belém catchment, see Chapter 2.

To identify and map flood extend and flood depth at different RP, we performed hydraulic modeling with the software HEC-RAS 5.0.7. HEC HAS model is widely used for mapping floodable areas in both natural and rectified channels. The model performs 1D water surface profile calculations for steady flow and 1D/2D for unsteady flow (BRUNNER, 2016). Hicks and Peacock (2005) point out that even the program's one-dimensional modeling option has shown performance comparable to sophisticated two-dimensional approaches. In this research, we considered that the regime flow is steady and gradually mixed.

The input data required for modeling are the geometric and steady flow data. The procedures required for modeling are summarized in Figure 4.3 and described below.

4.3.1.1 Geometric Data

The geometric data were set in ArcGIS software, using the HEC-GeoRAS extension. Initially, a Digital Terrain Model (DTM) was obtained by interpolating IPPUC (2013) and Parallela (2018) contour lines, both with 1 meter of equidistance. IPPUC (2013) corresponds to an aerial photogrammetric survey of Curitiba carried out in December 1990. Parallela (2018), in turn, corresponds to the Belém river topographic survey, held in 2018. The interpolator used to generate the DTM was the Triangulated Irregular Network (TIN). According to Cameron and Ackerman (2012), the TIN is the most suitable format for representing linear features in hydraulic surfaces modeling, allowing to produce more reliable cross-section data.

The layers vectorized in HEC-geoRAS were stream centerlines, cross-sectional cut lines, layers bank lines and bridges. The stream centerlines were vectorized from upstream to downstream, following the central stream flow lines, resulting in eleven river reaches delimited to each of the existing confluences (FIGURE 4.4A). We chose to model the reaches that are not channeled underground.

We defined 134 cross-sectional cut lines along the modeled tributaries and the main channel floodplains (FIGURE 4.4B and APPENDIX 1). Following Brunner's (2016) recommendation, we prioritized delimitating the cross sections in representative locations, where there are changes in the channel's slope, shape, or roughness, and close to hydraulic structures or tributaries.

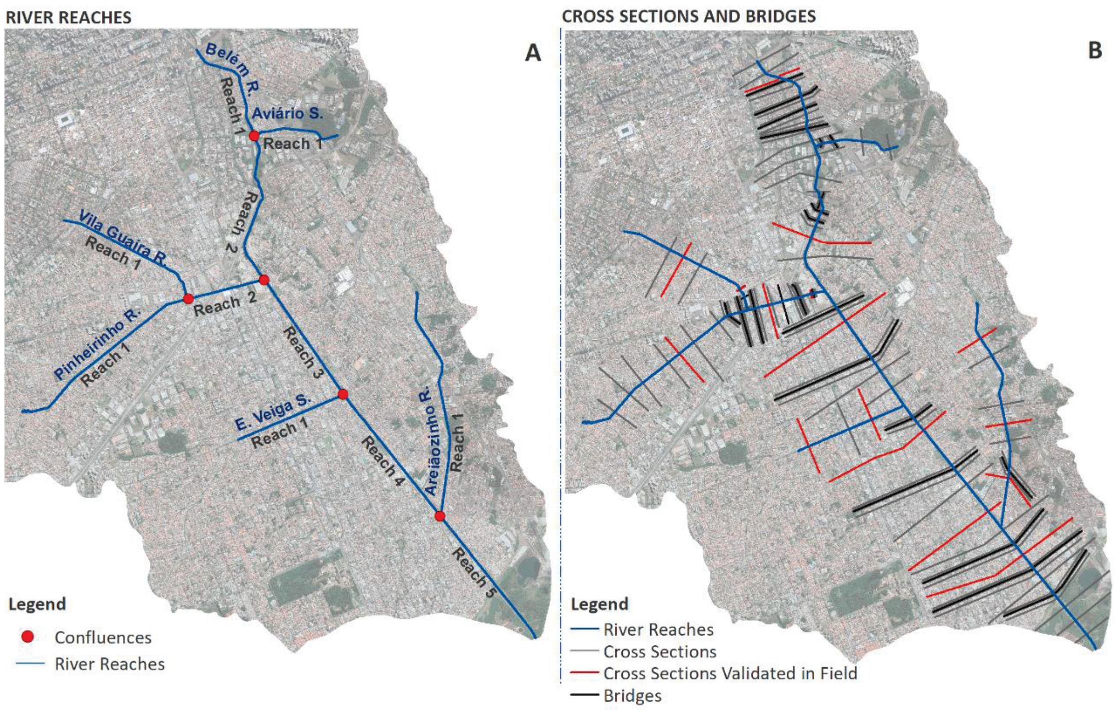


Figure 4.4 - Geometric Data: a) River reaches; b) Cross sections and bridges

The bank lines and bridges vectorizing were done manually, based on Google Earth Pro 7.3 (2019) satellite images. Fourteen existing bridges in the modeled area of the main channel and ten other main bridges located in the tributaries were represented (FIGURE 4.4B).

The HEC-RAS model simulates the energy loss caused by hydraulic structures, such as bridges, in three stages: immediately downstream, when the flow expands; in the structure itself; and immediately upstream, where there is flow contraction (BRUNNER, 2016). To do so, the program uses four cross sections previously defined by the user. Section one must be located sufficiently downstream of the bridge so that the structure does not affect the flow. Section two is normally located near the toe of the downstream road embankment. It should represent the natural ground just downstream of the bridge. Section three, in turn, is located near the toe of the upstream road embankment. Finally, section four is the most upstream section, where the flow is fully effective (BRUNNER, 2016).

The extension of the flow contraction movement occurs at a smaller distance than the expansion (BRUNNER, 2016). The selected contraction and expansion coefficients were, respectively, 0.1 and 0.3. These are standard coefficients suggested by Brunner (2016). To calculate the energy loss in hydraulic structures, we opted for the energy method, both for low and high flows.

After setting the geometric data, we extracted the elevation of the vectorized layers from the TIN. After generating the RAS-GIS import file, data was transferred to HEC-RAS for minor adjustments.

Then, we carried out an individual cross-section verification, code assignment and executed minor adjustments. To validate the cross-sections, main channel width and depth measurements were taken in field in sixteen representative sections distributed throughout the study area. The Google Earth Pro altitude measurement and verification tools were also used to verify measurements, accepting the planialtimetric error intrinsic to the program (MENEZES *et al*., 2019).

Additional bridge data were also entered into the HEC-RAS software. Each bridge received a name, bridge deck width, distance between the upstream side of the bridge deck and the cross section immediately upstream of the bridge, structure design, height from the bottom of the channel and pier dimensions. Such information was collected in field and in bridges images made available by Street View tool in Google Earth Pro. The distance to the next upstream section was extracted in GIS software.

Recently built levees were also inserted into the model. Its dimensions were measured in field. Finally, the insertion of levee points in some of the cross sections delimited areas where the water cannot pass until that a specific elevation is exceeded (BRUNNER, 2016). The model assumes that the water profile height is distributed over all the cross sections areas with the same altitude. Levee points must be defined based on the user's knowledge of the study area (BRUNNER, 2016).

4.3.1.2 Steady Flow Data

The input data required for modeling steady and gradually mixed flow are the number of profiles to be calculated, streamflow data per reach, and upstream to downstream boundary conditions (BRUNNER, 2016). Water surface profiles are computed from one cross-section to the next by solving the Energy Equation (EQUATION 4.1):

$$Z2 + y2 + \frac{a2.V2^2}{2g} = Z1 + Y1 + \frac{a1.V1^2}{2g} + he \quad (4.1)$$

where *Z*1 and *Z*2 are the elevation of the main channel in the two sections, Y1 and Y2 are the depth of water at cross sections, V1 and V2 are the average velocities, *a*1 and *a*2 are velocity weighting coefficients, *g* is the gravitational acceleration and *he* is the energy head loss. The energy head loss comprises energy losses due to friction, contraction, and expansion between two adjacent sections, being defined by Equation 4.2:

$$he = L\bar{S}f + C\left|\frac{a2.V2^2}{2g} - \frac{a1.V1^2}{2g}\right| \quad (4.2)$$

where *L* is the discharge weighted reach length, $\bar{S}f$ is the representative friction slope between two sections, and *C* is the expansion or contraction loss coefficient. Note that when a flow value is entered, it is assumed to remain constant until another flow value is added downstream.

Whenever the water surface passes through critical depth, usually in hydraulic structures such as bridges, or during a hydraulic jump or stream junctions, the energy equation is not considered applicable because water velocity varies rapidly. Therefore, the model uses the momentum equation derived from Newton's second law.

Four water profiles were simulated in this research. They correspond to the resulting streamflow in the same events simulated in chapter 02. They refer to some events of intense rainfall that triggered floods between 1999 and 2019. Precipitation volumes correspond to 2, 5, 25, and 100 RP. We calculated the RP for each rainfall episode using the Gumbel method (GUMBEL, 1941), based on a 30-year rainfall series. In the Gumbel distribution (EQUATION 4.3):

$$x = \bar{x} - s\left\{0{,}45 + 0{,}7797.\,ln\left[ln\left(\frac{RP}{RP-1}\right)\right]\right\} \quad (4.3)$$

x is the precipitation corresponding to the return period, $\bar{x}$ is the mean of the sample values, *s* is the standard deviation, and RP is the return period to be calculated.

The precipitation values obtained were inserted in the Aquacycle model to obtain the mean daily streamflow in each reach modeled in the HEC-RAS. In most cases, however, the mean daily streamflow *(Qm)* is not enough to supply hydraulic models when simulating floods, especially in small and densely urbanized catchments (FILL and STEINER, 2003). In the Belém catchment, where the RP is low, it is necessary to estimate the peak flow (*Qmax*). The RP in the study area was estimated at 144 minutes using the Kirprich method, showing a potential gap between *Qm* and *Qmax*. According to Tucci (2002), the difference between *Qm* and *Qmax* increases as the catchment size decreases.

Many hydrologic methods are available for estimating peak flows, but no single method is applicable to all basins. The methods for estimating *Qmax* proposed in Fuller (1914), Tonini (1969), Gray (1973), Correia (1983), Tucci (1991) (all cited by SILVA and TUCCI, 1998) were tested to estimate *Qmax* in Belém Catchment. Other methods, such as Sangal (1983) and Fill and Steiner (2003), were not tested because they are not recommended for catchments with RP lower than 24 hours. The tests were carried out with daily precipitation events which the RP was higher than one year (50mm/day), whose precipitation intensity was greater than 25mm/h, and the streamflow was recorded with by a limnigraph every 15 minutes at the Prado Velho fluviometric station (65011400) (FIGURE 4.1). Events between 2005 and 2014 were used due to the availability of data recorded by the limnigraph. The tested methods underestimated or superestimated *Qmax* compared to the evaluated events' measured data.

Thus, we adjust Equation 4.4 based on fifteen selected intense rainfall events to estimate *Qmax* in the Belém catchment:

$$Qmax = Qm.(1 + 50.A^{-0,5}) \quad (4.4)$$

where *A* is the catchment area given in km². The R^2 obtained in the equation was 0,98.

After calculating and inserting peak flow data for each profile, we set boundary conditions, selected the normal depth option, and established the initial water depth. For that, the channel bottom slope was inserted in each simulated reach (BRUNNER, 2016).

4.3.1.3 HEC RAS Calibration and Validation

HEC-RAS calibration is conducted by choosing and adjusting the Manning coefficients for the river channel and floodplain until the simulated water level of pre-selected profiles is equal to the measured gauge height. Herein, we selected the 02/21/1999 (PF1) episode for calibration, and 11/19/2009 (PF2) and 02/21/2019 (PF3) for validation. PF1 and PF3 are the two major floods recorded in the study area in the last 30 years.

To select the events, we verified the episodes of intense rainfall that resulted in flooding and selected those with the highest number of checkpoints available to validate the flooded areas. We used the peak gauge height measured at the Prado Velho fluviometric station and data from flooded areas obtained from local newspaper reports, Civil Defense reports, photographic records, and testimonials from the local population as checkpoints. Manning's coefficients were selected based on Chow (1959), De Roo (1999), and Porto (2006) for urban catchments and channeled rivers. The previously mentioned levees were considered only in PF3 as they were recently built.

At each attempt to calibrate the HEC RAS model, we exported the RAS GIS file and checked if the flooded areas were correct in the HEC-GeoRAS. After verifying the necessary adaptations, we returned to the HEC RAS to adjust the Manning coefficients and cross-sections. Such process was successively repeated until the flood extent and depth of the simulated events were satisfactory when comparing to the checkpoints.

4.3.2 Assessing flood dynamics

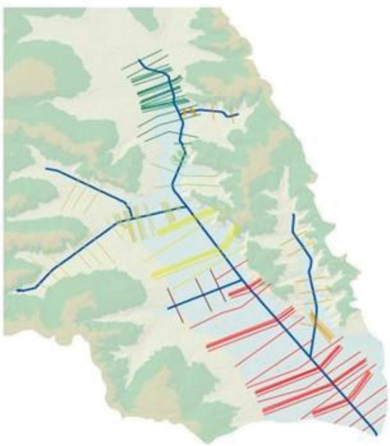
After generating and verifying the geometric elements, defining the peak flow equation to determine the steady flow data, and setting the Manning coefficients, we simulated the flood events at 2, 5, 25, and 100 RP. We exported the results to RASExport.sdf file and processed in HEC-GeoRAS, where the polygons of the flooded areas and the water surface TIN were created to elaborate the flood maps.

The mean daily streamflow obtained in the hydrological modeling was also analyzed and mapped for each simulated event, in order to identify the HSA that most contribute to floods. The results were organized in an infographic, which comprised the flooding areas and the streamflow spatialization, distribution graphs with the percentage proportion of the HSA´s area, and streamflow, and another distribution plot represents the percentage of impervious areas in the HSA.

4.4 RESULTS AND DISCUSSION

4.4.1 HEC RAS calibration and validation

The Manning coefficients resulting from HEC RAS calibration (PF1) and validation (PF 2 and 3) processes are listed and illustrated in Figure 4.5. They range from 0.01 to 0.08 for river channels and from 0.06 to 0, 1 for the floodplain. The coefficients were selected for each cross section based on Chow (1959), De Roo (1999), and Porto (2006) according to local urban characteristics.



MANNING COEFICIENTS

PF1/PF2 Floodplain	PF1/PF2 River	PF3 Floodplain	PF3 River
0,06	0,012	0,06	0,012
0,06	0,018	0,06	0,018
0,06	0,02	0,06	0,02
0,06	0,022	0,06	0,021
0,06	0,035	0,06	0,035
0,06	0,04	0,06	0,04
0,1	0,078	0,1	0,078

Figure 4.5 - Floodplain and river Manning coefficients by cross section

The results reveal correspondence between the observed and simulated flooded areas in the three selected events. Figure 4.6 shows the resulting flood and the checkpoints collected in newspapers, Civil Defense reports, photographs, testimonials from the local population, and the peak gauge height recorded at the Prado Velho fluviometric station.

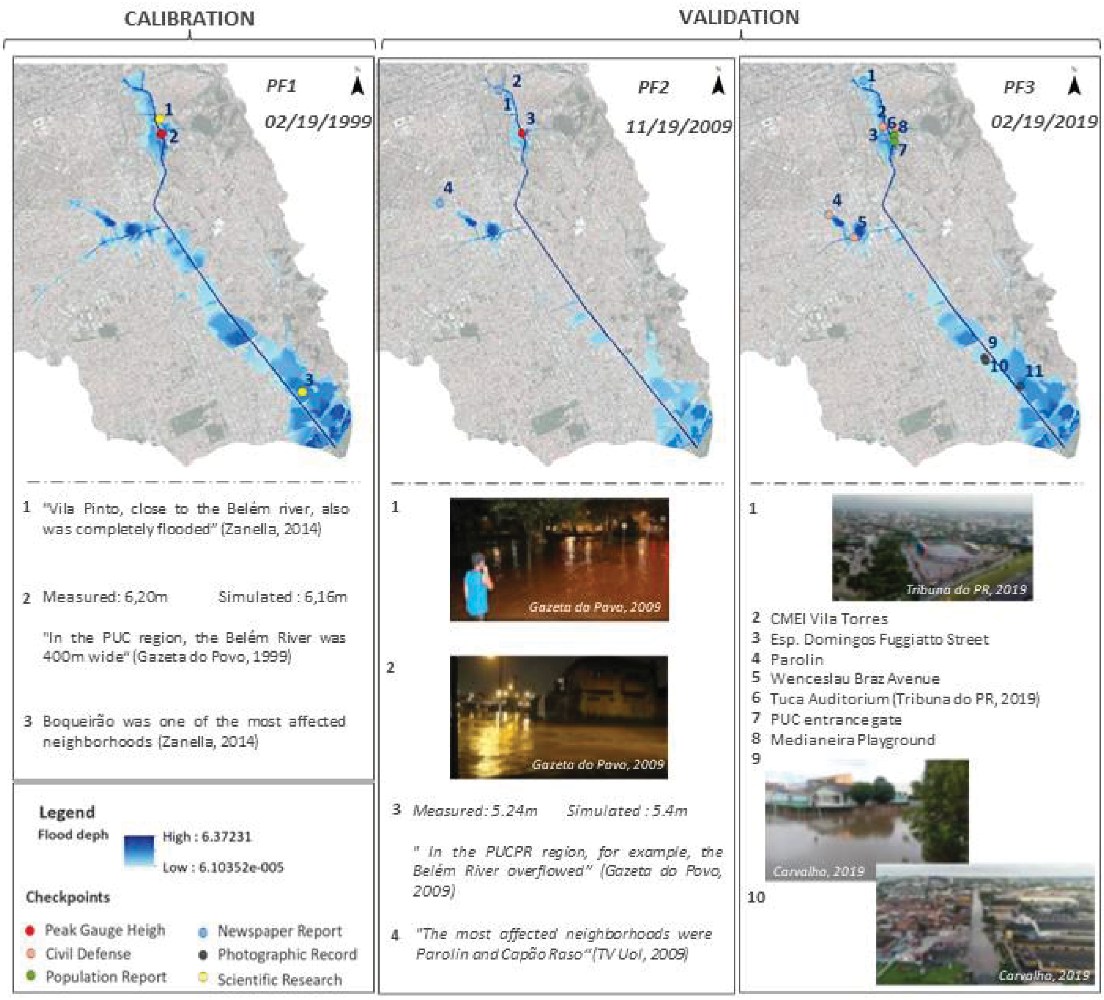


Figure 4.6 HEC RAS calibration and validation

Three checkpoints were verified in PF1. Points 1 and 3 are flooded areas reported in Zanella (2014). Point 2, in turn, corresponds to the peak gauge height observed at the fluviometric station. A negative deviation of 0.6% between the measured and the simulated peak gauge height shows adherence between the observed and simulated water profiles.

Four checkpoints were verified in PF2. Points 1, 2, and 4 are flooded areas recorded in newspapers, some of them with photographic reports. Point 3 is the peak gauge height observed at the fluviometric station. There is a positive deviation of 3% between the measured and the simulated peak gauge height, showing adherence between the observed and simulated water profiles.

In the event PF3, the Prado Velho fluviometric station was disactivated. Therefore, there is no peak gauge height observed on this date. However, the event presents the highest number of checkpoints and diversity of sources. Points 1 and 6 are flooded areas recorded in newspapers. Points 2, 3, 4, and 5 correspond to the flooded areas reported by the Civil Defense. Points 7 and 8 were obtained through testimonials made by the local population. Points 9 and 10 were verified through our own VANT photographic records.

4.4.2 Flood dynamics

The hydrological and hydraulic modeling results that represent the flood dynamics in the Belém catchment are synthesized in Figure 4.6. The infographic displays the flood's extent and depth and the streamflow volume generated at each HSA in different RP. As previously mentioned, we mapped areas susceptible to flooding in unchanneled reaches of the Belém River and its main tributaries under intense rainfall conditions. There are also distribution graphs with the percentage proportion of the HSA's area and streamflow production. Farther, a distribution plot represents the percentage of impervious areas in each HSA. Note that the numbering of the HSAs is on a scale of increasing impermeability, where HSA I is the most pervious (18%), and HSA VI is the most impervious (89%).

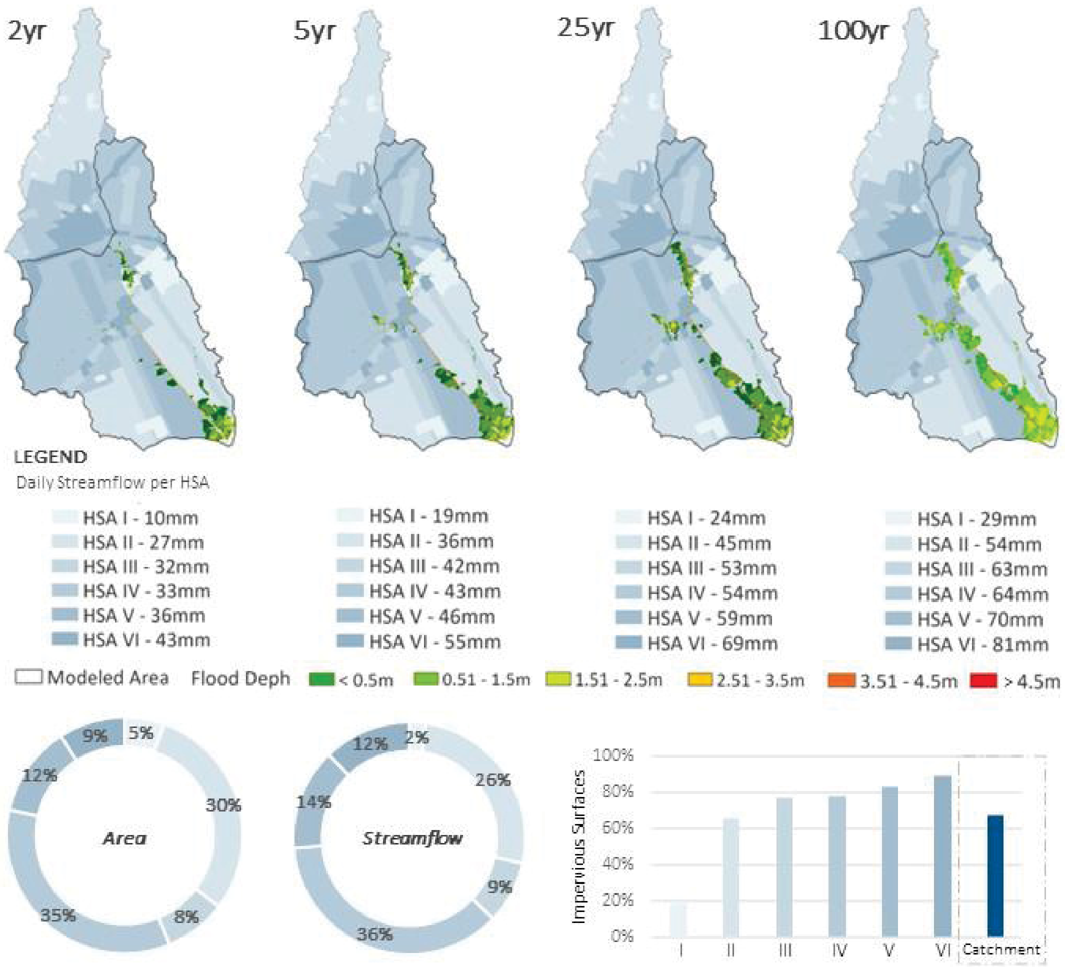


Figure 4.7 - Infographic with flood maps at 2, 5, 25 and 100 yr RP and daily streamflow spatialized by HSA; graphs with the percentage representativeness of the area and streamflow contribution of each HSA; bar chart with percentage of impervious areas per HSA

For a 2-year RP, corresponding to approximately 80mm, we verified that the areas susceptible to flooding are concentrated in further downstream and further upstream areas. The affected regions in the downstream area are adjacent to the Belém River and Areiaozinho Stream in the Boqueirão and Uberaba neighborhoods. In the upstream regions, the occurrence of meanders leads to a decrease in the streamflow speed compared to the other modeled reaches. Episodes with a 5-year RP, corresponding to 98mm, increase in 50% the extent of flooded areas compared to a 2-year RP episode. We note that affected areas are also close to the Guaíra, Pinheirinho, and Aviário Streams, regions where are Parolin and Vila Torres communities. Areas close to the Ev. da Veiga Stream and Belém River confluence are also affected.

In events of a 25-year RP, equivalent to intense rainfall of 125mm, as observed on 02/19/2019, there is an increase of 40% in the extent of flooded areas compared to a 5-years RP episode and of 175% compared to a 2-year RP event. The flooded areas are expanded in the upstream and downstream regions and distributed along all the modeled reaches.

In rare 100-year RP events, equivalent to a 146mm rainfall, as observed on 19/02/1999, there is an increase of 20% in the extent of flooded areas when compared to a 25-year RP event, 165% when compared to 5-year RP event and 293% when compared to a 2-year RP event. Floodable areas are observed along all modeled reaches, affecting populations in different regions.

It is noteworthy that the most affected areas in all RP are located close to the Belém and Iguaçu rivers confluence. Even during more frequent rainfall episodes (2-year RP), those areas concentrate significant extensions of floodable areas. It is a peripheral region with houses along the floodplain and close to the river. In addition to being naturally characterized as a floodplain area, flood extent, depth, and magnitude may have been intensified by works carried out in the upstream drainage area. Both soil impermeabilization in areas close to downtown and river channeling works employed throughout the catchment may transfer impacts and make the downstream areas more susceptible to flooding, corroborating Assumpção and Marçal (2012), Cunha (2012), and Sartório (2018).

Modeling the water balance by HSA reveals how intraurban spatial heterogeneity results in different results in streamflow, mainly due to the runoff generated in zones of high concentration of impervious areas. We emphasize that the HSA were delimited based on grouping zones from the Curitiba Zoning Law that presented similar spatial and hydrological characteristics (CHAPTER 2). The HSA I comprises parks and educational and military institutional zones. The HSA II is composed of single-family housing areas, and the HSA III is composed of densification, transition, and historic zones. HSA IV comprises connection zones and medium to high-density housing areas. HSA V is composed of service, mixed-use, and public institutional zones. Finally, HSA VI comprises downtown, densification, and connection zones.

From the analysis of streamflow generation per HSA, the results reveal that the most susceptible to flooding areas are not necessarily the main contributors to streamflow. There is a wide variation in streamflow volume among the HSA in all the simulated events. Streamflow ranges from 10mm on HSA I to 43mm on HSA VI in a 2-year RP event. The difference grows as rainfall increases, with 29mm in HSA I and 84mm in HSA VI in a 100-year RP episode. Representing only 21% of the Belém catchment, the HSAs with the highest percentage of impervious areas (V and VI) contribute 26% of the total streamflow. Those areas are located close to downtown and around higher population density structural axes. Such results point to the areas with the most significant relative weight in the contribution of water volume to flood events.

On the other hand, the HSAs with the lesser percentage of impervious areas (I and II) represent 35% of the catchment area but only 28% of the total streamflow. Those zones are primarily concentrated in the farther upstream and downstream portions of the Belém catchment. In other words, the downstream areas are the minor contributors to streamflow but the most affected by floods in all RP.

Thus, the results indicate that the intensification of soil sealing in upstream areas results in a more outstanding runoff production. In association with rectification works that increase the streamflow speed in those areas, impacts are transferred downstream, affecting the areas that least contribute to the streamflow. Furthermore, the higher the percentage of impervious areas, the sooner intense rainfall episodes are converted into higher and faster peak flows, intensifying flash floods.

Using the Aquacycle and HEC RAS models to study urban flooding showed satisfactory results in the Belém catchment. The Aquacycle model is specific to urban environments, making it possible to model urban water dynamics with higher precision. It includes composing the streamflow with all the possible variables in an urban environment and representing the different intraurban spaces' water dynamics.

Our results reveal that the Belém catchment presents significant extensions of areas susceptible to floods from the most frequent events to the rarest, which explains the recurrent record of floods verified in the literature in the study area. In addition, it is worth mentioning that, as indicated by PBMC (2014), Santos *et al*. (2020), Carvalho, Iensen and Santos (2021), and Marengo *et al*. (2021), climate change scenarios project an increase in extreme rainfall events in the Southern region, possibly increasing precipitation volumes and expanding areas susceptible to flooding until 2100.

4.5 CONCLUSION

In this research, we mapped areas susceptible to flooding at different return periods and verified the streamflow contribution of six Hydrologic Similarity Areas in the Belém catchment. In the hydraulic modeling, the calibration process showed good correspondence between the observed and simulated flooded areas in the selected events.

We found an increase of 50% in the extent of flooded areas from a 2-year RP to a 5-year RP event, 40% from a 5-year RP to a 25-year RP event, and from 20 % from a 25year RP to a 100-year RP event. Areas susceptible to flooding were identified in all modeled reaches, with emphasis to downstream areas, close to the Belém and Iguaçu and Areiaozinho and Belém confluences, which presented the most extensive floodable areas in all RP.

From the analysis of streamflow generation per HSA, the results reveal that the most susceptible to flooding areas are not necessarily the main contributors to streamflow. There is a wide variation in streamflow volume among the HSA in all the simulated events, which ranges from 10mm to 43mm 2-year RP event and from 29mm to 84mm in a 100-year RP episode. The higher the percentage of impervious areas in the HSA, the higher the streamflow. We also verified that the downstream areas are the minor contributors to streamflow but the most affected by floods in all RP. Thus, the results indicate that with the intensification of soil sealing and rectification works carried out in upstream areas, the impacts are transferred downstream.

Using the Aquacycle and HEC RAS models to study urban flooding showed satisfactory results in the Belém catchment. The Aquacycle model is specific to urban environments, making it possible to model urban water dynamics with higher precision. It includes composing the streamflow with all the possible variables in an urban environment and representing the different intraurban spaces' water dynamics. Therefore, we recommend using both models in future research to study urban floods.

Finally, our study to assess urban flood dynamics in the Belém catchment contributes as a non-structural solution for flood mitigation and management. It also demonstrates that studying floods based on understanding the systemic relationship between rivers and catchments can contribute to implementing more effective structural measures in urban spaces. Also, considering that the climate change scenarios indicate increases in flood magnitude and frequency, we suggest that future research on flood mitigation, resilient cities alternatives, and simulation of scenarios with sustainable urban drainage be carried out.

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5. EVALUATING THE EFFECTS OF DESCENTRALIZED NATURE-BASED SOLUTIONS DISTRIBUTED IN HYDROLOGIC SIMILARITY AREAS ON WATER BALANCE AND URBAN FLOODS

Abstract: Nature-based Solutions (NbS) for urban drainage have been presented as a sustainable alternative to reduce the adverse effects of urbanization on the water balance and mitigate urban floods, especially face to the intensification of extreme events. However, there is a lack of studies about methodologies and performance of implementing decentralized and multiple NbS. There is also a lack of studies about realistic scenarios considering the pre-existing intraurban spatial configuration, since deconstructing consolidated cities is spatially and economically unfeasible and that not all NbS are suitable for all conditions. Herein, we aim to set scenarios with NbS implementation in the Belém catchment´s Hydrologic Similarity Areas and simulate its effects on water balance and urban flood dynamics. To do so, we simulate three scenarios with multiple and decentralized NbS, accordant to the spatial preconditions. We applied Aquacycle for hydrological modeling, and HEC RAS for hydraulic modelling. The annual water balance results show that NbS scenarios can increase evapotranspiration by up to 8% and infiltration by 19%. It can also reduce runoff by up to 20%, and streamflow by up to 8%. In the daily water balance, we observe increases ranging from 7% to 41% for infiltration rates and reductions ranging from 3.6% to 29% for runoff, depending on the scenario, precipitation volume, and antecedent humidity conditions. Regarding the flood dynamics, we observe reductions of up to 16.3% in peak flows and up to 22% in flood extent. Thus, we conclude that scenarios composed of multiple and decentralized NbS, accordant to the spatial preconditions, can mitigate floods and urbanization's adverse effects on the water balance.

Keywords: Sustainable Drainage; Intraurban Spatial Configuration; Flood Mitigation, Ecosystem Services.

5.1 INTRODUCTION

Nature-based Solutions (NbS) is an umbrella concept for ecosystem-related approaches, defined as actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges, simultaneously providing human well-being and biodiversity benefits (COHEN-SHACHAM *et al*., 2016). Urban Hydrology has a range of sustainable drainage concepts aimed at reducing the adverse effects of urbanization on the hydrological cycle (FLETCHER *et al*., 2015), which converge to NbS principles and are covered by its conceptual umbrella as Low Impact Development (LID), Sustainable Drainage System (SuDS), Water Sensitive Urban Design (WSUD), Sponge Cities, and Green Infrastructure (GI) (CHAPTER 1).

Some examples of NbS for urban drainage are green roofs, green walls, rainwater tanks, rain gardens, swales, urban agriculture, permeable pavements, and parks (WATER, 2018; CHAPTER 1). Such practices aim to re-establish hydrological processes once desnaturalized through soil impermeabilization (SHARMA *et al*., 2008; LEE *et al*., 2010; MEJÍA, 2014; CARVALHO and SANTOS, 2020), traditional urban drainage and rivers´ rectification and canalization works (ASSUMPÇÃO and MARÇAL, 2012; CUNHA, 2012; SARTÓRIO, 2018), which increase peak flows and intensify flash floods. They have also been applied as strategies to build more resilient cities in the face of the projected increase in extreme events arising from climate change (ASADIEH and KRAKAUER, 2017; WATER, 2020).

The literature shows that NbS can delay and reduce runoff through increased infiltration, water storage, and evapotranspiration, reducing stormwater discharge, peak flows, and, therefore, flood risk. Lekkas, Manoli and Assimacopoulos (2008) simulate the implementation of rainwater tanks in Athens/Grece, reaching a reduction of up to 27% in the runoff. Basu *et al*. (2020) conclude from empirical research that an effective green roof system has the potential to develop a robust flood control network. Akter, Tanim and Islam (2020) simulate reductions of 28.66% in flood extent during the monsoon season in Chittagong/Bangladesh with rainwater tanks. Calixto, Wendland and Melo (2020) examine the hydrologic performance of on-site retention tanks at the lot scale. A peak flow reduction of 18% was reached. Twohig, Casali and Aydin (2022) found that the simulation of green roofs in Helsinki/Finland results in a decrease of up to 13% in the average flood depth and a reduction in the number of vulnerable sites.

In addition to reducing the risk of flooding, other benefits associated with the NbS ecosystem services production are verified, such as improved water and air quality (DERKZEN, ASTRID, and VERBURG, 2016; CONNOP *et al.*, 2016; KULLER *et al*., 2019; ZHANG *et al*., 2019; McCLYMONT *et al*., 2020; KOZAK *et al*., 2020), thermal comfort and reduction of heat islands (DERKZEN, ASTRID and VERBURG, 2016; KULLER *et al*., 2019; DUSHKOVA *et al*., 2020), carbon storage (DERKZEN, ASTRID and VERBURG, 2016; CONNOP *et al.*, 2016; JU *et al*., 2020), food and water safety (RONCHI, ARCIDIACONO and ANDREA, 2019; DUSHKOVA *et al*., 2020), visual amenity (WATER, 2018), human health and well-being (CONNOP *et al.*, 2016), and support for biodiversity (CONNOP *et al.*, 2016; ALVES *et al*., 2019; KULLER *et al*., 2019; DUSHKOVA *et al*., 2020; JU *et al*., 2020).

Despite being a promising approach in Urban Hydrology, many gaps still need to be addressed, mainly due to its recent insertion in the scientific literature. In a systematic review, Stroud, Peacock and Hassall (2022) verify that few studies reported on the use of NbS in ecosystem service provision by urban blue and green space, and of these, 80% focused on a single NbS. Majidi *et al*. (2019), Ferreira *et al*. (2020), and Vojinovic *et al*. (2021), however, identify that the most effective performance of NbS in terms of flood mitigation and ecosystem services providing is achieved by applying different measures in different locations, in a decentralized way. In this sense, studies on strategies and performance of hybrid and decentralized measures are necessary to understand how NbS can result in significant responses in reducing impacts on urban water dynamics.

Another gap concerns developing realistic implementation strategies considering pre-existing urban spatial conditions, especially in the Global South context (CHEN *et al*., 2021). Considering that deconstructing consolidated cities is spatially and economically unfeasible, it must be understood that there are areas with greater potential for adapting to specific measures than others and that there are more effective and adaptable measures for each type of urban spatial configuration. In this sense, Zölch *et al*. (2017) argue that not all NbS are suitable for all conditions. However, many studies simulate the implementation of NbS where they are not applicable or unfeasible scenarios.

Our previous studies (CARVALHO and SANTOS, 2021; CHAPTER 2) presented a methodology to delimit Hydrologic Similarity Areas (HSA) based on the intraurban spatial configuration analysis. Based on a pilot application at Belém Catchment, we found that different urban spatial configurations fit different responses in the water balance (CHAPTER 2) and contribute in different ways to the flood dynamics (CHAPTER 3). Thereby, we argue whether these same HSA present different limitations and potentialities in implementing NbS for urban drainage.

Based on the abovementioned issues, this research aims to set scenarios with Nature-based Solutions implementation in the Belém catchment´s Hydrologic Similarity Areas and simulate its effects on water balance and urban flood dynamics. To do so, we simulated the urban water balance in the Aquacycle hydrological model, and the floodable areas at different return periods (*RP*) in HEC RAS hydraulic model.

Our hypothesis is that the pre-existing urban spatial configuration limits the implementation of Nature-based Solutions for urban drainage. However, scenarios composed of multiple and combined measures into the HSA, accordant to preconditions, may present significant responses in the water balance, reducing the stormwater peak flows and the areas susceptible to flooding.

5.2 STUDY AREA

Belém is a headwater catchment of Iguaçu basin (FIGURE 5.1). With 87.8 km² of drainage area, it encompasses the most urbanized area of Curitiba, the capital of Paraná. It is representative of urban watersheds in Brazil in several aspects, including its diversity of spatial configuration patterns originated by the spontaneous urbanization and urban planning matchup (CHAPTER 2), the complex dynamics of water pathways in the urban drainage system (CARVALHO and SANTOS, 2021), and the frequent occurrence flash floods (IBGE, 2008; GOUDARD, 2019).

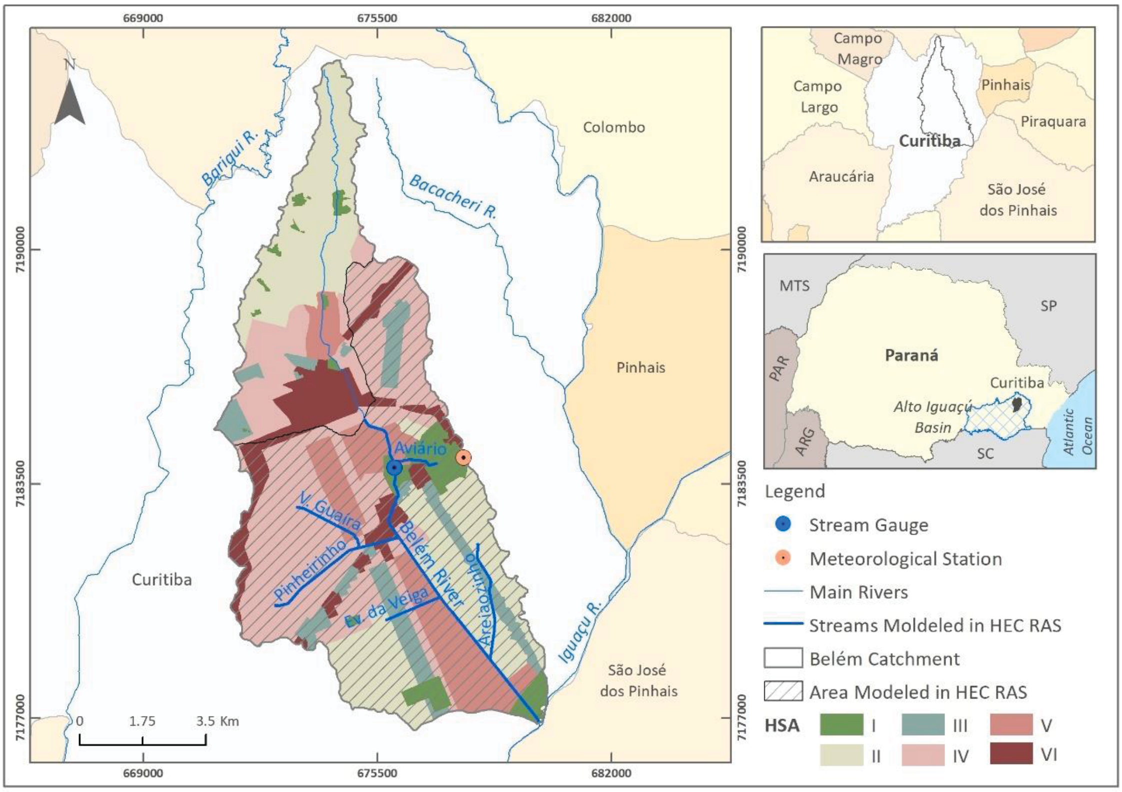


Figure 5.1 - Location map

The climate in the study area is subtropical, with very distinct seasons, absence of dry months, and well-distributed rainfall, being more expressive during the summer. The average annual rainfall is 1,619mm, and the mean maximum, average, and mean minimum temperatures are 24°C, 19°C, and 14°C, respectively (CHAPTER 2).

Floods are frequent throughout the catchment, especially in downstream areas. In the last 30 years, around 200 flooding episodes were registered in the city (GOUDARD, 2019), where short-term intense rainfall episodes were the primary triggers of urban floods (GOUDARD and MENDONÇA, 2020). They are mainly associated with heavy convective rains during the summer and advancing cold fronts throughout the year. Due to the study area reduced size, the high percentage of impermeable areas (CHAPTER 2), and channeling river works, the rainfall is rapidly converted into streamflow, causing flash floods (CHAPTER 3). For the same reason, the residence time is low, at about 144 minutes (FORTIN *et al*., 2020), and the difference between the peak flow (Qmax) and the mean daily streamflow (Qm) is high (CHAPTER 3; TUCCI, 2002). Farther, floods are triggered by precipitation at intensities of 20 to 30 mm/hour (FORTIN *et al*., 2020; GOUDARD and MENDONÇA, 2020).

In addition, the occurrence of floods in the region tends to increase due to the intensification of extreme events raising from climate change. PBMC (2014) projects scenarios with an increase of up to 30% in precipitation by 2100 for Southern Brazil. Further, Carvalho, Iensen and Santos (2021) modeled scenarios with the perspective of an increase in the annual volume of rainfall and a decrease of rainy days in Curitiba/PR until 2100, indicating the intensification of drought and extreme precipitation events.

In this research, we verify the result of implementing scenarios with NbS for drainage in the annual and daily water balance for the whole catchment. The NbS were simulated according to the intraurban spatial characteristics of the six HSA delimited in Chapter 2, illustrated in Figure 5.1. The performance of the scenarios in the floodable areas was modeled in the hatched region illustrated in Figure 5.1, which corresponds to the same area modeled in Chapter 3, where baseline conditions were simulated. This area corresponds to the unchanneled reaches of the Belém River and its main tributaries, which are the areas most affected by flooding.

5.3 METODOLOGY

5.3.1 Modelling approach

To simulate the effects of NbS implementation on water balance and urban flood dynamics in the Belém catchment we applied hydrological and hydraulic modeling. The effects on daily and annual water balance were simulated in the Aquacycle hydrological model. Floods extend was performed on the HEC RAS hydraulic model.

Aquacycle is a water balance model developed to simulate the complexity of water pathways in urban spaces, including natural and constructed drainage systems (MITCHELL, 2005). The model considers typical urban water pathways that are rarely approached in other water balance models (MITCHELL, 2005). Among them are imported water, supply system water leakage, indoor water use, irrigation, wastewater discharge, stormwater inflow into the wastewater system, and some sustainable drainage systems. The model also identifies the runoff generated in individual elements, such as paved areas, roofs, roads, and permeable areas (MITCHELL, MEIN, and McMAHON, 2001). In Chapter 2, we conducted a mathematical adaptation in the model to approach an illegal but ordinary reality in Brazilian cities: the wastewater inflow into streamflow. This adaptation was also used in the current research.

The model spatial scales are block, cluster, and watershed. Each block corresponds to a city lot, and the land use categories are divided into permeable (garden) and impervious (roof and paved area) surfaces. It allows an understanding of the effect of individuals or sets of elements in the drainage dynamic. A cluster is a set of blocks in addition to the roads (impervious surfaces) and open public space (pervious surfaces) of a given area. The user defines the criteria for delimiting clusters. Herein, as well as in Chapter 2 and Chapter 3, the clusters were defined as HSA, as illustrated in Figure 5.1. Finally, the watershed is a set of clusters.

The required input files for modeling are climate data, water use, spatial, and calibration parameters (MITCHELL, MEIN, and MCMAHON, 2001). The model's data output occurs in daily, monthly, and annual time scales. In Chapter 2, we conducted model calibration at Belém catchment and simulated annual and daily water balance under baseline conditions. The annual water balance was simulated based on the 2003-2017 historical series. The daily water balance was analyzed by selecting some events with different RP that triggered floods in the study area between 1999 and 2019. The same data were used in this research to evaluate the performance of scenarios with NbS implementation. For more details on the input data and calibration process in the Belém catchment under baseline conditions, see Chapter 2.

The scenarios with the implementation of NbS for urban drainage were simulated in the Aquacycle model, changing the necessary parameters for inserting sustainable drainage systems, as described in the following item (5.3.2). The results were analyzed on the annual and daily time scales.

The daily results obtained in the hydrological modeling were also used to calculate steady flow input data for HEC RAS model, in which we considered that the flow regime is steady and gradually mixed. The *Qm* obtained in Aquacycle was converted into *Qmax* through the equation defined for the Belém catchment in Chapter 3, based on intense rainfall events recorded at station 83842:

$$Qmax = Qm.(1 + 50.A^{-0,5}) \quad (5.1)$$

where *A* is the catchment area given in km².

It was necessary to estimate the peak flow because *Qm* is generally lower than *Qmax* in small and densely urbanized catchments (TUCCI, 2002). Therefore, it is not enough to supply hydraulic models when simulating floods (FILL and STEINER, 2003).

HEC RAS is a hydraulic model widely used for determining inundation extent (BRUNNER, 2016) and simulating the effect of NbS designs (MATSLER *et al*., 2021). The input data required for modeling are the geometric and streamflow data. To model steady and gradually mixed flow, it is necessary to inform the number of profiles to be calculated (number of events), streamflow data per reach, and upstream to downstream boundary conditions (BRUNNER, 2016). Water surface profiles are computed from one cross-section to the next by solving the Energy Equation. When a flow value is inserted, it is assumed to remain constant until another flow value is added downstream.

In Chapter 3, we calibrated the HEC RAS model for the Belém catchment and simulated flood events of 2, 5, 25, and 100 yr RP for the area and streams indicated in Figure 5.1. The geometric data were set in ArcGIS software, using the HEC-GeoRAS extension, where 134 cross-sectional cut lines along the modeled reaches' floodplain were vectorized, as well as the stream centerlines, the bank lines, bridges, and levees. The same calibration data, geometric data, steady flow, and flood maps under baseline conditions were used in this research to compare and evaluate the performance of scenarios with NbS implementation. For more details on the input data and HEC RAS calibration process in the Belém catchment under baseline conditions, see Chapter 3.

5.3.2 - Formulation of scenarios

The scenarios with NbS implementation were formulated in line with our hypothesis, thus choosing NbS with as simple as possible execution. Considering that deconstructing consolidated cities is spatially and economically unfeasible, it must be understood that there are areas with more significant potential for NbS adapting and that there are more effective and adaptable NbS for different intraurban spatial configuration patterns. Thence, the NbS were simulated according to the pre-existing spatial characteristics in Hydrologic Similarity Areas. The choice of NbS was also based on the sustainable drainage solutions most discussed in the literature, as identified in Chapter 1.

Scenario 1 (Sc1), Scenario 2 (Sc2), and Scenario 3 (Sc3) were simulated. The complexity of implementation and the NbS number increase from Sc1 to Sc3. Thus, measures are added to each scenario, and none of them are suppressed in the following one. The HSA main features and the NbS simulated in each scenario are described and illustrated in Figure 5.2.

HSA	MAIN FEATURES	SIMULATED NBS		
		Sc1	Sc2	Sc3
I	AREA: 4.75Km² IMPERVIOUS SURFACES: 18% PARKS, EDUCATIONAL AND MILITARY INSTITUTIONAL ZONES	DISCONNECT ALL IMPERVIOUS AREAS FROM THE DRAINAGE NETWORK	SC1+ -	SC1+ -
II	AREA: 26.18Km² IMPERVIOUS SURFACES: 66% SINGLE-FAMILY RESIDENTIAL AREAS	DISCONNECT ROOFS FROM THE DRAINAGE NETWORK	SC1+ -	SC2 + REDUCE 50% OF *EPA*; CONVERT 5% OF PAVED AREA INTO PERMEABLE PAVEMENT; CONVERT 5% OF PAVED AREA INTO RAIN GARDEN; REDUCE 30% OF *ERDA*
III	AREA: 7Km² IMPERVIOUS SURFACES: 76% DENSIFICATION, TRANSITION, AND HISTORIC ZONES	SWALES IN THE MAIN AVENUES	SC1+ RAINWATER TANKS (3000L)	SC2+ -
IV	AREA: 30Km² IMPERVIOUS SURFACES: 78% MEDIUM TO HIGH DENSITY RESIDENTIAL AREAS	URBAN AGRICULTURE IN TERRACES IN 20% OF ROOF AREA	SC1+ RAINWATER TANKS (3000L)	SC2 + CONVERT 5% OF PAVED AREA INTO PERMEABLE PAVEMENT; CONVERT 5% OF PAVED AREA INTO RAIN GARDEN; REDUCE 20% OF *ERDA*
V	AREA: 11Km² IMPERVIOUS SURFACES: 83% SERVICE, MIXED-USE, AND PUBLIC INSTITUTIONAL ZONES	-	SC1+ RAINWATER TANKS (3000L)	SC2 + CONVERT 5% OF PAVED AREA INTO PERMEABLE PAVEMENT; CONVERT 5% OF PAVED AREA INTO RAIN GARDEN; REDUCE 20% OF *ERDA*
VI	AREA: 8Km² IMPERVIOUS SURFACES: 89% DOWNTOWN, DENSIFICATION, AND CONNECTION ZONES	URBAN AGRICULTURE IN TERRACES IN 20% OF ROOF AREA	SC1+ RAINWATER TANKS (5000L)	SC2 + CONVERT 5% OF PAVED AREA INTO PERMEABLE PAVEMENT; CONVERT 5% OF PAVED AREA INTO RAIN GARDEN; REDUCE 20% OF *ERDA*

Figure 5.2 - The HSA Main Features And The Formulation Of Scenarios With Nbs Implementation

In Sc1 we chose the NbS that we consider of low complexity implementation in the study area. At HSA I, we simulated the disconnection of all impervious areas (paved areas, roofs, and streets) from the drainage network, as they are public and predominantly permeable areas (82%). It is done by reducing the effective paved area (EPA), effective roof area (ERA), and effective road area (ERDA) parameters to zero in Aquacycle. Thus, the rainwater originating in those areas drain to adjacent permeable areas for infiltration. The water drains to the rainwater network only after soil saturation.

At HSA II we simulate the disconnection of roofs from the drainage network by reducing ERA to zero. The HSA II is characterized by single-family residential areas, where there is a greater proportion of gardens compared to the other HSA. Such measure can be carried out thoroughly, redirecting the water from the gutter to the garden, as illustrated in Figure 5.3A. The massive implementation of roofs disconnection can be made feasible through payment of environmental services, granting discounts on Property and Urban Land Tax for residents that implement such measure, for example.

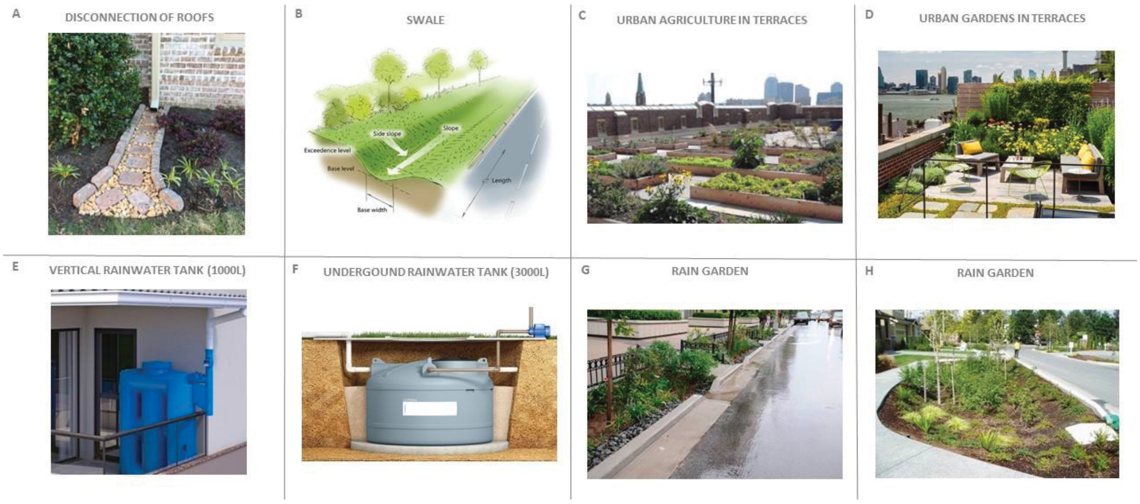


Figure 5.3 - Examples of Simulated NbS.
Sources: A) Lavorist (2022); B) Innovyze (2022); C) Greenroofs.com (2022); D) Viva Decora (2022); E) Soluções Industriais (2022); F) Barbosa (2022); G) Igui Ecologia; F) E-Landscape LLC (2022)

HSA III comprises transition and densification areas that encompass some of Curitiba's main connection avenues. In this HSA, we simulated the implementation of swales (FIGURE 5.3B) in avenues with available green space. Adaptations in drainage and infiltration dynamics would be necessary to convert such green spaces into swales.

HSA IV is characterized by medium to high-density residential areas, has 78% impervious areas, and is the largest HSA in the study area. Due to the higher percentage of impervious areas, reduced garden area, and a significant number of residential buildings with terraces, we simulated the implementation of urban agriculture or urban gardens in 20% of the HSA roof area. Urban agriculture (FIGURE 5.3C) or urban gardens (FIGURE 5.3D) on terraces are classified as extensive green roofs. They are considered low complexity compared to intensive green roofs since they are composed of plant vases and raised beds and causes lower overload on the building structure (VIEIRA *et al*., 2018). According to IGRA (2022), extensive green roofs demand a soil layer ranging from 6 to 20cm deep, representing a structural load of 60kg/m² to 150kg/m² respectively. There is great potential for urban agriculture on terraces diffusion, not only due to its economic viability but also because of its visual impact, enabling its use as roof gardens that provide leisure, human well-being, thermal comfort, spaces for biodiversity and food production. Green roofs were simulated in the Aquacycle model by converting runoff into evapotranspiration by increasing the roof initial loss, following Mitchell´s *et al*. (2008) example.

Urban agriculture on terraces was also simulated under the same conditions in the HSA VI, which is composed of downtown, densification, and connection zones. We considered it a suitable alternative to the HSA with the highest percentage of impervious areas in the study area, which is mainly composed of high buildings. No NbS were simulated in HSA V in Sc1.

In Sc2, in addition to the NbS simulated in Sc1, we set 3000L rainwater tanks in HSAIII, HSA IV, and HSA V, and 5000L rainwater tanks in HSA VI. One rainwater tank has been added in each unit block. We emphasize that we simulated small rainwater tanks in order to model alternatives of easier implementation, which can be installed as a sequence of 1000L vertical rainwater tanks (FIGURE 5.3E) or underground with the desired final capacity (FIGURE 5.3F). The use of rainwater was simulated in garden irrigation and in the laundry, for washing sidewalks and other general cleanings.

In Sc3, in addition to the NbS simulated in Sc1 and Sc2, we simulated NbS that increase the implementation complexity but are still considered spatially viable in the study area. In the HSA II, we simulated the disconnection of 50% of the paved areas from the drainage network, reducing EPA. We also simulated the conversion of 5% of paved areas into permeable pavements (gardens or semi-permeable pavements). Furthermore, we simulated the conversion of 5% of the paved areas into rain gardens destined to drain part of the rainwater generated in the streets (FIGURE 5.3G and 5.3H). ERDA has been reduced by 30%. In the HSA IV, HSA V and HSA VI we also simulated the conversion of 5% of the paved areas into permeable pavements and the conversion of 5% of the paved areas into rain gardens. ERDA has been reduced by 20%.

The average annual water balance was calculated based on a 15-year data series (2003-2017). We compiled and organized the data into bar charts for the Belém catchment and each HSA in mm/year. Tables have been prepared to show the parameters percentage change in each scenario compared to the baseline conditions (Sc0). The analyzed parameters are actual evapotranspiration (ETo), infiltration, runoff, and streamflow.

We also analyzed the performance scenarios on the mean daily water balance by selecting precipitation events from the 1999-2019 historical series. The water balance was simulated for the antecedent climatic conditions as they occurred, but also changing the antecedent humidity conditions. Therefore, the weather conditions were modified in the previous ten days of each event, aiming to assess the performance of the scenarios with antecedent humidity (AH) and with no antecedent humidity (NAH). Thereby, performance range charts were set.

Regarding the flood dynamics, we simulated in the HEC RAS model the same events modeled in Chapter 3 (flood events of 2, 5, 25, and 100 years RP), aiming to assess the effect of NbS scenarios on the floods´ extent. These events correspond to the floods that occurred on 10/03/2008, 06/06/2014, 02/22/2019, and 02/22/1999, and therefore consider the actual antecedent humidity conditions that occurred (FIGURE 5.4). The antecedent conditions of each event and their respective flood areas simulated in Chapter 3 are described and illustrated in Figure 5.4.

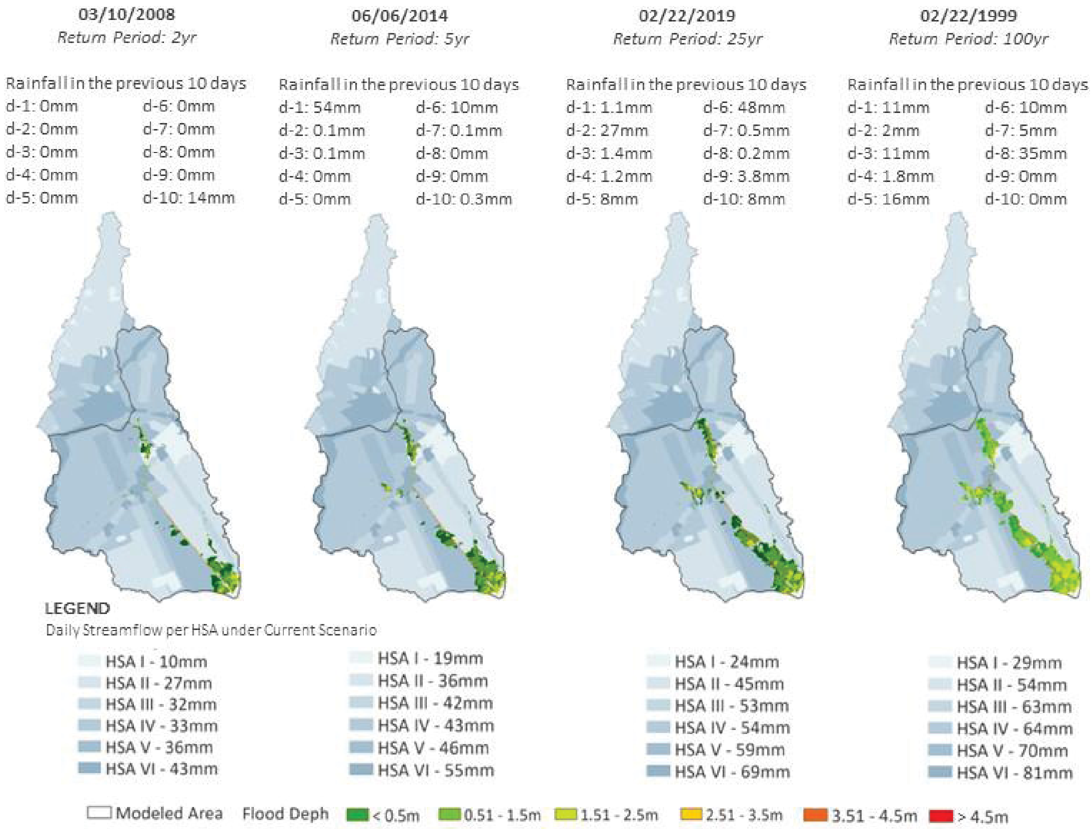
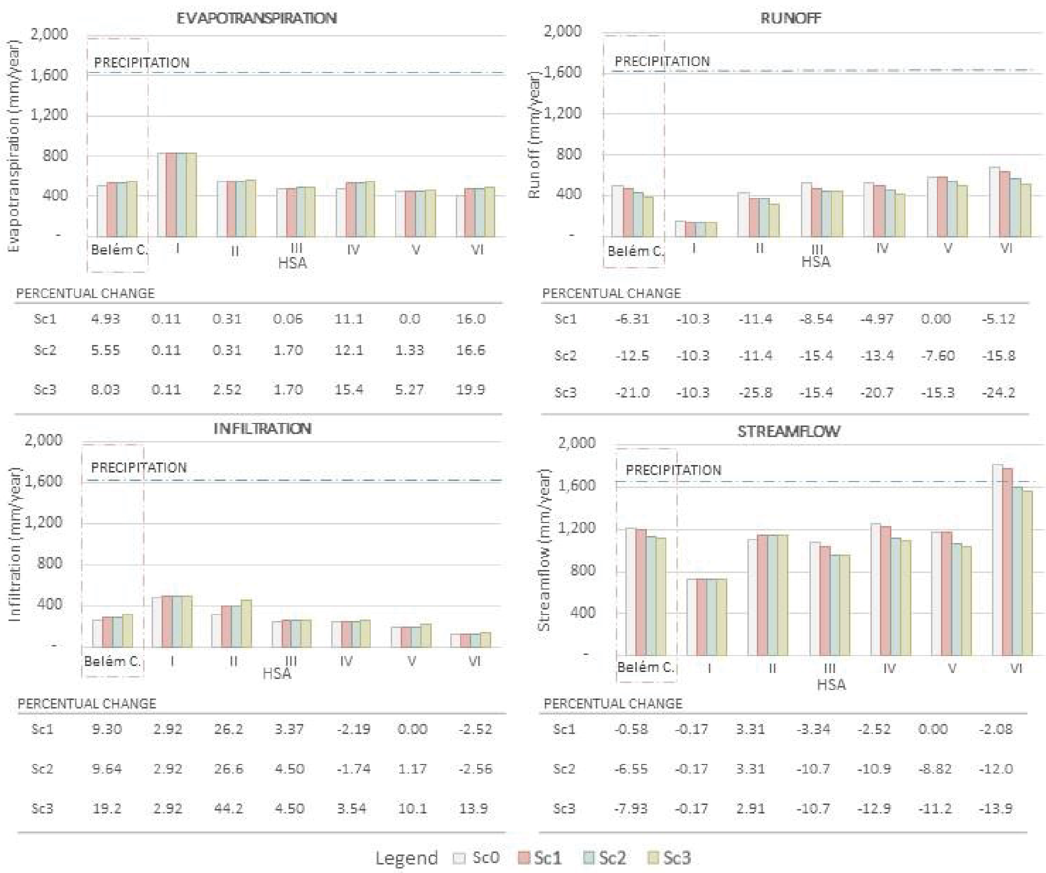


Figure 5.4 - The antecedent conditions of the flood events of 03/10/20018, 06/06/2014, 02/22/2019 and 02/22/1999 and their respective flood areas simulated in Chapter 3

5.4 RESULTS AND DISCUSSION

5.4.1 Performance of scenarios in the annual water balance

With the simulation of scenarios in the Aquacycle model, we assessed the results in annual and daily time scales for each HSA and for the whole catchment. The Figure 5.5 synthesizes the results obtained on a yearly scale for the 2003-2017 period. The bar graphs display the Eto, runoff, infiltration, and streamflow results for the Belém catchment and per HSA for all simulated scenarios. The tables below the graphs show the parameters' percent change in the scenarios compared to Sc0.



EVAPOTRANSPIRATION – PERCENTUAL CHANGE

	Belém C.	I	II	III	IV	V	VI
Sc1	4.93	0.11	0.31	0.06	11.1	0.0	16.0
Sc2	5.55	0.11	0.31	1.70	12.1	1.33	16.6
Sc3	8.03	0.11	2.52	1.70	15.4	5.27	19.9

RUNOFF – PERCENTUAL CHANGE

	Belém C.	I	II	III	IV	V	VI
Sc1	-6.31	-10.3	-11.4	-8.54	-4.97	0.00	-5.12
Sc2	-12.5	-10.3	-11.4	-15.4	-13.4	-7.60	-15.8
Sc3	-21.0	-10.3	-25.8	-15.4	-20.7	-15.3	-24.2

INFILTRATION – PERCENTUAL CHANGE

	Belém C.	I	II	III	IV	V	VI
Sc1	9.30	2.92	26.2	3.37	-2.19	0.00	-2.52
Sc2	9.64	2.92	26.6	4.50	-1.74	1.17	-2.56
Sc3	19.2	2.92	44.2	4.50	3.54	10.1	13.9

STREAMFLOW – PERCENTUAL CHANGE

	Belém C.	I	II	III	IV	V	VI
Sc1	-0.58	-0.17	3.31	-3.34	-2.52	0.00	-2.08
Sc2	-6.55	-0.17	3.31	-10.7	-10.9	-8.82	-12.0
Sc3	-7.93	-0.17	2.91	-10.7	-12.9	-11.2	-13.9

Figure 5.5 - Simulation of scenarios result in the annual ETo, runoff, infiltration, and streamflow

The results show a progressive increase in the annual ETo as NbS are added, due to the conversion of runoff into ETo. We observed an increase of 5.93% in Sc1, 5.55% in Sc2, and 8.03% in Sc3 compared to Sc0. Eto represents 31% of rainfall annual volume in Sc0, 33% in Sc1 and Sc2, and 34% in Sc3.

The most significant increment observed to the ETo rates comes from implementing urban agriculture on terraces in the HSA IV and HSA VI, increasing the HSA´s ETo in 11.1% and 16%, respectively. In addition to the benefits related to runoff reduction, urban agriculture on terraces here simulated reveals potential to contribute to thermal comfort, heat island reduction, and air quality improvement, thus enhancing human well-being in those areas, which present high percentage of impervious surfaces. The increase in permeable vegetated areas in HSA III (Sc1), HSA II, HSA IV, HSA V, and HSA VI (Sc3), and the reduction of ERA, EPA, and ERDA also contribute to the ETo raising, because part of the water retained in the soil is latter converted into ETo.

The results also reveal a progressive increase in infiltration as NbS are added. The catchment presents an increase of 9.3% in Sc1, 9.64% in Sc2, and 19.2% in Sc3 compared to Sc0. We highlight the performance of the disconnection of roofs from the drainage network by reducing ERA in the HSA II. This relatively simple measure results in a 26.2% increase in HSA infiltration. Sc3 also significantly increased infiltration volume, with 44.2% in HSA II, 13.9% in HSAVI, 10.1% in HSA V, and 3.54% in HSA IV, revealing the potential of the simulated measures, especially the rain gardens and ERA reduction. The NbS simulated in HSA I resulted in a 2.92% increase in infiltration, demonstrating that even the most permeable areas of the study area have the potential to enhance their hydrological processes. At HSA III, the swales in the main avenues resulted in a 3.37% increase in the annual groundwater recharge. Notice that the increase in the infiltration volume does not result in annual streamflow reduction. It decreases runoff and peak flows and raises the water residence time by renaturing the natural groundwater recharge process, converting runoff especially into baseflow. The conversion of runoff into baseflow also improve de river water quality by filtering pollutants and reducing diffuse pollution.

A progressive decrease is observed in the annual runoff as the NbS are added to the scenarios. The results reveal a reduction of 6.31% in the catchment´s annual runoff in Sc1, 12.5% in Sc2, and 20% in Sc3 compared to Sc0. Runoff represents 31% of rainfall annual volume in Sc0, 29% in Sc1, 27% in Sc2, and 24% in Sc3. In the HSA, implementing NbS can reduce runoff from 10.3% (HSA I) to 25.8% (HSA II). Among the most impervious HSA, it is possible to observe decreases in runoff ranging from 7.6% to 15.8% in Sc2 and from 15% to 24% in Sc3, suggesting the potential to lessen peak flows and floods. Even with reduced capacity (1000L in HSA III, HSA IV, and HSA V; 3000L in HSAVI), the insertion of rainwater tanks in Sc2 reduced runoff by 10.68% in HSA VI, 7.6% in HSA V, 8.43% in HSA IV, and 6.86% in HSA III. Additionally, water harvesting also results in decreasing imported water in 10% and, consequently, decreasing the water system leakage volume.

Regarding the streamflow, our simulations resulted in a reduction of 0.58% in Sc1, 6.55% in Sc2, and 7.93% in Sc3 compared to Sc0. The percentage reduction is lower in streamflow compared to the other water balance parameters analyzed here. However, it does not mean that the results are of less significance. Streamflow is given in mm/year and does not necessarily reflect daily streamflow behavior during rainfall events. The runoff volume converted into groundwater recharge is still added to the streamflow. What changes in this process are the baseflow rate and the water residence time. Additionally, part of runoff is illegally discharged into the wastewater network, reducing its influence on streamflow behavior, especially on an annual time scale. Thus, based on the scenarios established here, the parameters that directly influence the annual streamflow reduction are Eto increase, water harvesting in rainwater tanks, and water system leakage reduction.

Regarding streamflow results, we also highlight that the most significant reductions were observed in the HSA with the highest percentage of impervious areas, that is, in the highest runoff producers. We observed reductions ranging from 8.82% to 12% in HSA III, IV, V, and VI in SC2 and from 10.7% to 13.9% in the same HSA in Sc3.

Thereby, our results show that the implementation of scenarios composed of multiple and combined measures into the HSA, accordant to spatial preconditions, present significant responses in the annual water balance, resulting in increased Eto and infiltration and decreased runoff and streamflow mainly in the most impervious HSA.

5.4.2 Performance of scenarios in the water balance of daily events

The water balance results of the simulated scenarios were also analyzed on a daily time scale. We selected some precipitation events that triggered floods from the 1999-2019 data series and simulated the performance of scenarios in those events under the antecedent climatic conditions as they occurred, but also changing the antecedent humidity conditions (AH and NAH) to access the scenarios´ range performance. Figure 5.6 summarizes the results obtained for the daily average runoff, infiltration, and streamflow parameters in Sc1, Sc2, and Sc3 into performance range charts. Values are given in percentage of change compared to Sc0.

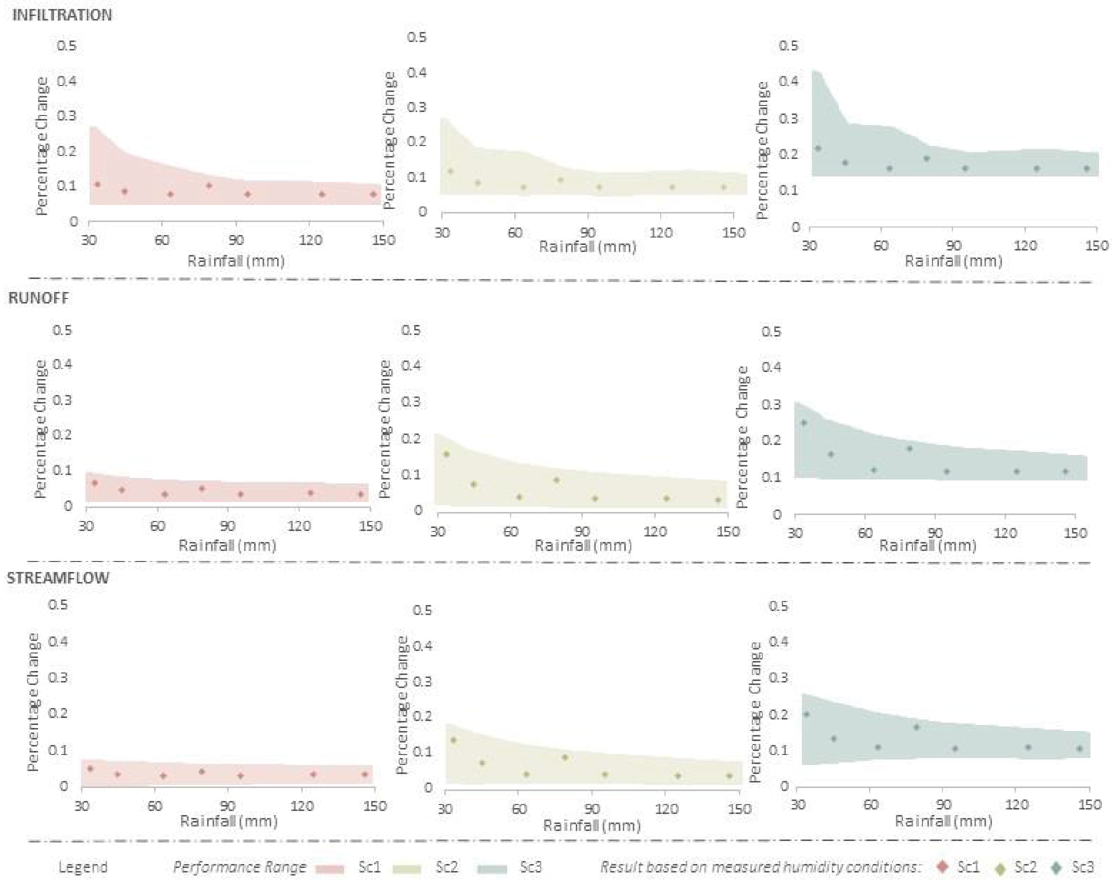


Figure 5.6 - Range Performance of Scenarios in the Water Balance of Daily Events

As expected, the range performance enlarges in all analyzed parameters as the NbS are added to the scenarios and decreases as the volume of rainfall increases. Furthermore, the best performance of NbS for urban drainage occurs under NAH conditions, when surfaces, soil, and rainwater tanks have a greater capacity for infiltration or storage. Changes can also be verified in all parameters and scenarios under AH conditions, but the percentages remain practically constant as the rainfall volume increases. We emphasize that the percentages of change are normalized and presented with positive values. However, runoff and streamflow perform negative variations, reducing volume as NbS are implemented, while infiltration perform positive variations.

Infiltration is the parameter that presents the most significant changes. In Sc1, we observed a 7% increase in groundwater recharge across the entire range of rainfall volume under AH. Under NAH conditions, we verified increases of up to 25% in 30mm rainfall events, reaching 11% in 80mm events and 8.5% in 140mm events. In Sc2, the percentage of change slight reduces compared to Sc1 in events up to 45mm under NAH. It happens due to rainwater tanks storing the initial rainfall, which in Sc1 is converted into infiltration or runoff. Under AH, the percentage is unchanged from Sc1, holding the same 7%, but more than doubles at Sc3, reaching 16%. In Sc3, we verified significant changes in infiltration compared to Sc0, reaching 41% in 30mm rainfall events, 20% in 80mm events, and 18% in 140mm events under NAH conditions. In all scenarios, there is a more significant increase in infiltration in lower precipitation, gradually reducing this percentage gain with the increase in simulated rainfall.

The results also showed significant reductions in runoff in all scenarios. In Sc1, we observed decreases of up to 7.5% in 30mm events, 5% in 80mm events, and 4.3% in 140mm events under NAH conditions. Under AH conditions, the percentage remains constant at 3.6% across all precipitation volumes. Unlike infiltration, runoff changes significantly in Sc2, especially under NAH, reaching 19% in 30mm events, 9.3% in 80mm events, and 9% in 140mm events. Under AH conditions, the percentage decreases as rainfall increases, ranging from 4.6% to 3.7%. In Sc3, we observed changes of up to 29% in 30mm events, 18% in 80mm events, and 14% in 140mm events under NAH conditions. We also observed significant increases in implementing NbS under AH conditions in Sc3, with values ranging from 11.4% to 12.3%.

Increasing variations in mean daily streamflow are also observed as NbS are added, and decreasing variations are observed as rainfall volume raises. In Sc1, the variation ranges from 5.6% to 4% under NAH and between 1.8% and 3.1% under AH. In Sc1, streamflow decreases up to 16.1% in 30mm events, 8.8% in 80mm events, and 5.4% in 140mm events under NAH conditions. Under AH conditions, the percentages vary between 3.2% and 3.4%. Finally, in Sc3, the results show potential for runoff reduction by up to 23.6% during 30mm events, 16.6% in 80mm events, and 13.1% in 140mm events under NAH conditions. Under AH conditions, the percentages vary between 8.3% and 10.2%. Thus, the daily average results also demonstrate that the implementation of scenarios presents significant hydrological responses in the catchment.

5.4.3 Performance of scenarios on floods peak flow and extent

With the mean daily streamflow data, we calculated the peak flow for the precipitation events that occurred on 10/03/2018, 06/06/2014, 02/22/2019 and 02/22/1999, corresponding to 2, 5, 25 and 100yr RP for each of the simulated scenarios, and simulated the floodable areas. The flood maps are illustrated in Figure 5.7, as well as the Qmax reached in the catchment and the flood extent in all the simulated scenarios. Two zooms are highlighted for each RP to show some areas with largest flood extent reduction. The reductions observed in Qmax can be interpreted universally. On the other hand, the reductions in the flooded area are specifically dependent on local relief characteristics.

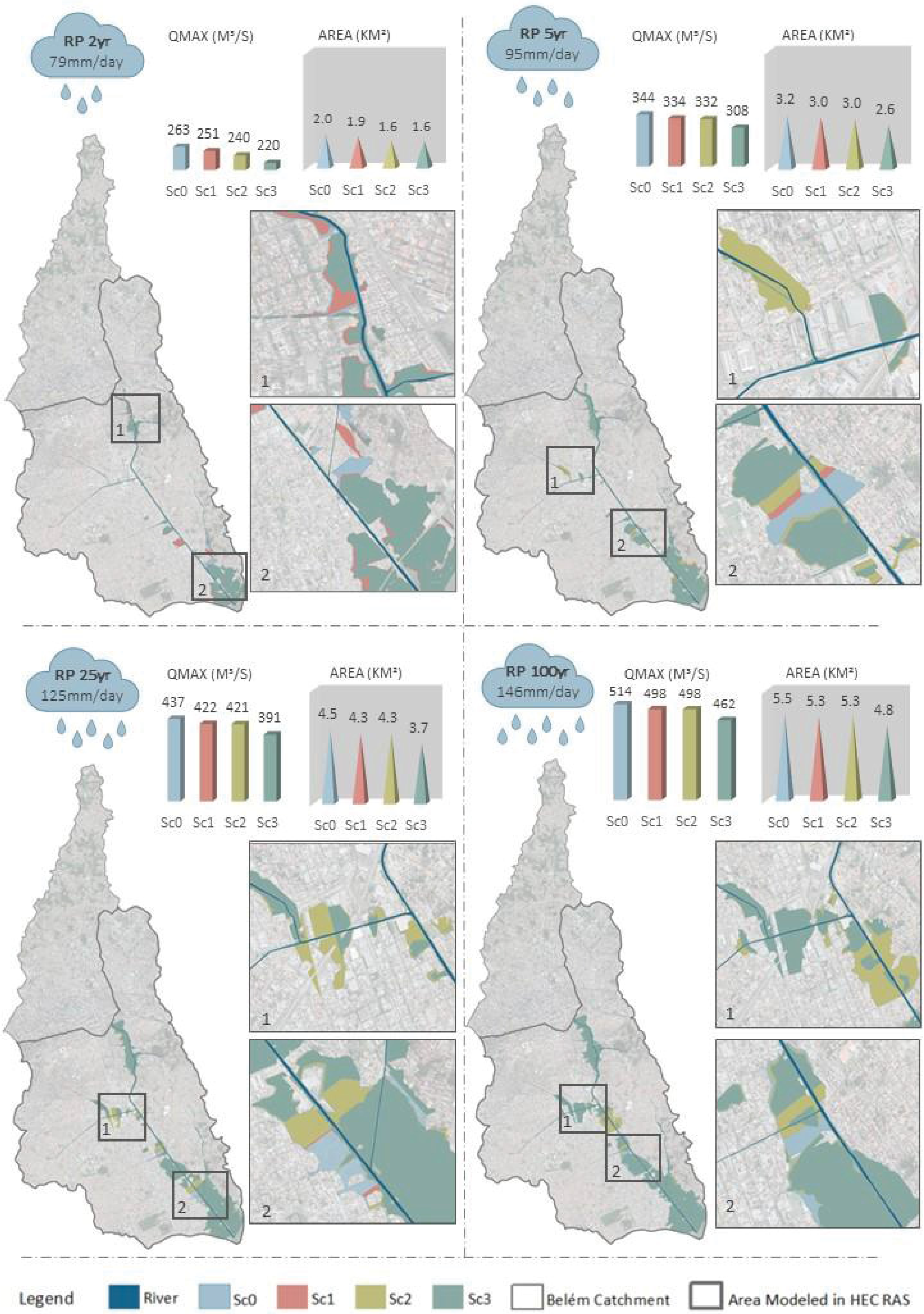


Figure 5.7 - Infographic with areas susceptible to flooding under Sc0, Sc, Sc2 and Sc3 for 2, 5, 25 and 100yr RP, and bar graphs with Qmax and flood extent in each scenario

Our results show that NbS implementation causes more significant changes in lower rainfall events. For events with 2yr rp, we observed a reduction of 4.3% in Qmax in Sc1 (from 263 to 251 m^3/s), 8.7% in Sc2 (to 240 m^3/s), and 16.3% in Sc3 (to 220 m^3/s). At flood extent, decreases of 7% were observed in Sc1, and 22% in Sc2 and Sc3. The scenarios simulated under 2yr RP reflect the maximum performance of NbS, since there is practically no antecedent humidity in this simulation. We verified significant reductions in the flood extent in the further upstream simulated areas, especially with Sc2 implementation (Figure 5.7, RP 2yr, zoom 1) and in the Pinheirinho river floodplain in Sc1 (Figure 5.7, RP 2yr, zoom 2).

On the other hand, the simulations performed under 5yr RP were driven under antecedent humidity conditions, where a rainfall event of 54mm was recorded on the previous day, thus testing the capacity of NbS systems under AH. Even under such conditions, we observed significant changes on flood dynamics, decreasing Qmax in 3.1% (from 344 to 334 m^3/s) in Sc1, 3.7% in Sc2 (to 332 m^3/s), and 10.6% in Sc3 (to 308 m^3/s). At flood extent, reductions of 4% were observed in Sc1, 6% in Sc2, and 18% in Sc3. Sc3 reveals to be able to avoid floods in the V. Guaíra floodplain under 5yr RP (Figure 5.7, RP 5yr, zoom 1). Progressive reductions in flood extent are also observed downstream the confluence with Ev. da Veiga stream (Figure 5.7, RP 5yr, zoom 2).

Simulations under 25yr RP perform better than those simulated under 5yr RP because the antecedent rainfall volume is slightly lower in this event. Thus, we observe decreases of 3.4% (from 514 to 498 m^3/s) in Qmax in Sc1 and Sc2, and 10.3% in Sc3 (to 391 m^3/s). At flood extent, reductions of 6% are observed in SC 1 and Sc2, and 19% in Sc3. Significant changes are observed mainly in the Pinheirinho river floodplain in Sc3, (Figure 5.7, RP 25yr, zoom 1), and in the Boqueirão region (Figure 5.7, RP 25yr, zoom 2) upstream of the confluence with o Areiaozinho stream, with progressive reductions from Sc1.

For events with 100yr rp, we observed a 3.2% reduction in Qmax of Sc1 (from 437 to 422 m^3/s), 3.3% in Sc2 (to 391 m^3/s), and 10.1% in Sc3 (to 462 m^3/s). In the flood extent, decreases of 3% in Sc1 and Sc2, and 13% in Sc3 are observed. The most significant changes occur at the Pinheirinho and V. Guaíra streams floodplain, especially with Sc3.

We emphasize that these simulations were based on real flood events, according to different conditions of antecedent humidity. For this reason, the results in events with different antecedent humidity conditions can suffer positive or negative variations both in Qmax and flooded areas. The events are also simulated under short intense rainfall conditions. Rainfall with the same volume distributed in one day will result in different flood dynamics due to the reduced water residence time in the Belém catchment.

Our results show that the implementation scenarios composed of multiple and decentralized NbS are spatially feasible and can mitigate floods and urbanization's adverse effects on the water balance. In addition, they can improve the provision of ecosystem services such as carbon storage, water safety, water and air quality, thermal comfort, food security, and support biodiversity. The main novelty of this research is to present an efficient response with simpler measures, spatially distributed according to the pre-existing intraurban spatial characteristics, here spatialized into HSA.

It is evident that implementing the suggested NbS scenarios can reduce floods, but more is needed to completely solve flooding issue in the study area. Extensive green roofs with greater water storage capacity could be simulated on some HSAs to enhance performance in reducing daily runoff. This measure was not simulated due to the limitations of the Aquacycle model for simulating extensive green roofs. In order to build a resilient urban environment, especially in the face of scenarios of intensification of extreme events, it is necessary to implement hybrid measures, create linear parks and relocate populations of risk areas. Such measures remain as suggestions for future studies.

5.5 CONCLUSION

Our research investigated the performance of scenarios with decentralized and multiple Nature-based Solutions for urban drainage in the Belém catchment water balance and flood dynamics. The NbS were simulated according to the pre-existing spatial characteristics in each of the six Hydrologic Similarity Areas delimited in the study area, considering that deconstructing consolidated cities is spatially and economically unfeasible and that not all NbS are suitable for all conditions.

Our first contribution refers to the study proposal for implementing NbS for urban drainage in urban environments based on the delimitation and analysis of HSA, identifying the pre-existing spatial conditions and the easiest and most effective adaptation measures for each of the spaces delimited. We emphasize that it is possible to delimit HSA in any urban catchment based on the particular spatial parameters. Our study also contributes to the existing gaps in implementing hybrid and distributed alternatives once most studies have simulated only one type of NbS.

Our results show significant changes in the annual and daily water balance and flood dynamics. The annual water balance results show that NbS scenarios can increase evapotranspiration by up to 8% and infiltration by up to 19%. It can also reduce runoff by up to 20% and streamflow by up to 8%. The most significant contribution to increasing Eto comes from urban agriculture on terraces. In terms of increasing annual infiltration, the disconnection of roofs from the drainage network stands out. In the daily water balance, the simulation under different conditions of antecedent humidity allowed us to visualize a performance range for different rainfall events. As expected, the range performance enlarges in all analyzed parameters as the NbS are added to the scenarios and decreases as the volume of rainfall rises. Increases ranging from 7% to 41% for infiltration rates and reductions ranging from 3.6% to 29% for runoff were observed, depending on the scenario, precipitation volume, and antecedent humidity conditions.

Regarding the flood dynamics, our results show that NbS implementation causes more significant changes in lower rainfall events. We observed reductions of up to 16.3% in peak flows and up to 22% in flood extent. The reductions observed in Qmax can be interpreted universally. On the other hand, the reductions in the flooded area are specifically dependent on local relief characteristics.

Thus, we conclude that scenarios composed of multiple and decentralized NbS, accordant to the spatial preconditions, can mitigate the urbanization's adverse effects on the water balance and floods in the Belém catchment, thence confirming our hypothesis. Additionally, the NbS simulated here can also contribute to the other societal challenges of the 21st century described by IUCN, building more resilient cities and providing multiple ecosystem services.

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6. GENERAL CONCLUSION

This doctoral thesis, elaborated in the format of articles collection, investigated how the implementation of Nature-based Solutions (NbS) distributed in Hydrologic Similarity Areas (HSA) can reduce the impacts of urbanization on water balance and flood dynamics in the Belém catchment, considering the limitations of the pre-existing intraurban spatial configuration. The format of articles collection adopted in this research demonstrated to be valuable and functional once it facilitates later research submission to scientific journals and that each article associates with one another to achieve the main objective and validate the research hypothesis.

The first contribution of this research arises from Article 1 (Chapter 2), which investigated the existing interfaces among NbS and the Urban Hydrology concepts linked to sustainable drainage. No research has explored such relation so far, mainly because NbS is a recent concept in the scientific literature. Therefore, the theoretical analysis and the structured systematic review conducted here were essential to deepen the understanding of one of the key-concepts of this research in the context of Urban Hydrology, also serving as a subsidy for Article 4 (Chapter 5).

By exploring the relationships between the concepts of Low Impact Development (LID), Sustainable Drainage Systems (SuDS), Water Sensitive Urban Design (WSUD), Re-naturing Cities, Sponge Cities, and Green/Glue Infrastructures (GBI) and NbS in the literature, this research attested to the ontological and epistemological coherence of classifying sustainable urban drainage concepts as part of the NbS conceptual umbrella. Furthermore, the questions applied to each selected manuscript provided a comprehensive view of the strengths and weaknesses in associating the concepts, revealing to be fundamental that the relationships are clearly established so that their use is appropriately applied and operationally valid. The results also showed that the multidisciplinary character is inherent to NbS for urban drainage.

Article 2 (Chapter 3) contributed to investigating the urban spatial heterogeneity's role in the water balance by applying the HSA delimitation method and hydrological modeling in the Belém catchment. The modeling fit satisfactory calibration and showed significant variability in the responses of the water balance parameters in the HSA. The evapotranspiration rates represented between 25% and 50% of precipitation, depending on the HSA. Moreover, infiltration varied up to 5 times, and runoff up to 3.5 times among the HSA.

Article 2 also contributed to enhancing the methodology to delimitate the HSA. The insertion of cluster analysis using parameters that could represent zoning and spontaneous urbanization proved to be effective in identifying areas with the same spatial configuration patterns and, therefore, similar water dynamics. We believe that the methodology can be applied to other urban spaces. Although the particularities of cities' historical formation may result in an infinity of elements available for analyzing the diversity of intraurban spaces, every urban environment presents heterogeneity in the spatial configuration, allowing its compartmentalization into HSA. Thence, Article 2 provided input for the two subsequent articles.

Article 3 (Chapter 4) contributes to providing subsidies for understanding the flood dynamics under intense rainfall conditions in the study area, providing flood maps in different return periods (RP) and the streamflow contribution from each HSA. In the hydraulic modeling, the calibration process showed good correspondence between the observed and simulated flooded areas in the selected events. The results reveal that the most susceptible to flooding areas are not necessarily the main contributors to streamflow, and that the downstream areas are the minor contributors to streamflow but the most affected by floods in all RP. Thus, the results indicate that with the intensification of soil sealing and rectification works carried out in upstream areas, the impacts are transferred downstream.

The results of Article 3 also contribute as a non-structural solution for flood mitigation and management in the study area. It also demonstrates that studying floods based on understanding the systemic relationship between rivers and catchments can contribute to implementing more effective structural measures in urban spaces, providing links to the next chapter.

Article 4 (Chapter 5) used the results, and theoretical and methodological bases of the three previous chapters to simulate scenarios with NbS implementation and thus validate the research hypothesis. One of the contributions of this study is the proposal for implementing NbS for urban drainage in urban environments based on the delimitation and analysis of HSA, identifying the pre-existing spatial conditions and the easiest and most effective adaptation measures for each of the delimited spaces. The study also contributes to the existing gaps in implementing hybrid and distributed alternatives since most studies have simulated only one type of NbS.

Significant results were found for both water balance and flood extent dynamics. The results showed that NbS scenarios could increase evapotranspiration by up to 8%, infiltration by 19%, reduce runoff by up to 20%, and streamflow by up to 8% on an annual scale. In the daily water balance, increases ranging from 7% to 41% for infiltration rates and reductions ranging from 3.6% to 29% for runoff were observed, depending on the scenario, precipitation volume, and antecedent humidity conditions. Regarding the flood dynamics, reductions of up to 16.3% in peak flows and up to 22% in flood extent were obtained.

Finally, the hypothesis is validated, concluding that the pre-existing urban spatial configuration limits the implementation of NbS for urban drainage. However, scenarios composed of multiple and combined measures into the HSA, accordant to preconditions, may present significant responses in the water balance, reducing the stormwater peak flows and the areas susceptible to flooding.

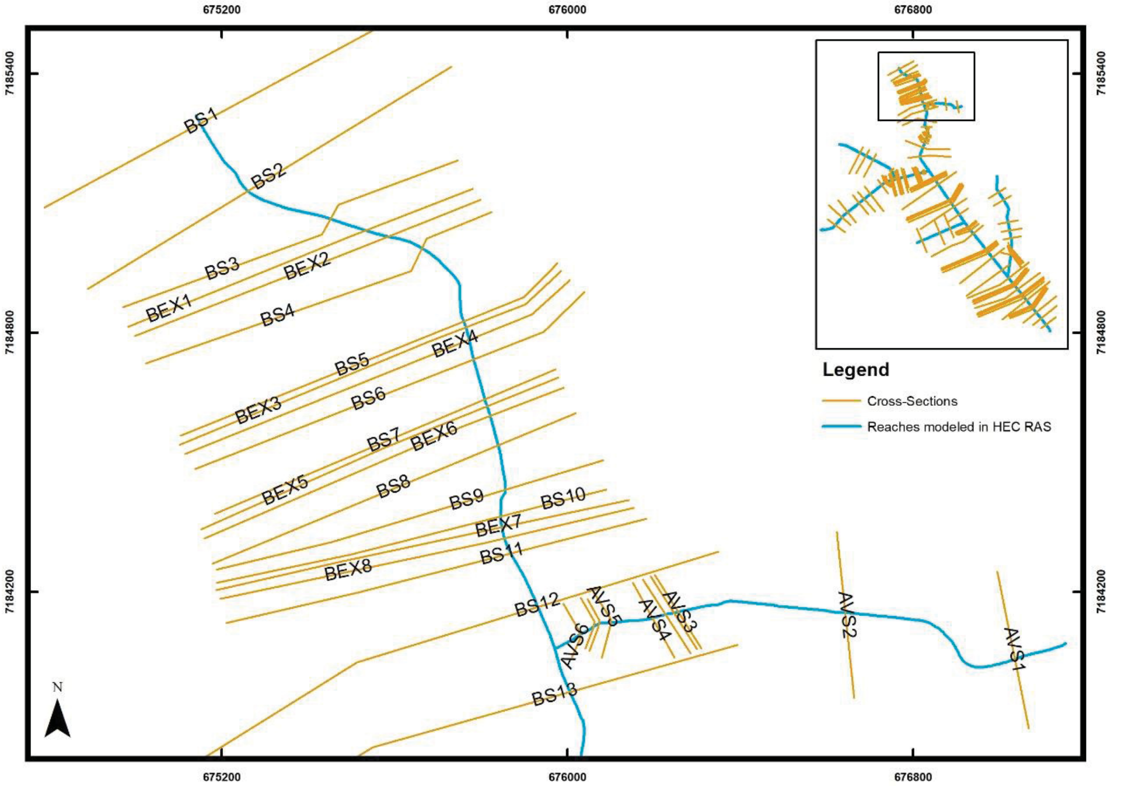
The main limitations of this research are linked to simplifications inherent to the modeling processes. When simulating natural phenomena in mathematical models, we need to accept certain conditions that simplify the problem in order to make it tractable. Among the main ones, we highlight the difficulty of monitoring and accurately representing complex phenomena in a study area such as this one, which presents low residence time and sub-daily data behavior. It is also important to consider that the simulations involving the peak flow estimation in this study are valid for short intense rainfall episodes, considering events uniformly distributed in the catchment. Additionally, there is a limitation of the Aquacycle model in mathematically representing some types of NbS, such as intensive green roofs, ponds, lakes, retention and detention basins.

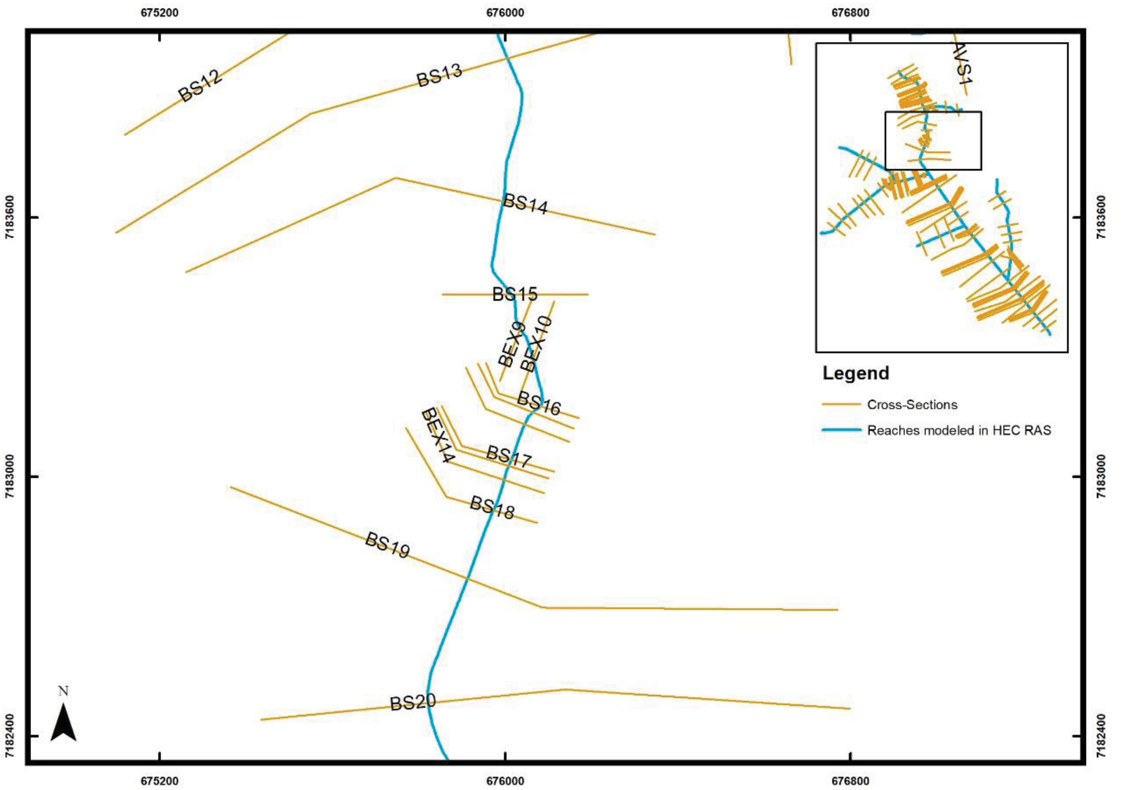
This research showed that NbS for drainage has great application potential in economically and spatially viable scenarios, especially face to the societal challenges of the 21st century described by the IUCN. The NbS here simulated can not only mitigate flood, but also contribute to the production of a range of ecosystem services, thus emphasizing the multidisciplinary character inherent to the NbS concept.

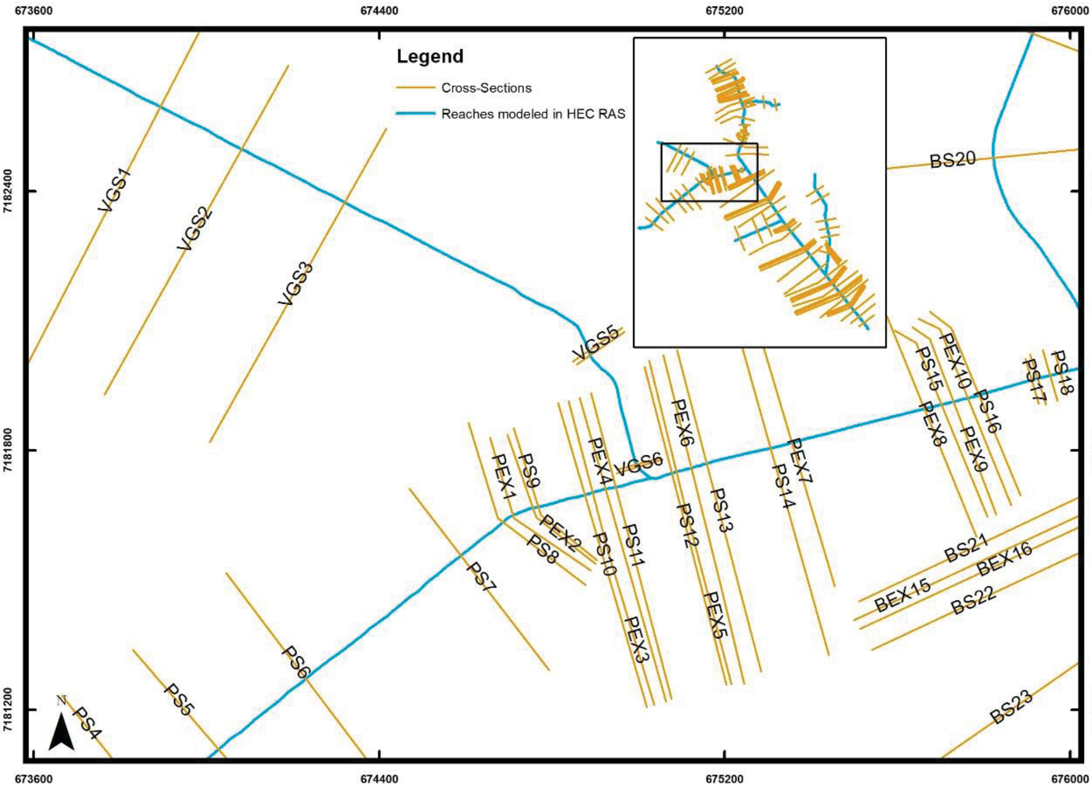
Due to its recent inclusion in the scientific literature, many are the possibilities for future studies. New theoretical studies can be conducted to investigate the relations among NbS and other ecosystem-related concepts. Mathematical models can be developed or adapted to represent and simulate all the possible alternatives in sustainable urban drainage. Modeling or empirical studies also need to be carried out to deepen the understanding of NbS optimization and management. While theoretical, empirical, and modeling studies keep being conducted, the NbS seeks building tangible paths to achieve global relevance in the water resources field and to contribute to edifying more resilient cities.

APPENDICES

1 Cross-sections used in HEC-RAS



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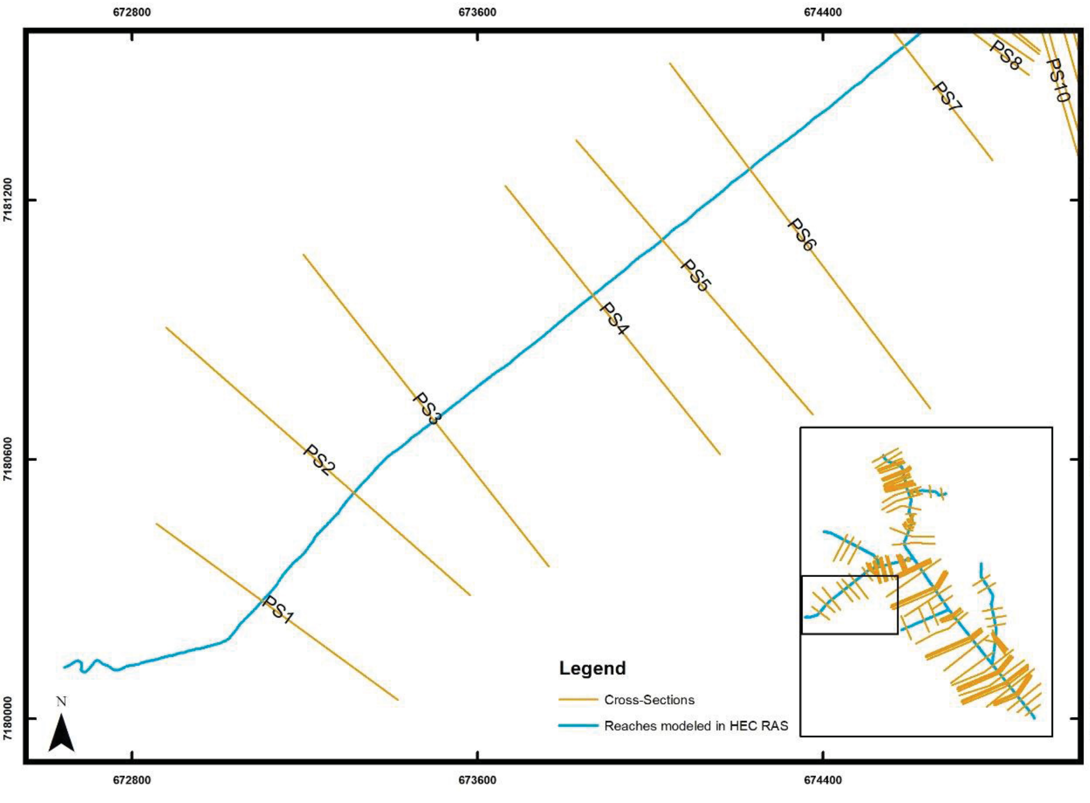
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Reaches modeled in HEC RAS
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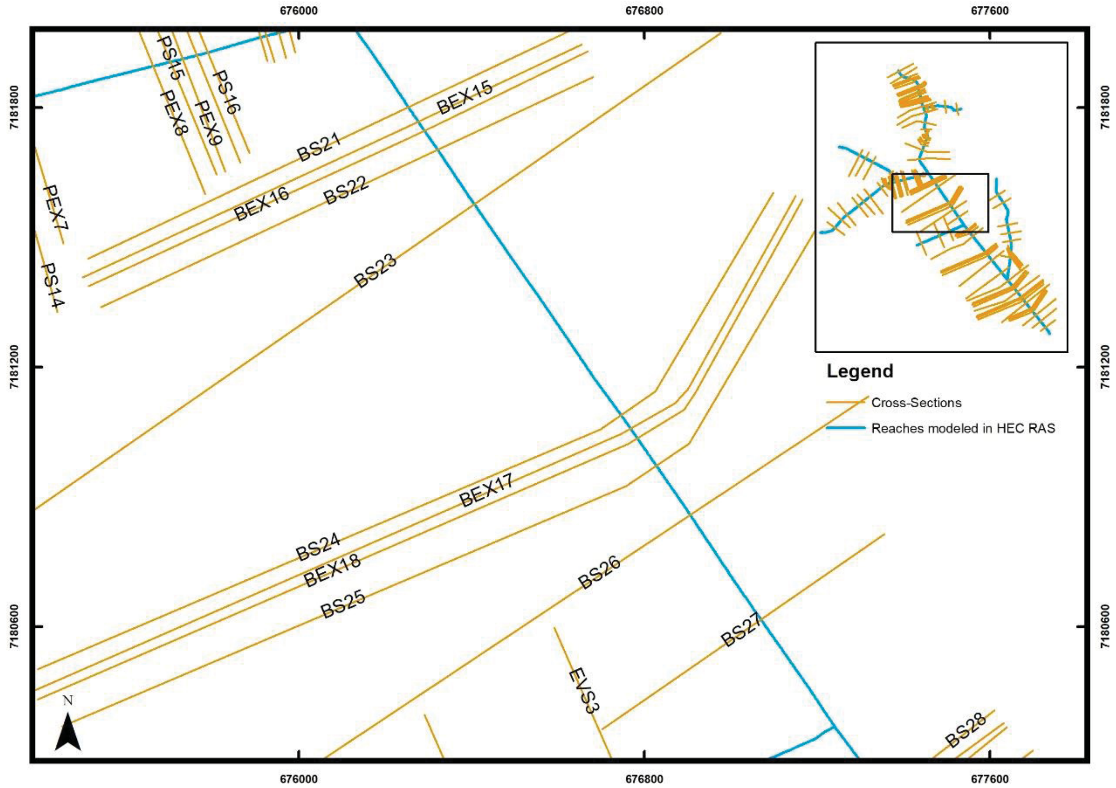
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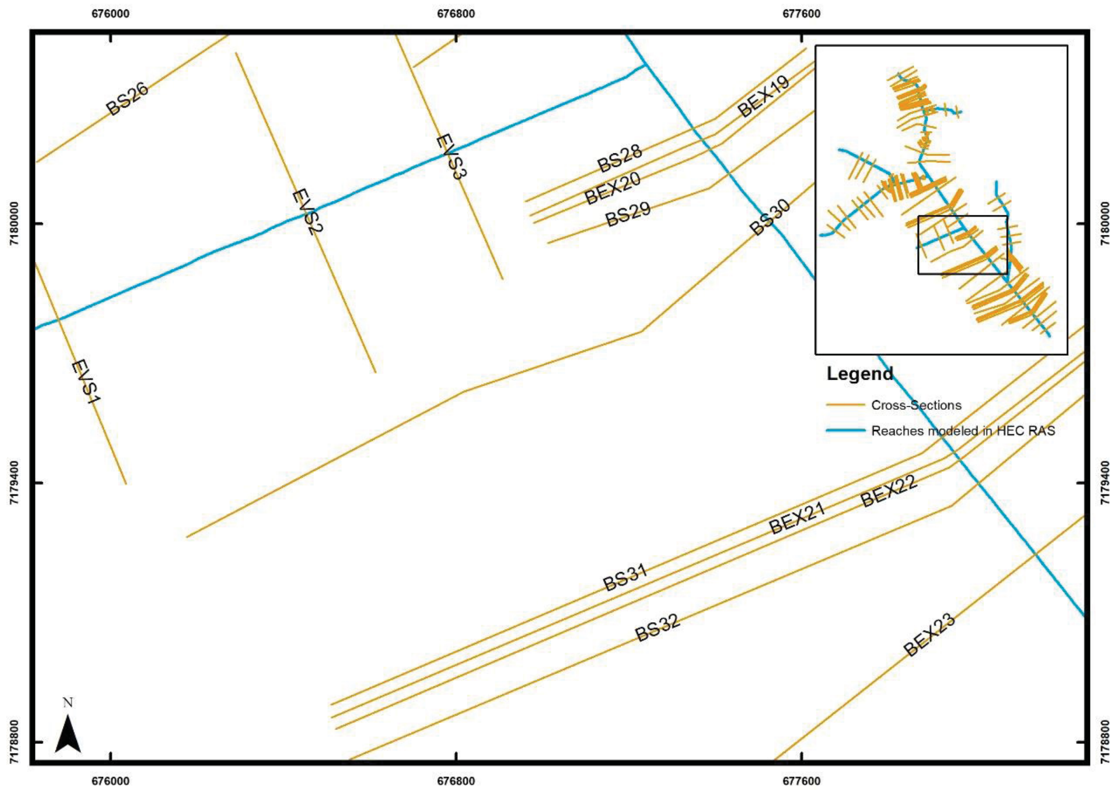
Reaches modeled in HEC RAS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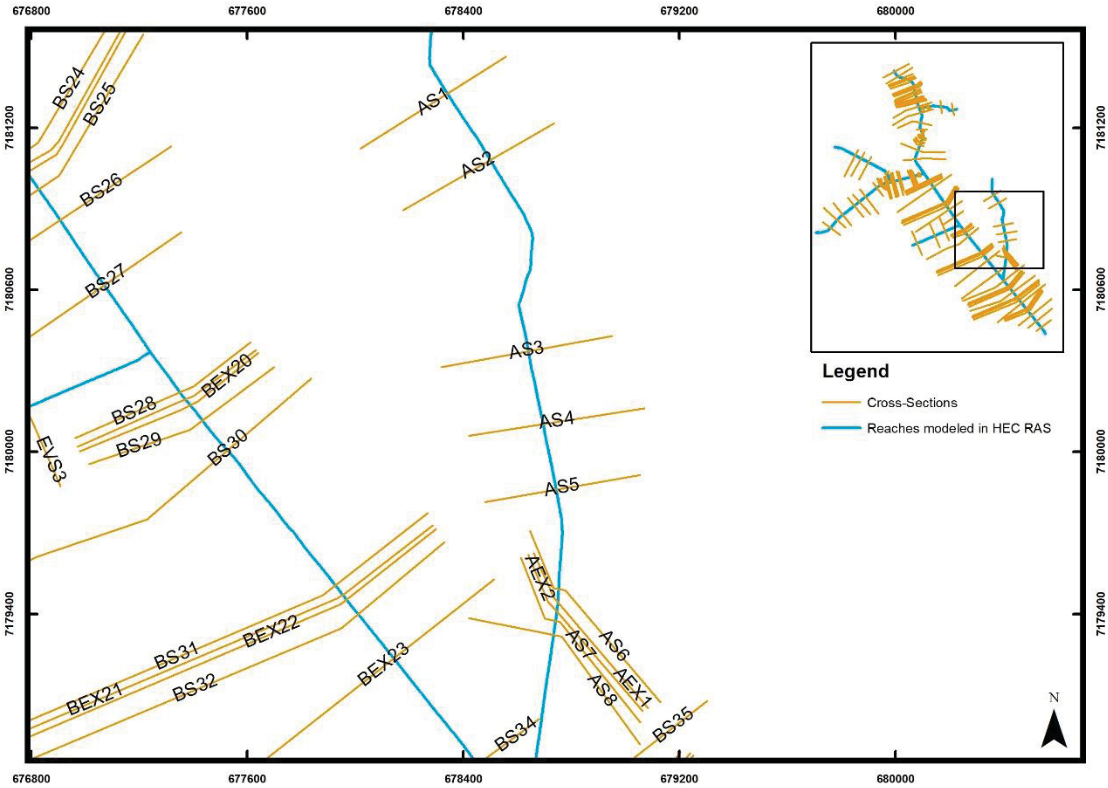
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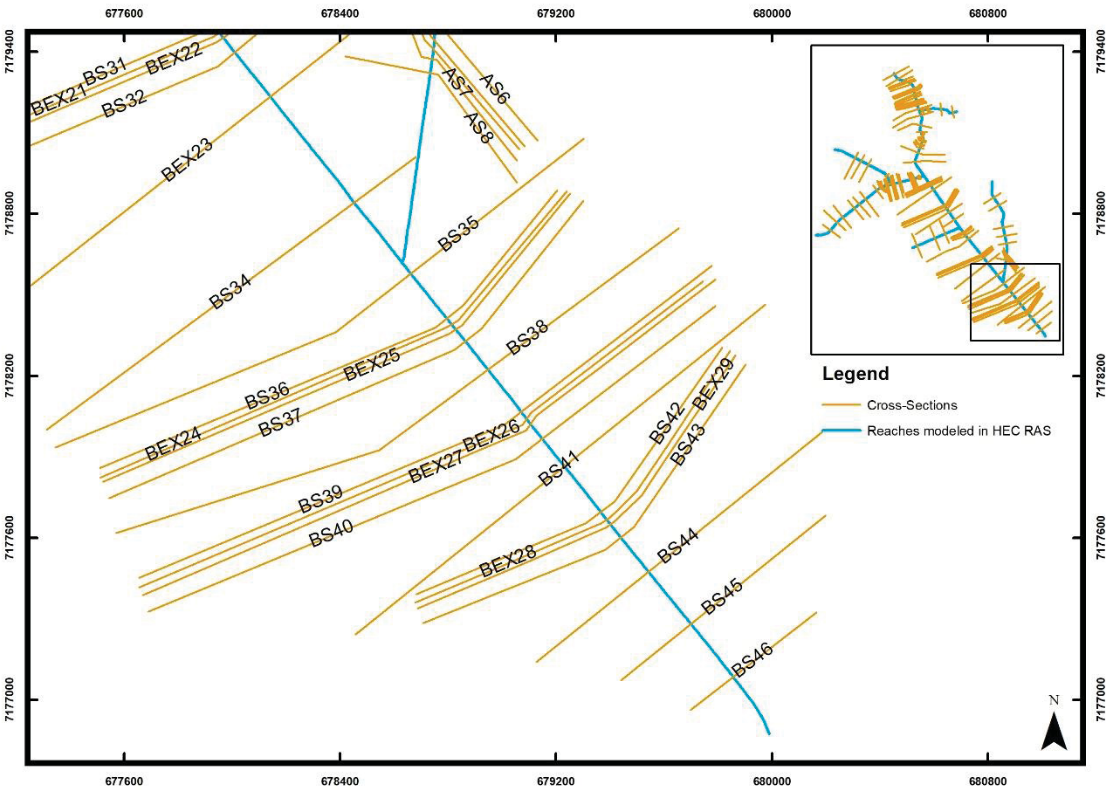
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