An integrated spatial-participatory framework for flood risk mitigation in the semiarid region of Brazil

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

Signature: Priscila Barros Ramalho Alves ……………………………………………………………………………

ABSTRACT

As flooding continues to impact cities worldwide, engineering studies are focused on finding best strategies for Flood Risk Reduction (FRR) aiming mainly to the return of the pre-development state (before urban growth). However, current approaches provide a minor reflection of how communities at risk can adapt, reorganise, and sustain changes for the future. This thesis contributes to this context, by including the perspective of FRR as a "social phenomenon", enabling the discussion of (1) why some places experience catastrophic risk impacts with losses of properties and lives, and (2) what are the barriers and challenges to move FRR forward in vulnerable regions. In this context, the main objective of this thesis is to develop an integrated spatial-participatory framework for FRR in a Brazilian vulnerable area, the semiarid region. The framework was applied in the city of Campina Grande, located in Paraiba state. Campina Grande represents a middle-sized city with more than 400,000 inhabitants who face urban growth, social inequalities, water-related disasters, pluvial flooding (FR), and water shortage (WSR) risks. The integrated framework was built with the assumption that characterising the current NEEDS, enlightens the selection of appropriate ACTIONS and solutions for FRR in the local scale (i.e., NEEDS for ACTION). The framework combines participatory planning strategies with spatial tools, such as ArcGIS Pro (ESRI), Cellular Automata Dual-DrainagE Simulation (CADDIES) model, and Storm Water Management Model (SWMM). The participatory approach entitled as the PLANEJEEE Project (To Plan Extreme Events – "*Planeje Eventos Extremos*" in Portuguese) was formulated with the participation of residents, local authorities and specialists. 255 people participated of different strategies, including online and in-person surveys, informal meetings, workshops, and focus groups in 2019 and 2021. Results from the surveys shows that socio-economic, geographical, informational and contextual factors impact the risk perception and coping capacity of residents. When comparing FR and WSR perceptions, findings shows that resources related to information (communication), incentives and trust should be provided for improving residents' coping capacity before, during, and after the water-related events. Also, FRR challenges and future solutions are discussed in relation to issues with management, legislation, governance, society, and collaboration. The approach also developed mappings with spatial datasets for representing the current and future distribution of flood hazard, vulnerability and exposure. These maps show how residents are differently exposed and vulnerable to flood risk, leading to more inequalities in the city. The thesis is concluded with the analysis of Nature-Based Solutions (NBS), green roofs, rain gardens, permeable pavement, green areas, and rainwater harvesting for Campina Grande. Findings show that solutions can provide environmental, social and economic benefits for the city, especially when they are combined; however, benefits are varied and located in different areas in the city. Benefits are context-specific, influenced by the place's inherent aspects, such as current needs, the location, and the application area. The thesis finalises with a discussion about how territorial exposure and vulnerability are linked spatial inequalities. Finally, recommendations for FRR in the Brazilian context are provided.

Keywords: flood risk reduction, vulnerability, spatial tools, participatory approach, NBS, multiple benefits, inequalities.

“**Flourish** to eternity”
Psalm **92**

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LIST OF ABBREVIATIONS

AESA: Executive Agency of Water Management of Paraíba

ANA: Water and Sanitation National Agency

BGI: Blue-Green Infrastructure

BMP: Best Management Practices

CAGEPA: Water and Sewage Agency of Paraíba state

CAS: Complex Adaptive Systems

CC: Coping Capacity

CHIRPS: Climate Hazards Center InfraRed Precipitation with Station data

CT: Compensatory Techniques

DR: Disaster Risk

DRR: Disaster Risk Reduction

DROP: Disaster Resilience of a Place

DV: Disaster Variables

EbA: Ecosystem-based Adaptation

EC: European Commission

Eco-DRR: Ecosystem-based Disaster Risk Reduction

ES: Ecosystem Services

FR: Flood Risk

FRM: Flood Risk Mitigation

GI: Green Infrastructure

GSI: Green Stormwater Infrastructure

IUCN: International Union for Conservation of Nature

IPCC: Intergovernmental Panel on Climate Change

IUWM: Integrated Urban Water Management

LID: Low Impact Development

NBS: Nature-Based Solutions

OIEWG: Open-ended Intergovernmental Expert Working Group

PMCG: Prefeitura Municipal de Campina Grande (City Council of Campina Grande)

RP: Risk Perception

SUWM: Sustainable Urban Water Management

SUDS: Sustainable Urban Drainage Systems

UNDRR: United Nations of Disaster Risk Reduction

WSR: Water Shortage Risk

WSC: Water Sensitive Cities

WSUD: Water Sensitive Urban Design

CHAPTER 1
Introduction

This section presents the introduction of this study. It is divided into four topics comprising the background and motivation of this study (1.1), general and specific objectives (1.2), organisation (1.3) and publications (1.4).

Chapter 1 - Introduction

1.1 Background and motivation

> “1,2 million and 2,9 billion of people were killed and affected by disasters from 2000 and 2012 worldwide, and more than 1,7 trillion of dollars were spent with damages (UNISDR, 2012)”.

Citations like this are often used in the media introducing the likelihood and impacts caused by disasters around the globe. In 2021, the release of the Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) received attention in the media, showing evidence that human-induced activities have contributed to the increment of droughts, heavy precipitation, hot extremes, and extreme compound events in every region across the globe (IPCC, 2021). Even though governments, institutions, and academia have accomplished much in the last decades, literature still shows the impacts of disasters are due to increase in the future (IPCC, 2012, 2014; UNDRR, 2019). Different reports indicate the number of populations impacted by disasters will rise considerably in the next years (IPCC, 2012, 2014, 2021; UNISDR, 2021).

There are diverse and debatable views on what a disaster is. From one perspective, there is the “hazards-disaster tradition” that, as the terminology says, is focused more on the hazard studies, such as earthquakes, tornadoes, flood and so forth (Rodríguez *et al.*, 2007). The initial emphasis of this view is on the processes associated with the hazard occurrence by considering the disasters as the events that take place as part of normal environmental processes, not being the principal focus of study. From the other perspective, disasters are considered as a “social phenomenon”, with a variety of concepts built within the context of social change, illustrated by Kreps (1998), Gilbert (1998), Mileti (1999), and Quarantelli (2005). Gilbert (1998) conceptualises “disasters” as a function of agents and social in origin. Similarly, Mileti (1999) represented disasters as overlapping the physical, built, and social environments, being “social in nature”. For Quarantelli (2005), disasters represent vulnerability, reflecting “weaknesses in social structures or social systems”. These definitions share a conception that disasters firmly take place in social relations, characterised as a social disruption, originated in the social structure that might be remedied through social structural manipulations (Rodríguez *et al.*, 2007).

However, the differences between the “hazard” and “social” traditions directly affect how disasters are managed. Cutter *et al.* (2003) argued the main barrier of the hazards-disasters tradition approach lies in placing the origin of disaster in the hazard context instead of vulnerability. Hazards researchers studying disasters have moved slightly from what was considered as an “agent centred” approach to a greater focus on the “vulnerability” and “resilience” views for the reduction of impacts (Cutter, 2005; Cutter *et al.*, 2008; Cutter *et al.*, 2003; Mileti, 1999; Quarantelli, 2005). In this sense, to contribute to the management of risks, different disciplines, including disaster management, development, economics, health sociology, environmental studies, have developed their definitions of vulnerability (Bergstrand *et al.*, 2015). The search for appropriate definitions indicates the importance of vulnerability in developing disaster risk reduction (DRR) approaches. For example, environmental engineering usually assesses vulnerability in terms of damage ratio (Maletta *et al.*, 2020). In contrast, social studies measure their impact on societies, including livelihood, poverty, and disaster reduction (Frigerio *et al.*, 2016a).

The inclusion and recognition of vulnerability on the Sendai Framework of Disaster Risk Reduction 2015-2030 (UNDRR, 2015) are considered a “historical moment” of DRR approaches. The United Nations framework promotes the shift between hazard to vulnerability paradigms and the move from top-down approaches, focusing on response and relief, emphasizing on community-based and bottom-up approaches for risk mitigation (Šakić Trogrlić *et al.*, 2017; Ward *et al.*, 2020). However, scholars highlight that no model is appropriate for all local contexts and hazardous circumstances (Di Baldassarre *et al.*, 2019; Mondino *et al.*, 2020; Šakić Trogrlić *et al.*, 2017; Scolobig *et al.*, 2015). Regardless of risk and vulnerability definitions, which will be detailed further in this thesis, researchers have argued the primary goal of DRR actions and solutions should focus on tackling the underlying disaster causes (López-Martínez *et al.*, 2019). However, part of the current approaches focuses on vulnerability regarding impacts and damage reduction, with less attention to the social and institutional vulnerabilities involved in the DRR process (Crosweller *et al.*, 2020; López-Martínez *et al.*, 2019; Marchezini *et al.*, 2017). Different authors (Bergstrand *et* *al.*, 2015; Birkmann, 2007; de Loyola Hummell *et al.*, 2016; Fuchs *et al.*, 2011; Hendricks *et al.*, 2021) term “institutional” and “social” aspects as the “root causes” of vulnerability, (Pescaroli *et al.*, 2019) including their multiple dimensions (Birkmann, 2007).

In this context, another barrier is that when the proposal of actions and solutions includes the analysis of vulnerabilities, the social context receive more attention in studies. For example, many scholars suggest two main explanations for the lengthy impacts of flood risk on societies: climatic and social factors (Birkmann, 2007; López-Martínez *et al.*, 2019), indicating there is the influence related to the climatic oscillations (Hammond *et al.*, 2018; IPCC, 2014; Khan *et al.*, 2018) but also the socio-economic factors related to the areas in risk of disasters (Kelman, 2020; Sharma *et al.*, 2019). However, the roots causes of vulnerability should also incorporate the premise that risk is ultimately the result of decisions that people make, either individually or collectively (Kelman, 2020), including the behaviours and attitudes of governance and urban planning actors.

The Global Assessment Report of the UNDRR (2019) highlights the consequences of inaction in addressing the systemic nature of risk to individuals, organisations, and society are becoming increasingly apparent in different contexts. This may explain why, in 2010, research of the Global Facility for Disaster Reduction and Recovery (GFDRR) showed that about 85 percent of households vulnerable to flooding lived in developing countries (Danso *et al.*, 2016). Countries in the South American and African continents such as Ghana, Brazil, Botswana, and Nigeria are known nations that strive to manage risk and reduce impacts in their societies (Danso *et al.*, 2016; Daramola *et al.*, 2016; Londe *et al.*, 2015; Lund Schlamovitz *et al.*, 2020). In the case of Brazil, significant disasters such as floods, flash floods, landslides, droughts, and windstorms, have severely impacted the country in the last 20 years (Assis Dias *et al.*, 2018; Ávila *et al.*, 2016). For Lorentz *et al.* (2016), only in 2011, more than 510 water-related disaster events took place in the Brazilian territory, affecting 12,5 million people and resulting in approximately 1100 victims (Assis Dias *et al.*, 2018).

Despite what is said in the traditional approach of “natural” disasters, which reflects the historical idea that disasters are random, exceptional events or acts of nature (Peduzzi, 2019), the reflection of disasters as the materialisation of the underlying conditions induced by human activities and decisions provides insights of how DRR approaches can be improved (Birkmann, 2007; IPCC, 2021; Kelman, 2020). For example, in Brazil, the ineffective fulfilment of the land use legislation, natural conservancy interests, engineering principles, and unprecedented levels of heavy rains for an extended period are the causes of the 2011 disaster (Ultramari, 2013). Notably, the country experiences climatic specificities, with high temperatures and precipitation, but also a considerable amount of densely occupied areas, the construction of marginal settlements in risk-prone areas, and inadequate drainage infrastructure, considered frequent causes of disasters in the territory (McClymont *et al.*, 2020).

Although the so-called "natural" disasters are recurrent in the country, the impacts generated in a flood risk event go beyond climate characteristics, involving the social and institutional root causes of vulnerabilities (Londe *et al.*, 2015), which indicates that specific solutions targeting these vulnerabilities are needed. An equally significant aspect of the flood risk in Brazil is that, since more disasters have been occurring in the last decades, lessons from past events are far from being fully learned, which makes DRR solutions indispensable (Ultramari, 2013). This reflection can indicate that since the country has not planned and prepared for the extreme events, nature's hazards over any period may lead to damage and losses, life, livelihood, and infrastructure – in effect, a disaster.

In this regard, how disasters are understood and managed affects how the proposal of solutions is developed. Cities, or the urban landscapes, are essentially the combination of city's natural systems (i.e., the water, trees, air quality, open space, and biodiversity) and the human systems (i.e., people, sidewalks, land use, transit systems, and infrastructure) (ARUP, 2018). The systems indicate that natural and human aspects (i.e., also called human-environment elsewhere) plays a central role for risk mitigation and adaptation and should be integrated (Bertilsson *et al.*, 2019; Ciullo *et al.*, 2017; Di Baldassarre *et al.*, 2019; Di Baldassarre *et al.*, 2013; Fuchs *et al.*, 2017; Fuchs *et al.*, 2011). Therefore, DRR solutions should consider moving from focusing mainly on physical characteristics of the place to incorporating the interaction between people and the environment, including the conditions that make people more vulnerable in social, political, physical, structural, and institutional contexts (Ajibade *et al.*, 2014; Pescaroli *et al.*, 2019). In this regard, the integration of environmental and human aspects in the context of DRR is suggested by authors such as Birkmann (2007), Di Baldassarre *et al.* (2013), Mondino *et al.* (2020), and Ciullo *et al.* (2017). For Di Baldassarre *et al.* (2013), risk mitigation should analyse the influence of a given hazard on the society, but also how the community responds and influence in one or more components of risk (i.e., defined as a combination of hazard, vulnerability, and exposure on IPCC (2014)) via policies and measures for DRR.

To conclude, much is also being said about the need for having sustainable attitudes for DRR and management, especially after the UN Brundtland Commission (WCED, 1987). Cities are required to move towards a more sustainable future and development, being recognisably critical to adapt to and address contemporary challenges such as urban growth and climate change (ARUP, 2014, 2018; Nesshover *et al.*, 2017; Shah *et al.*, 2020). Similar to disaster risk and vulnerability, sustainable solutions are termed differently in studies for flood risk mitigation (Eckart *et al.*, 2017; Fletcher *et al.*, 2014; Matsler *et al.*, 2021; Raymond *et al.*, 2017), and with the growing search for sustainability, their recommendation and implementation in the built environment are increasing around the globe (IUCN, 2020). However, flood risk solutions are still largely analysed with the aim of returning to the characteristics before urban development (de Macedo *et al.*, 2019), with a minor reflection of what are the barriers to move forward (O'Donnell *et al.*, 2018; Wright *et al.*, 2020), how communities in risk can adapt, reorganise, and sustain changes for the future (Danso *et al.*, 2016; Fuchs *et al.*, 2017), and what range of benefits can be acquired with solutions (Eggermont *et al.*, 2015; Raymond *et al.*, 2017; Ruangpan *et al.*, 2020).

Risk mitigation goes beyond the analysis of the hazard and technical aspects of the solutions itself, being significantly influenced by the specificities of the place, in both environmental and human systems, which may create vulnerabilities for society. The problem is that, by considering mainly the “hazard-perspective”, without the reflection of the context where disasters are taking place, or vulnerabilities, societies perceptions and attitudes, and the full understanding of risk and benefits to be obtained, the integration between environmental-human systems and sustainability goals will not be achieved (Birkmann, 2007; Cutter *et al.*, 2008; Klijn *et al.*, 2015; Peduzzi, 2019).

All things considered, this short introduction has attempted to summarise factors and challenges that can difficult the proposal of actions and solutions for DRR. It is acknowledged how this field has been on a continuous development since, as explained beforehand, it is the topic of different research areas (Bergstrand *et al.*, 2015; Birkmann, 2007; Cutter *et al.*, 2008; López-Martínez *et al.*, 2019). However, as the studies constantly develop, barriers remain. First, it is highlighted that, as disasters are a social phenomenon, much is left aside when proposing solutions without reflecting the context in which it occurs. Disorderly urban growth, changing climate, lack of structure, and conditions of communities at risk are a few characteristics of the place that can influence the intensity of impacts generated in a disaster. Secondly, the manner that people act also affects disaster occurrence and the generation of impacts, which indicate that social and institutional vulnerabilities, including governance, must be adequately analysed to assess the societal challenges faced by the population. In this regard, identifying how citizens and policymakers perceive and cope with the risk can provide guidance for increasing the uptake of solutions for DRR. Thirdly, the solutions, especially in the context of sustainability, are enormously suggested by worldwide reports and guidelines to be inserted in the built environment. However, assessment approaches provide less attention to the human-environmental systems, including less focus on the different benefits, beyond the environmental aspects that can be acquired with the use of solutions (Kumar *et al.*, 2020; Ruangpan *et al.*, 2020; Sahani *et al.*, 2019; Shah *et al.*, 2020).

In this sense, this thesis builds upon the paradigm shift change for DRR and management, from the “hazards” to “vulnerability” focus, integrating not only the understanding of environmental (i.e., or natural) aspects for proposing solutions for risk mitigation but also the knowledge of about the human systems, called as the “social aspects” of the area. The social and institutional aspects, including perceptions and attitudes of stakeholders, are analysed. Additionally, it is highlighted that, to achieve sustainability goals, it is important to discuss current governance and legislation schemes and evaluate how the solutions can be inserted within governance and urban planning in the present and future contexts. Finally, the thesis assesses the provision of benefits acquired with the implementation of solutions, not only with environmental aspects but also with social and economic benefits, the triad of sustainability (WCED, 1987).

The thesis specifically targets flood risk mitigation in the semiarid region of Brazil, arguing that a combination of spatial and participatory approaches, in a risk-based framework, will uncover specific barriers that should be integrated for the analysis and proposal of solutions for risk mitigation, especially when focusing the sustainable strategies. The integrated "spatial-participatory" framework was built based on the understanding of the *needs* of the place and how those needs can be addressed with *actions* to reduce the impacts of risk and generate resilience, described in chapter 3.

In this study, it is also acknowledged that reducing the vulnerability of sectors, societal challenges, and strengthening capacity to address the risks involves more than only assessing vulnerability, but includes urban planning, policy actions, and developing collaboration with local actors, especially marginalised and vulnerable people (Crosweller *et al.*, 2020; Eriksen *et al.*, 2021; McEwen *et al.*, 2018). Therefore, a participatory approach was developed in the city of Campina Grande - Brazil, for increasing the understanding of what are the conditions of the communities in risk of pluvial flooding, how the exposed population perceive and cope with the disaster, what are the underlying needs of the place that can affect DRR, how policymakers and specialists see the challenges and solutions faced by the population, and how government and management act towards flood risk reduction.

Since the severity of a disaster depends on how much impact a hazard has on vulnerable and exposed society or environment (Daramola *et al.*, 2016; Kelman, 2020), the framework assesses the spatial distribution of flood hazard, vulnerability, exposure, and risk with the integration of spatial and hydrological tools, namely ArcGIS Pro (ESRI), Storm Water Management Model – SWMM (USEPA) and the Cellular Automata Dual-DrainagE Simulation (CADDIES) model (University of Exeter, 2016), which are described in Chapter 3. The integration of social and environmental perspectives of flooding risk is used to assess the effectiveness of sustainable solutions and the provision of social, environmental, and economic benefits in Campina Grande municipality, Brazil.

1.2 Objectives

The main aim of this thesis is **to develop an integrated spatial-participatory framework for flood risk mitigation in vulnerable regions, especially for the case of the semiarid region of Brazil**. The integrated framework support specialists and authorities to advance the current knowledge in the development and proposal of enhanced strategies, especially **sustainable solutions**, considering the interrelationship between *environmental* and *social* elements, such as *vulnerability*, *exposure*, *flood-prone areas*, *climate*, *risk perception*, *coping capacity* and *sustainability*.

The thesis' objectives are rooted in the assumption that the proposal of solutions for risk mitigation must be accompanied by the social understanding of the area at risk. Initially, the thesis explores that, since disaster risk takes place in a geographical area, with spatial attributes that shape the environmental-human systems, proposals for risk mitigation should include the use of spatial tools (i.e., GIS – Geographic Information System). Secondly, it is considered that characterising the social and spatial contexts with stakeholder engagement can inform the selection of appropriate solutions and support the identification of the best pathways for implementing sustainable solutions in the local scale. Therefore, the central hypothesis of this study is that an integration of spatial and participative perspectives will improve the risk mitigation process by enabling (1) the understanding of social, institutional, and environmental aspects of the areas at risk of flooding, (2) the characterisation of how local actors perceive and act towards risk reduction, (3) the suggestion of appropriate solutions for flood risk mitigation with the input with stakeholders, spatial interactions and data availability, and (4) the spatial analysis of risk and the multiple benefits to be acquired with the sustainable solutions. For this, the following hypotheses were formulated:

1. Including a context-based perspective in the analysis of social and institutional vulnerabilities will provide specific guidance for flooding risk mitigation and can affect the maximisation of benefits in the long-term perspective of risk management.
2. The integration of spatial and social aspects of disaster risk and its drivers (i.e., vulnerability, exposure, and hazard) offers an opportunity to

comprehend the needs of the place and how the solutions can answer these needs.

3. Involving stakeholders, including local actors and end-users, in the proposal of solutions will uncover aspects inherent of the place that must be taken into account for achieving long-term resilience and reducing vulnerability.
4. The assessment of benefits of sustainable solutions should be developed with the inclusion of constraints posed by the context-based aspects of the place, such as urban planning regulations, climate specificities, conditions of the built environment, as well as the manners that social and institutional vulnerabilities can influence in the uptake of solutions.

In this context, the following **specific** objectives were formulated:

a. To develop a participatory process with collaboration between specialists, authorities, and citizens to engender a context-specific knowledge of water management in Brazil.
b. Evaluate the factors that most influence the social vulnerabilities, including the risk perception and coping capacity of residents, considering the multiple hazards in place and the institutional vulnerabilities of the region.
c. Select spatial criteria to model vulnerability and exposure areas with physical, urban, and social aspects, using pre-existing data, participatory and field surveys, mainly in GIS environment.
d. Develop the most appropriate method for positioning sustainable solutions for flood risk mitigation, inside a representative basin, with the inclusion of the built environment, climate, and governance aspects.
e. Model the effectiveness of sustainable solutions in the study area, under normal and extreme conditions, aiming for the provision of environmental, social, and economic benefits.
f. Formulate recommendations for the integrated and sustainable water management for the Brazilian context.

1.3 Structure of the thesis

This Ph.D. thesis has been organised into eight chapters. Details of each chapter, articles, research questions, and goals are presented in Figure 1.1 and Table 1.1.

Chapter 1 covers the introduction in which the key topics that form the base of this study are presented. Furthermore, the objectives and structure of the thesis are presented. **Chapter 2** outlines the main concepts used to build the integrated spatial-participatory framework for pluvial flood risk mitigation, including research gaps in the international and Brazilian context. Three shifts of focus are discussed for improving flood risk mitigation in vulnerable regions.

Chapter 3 focuses on presenting the study case, the city of Campina Grande - the semiarid region of Brazil, and the assumptions and tools used to construct the integrated framework. The spatial and participatory approaches are presented in this chapter.

Chapters 4, 5, 6, and 7 present the results of this study. The four chapters were constructed with five submitted journal articles, currently the articles are either published or under review. The papers were submitted along the research period to answer specific research questions, detailed in Table 1.1.

Chapter 4 is divided into two journal articles that together provide the analysis of the social context of Campina Grande. Social and institutional vulnerabilities of Campina Grande are analysed, including the risk perception, coping capacity of residents, and the challenges and solutions for flood risk mitigation in the city.

- Article 01:

  Alves, P.B.R.; Djordjević, S. & Javadi, A.A**.** Addressing social and institutional vulnerabilities for flood risk mitigation. Currently in review in the Journal of Flood Risk Management (Article 01 – Chapter 04 of this thesis).

- Article 02:
  Alves, P.B.R.; Cordão, M.J.D.S.; Djordjević, S; Javadi, A.A. (2020) Place-Based Citizen Science for Assessing Risk Perception and Coping Capacity of Households Affected by Multiple Hazards, *Sustainability*, volume 13, no. 1, pages 302-302, DOI:10.3390/su13010302 (Article 02 – Chapter 04 of this thesis).

Chapter 5 covers the development of a socioenvironmental approach for mapping flood vulnerability and exposure in the study case. Several factors that corroborate in increasing the flood vulnerability are discussed throughout.

- Article 03:
  Alves, P.B.R.; Djordjević, S. & Javadi, A.A. (2021) An integrated socio-environmental framework for mapping hazard-specific vulnerability and exposure in urban areas, Urban Water Journal, DOI: 10.1080/1573062X.2021.1913505 Article 03 – Chapter 05 of this thesis).

Chapters 6 and 7 assess the multiple benefits of implementing Sustainable Drainage Systems (SUDS) and Nature-Based Solutions (NBS) in the city. **Chapter 6** represents the inclusion of physical, climate, hydrological, and governance factors for assessing benefits in a representative area of Campina Grande.

- Article 04:
  Alves, P.B.R.; Rufino, I.A.A.; Feitosa, P.H.C.F.; Djordjević, S.; Javadi, A. (2020) Land-Use and Legislation-Based Methodology for the Implementation of Sustainable Drainage Systems in the Semi-Arid Region of Brazil, *Sustainability*, volume 12, no. 2, pages 661-661, DOI:10.3390/su12020661 (Article 04 – Chapter 06 of this thesis).

Chapter 7 focuses on reflections of how sustainable solutions can reduce vulnerability, exposure, and the increment of resilience in the entire city.

- Article 05:
  Alves, P.B.R.; Djordjević, S. & Javadi, A.A. Understanding the NEEDS for ACTING: An integrated framework for applying nature-based solutions in Brazil. *Water Sci Technol* 15 February 2022; 85 (4): 987–1010. doi: https://doi.org/10.2166/wst.2021.513 (Article 05 – Chapter 07 of this thesis).

Chapter 8 summarises the findings of this thesis, including the recommendation of actions, covering social and environmental aspects for flood risk mitigation in Campina Grande. Limitations and future research are provided.

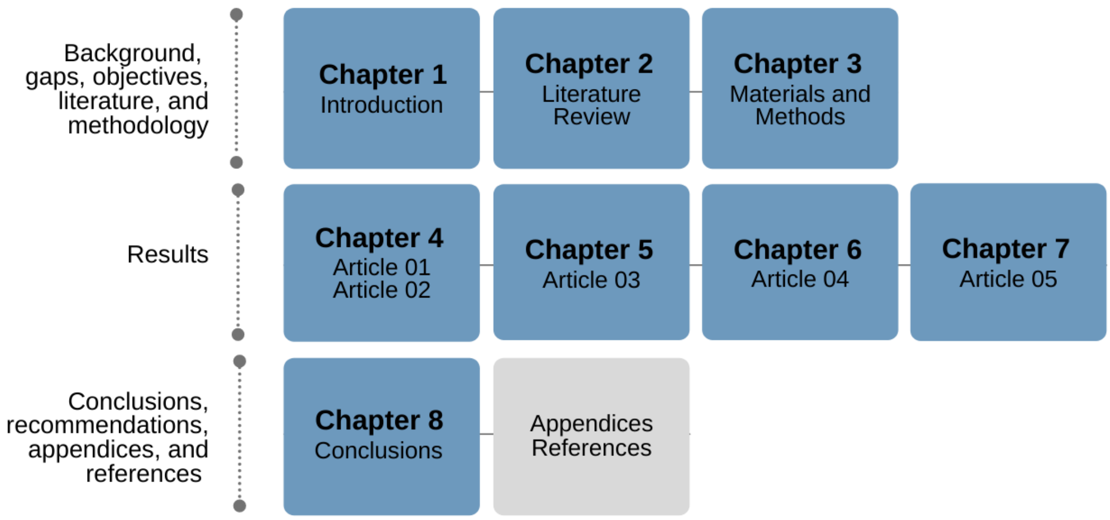


Figure 1.1 – Scheme of the organisation of this thesis. The study is presented in eight chapters, in which the results are shown with five papers in four chapters (from 4 to 7).

Table 1.1 - Organisation of the chapters of this thesis, including their research questions, specific goals, journal articles and current publication status.

CHAPTER	CHAPTER TITLE	RESEARCH QUESTIONS	SPECIFIC OBJECTIVES	JOURNAL ARTICLE	ARTICLE STATUS
Chapter 1	***Introduction***	-----	-----	-----	-----
Chapter 2	***Literature Review***	***Question 1:*** *How can the proposal of solutions for flooding risk mitigation be improved for management in different regions, especially in vulnerable areas?* ***Question 2:*** *How is the current context of the proposal of sustainable solutions in the Brazilian territory?*	f	-----	-----
Chapter 3	***Materials and Methods***	***Questions 3 to 12***	a	-----	-----
Chapter 4	***Understanding the social context of Campina Grande, Brazil***	***Question 3:*** *How can social and institutional vulnerabilities in the flood risk context be assessed with stakeholders' collaboration**?*** ***Question 4:*** *How do local actors perceive the challenges and solutions for flood risk mitigation?*	b	Article 01	Under review in "Journal of Flood Risk Management"
		Question 5: *In what way are the risk perception (RP) and coping capacity (CC) of residents similar (or different) when facing flooding and water shortage?* ***Question 6:*** *What are the main preferences of stakeholders for strategies to mitigate flood and water shortage risks?*	b	Article 02	Published in "Sustainability Journal" https://doi.org/10.3390/su1310302
Chapter 5	***Mapping hazard-specific vulnerability and exposure***	***Question 7:*** *How can social and environmental tools be integrated towards vulnerability and exposure mappings assessments?* ***Question 8:*** *How can the relationship between vulnerability and exposure be tackled on a spatial scale?*	c	Article 03	Published in "Urban Water Journal" https://doi.org/10.1080/1573062X.2021.1913505
Chapter 6	***Evaluating sustainable solutions in a representative catchment of Campina Grande, Brazil***	***Question 9:*** *How can physical, climate, hydrological and governance factors be incorporated in analysing the environmental benefits of sustainable solutions?* ***Question 10:*** *How is the current context of legislation (and governance) in the study area for the proposal of sustainable solutions?*	d	Article 04	Published in "Sustainability Journal" doi:10.3390/su12020661
Chapter 7	***Evaluating multiple benefits of sustainable solutions in Campina Grande, Brazil***	***Question 11:*** *How can the disaster risk be integrated into the Nature-Based Solutions (NBS) proposal?* ***Question 12:*** *How can the vulnerability, exposure, and future changes be incorporated to evaluate the multiple benefits and resilience that can be obtained by implementing NBS?*	e	Article 05	Published in "Water Science and Technology" doi:10.2166/wst.2021.513
Chapter 8	***Conclusions***	-----	f	-----	-----

1.4 Publications

Published journal articles:

(i) **Alves, P.B.R.**; Rufino, I.A.A.; Feitosa, P.H.C.F.; Djordjević, S.; Javadi, A. Land-Use and Legislation-Based Methodology for the Implementation of Sustainable Drainage Systems in the Semi-Arid Region of Brazil, *Sustainability 2020*, volume 12, no. 2, pages 661-661, DOI:10.3390/su12020661. (Article 04 – Chapter 06 of this thesis).

(ii) **Alves, P.B.R.**; Cordão, M.J.D.S.; Djordjević, S; Javadi, A.A. Place-Based Citizen Science for Assessing Risk Perception and Coping Capacity of Households Affected by Multiple Hazards, *Sustainability 2020*, volume 13, no. 1, pages 302-302, DOI:10.3390/su13010302 (Article 02 – Chapter 04 of this thesis).

(iii) **Alves, P.B.R.**; Djordjević, S. & Javadi, A.A. An integrated socio-environmental framework for mapping hazard-specific vulnerability and exposure in urban areas, Urban Water Journal 2021, DOI: 10.1080/1573062X.2021.1913505 (Article 03 – Chapter 05 of this thesis).

(iv) **Alves, P.B.R.**; Djordjević, S. & Javadi, A.A. Understanding the NEEDS for ACTING: An integrated framework for applying nature-based solutions in Brazil. *Water Sci Technol* 15 February 2022; 85 (4): 987–1010. doi: https://doi.org/10.2166/wst.2021.513 (Article 05 – Chapter 07 of this thesis).

Journal articles currently under review:

(i) **Alves, P.B.R.**; Djordjević, S. & Javadi, A.A. Addressing social and institutional vulnerabilities for flood risk mitigation. Currently in review in the Journal of Flood Risk Management (Article 01 – Chapter 04 of this thesis).

Published journal articles in collaboration:

(i) Cordão, M.J.D.S.; Rufino, I.A.A.; **Alves, P.B.R.**; Barros Filho, M. N. M. Water shortage risk mapping: a GIS-MCDA approach for a medium-sized city in the Brazilian semi-arid region, Urban Water Journal in 2020, 17:7, 642-655, https://doi.org/10.1080/1573062X.2020.1804596

(ii) Rufino, I.; Djordjević, S.; Costa de Brito, H.; **Alves, P.B.R.** Multi-Temporal Built-Up Grids of Brazilian Cities: How Trends and Dynamic Modelling Could Help on Resilience Challenges? Sustainability 2021, 13, 748. https://doi.org/10.3390/su13020748

Published conference articles:

(i) Rufino, I. A. A.; **Alves, P. B. R.**; Santos, K. A.; Grangeiro, E. L. A. Dynamic Scenarios and Water Management Simulations: Towards to an Integrated Spatial Analysis Approach in Water Urban Planning. At the 13th International Conference on Hydroinformatics (HIC) in July 2018.

(ii) **Alves, P.B.R.**, Djordjević, S. & Javadi, A. A**.** Assessment of a GIS-MCDM approach to Hazard, Vulnerability and Exposure Mapping in city-scale. At the 17th International Computing & Control for the Water Industry Conference in September 2019.

(iii) **Alves, P.B.R.**, Rufino, I, Djordjević, Slobodan & Javadi, Akbar A "Challenges for SuDS implementation in developing countries context: do governance arrangements make it harder?". At the VIII Oxbridge Conference on Brazilian Studies in October 2019.

(iv) **Alves, P.B.R.,** Rufino, I.A.A., Djordjévic, S., and Javadi, A.: Building a historical flooding map through spatial analysis, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-1183, https://doi.org/10.5194/egusphere-egu2020-1183

(v) **Alves, P.B.R.**; Djordjevic, S. ; Javadi, A. ; Lucena, D. P. M. ; Barbosa, G. A. ; Felinto Filho, G. G. ; Lacerda, M. C. ; Vieira, M. D. A. ; Simoes, P. C. ; Agra, S. T. M. C. ; Guedes, M. T. J. C. ; Costa, A. K. S. . Evaluation of a socio-environmental approach for disaster risk management. At the Water Efficiency Conference, online conference, Bristol (UK). Proceedings of the Water Efficiency Conference, September 2020.

(vi) **Alves, P.B.R.**, Rufino, I.A.A., Djordjević, S., Javadi, A. A. & Costa, A. K. S. Abordagem socioambiental para a calibração de modelos de alagamentos. At the XIII Encontro Nacional de Águas Urbanas: online conference. October (2020), Porto Alegre/RS, Brazil.

(vii) **Alves, P.B.R.**, Djordjević, S. & Javadi, A.A. Assessing the benefits and disbenefits of Nature-Based Solutions for flooding risk reduction in urban areas. At the virtual conference of AQUA≈360: Water for All. 31st August 2021 – 2nd September 2021, University of Exeter, United Kingdom.

CHAPTER 2
Literature Review

This section focuses on discussing key topics such as disaster risk, vulnerability, exposure, flooding proposals, and sustainable solutions that form the base of this research. The literature review was built to answer two research questions of this study:

- RQ1: *How can the proposal of flood risk mitigation solutions be improved for the management in different regions, especially in vulnerable areas?*
- RQ2: *How is the current context of the proposal of sustainable solutions in the Brazilian territory?*

This literature review is divided in the discussion of the wider and specific contexts of proposals for sustainable solutions. From topics 2.1 to 2.3, research areas and gaps are identified, whereas the topic 2.4 focuses on presenting barriers for proposals in the Brazilian context, the study case of this thesis. The chapter is concluded with a summary of findings in the topic 2.5. Due to the format of this thesis, from which the results chapters are designed with journal articles, the chapters 4, 5, 6 and 7 will also present a short literature review.

Chapter 2 - Literature review

2.1 Flooding and urbanisation

More than half of the world's population currently lives in urban areas, and over 500 cities shelter more than one million people worldwide (Nations, 2010). According to the United Nations, for the first time in human history, 66% of the population might live in urban areas by 2050 (Ferrer *et al.*, 2018).

The urbanisation consists of land use modifications associated with removal of vegetation, increase of impervious surface in place of pervious surface, reducing the soil infiltration and altering the hydrological cycle of the space (Xie *et al.*, 2017). The increase of urban development typically associated with impervious surfaces is responsible for numerous water management issues both within and outside cities (Versini *et al.*, 2016). For example, the uncontrolled expansion of urban areas is considered as one of the triggers to create cities more exposed to flooding that leads to economic losses and adverse social impacts (Ahiablame *et al.*, 2016; Xie *et al.*, 2017) (Thistlethwaite *et al.*, 2018), including human health and wellbeing (Raymond *et al.*, 2017). This process can have more intense impacts if it happens quickly with weak public policies and without infrastructure adequacy.

Changes in precipitation patterns, urbanisation, and disasters' frequency impose difficulties for water resources planning and management (Marengo *et al.*, 2009). For Overton *et al.* (2014), floods and drought are, in particular, water resource problems of many countries that can lead to massive loss of life, especially in countries still under development. Since 1990, 92% of mortality attributed to internationally reported disasters associated with natural hazards has occurred in low- and middle-income countries (UNDRR, 2019). As a result, communities are expected to experience more frequent disasters (Ruiter *et al.*, 2020). The number of recorded disasters caused by natural hazards has more than doubled since 1980, and the consequences have been more frequent and severe globally (Vo *et al.*, 2016). Flood disasters cause and will continue to drive damages beyond buildings and urban infrastructure with impacts in the long-term perspective.

Traditional water and wastewater management have provided water sanitation and flood management for more than a century worldwide using “grey infrastructure" (Ashley *et al.*, 2020). Traditional systems are intended to enlarge the drainage system infrastructure or expand existing structures' capacity to transport water downstream rapidly (Brasil *et al.*, 2021; Caprario *et al.*, 2019b). In Brazil, for example, urban drainage systems are mainly based on the assumption that "draining is necessary", in which most cities drain runoff through conduits (Caprario *et al.*, 2019b). Even though many of these systems are considered sustainable by stakeholders (Ashley *et al.*, 2020), the costs are high. As urbanisation advances, new expansions are needed at the systems (Brasil *et al.*, 2021). Besides, moving water downstream can direct the flooding and losses for neighbouring regions.

Since cities face environmental problems that tend to worsen with climate change (Batalini de Macedo *et al.,* 2021), sustainable techniques have been developed to address flooding in urbanised regions such as storm water ponds and retention basins, and infiltration systems (Versini *et al.*, 2016). These infrastructures require available land spaces, which are scarce in densely built urban areas (Versini *et al.*, 2016), making "land management" an important tool for the integration of landscape and water resources management (Lourenço *et al.*, 2020; Miguez *et al.*, 2015b). The advent of sustainability in context with disaster risk enabled to (re)think about environmental solutions that mitigate the risk and contribute to resilience (Fileni *et al.*, 2019).

2.2 The sustainable management and mitigation

Sustainability emerges as a relatively new concept encompassing multidisciplinary fields with engineering, economic, social, and environmental sciences (El-Diraby, 2011; Ferrer *et al.*, 2018). The Brundtland Commission defines sustainability as "the ability to meet the needs of the present generation without compromising the changes of the future generation to fulfil their own needs" (WCED, 1987).

Urban areas are essential for sustainability. For Lourenço *et al.* (2020), while cities concentrate and enhance physical, intellectual, and creative energy, they are harmful to the environment, to the point of representing a threat to urban survival. Rapid urbanisation results in ecosystem degradation while climate change increases the frequency, intensity, and magnitude of disasters, leading to fatalities, injuries, and economic losses. In recent years, strategies for land-use planning (i.e., or land resource planning) have emerged to support decision-makers and land users in selecting and putting into practice the uses that best meet the needs of people while safeguarding natural resources and ecosystem services for the current and future generations (Lourenço *et al.*, 2020). However, there are many barriers to moving to more sustainable management, especially in the field of water resources.

The principles of Integrated Urban Water Management (IUWM) and Sustainable Urban Water Management (SUWM) have emerged in the past (Ashley *et al.*, 2020; Brown *et al.*, 2009; Ferrer *et al.*, 2018; Lashford *et al.*, 2019; Leigh *et al.*, 2019; Ribeiro *et al.*, 2019). In 2009, Brown *et al.* (2009) detailed how the progress towards SUWM was still slow and proposed a conceptual tool to inform the management and urban water transitions policy. One of the key messages of the framework is the concept of the "*hydro-social contract*", which refers to the pervading values and implicit agreements between communities, governments, and businesses on how water should be managed. The concept has led to the analysis of "sustainable" manners for managing cities and to the progress of different concepts which are intrinsically related to IUWM and SUWM (Angheloiu *et al.*, 2020; Elmqvist *et al.*, 2019; Santos *et al.*, 2021), such as:

- "Green urbanism": considers the integration between urban climate change adaptation and mitigation solutions for reducing impacts. Urban design and land use planning, transportation, building, waste, energy, green and blue infrastructure, water, urban governance, and behavioural issues are considered (Santos *et al.*, 2021).

- "Urban sustainability": Resource management of urban regions through ways that guarantee the wellbeing of current and future generations, ensuring distributional equity (Elmqvist *et al.*, 2019). The concept is interlinked with social inequality and "finding solutions for the urban poor" (Angheloiu *et al.*, 2020).

- "Urban resilience": The capacity of an urban system to absorb disturbance, reorganise, maintain essentially the same functions and feedbacks over time and continue to develop along a particular trajectory (Elmqvist *et al.*, 2019). Offer a multidisciplinary dialogue between traditionally disparate such as disaster risk reduction, community development and urban planning (Angheloiu *et al.*, 2020).

- "Urban transition": The process of multiple actors contributing for a sociotechnical change through innovation, adaption, and adoption usually towards sustainable modes of urban production and consumption (Angheloiu *et al.*, 2020).

- "Urban transformation": The process and the outcome of changing the systemic configuration of urban areas, mostly studied with a view to its sustainability performance or achievements (Angheloiu *et al.*, 2020; Wolfram *et al.*, 2016).

Together, these concepts have captured and highlighted important aspects needed for guiding urbanisation and urban change (Elmqvist *et al.*, 2019). However, even though these definitions go beyond water management, the water sector is central for their implementation (Santos *et al.*, 2021). This indicates that actions towards SUWM are interdisciplinary, and efforts should be targeted to enable the convergence among disciplines, with an integration of a broad range of stakeholders. Besides, to prioritise adaptation interventions, it is essential to examine the feasibility of different options, by considering the dialogue, social inequality, equity, and behavioural issues, with the integration of urban sustainability and resilience (Angheloiu *et al.*, 2020).

Despite the growing number of research and cases, experiences with applying sustainable interventions in management have been mixed in both developed and developing countries. Still, they face many challenges to enhance urban flood reduction (Caprario *et al.*, 2019a). Applying sustainable principles can be especially challenging in developing countries and is highlighted as a relevant research gap (dos Santos *et al.*, 2021). Therefore, it could be argued that understanding and addressing barriers can widen the intervention proposal accuracy (Elmqvist *et al.*, 2019; Elmqvist *et al.*, 2015; Santos *et al.*, 2021). In this regard, this literature review focus in presenting some of the barriers and challenges for the proposal of solutions for flood risk mitigation with a multidisciplinary perspective, that is a combination of multiple concepts in different fields, that when analysed together provide insights of how the application of solutions can be improved in different contexts.

2.3 Sustainable solutions

The so-called "sustainable strategies" arise from the need to combine green and blue spaces within urban areas (Raymond *et al.*, 2017) to minimise the impacts of urbanisation and create resilience to the impacts of climate change (Brown *et al.*, 2009). The general characteristics of sustainable solutions are discussed in this section to complement the context of IUWM and SUWM; however, more details for sustainable solutions proposals are described in chapters 6 and 7.

With the growing search for more sustainable approaches to reduce environmental disasters, countries are entitled to look for options that cause less harm to nature. The promotion of "sustainability" by reports and guidelines has led to the rapid incentive of solutions in different regions (IPCC, 2012). Initially, developed countries included sustainable strategies in governance regulations, with cases in the United States of America (USA) (Benton-Short *et al.*, 2017), Australia (Roy *et al.*, 2008), and the United Kingdom (UK) (Emmanuel *et al.*, 2015; Jarvie *et al.*, 2017). Satisfactory implementations are detailed with examples in Belfast (Northern Ireland), Vancouver (Canada), New York City, and Portland (USA) (ARUP, 2018). In addition, other studies have analysed the benefits of sustainable solutions with experiences in China (Akter *et al.*, 2020), Spain (Alves *et al.*, 2018a), Italy (Liquete *et al.*, 2016), Thailand (Alves *et al.*, 2018a), Bangkok (Majidi *et al.*, 2019), Sint Maarten Island (Alves *et al.*, 2019) and Brazil (Momm-Schult *et al.*, 2013), despite others.

Sustainable solutions are differently acknowledged in the context of stormwater management, with examples of Sustainable Urban Drainage Systems (SUDS), Low Impact Development (LID), Water Sensitive Urban Design (WSUD), Water Sensitive Cities (WSC), Nature-Based Solutions (NBS), Green Infrastructure (GI) and Blue-Green Infrastructure (BGI). These terminologies have slightly different meanings but overall promote the inclusion of sustainable concepts in urban, and sometimes rural, environments with different objectives, including the reduction of runoff volumes and flow rate (Kennedy *et al.*, 2007; Qin *et al.*, 2016; Semadeni-Davies *et al.*, 2008; Xu *et al.*, 2017), but also to achieve long-term urban sustainability and resilience (Eggermont *et al.*, 2015; Raymond *et al.*, 2017). Sustainable strategies express efforts to recognise nature as essential for human existence and good quality of life (IUCN, 2020).

The “proposal of actions and solutions” is not a sole and separate element in IUWM and SUWM. Moreover, it represents the intersection of multiple research fields from which each area will have challenges beyond engineering science. In this review, the proposals' challenges are divided into four elements (or groups) that together can provide insights into how the proposal can be improved (Figure 2.1). The following sections of this chapter refer to the discussion of the four elements separately and consider their interconnections as an attempt to identify the way forward for propositions.

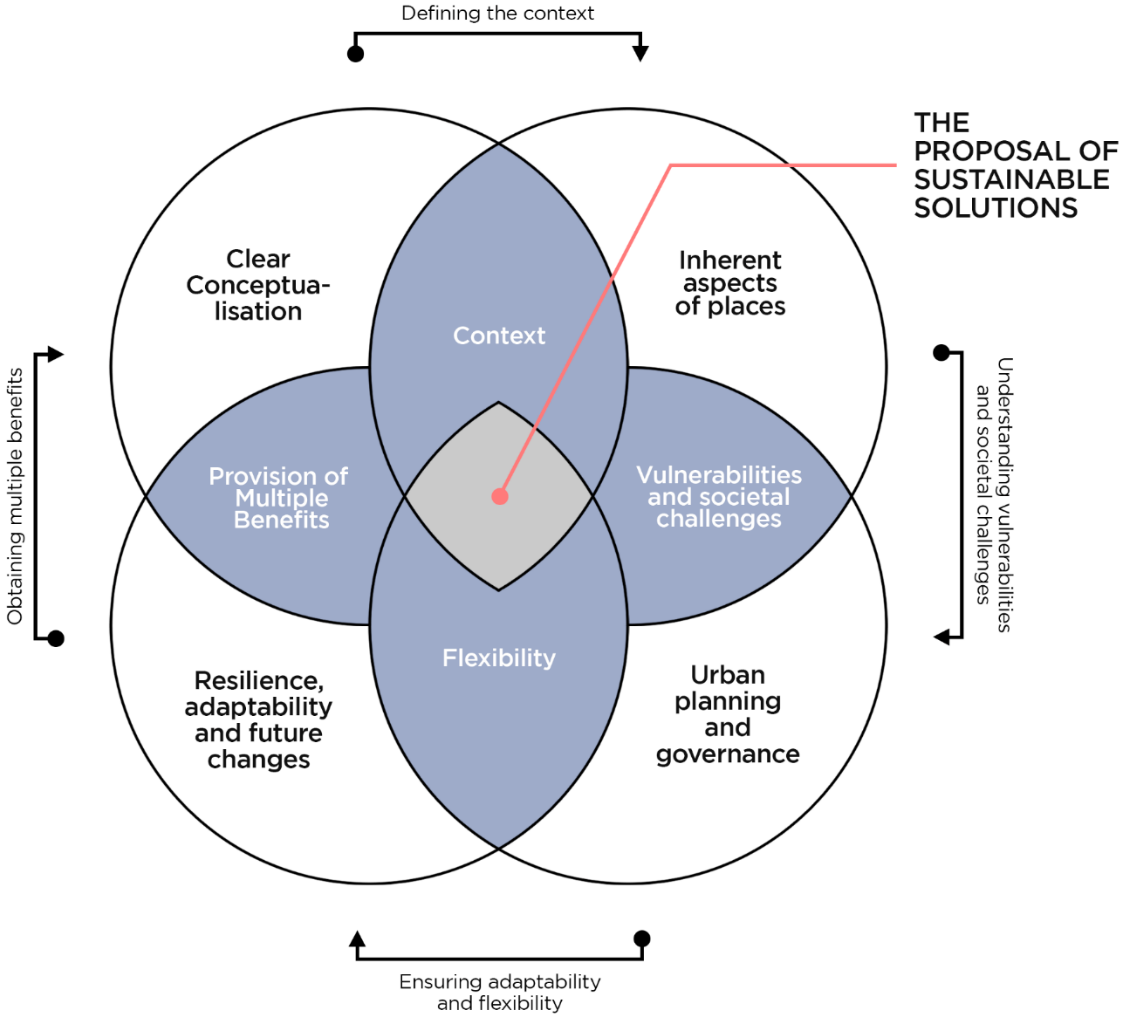


Figure 2.1 - Conceptualisation of four research areas that affects the proposal of solutions and actions for Flood Risk Mitigation (FRM). The areas refer to research gaps and challenges for the implementation of solutions in different regions.

2.3.1 The clear conceptualisation of sustainable solutions

Even though “sustainable solutions” have different terms (i.e., see terminologies in section 2.3), many researchers and practitioners define strategies as synonyms in academic studies (Fletcher *et al.*, 2014; Matsler *et al.*, 2021). This is highlighted in a recent study from Matsler *et al.* (2021) that performed a green and grey literature review (i.e., the “grey” review refers to reports and guidelines by organisations) about the use of GI. Results suggest an overlap of conceptualisations of GI, LID, NBS, SUDS, WSUD, Ecosystem Services (ES), Best Management Practices (BMP), despite others.

The distinguishing characteristic between the concepts of sustainable solutions is how they address social, economic, and environmental challenges (Ruangpan *et al.*, 2020). LID strategies perform “a design with nature approach” aiming to achieve natural hydrology with site layout and integrated control measures (Fletcher *et al.*, 2014). The first LID cases were published by Barlow *et al.* (1977) in a report on land use planning in Vermont, USA (Figure 2.2). Originally, LID strategies encompassed only small-scale stormwater devices such as bioretention systems, green roofs, and swales. However, the LID drifted from its initial concept to contain any set of practices that treated stormwater (Fletcher *et al.*, 2014). Specifically, the strategies aim to minimise imperviousness and retain natural areas, with many applications in North America and New Zealand (Matsler *et al.*, 2021).

BMPs are a structured approach to prevent pollution as a stormwater practice mainly used in the United States and Canada (Moura *et al.*, 2016). BMPs have been applied since the 1980s as an alternative to address the issues of runoff quantity and quality (Baptista *et al.*, 2011). They are acknowledged as a form of LID techniques or “Compensatory Techniques” (CT). The definition of BMPs has since matured into a universal term referring to pollution prevention activities (Fletcher *et al.*, 2014). The BMPs utilise bioretention elements and principles that seek to mimic pre-urban hydrologic conditions using more naturalised retention, infiltration, and evapotranspiration techniques, such as rain gardens, storm water ponds and bioswales.

In 1992, the concept of WSUD was vast, covering principles of water balance, water quality, and water conservation, including stormwater. When approaching the year 2000, the concept was adapted to a “philosophical approach to urban planning and design that aims to minimise the hydrological impacts of urban development on the surrounding environment” (Wong, 2000). Even though the WSUD definition was initially quite extensive, its principal application was around stormwater management. Later, WSUD migrated to stormwater management within an integrated framework considering the entire urban water cycle (Mouritz *et al.*, 2006), inspiring concepts such as “climate-sensitive urban design” (Coutts *et al.*, 2012; Norton *et al.*, 2015) and working in parallel with the term “Water Sensitive Cities”. WSUD works explicitly across all scales and attempts to engage diverse disciplines such as architects, planners, social scientists, and ecologists (Fletcher *et al.*, 2014).

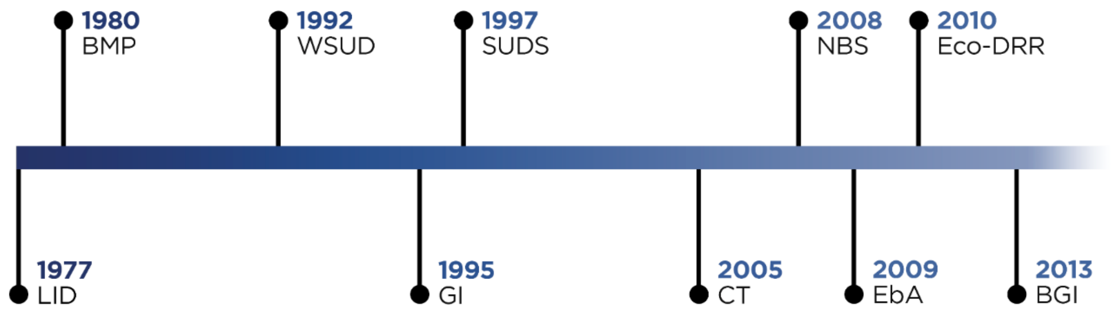


Figure 2.2 – The advent of sustainable solutions in a timescale, adapted from Ruangpan *et al.,* (2020). LID refers to “Low Impact Development”, BMP to “Best Management Practices”, WSUD to “Water Sensitive Urban Design”, GI to “Green Infrastructure”, SUDS to “Sustainable Urban Drainage Strategies”, CT to “Compensatory Techniques”, NBS to “Nature-Based Solutions”, EbA to “Ecosystem-based Adaptation”, Eco-DRR to “Ecosystem-based Disaster Risk Reduction” and BGI to “Blue-Green Infrastructure”.

Also called Green Stormwater Infrastructure (GSI), GI solutions are used to supplement or even replace grey infrastructure with vegetation to manage rainwater (Dagenais *et al.*, 2016; Fletcher *et al.*, 2014). Widely used in North America and Europe, GI is considered a “green chameleon” concept that advocates delivering on promises of multi-benefit provision (Matsler *et al.*, 2021). The evolution of GI concepts has differences according to the region where it is applied, for example GI is more related to the decentralised stormwater management in USA whilst in Europe it is conceptualised around the “socio-economic functions of greenspace” (i.e., see Matsler *et al.* (2021), Mell (2017), and Bissonnette *et al.* (2018) for more details). Although definitions vary depending on context and objectives, GI is well integrated in a discourse on urban planning by many groups in developed countries that promote an integrated and participatory vision of green space (Bissonnette *et al.*, 2018). The summary of terminologies can be seen in Table 2.1.

Table 2.1 – The summary of definitions given to sustainable solutions in the context of water studies.

Sustainable solutions	Definitions	Citation
Best Management Practices (BMP)	A type of practice or structured approach to prevent pollution, targeted stormwater run-off constituents and contaminants from reaching receiving water.	Ruangpan *et al.* (2020)
Low Impact Development (LID)	Attempts to minimise the cost of stormwater management, by taking a "design with nature" approach and to achieve a "natural" hydrology by use of site layout and integrated control measures. Moved for a broader concept by aiming the reduction of imperviousness.	Baptista *et al.* (2011)
Water Sensitive Urban Design (WSUD)	Manage the water balance, maintain and where possible enhance water quality, encourage water conservation and maintain. water-related environmental and recreational opportunities.	Mouritz *et al.* (2006)
Green Infrastructure (GI)	Planning concept to improve urban green space systems as a coherent planning entity.	Bissonnette *et al.* (2018)
Sustainable Urban Drainage Systems (SUDS)	A range of technologies and techniques used to drain stormwater and surface water in a manner that is more sustainable than conventional solutions.	Butler *et al.* (1997)
Compensatory Techniques (CT)	Refers to every strategy to mitigate flooding impacts, in urban and rural settlements; works by reducing runoff from impervious surfaces by slowing and filtering water runoff.	Baptista *et al.* (2011)
Nature-Based Solutions (NBS)	Solutions inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience.	MacKinnon *et al.* (2008)
Ecosystem Services (ES)	*EbA*: use of biodiversity and ecosystem services to help people adapt to the adverse effects of climate change as part of an overall adaptation strategy. *Eco-DRR*: the sustainable management, conservation, and restoration of ecosystems to reduce disaster risk, with the aim of achieving sustainable and resilience development.	Webb *et al.* (2018)
Blue-Green Infrastructure (BGI)	New variant of the GI concept specifically focusing on water features. A strategically planned and managed, spatially interconnected network of multi-functional natural, semi-natural and man-made green and blue features including agricultural land, green corridors, urban parks, forest reserves, wetlands, rivers, coastal sand other aquatic ecosystems.	Everett *et al.* (2018)

Adapted from Fletcher *et al.* (2014), Ruangpan *et al.* (2020) and Matsler *et al.* (2021).

In the UK, SUDS consists of a range of technologies and techniques used to drain stormwater and surface water in a more sustainable manner than conventional solutions (Matsler *et al.*, 2021). They are based on the philosophy of replicating as closely as possible the natural, pre-development drainage from a site, consistent with the previously described principles behind LID. The CT is a well-known research expression in the Brazilian context (from Portuguese: "*Medidas compensatórias de alagamentos*") (Baptista *et al.*, 2011) that refers to every strategy to mitigate flooding impacts in urban and rural settlements. CT works by reducing runoff from impervious surfaces (e. g., using green roofs and porous pavement) by slowing and filtering water runoff (e.g., rain gardens and detention/retention ponds) (Alves *et al.*, 2020e). SUDS, LIDs, BMPs, and CTs are similar since their focus is mainly on restoring the pre-development characteristics of the area (Matsler *et al.*, 2021; Moura *et al.*, 2016).

MacKinnon *et al.* (2008) coined initially NBS as "strategies that tend to be more resilient to water stress than human-engineered infrastructure because of their inherent enhanced resilience" (Snep *et al.*, 2020). For Ruangpan *et al.* (2020), NBS offers the possibility of working closely with nature to adapt to future changes, reduce the impact of climate change, and improve human well-being (Cinner *et al.*, 2018). NBS promotes nature to provide solutions to climate mitigation and adaptation challenges (IUCN, 2020). Within Europe, NBS have been integrated in the new framework programme for research and innovation "Horizon 2020", providing a new narrative for involving biodiversity and ecosystem services aligned with goals for innovation for growth and job creation (Nesshover *et al.*, 2017), Recently, both the European Commission (EC) and the International Union for Conservation of Nature (IUCN) have published specific guidelines for the implementation of NBS, especially in the European context (Commission, 2021; IUCN, 2020).

For the IUCN, Ecosystem-based Disaster Risk Reduction (Eco-DRR) is defined as the sustainable management, conservation, and restoration of ecosystems to reduce disaster risk to achieve sustainable and resilient development (IUCN, 2020). Ecosystem-based Adaptation (EbA) is defined as the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change (Bourne *et al.*, 2016). In other words, in terms of implementation, both Eco-DRR and EbA approaches are grounded on the definitions of Ecosystem Services (ES) and are part of NBS conceptualisation (Commission, 2021). Finally, the most recent terminology, the Blue-Green Infrastructure (BGI) (or "Blue-Green City") was created in 2013

(Figure 2.2) and aims to recreate a naturally oriented water cycle while contributing to the amenity of the city by bringing water management and green infrastructure together (Alves *et al.*, 2019; O'Donnell *et al.*, 2017). The "Blue-Green approach" reduces stress on subsurface piped "grey" infrastructure by managing water above ground and generates multiple benefits from multifunctional use of BGI spaces and corridors under flood and non-flood conditions (O'Donnell *et al.*, 2017; Thorne *et al.*, 2018).

In this regard, this review presented how the terminologies changed their meaning and interpretation over time as a function of understanding and adaptation by various interest groups (Fletcher *et al.*, 2014). Throughout the evolution of the terms, there were similarities and differences in the meanings of most of the strategies (Table 2.1). The similarities of NBS, GI, BGI, EbA and Eco-DRR are the participatory, holistic, and integrated approaches to improve human well-being and health, enhance vegetation growth and connect habitat and biodiversity (i.e., a complete description can be seen in Ruangpan *et al.* (2020)). The differences can be seen in the main motivations behind strategies. For example, LIDs, SUDS, CT, and WSUD are mainly applied in stormwater management, whist GI, BGI, EbA, and Eco-DRR focuses more on technology-based infrastructures by using natural alternatives for solving a specific activity (Ruangpan *et al.*, 2020). EbA, Eco-DRR, GI, and BGI provide more specific solutions to more specific issues, while NBS offers a broad concept with applications in different fields.

In this sense, the lack of a clear conceptualisation creates challenges for management and the inclusion of solutions. First, previous studies confirm that stakeholders tend to consider the solutions as synonyms, restricting the applicability of solutions (Alves *et al.*, 2018a; Fletcher *et al.*, 2014; Matsler *et al.*, 2021; Snep *et al.*, 2020). For Snep *et al.* (2020), most urban development professionals are not experienced with sustainable solutions and do not know the distinction between different types of solutions and performance attributes. If the terminologies are not clarified, professionals can develop an understanding inconsistent with the principles and objectives that underpin specific terms (Fletcher *et al.*, 2014). Secondly, many professionals and studies still lack understanding of the variances in terminologies (Matsler *et al.*, 2021; Mell, 2017). For Mell (2017), many published frameworks do not provide proper nomenclatures but instead focus only on a specific type of solution or benefit. The description and understanding of the terminologies are essential for the appropriate application and for obtaining their full potential. In this context, to avoid confusion in the creation of local and international standards, it is mandatory to clarify "what" the strategy is, "how" it can be developed, and "why" it is essential to integrate the sustainable solutions with urban planning (Matsler *et al.*, 2021; Mell, 2017).

2.3.2 The inherent aspects of places

Despite the challenges with the terminologies for obtaining the full potential of solutions, the location that these strategies will be implemented also influences their performance. Characteristics of "locations" are usually considered in proposals with the use of several variables or indicators such as different rainfall intensities (Qin *et al.*, 2013), placement (Ahmed *et al.*, 2017; Passeport *et al.*, 2013), type of solutions (Fletcher *et al.*, 2014; Martin-Mikle *et al.*, 2015) and construction techniques (Martin-Mikle *et al.*, 2015). Studies have focused on finding the best strategies (Wang *et al.*, 2017; Xie *et al.*, 2017) and proposing for different land uses (Emmanuel *et al.*, 2015; Norton *et al.*, 2015); however, many tools have difficulties to be applied in reality. Nevertheless, even though there is a tendency in scientific discourse to generalise frameworks for different regions and sometimes countries, the locations in which solutions are applied have prior characteristics that interfere directly in their performance, and therefore should be thoroughly examined. Because of this, other studies suggests there is no "one-size-fits-all" approach that can be applied everywhere (Colléony *et al.*, 2019), and that the lack of "locally-oriented" information can harm proposals (Kuller *et al.*, 2017; Nesshover *et al.*, 2017).

Recently, there has been a growth of approaches that suggests the first steps for the proposal of solutions should be the "contextualisation" and the definition of "societal challenges" (Albert *et al.*, 2020; Eggermont *et al.*, 2015; Nesshover *et al.*, 2017; Raymond *et al.*, 2017). In the case of NBS, Albert *et al.* (2020) discussed how the selection of natural processes and techniques are critical for proposals, however, the authors also argue that "solutions" refer to a *particular* challenge or problem that should be solved in the area of application. In this regard, it is fundamental to understand the key societal challenges of the place that solutions will address. For Albert *et al.* (2020), NBS are as actions that (i) alleviate a well-defined societal challenge, (ii) utilise ecosystem processes of spatial, blue, and green infrastructure networks, and (iii) are embedded within viable governance or business models for implementation. Similarly, Debele *et al.* (2019) argue that solutions may contribute to conservation by addressing specific societal challenges and implementing interventions at the scale needed. As an attempt to improve the uptake of solutions, practitioners (i.e., in particular the IUCN) and policy (i.e., EC) have suggested significant challenges and priority areas for NBS development (Table 2.2). "Major challenges" refers to the challenges faced by society as a combination of hazards and disasters in current and future systems, whereas the "areas of research" involve research fields and benefits that should be incorporated in proposals (Table 2.2).

Table 2.2 – Definition of societal challenges and research areas by the International Union for Conservation of Nature (IUCN) and European Commission (EC).

Major challenges	Water security, flood security, human health, disaster risk reduction and climate change	(IUCN, 2020)
Areas of research and innovation	Regeneration, well-being, carbon sequestration, coastal resilience, watershed management and ecosystem restoration	(Commission, 2021)

Both IUCN and EC were very quick in supporting the inclusion of NBS in management since the term was only first used in 2008 (Figure 2.2). In 2021, the European Environment Agency released a report to position Europe as one of the leaders in this field. It is important to emphasise that alternatives are not always the "best" solution for the place and exploring the place-specific implications of each alternative will enable the appropriate selection of solutions. Therefore, understanding the *inherent aspects of places* (Figure 2.1) is crucial for the proposal and evaluation of solutions.

The definition of societal challenges, or inherent aspects of places, is linked with the understanding of Disaster Risk (DR). Disasters are defined as the occurrence of an extreme, and sometimes infrequent, hazard that affects vulnerable communities or geographic areas, causing substantial damage, disruption, and perhaps causalities and leaving the affected communities unable to function normally (Daramola *et al.*, 2016). For the United Nations of Disaster Risk

Reduction (UNDRR), the disaster is a severe disruption of the functioning of a community or society, at any scale, due to hazardous events interacting with conditions of exposure, vulnerability, and capacity, leading to losses. However, in practice, there are many discussions of what a disaster is. From the different “hazards” to the “social” traditions, disasters definitions are used mainly by natural scientists and engineers to social scientists and planners, respectively (Klijn *et al.*, 2015), in which the hazard tradition focus more on modelling and representing the hazard, without placing the origin of disasters in the vulnerability (Cutter *et al.*, 2003). The social tradition argues that disasters are rooted in a social condition, which indicates that an event will only become a disaster if it affects vulnerable communities (Peduzzi, 2019). In this perspective, exposure and vulnerability represent a pre-disaster state (Cutter *et al.*, 2008; Kelman, 2020; Sharma *et al.*, 2019). For example, hazard events will only become disasters if they reach elements (i.e., assets, people, or infrastructure) located in a vulnerable area (IPCC, 2014). The vulnerability represents the conditions that can increase the susceptibility of an individual, community, or systems to the impacts of hazards. In contrast, exposure is the situation of these people (…) located in hazard-prone areas (UNISDR, 2021). In this sense, the understanding of disasters variables (DV) indicates that hazards over any period can lead to damage (and losses) of life, livelihood, and infrastructure (i.e., exposure) if the area is vulnerable. Risk will be a function of hazard, vulnerability and exposure, as illustrated in Equation 2.1. DV’s definitions are shown in Table 2.3, according to the United Nations International Strategy for Disaster Reduction (UNISDR).

$$Disaster\ Risk\ (DR) = f(Hazard, Vulnerability, Exposure) \qquad \text{Equation (2.1)}$$

Table 2.3 – The definitions of hazard, vulnerability, and exposure that form the concept of Disaster Risk (DR).

Disaster variables (DV)	**Definitions**
Hazard	A process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption, or environmental degradation.
Vulnerability	The conditions determined by physical, social, economic, and environmental factors or processes which increase the susceptibility of an individual, a community, assets, or systems to the impacts of hazards.
Exposure	The situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas.

Source: UNISDR (2021)

Understanding what makes society vulnerable should also be part of the proposal of solutions for risk mitigation (Climent-Gil *et al.*, 2018; Klijn *et al.*, 2015). Only recently, based on the Sustainable Development Agenda (United Nations), the Sendai Framework (2015 – 2030), and the report of the Open-ended Intergovernmental Expert Working Group (OIEWG) (UNDRR, 2019), the definition of hazard in the context of Disaster Risk Reduction (DRR) has been broadened considerably to include phenomena, processes, and “activities”. The debate considers especially the definitions of “man-made” disasters that are created by choices and attitudes of people (i.e., citizens, governments, policymakers) (UNISDR, 2021). The management of disasters is being widened to consider that decisions will also create risk, especially in the generation of vulnerabilities and exposure.

Very similar to disasters, many definitions, and notions exist for flood risk (FR) and flood risk mitigation (FRM), being sometimes even ambiguous. Among the hazards approach, the most common definition of FR encompasses the probability of flooding and their consequences, as indicated in Equation 2.2. At this definition, the reduction of the probability of flooding is generally looked by means of flooding protection calculating risks. For example, the risk can be quantified by multiplying the probability of a defence breach with its consequences, where the vulnerability of the area, the flood extent and depth and the exposure are combined into the “consequences” (i.e., see details in Klijn *et al.* (2015)). This is based on the analysis of the Language of Risk (Gouldby *et al.*, 2009) that considers “consequences” as the event's impacts.

$$Flood\ Risk\ (FR) = probability_{(of\ flood)} \times consequences_{(of\ flood)} \qquad \text{Equation (2.2)}$$

$$Flood\ Risk\ (FR) = flood_{(hazard)} \times\ vulnerability_{\left(of\ the\ exposed\ \frac{society}{area}\right)} \qquad \text{Equation (2.3)}$$

An alternative concept that social scientists and planners often prefer is indicated in Equation 2.3, considering flood hazard as a given influencing people’s behaviour as the means to adapt to the hazard. This concept assumes that a natural hazard can only occur to a vulnerable and exposed society or area. The “exposure” will indicate the presence of receptors, and their character is shown with “vulnerability”, as suggested in the definitions presented in Table 2.3.

In this context, there has been a growing agreement for the past few years that solutions should tackle the root causes of disasters, i.e., that is the vulnerabilities, of hazard-prone areas (Cutter *et al.*, 2008; Kelman, 2020; Lund, 2015). For example, studies in different fields (Gheshlaghi *et al.*, 2017; Kanani-Sadat *et al.*, 2019) have provided examples of frameworks to manage and reduce the impacts of disasters with coping and adaptation strategies targeting the reduction of vulnerability to a given hazard (Bryan *et al.*, 2019; Danso *et al.*, 2016). For Klijn *et al.* (2012), the proposal of flood mitigation solutions should equally take into account measures aimed at: (1) reducing flood hazard probability, (2) reducing exposure to floods and (3) reducing vulnerability of people and property and treat these as equivalent and mutually exchangeable (Figure 2.3).

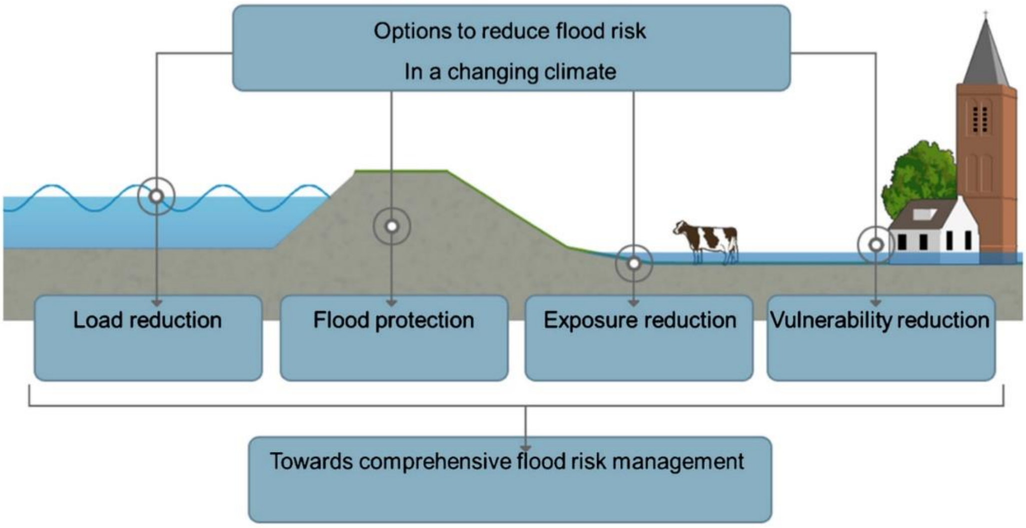


Figure 2.3 – The conceptualisation of a comprehensive flood risk management approach with interventions that addresses the components of risk. Source: Klijn *et al.* (2015).

Therefore, it could be argued that understanding the three constituents of risk may help identify and select measures and policy instruments to influence the development of each of these (Klijn *et al.*, 2015; Shah *et al.*, 2020). The clarification of what makes the area more vulnerable and communities more exposed will lead to a comprehensive FRM approach (Figure 2.3). The conditions that make people more vulnerable or exposed will vary considerably according to the place studied (Di Baldassarre *et al.*, 2013; Mondino *et al.*, 2020), hence the call for an integrative management approach based on multi-disciplinary concepts taking into account different theories, methods and conceptualisations, including risk perception and coping capacity (Fuchs *et al.*, 2017).

However, just as risk is systemic and interconnected, so too is vulnerability. Vulnerabilities may emerge, change, compound, and persist over long periods, and can contribute to the transmission of vulnerability and widening inequalities (de Brito *et al.*, 2017; Pescaroli *et al.*, 2019; UNDRR, 2019), making it essential to properly understand what cause vulnerabilities for then proposing solutions for risk mitigation. For example, in places where people lack adequate shelter, floods could directly affect their health through injuries, the transmission of infectious diseases and displacements (IPCC, 2012), or indirectly affect their living conditions through the impact on properties, infrastructure, and livelihoods (Ajibade *et al.*, 2014). Such negative impacts could compound existing vulnerabilities while also increasing inequalities that can be in place.

This context is even more critical to regions that simultaneously face multiple hazards since it can escalate the impacts of the disasters (Ruiter *et al.*, 2020; Ward *et al.*, 2020). For example, the challenges that a community face when being hit by a subsequent disaster while still recovering from an earlier disaster are substantially different than the impacts of two static events (Ruiter *et al.*, 2020; Ward *et al.*, 2020). Therefore, the proposal of solutions is not only dependent on the physical characteristics of the measures itself or the target area for adoption but also are influenced by the inherent aspects of the place, including a combination of social and political contexts (Ajibade *et al.*, 2014).

Finally, the understanding of social justice, vulnerability and resilience is also crucial for mitigating FR, especially in developing countries. This is from the evidence that socio-economic challenges in the developing nations make it more difficult to solve problems related to water protection when compared to developed nations (Goncalves *et al.*, 2018). In practice, in less advanced regions, building adaptive capacity requires a combination of interventions that address climate-related risks and the structural deficits (e.g., lack of income, education, health, political power) that form vulnerabilities and inequalities (Lemos *et al.*, 2016). Inequalities refer to the situation when people (or organisations and systems) do not all have the same ability to make the best choices, using available skills and resources, to manage adverse conditions, risk or disasters, hence a low coping capacity (UNISDR, 2021). In this context, the link between inequalities and "resilience" is highlighted as essential for risk reduction, as the resilience reflects the "ability to cope with disturbances or changes" (Meerow *et al.*, 2016). In summary, understanding the relationship between vulnerabilities x inequalities x resilience require the identification of conditions that make people and places more vulnerable, their exposure to the risk, the different distributions of hazard, and the understanding of adaptability, coping capacities and perceptions (Cutter, 1996; Cutter *et al.*, 2008; Cutter *et al.*, 2003).

2.3.3 Resilience, adaptability, and future changes

Throughout important urban policy frameworks (UN Urban Agenda, Sustainable Development Goals, Sendai Framework for DRR, Paris Climate Agreement, among others), resilience and sustainability have been used almost interchangeably (Chelleri *et al.*, 2021; Elmqvist *et al.*, 2019).

Likewise disaster and FR definitions, resilience has been conceptualised differently in many scientific fields, which lead to criticisms that the concept may be inappropriate and imprecise (Norris *et al.*, 2008; Rezende *et al.*, 2019), especially because multiple definitions of resilience exist within the literature, with no broadly accepted single definition (Cutter *et al.*, 2008). Studies acknowledge that the discrepancy of concepts lead to more confusion than understanding that resilience is a fundamental component of sustainability (Ashley *et al.*, 2020; Chelleri *et al.*, 2021; Coaffee *et al.*, 2018; Marana *et al.*, 2019), which can reduce the strength and consistency of resilience application (Chelleri *et al.*, 2021). Coaffee *et al.* (2018) suggest that the uncritical over-simplification in linking urban sustainability and resilience has contributed to many conceptual misalignments, inconsistencies, and challenges for urban resilience implementation.

When most people think of resilience, it is generally in response to sudden shocks or continuous stresses; however, the resilience concept goes far beyond the mere recovery from disturbances (Elmqvist *et al.*, 2019). Academic discourse has widely explored two main facets of resilience that are different in engineering and ecological fields, referring to either "bouncing back" or "bouncing forward" approaches. The term resilience is from the ecological literature. Holling (1973) labels "ecological resilience" to a system as having multiple stable states. In contrast, the engineering literature refers to resilience as having one equilibrium.

Inspired by academic discourses, Folke (2006) divided the resilience concepts into three possibilities: engineering, ecological/ecosystem, and social-ecological resilience (Figure 2.4). At these definitions, resilience has multiple facets, applying to individuals, communities, physical infrastructure, or governance institutions and encompass the capacity of the whole system to “reorganise”, “withstand”, “sustain” and “develop” while undergoing change, in the long term, as to enable it to function normally (Figure 2.4) (Elmqvist *et al.*, 2019; Folke, 2006; IPCC, 2014).

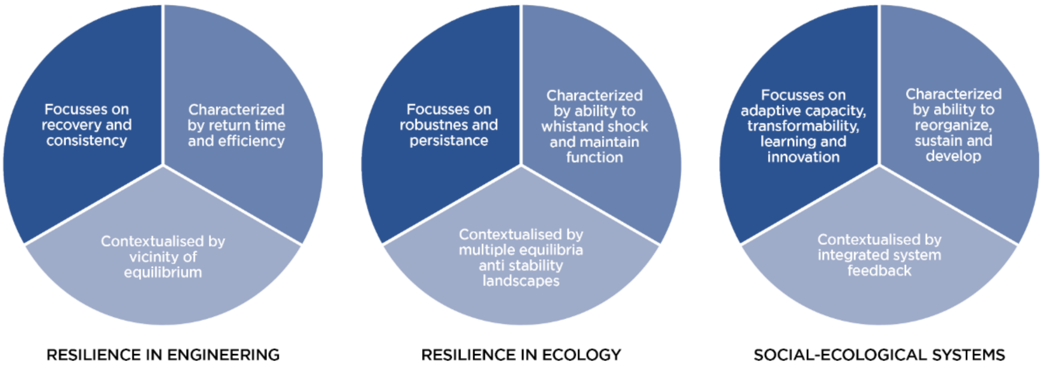


Figure 2.4 – Graphical representation of the resilience concepts in engineering, ecology, and social-ecological literature (adapted from Urban Resilience Hub and Folke (2006).

The main differences of definitions converge to defining “what” will indicate if a system is more or less resilient, and “who” is the system (or community) that is being analysed. The engineering concept of resilience refers to resistance to a disturbance or stressor and recovery speed to stability near an equilibrium-steady state (Pimm, 1984). For example, for CIRIA (2010), resilience is the ability of an infrastructure asset to maintain its functions even under uncommon events and recover and reassume its normal functions after the event (CIRIA, 2010). The concepts of the engineering perspective analyse resilience regarding a recovery trajectory that returns to baseline functioning after an extreme challenge (Ribeiro *et al.*, 2019). Recent studies in the engineering perspective have addressed the need to provide safe water management that is also resilient and sustainable in the face of emerging threats (i.e., The Safe and Sure Approach) (Butler *et al.*, 2014; Butler *et al.*, 2017), and also connecting global challenges, climate change, public policies and other drivers such as in the CORFU approach (Djordjević *et al.*, 2011). The RESCCUE Project also contributes to the field, suggesting tools for supporting cities to become more resilient to physical, social, and economic challenges, using the water sector as the central point of the approach (Velasco *et al.*, 2020).

In the case of ecology systems, Holling (1973) introduced the term by supporting that “resilience determines the persistence of relationships within a system and is a measure of the ability of these systems to absorb changes of state variables, driving variables, and parameters, and still persist.” In this definition, resilience is the property of the system, and the persistence or probability of extinction is the result. This type of resilience is focused on the capacity to absorb shocks and still maintain function (Holling, 1973). Further, Holling’s concept was adapted for further understanding complex adaptive systems (CAS), which involves the capacity to renew, re-organise, have flexibility, learning, and develop based on adaptive management (Cutter *et al.*, 2008; Folke, 2006). Named as the social-ecological resilience, it led to the formulation of many concepts, including the UNISDR (2009) that defines resilience as the ability of a system, community, or society exposed to hazards to resist, absorb, accommodate to, and recover from the effects of hazards in a timely and efficient manner (UNISDR, 2009). The ecological and socio-ecological conceptualisations refer primarily to the social perspective of resilience, linked to “community” resilience (Figure 2.4).

There are many debates on “who” is considered a community in literature since it will have implications for how resilience can be assessed within the community context (Bryan *et al.*, 2019). The definition used in this thesis considers a community as an entity with geographic boundaries (i.e., spatial scale), composed of built, natural, social, and economic environments that influence one another in complex ways (Norris *et al.*, 2008). For Cutter *et al.* (2008) the resilience of a community is the ability of a social system to respond and recover from disasters. It includes those *inherent conditions* that allow the system to absorb impacts and cope with an event and the post-event and adaptive processes that facilitate the social system's ability to (re)organise, change, and learn in response to a threat. As a result, the community will understand and act forward-looking in anticipation of desired future states (Lorentz, 2013). However, scholars argue that community resilience was at an early stage of theoretical development, with a reduced number of approaches in the past (Cutter *et al.*, 2008; Folke, 2006; Norris *et al.*, 2008) and more recently (Chelleri *et al.*, 2021; Coaffee *et al.*, 2018; Lund, 2015; Marana *et al.*, 2019).

Such debates in academic discourse are not unexpected given the multidisciplinary mix of normative and positive interpretations of resilience concerning themes of vulnerability, risk, governance, sustainability, and adaptation (Parsons *et al.*, 2016). For example, inspired by the ecology and social-ecological definitions, Rezende *et al.* (2019) discusses how the reduction of vulnerabilities and the understanding of how communities perceive risk are crucial for developing resilience in a community. Meerow *et al.,* (2016) discusses how the spatial-temporal scales of regions will shape the manner that urban resilience is characterised, and, because of this, the urban resilience literature is also inconsistent. However, even though many benefits related to resilience are seen, there is a need to debating about "resilience as an always a positive concept", since not all stakeholders will benefit equally from resilience-based actions, and the concept may be used to promote political agendas or retain systemic inequality (Meerow *et al.*, 2016). At the same time, it is agreed that resilience and inequalities are interlinked, since resilience refers to the ability of human settlements to withstand, recover quickly and adapt from any plausible hazards, as seen in Cardoso *et al.* (2020).

Therefore, it can be concluded that improving city resilience is linked to multidisciplinary fields that reflect the important search for "uniformly" enhancing the conditions of communities, especially in territories that are most at risk. For Norris *et al.* (2008), the path for creating more resilient cities is a combination of the understanding of physical and social contexts, including economic resources, risk, inequalities, and vulnerabilities (i.e., see phase 1 in Figure 2.5a), engagement with local people and organisations (phases 2 and 3), interventions for social and environmental contexts and (phase 4) enhancing planning, flexibility, information, and communication (phase 5).

Similarly, Cutter *et al.* (2008) developed the disaster resilience of a place (DROP) model, which recognise the importance of understanding the resilience to a specific threat (Figure 2.5b). The DROP model considers that places have antecedent conditions (i.e., vulnerability, resilience, built environment, natural and social systems) that will generate the disaster impact with the extreme event and coping responses (Cutter *et al.*, 2008). Therefore, resilience will assist in the community's degree of recovery and is linked to the provision and development of strategies and plans for improving the societal capacity (Figure 2.5b).

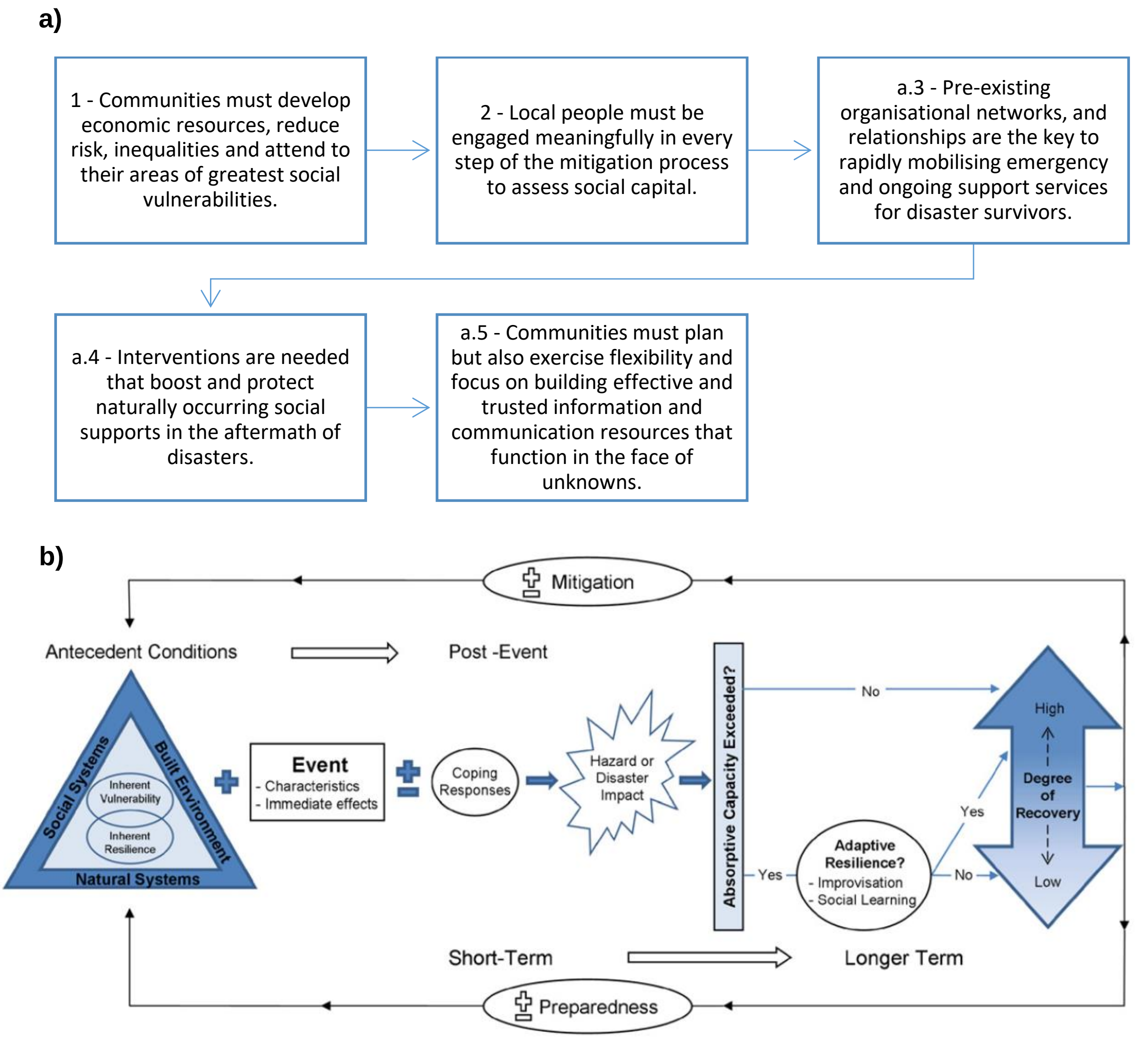


Figure 2.5 – a) The roadmap for enhancing community resilience according to Norris Norris *et al.* (2008), b) Schematic representation of the disaster resilience of place (DROP) model by Cutter *et al.* (2008).

In summary, there are several possibilities for discussing city resilience and strategies for its improvement. Differences exist for conceptualising the types of "resilience", which can reduce their applicability (Chelleri *et al.*, 2021; Elmqvist *et al.*, 2019; Rezende *et al.*, 2019), and approaches that consider community resilience remain largely non-practiced in contemporary urban planning (Chelleri *et al.*, 2021; Coaffee *et al.*, 2018; Lund, 2015; Marana *et al.*, 2019). In this regard, this literature review acknowledges that mitigation solutions have an important role in building resilient spaces and communities, especially when the inherent aspects are known and considered, as illustrated in Figures 2.5a and 2.5b. Although proposing a resilience-based actions is not the main objective in this thesis, this topic aims to recognise how the resilience must be incorporated for a sustainable urban management, linking vulnerabilities, adaptability, inequalities and risk with the proposal of mitigation and adaptation solutions (Figure 2.1).

Additionally, it is also argued that public policies, governance, and legislation are intrinsically related to resilience, adaptability, and vulnerability (Djordjević *et al.*, 2011; Hammond *et al.*, 2018). Therefore, the following section discusses barriers for improving FR, FRM, and disaster resilience aligned to governance and management, especially with urban planning (Ashley *et al.*, 2020). In addition, some reasons for the failure of proposals in developing nations are suggested and discussed shortly.

2.3.4 Urban planning and governance

Building urban and city resilience requires long-term and integrated approaches linked with urban planning and governance (Bush *et al.*, 2019). For Albert *et al.* (2020), governance research can be understood as the study of characteristics, effects, and dynamic interactions between institutions and actors that create changes in the built environment (Albert *et al.*, 2020; Roy *et al.*, 2008). Urban planning is the intentional and explicit intervention in the built environment through the development of plans, programs, and design (Bush *et al.*, 2019). The "landscapes" are the outcome of these interventions after the actions and decisions of stakeholders (Albert *et al.*, 2020; Kelman, 2020). Therefore, planning is a continuous process of choosing strategically through time which creates changes in the landscapes of cities (Bush *et al.*, 2019).

As seen in topics 2.3.2 and 2.3.3, studies have shown manners in which sustainable solutions can increase urban resilience (Ahmed *et al.*, 2017; Albert *et al.*, 2020; Ciullo *et al.*, 2017; Raymond *et al.*, 2017; Shah *et al.*, 2020). However, even though the scientific literature has obtained much guidance for creating "sustainable and resilient cities" (Brown *et al.*, 2009; Colléony *et al.*, 2019; Norris *et al.*, 2008; Santos *et al.*, 2021), there are many challenges for the practical application of sustainable solutions through the integration into urban planning and governance (Bush *et al.*, 2019).

First, there are regions with a low number of policies - or no policies - that demand the inclusion of sustainable solutions in the city-scale. Since good practice in urban development can contribute much to DRR (IPCC, 2014), the establishment of policies by governments is manifestly critical to governing water resources in an integrated manner (Gain *et al.*, 2013). All those facts are particularly important to developing economies, which face rapid and transformative changes. In Africa, although the frequency of extreme events has increased in the last decade, the awareness among those who govern the national framework for disaster prevention or make plans for disaster management is considered poor and scarce (Nguimalet, 2018). Cities such as Cape Town, Lusaka, Kampala, and Mombasa, to name a few, have the provision of sustainable services uncertain. Those cities are categorised as struggling economies with lack of investment and sustainable financing, large proportions of non-revenue water, and inadequate institutional capacity and maintenance also influence water services' efficiency and effectiveness (ARUP, 2018).

Similarly, many Brazilian municipalities face problems due to the lack of planning and investment in drainage (Caprario *et al.*, 2019a). Inadequate planning actions are frequently seen in Brazilian territory that completely alter landscapes, such as the modifications of the riverbeds with the construction of channels, construction of households located in flood-prone areas, urban environments without drainage network or with a mixture of sewage and drainage systems (Marchezini *et al.*, 2017; Tucci, 2007). In Brazil, as in most developing countries, the use of sustainable strategies is not yet widespread, mainly due to the resistance to their application on the part of public managers, in addition to a natural opposition to innovation (Caprario *et al.*, 2019a).

Another challenge refers to areas with public policies and programmes for FRM and management, but do not entirely fulfil the legislation, or the laws should be improved. For example, this is the case of Ghana, which has documented policies to address flood risk and its related implications but still struggles to lessen flood disasters in urban areas (Danso *et al.*, 2016). Almoradie *et al.* (2020) suggest the recurrence of flood disasters contradicts the effectiveness of existing FRM regimes in the country. Similarly, significant impediments to the effective implementation of SUDS in the UK were suggested by Melville-Shreeve *et al.* (2018). Despite the application beginning to become the norm, policy changes are advised to make SUDS obligatory in the country. Thorne *et al.* (2018) provide evidence that BGI, SUDS or BMP uptake remains stubbornly sluggish in Portland (USA) despite the proven advantages over grey infrastructure. Portland (USA) is recognised as a leader in green stormwater management, but the implementation of strategies by citizens and institutions is largely opportunistic and voluntary (Thorne *et al.*, 2018).

Challenges may indicate trade-offs and divergences between scientific and municipal guidance that act as barriers for the effective implementation (Almoradie *et al.*, 2020; Danso *et al.*, 2016; Marana *et al.*, 2019; Parsons *et al.*, 2016; Thorne *et al.*, 2018). For Marana *et al.* (2019), addressing questions on building resilience and how the impact of events can be managed requires a multi-disciplinary approach across city sectors. However, to accomplish this, policymakers need to work together to identify the needs of the place and the appropriate mitigation approaches. The reality is that both “the lack of policies” or “inconsistent management policies” tend to limit the ability to promote consistent use of solutions throughout watersheds (Benton-Short *et al.*, 2017). When the competence of city governments is not strengthened, it is common to have crisis of urban poverty, rapidly growing informal settlements and a growing number of urban disasters (Robinson *et al.*, 2019), which makes essential to have coordination across sectors and jurisdictions to understand all relationships between the environment, urban development and human behaviour (Cinner *et al.*, 2018; Fuchs *et al.*, 2017). For Roy *et al.* (2008), the lack of institutional capacity and the fragmented responsibility in governments and municipalities as impediments to the implementation of sustainable solutions in the USA and Australia.

Policy analysis studies have identified the importance of stakeholder participation of relevant actors to ensure sustainable natural resource and disaster risk management (Sahani *et al.*, 2019). An example is seen with the IPCC report in 2014 that promoted a definition for adaptation and mitigation measures for climate change as “many adaptation and mitigation options can help address climate change, but no single option is sufficient by itself. Effective implementation depends on *policies* and *cooperation* at all scales. It can be enhanced through integrated responses that link mitigation and adaptation with other societal objectives”.

Therefore, the “wide and extensive participation” is suggested for increasing the uptake of sustainable solutions and create successful sustainable management (Gain *et al.*, 2013; Leidel *et al.*, 2012; Webb *et al.*, 2018). This is from the evidence that there is a need for facilitating the transition from theory to practice and that governments and practitioners need more support and guidance to build resilience in an optional manner (Marana *et al.*, 2019). The inclusion of multidisciplinary groups can overcome other barriers for adopting solutions such as the lack of experience and understanding of stakeholders of sustainable solutions (Ashley *et al.*, 2020; Ruangpan *et al.*, 2020; Shah *et al.*, 2020), the better inclusion of social impact analysis (Staddon *et al.*, 2018), the improvement of communication from academia to practice (Marana *et al.*, 2019), and the provision of a clear description of multiple benefits that can be obtained with solutions (O'Donnell *et al.*, 2017).

2.3.5 The assessment of sustainable solutions

The evolutions of terminologies for sustainable solutions include providing benefits not only in the water domain but also in other areas. For example, solutions can reduce flood depth and improve water quality (Dagenais *et al*., 2016), enhance human health, and reduce the heat island effect (Debele *et al.*, 2019). As shown from sections 2.2.1 to 2.2.3, benefits will depend on the implementation type and scale of solutions, impacting sustainability and planning in environmental and social contexts and enhancing resilience (Ashley *et al.*, 2020).

Approaches are being developed to evaluate the benefits of urban flood mitigation strategies (Hoang *et al.*, 2018), including their cascading effects (Vamvakeridou-Lyroudia *et al.*, 2020), equity planning (Heckert *et al.*, 2018; La Rosa *et al.*, 2020), spatial interactions (Morgan *et al.*, 2019) and resilience (Wang *et al.*, 2019). Benefits are time and context dependents, which require the provision of a robust option that is less sensitive to the possible changes and uncertainties that may come over time (Ashley *et al.*, 2020).

In terms of analysis, benefits can be divided into primary and secondary, in which, the primary benefits can be the hydrological performance and water quality, and the others are secondary, but also play a role in climate change adaptation and in quality of urban spaces (Dagenais *et al.*, 2016). The secondary benefits, or co-benefits, are defined as the various benefits that the solution can simultaneously provide over a certain period (Debele *et al.*, 2019; Kumar *et al.*, 2020; Raymond, 2017). In urban landscapes, co-benefits are increasingly recognised because of the provisioning and availability of urban green spaces (Raymond *et al.*, 2017). The multi-directional effects underline the importance of a holistic approach to design, implement and assess solutions considering synergies and potential trade-offs (Raymond *et al.*, 2017). However, current proposals of solutions still lacks in analysing the relationship between benefits and vulnerability (Dagenais *et al.*, 2016), without detailing practical alternatives for reducing risk (Dagenais *et al.*, 2016; Sahani *et al.*, 2019; Shah *et al.*, 2020) and exposure (Klijn *et al.*, 2015).

Because of the interdisciplinary nature of this study, tools for the proposal of actions and solutions for FRM are presented mainly focused in two variables: (1) spatial modelling tools and (2) participatory approaches. As this thesis is built with five journal articles, it is acknowledged that some information discussed may be similar in the following chapters. As an attempt to reduce repetition, at this stage, only a summary of tools is provided.

2.3.5.1 Spatial modelling approaches

Several models that analyse the benefits of sustainable solutions have been developed in the last years. The Storm Water Management Model (SWMM) enables the assessment of the hydraulic performance of urban drainage systems (Ahiablame *et al.*, 2016; Xu *et al.*, 2017). Another example is the System of Urban Stormwater Treatment and Analysis Integration (SUSTAIN), a decision support system that assists stormwater management for flow and pollution control to protect source waters and meet water quality goals. SUSTAIN is a tool capable of evaluating the optimal location, type, and cost of stormwater practices required to meet water quality goals (Gao *et al.*, 2015; Mao *et al.*, 2017). SWMM is a one-dimensional model and comes with no help to visualise urban flood extent and inundation depth simulation, and the focus of SUSTAIN is to apply practices mainly to reduce pollution values.

Integrated models such as MIKE URBAN (DHI, 2014) can also be used to model all urban water networks and solutions in an integrated system. Essentially, the main advantage of MIKE URBAN over SWMM is the capability to simulate 2D overland flow with spatial integration unlike in SWMM (Bisht *et al.*, 2016). The model manager includes Geographic Information Systems (GIS) based on data management and tools such as data validation, catchment delineation, and network simplification (DHI, 2014). The significant advantages of the system are the possibility to visualise the interaction of water on the surface and in the underground, comparison of scenarios, layout, and presentation easy to understand for both decision-makers and experts. MIKE URBAN has two possibilities of collection systems, SWMM and MOUSE, that can be chosen according to available data and which system (runoff or sewer) will be simulated. The software covers all water networks in the city, including water distribution systems, stormwater drainage systems and sewer collection in separate and combined systems.

Recent studies have applied the “Cellular Automata Dual-DrainagE Simulation” (CADDIES) model to simulating flood risk-prone areas. The software was developed by the University of Exeter (UK). CADDIES is a cellular automata-based surface water modelling tool (Guidolin *et al.*, 2016), with international applications (Vamvakeridou-Lyroudia *et al.*, 2020; Wang *et al.*, 2018; Webber *et al.*, 2019a; Webber *et al.*, 2019b; Webber *et al.*, 2018). Some applications of studies using CADDIES modelling are:

- Simulating flood-prone zones in current and future contexts (Liu *et al.*, 2018b; Wang *et al.*, 2019; Webber *et al.*, 2019b).
- Planning flood risk mitigation solutions and their environmental benefits (Liu *et al.*, 2018b; Wang *et al.*, 2019; Webber *et al.*, 2019b).
- Prioritise areas of flood risk with the implementation of different scenarios (i.e., with sewer, drainage system, interventions) (Webber *et al.,* 2018).
- Assessing catchment scale flood resilience of urban areas using a grid cell-based metric (Wang *et al.,* 2019).
- Assessing and visualising hazard impacts to enhance the resilience of critical Infrastructures to urban flooding (Vamvakeridou-Lyroudia *et al.,* 2020)
- Modelling urban flooding based on multiple information sources and urban features (Wang *et al.,* 2018)
- Flood modelling for large-scale problems, including the calibration and validation against widely-used commercial physically-based hydraulic models (Guidolin *et al.,* 2016)
- Investigating flood increase due to the built-up growth in developing countries (Rufino *et al.,* 2021)

Other frameworks support the location of flood mitigation solutions and understanding of their multiple benefits by analysing intensity changes (Blue-Green Cities GIS toolbox) and economic appraisals (BEST tool). O'Donnell *et al.*

(2018) used both models in collaboration to evaluate the multiple benefits of BGI in Newcastle (UK). Along with multiple benefits evaluations, one of the key conclusions of the study is the need of applying effective visualisation capability, for learning and communication activities with stakeholders. However, the lack of standard metrics to assess the multifunctionality of sustainable systems is one of the greatest challenges for proposing solutions (Wright *et al.*, 2020).

In this regard, different research introduced GIS (Geographic Information System, or *Geospatial Technologies*) with hydrological models to analyse multiple benefits and suggest solutions for a system (i.e., a city, neighbourhood, catchment) (Cortinovis *et al.*, 2020; Dagenais *et al.*, 2016; Kuller *et al.*, 2017; Kuller *et al.*, 2019; La Rosa *et al.*, 2020; Martin-Mikle *et al.*, 2015; Morgan *et al.*, 2019; Pappalardo *et al.*, 2017; Qin *et al.*, 2013; Xie *et al.*, 2017). GIS-based tools enable the spatial evaluation of attributes that can support the modelling of socio-economic, structural, and physical inherent factors of the system, called Multicriteria Decision Analysis (MCDA) (Malczewski, 1996). Figure 2.6 presents a scheme with the different layers that can be used in a GIS-MCDA. The layers represent the "multiple" kinds of data that can be integrated using their own spatial location, or geographical coordinates.

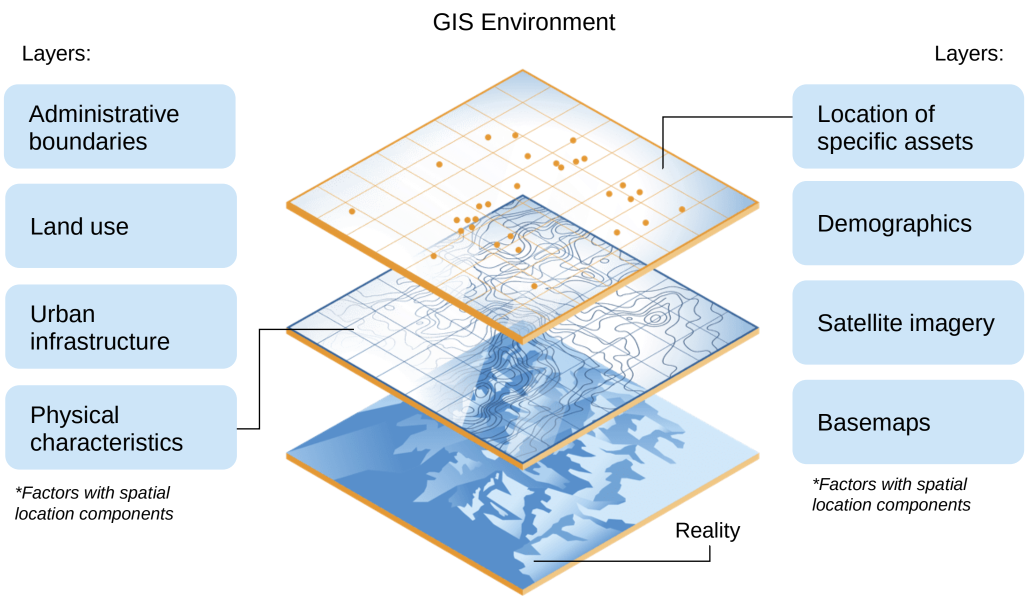


Figure 2.6 – Scheme representing the functionality of a GIS tool. The layers represent spatially located factors that, together, can be used to represent an environment with GIS-MCDA approach. Source: ESRI.

The integration of GIS-MCDA is a powerful and integrated tool that provides a rich collection of procedures and algorithms for structuring decision problems, designing, evaluating, and prioritising alternative solutions (Boroushaki *et al.*, 2010; Malczewski *et al.*, 2015). In this sense, GIS-MCDA methods have been applied in several studies in the water domain since data used by decision makers are geographical, examples can be seen with Hazarika *et al.* (2018) de Brito *et al.* (2018), Wang *et al.* (2017), Perera *et al.* (2019), Birgani *et al.* (2018), and Jiménez *et al.* (2019). Other studies focus on the placement of sustainable solutions, including GIS tools and the assessment of multiple benefits, such as Vercruysse *et al.* (2019), Xie *et al.* (2017), Ashley *et al.* (2018), Wang *et al.* (2019), Webber *et al.* (2019b), Dawson *et al.* (2020) and Wang *et al.* (2018).

Another example of a GIS-tool can be seen in Boroushaki *et al.* (2010) that developed a framework for GIS-MCDA using fuzzy majority approach and ordered weighted averaging (OWA) in two stages of mapping: 1) Solve the problem individually to create individual decision-makers solutions maps with OWA operations and, 2) combine individual maps using the fuzzy majority procedure to create a group solution map, synthetising most of the decision-makers preferences. The fuzzy logic principles are used to combine $i = 1$ to m rules from a fuzzy rule base into a mapping from fuzzy input sets to fuzzy output sets (Hong *et al.*, 2018). Similar GIS-MCDA approaches are applied by Kuller *et al.* (2017) and Kuller *et al.* (2019) based on a procedure by Malczewski *et al.* (2015) for building suitability maps: (1) selecting priority indicators and compiling in a geodatabase, (2) removing all areas where at least one aspect of the urban context constraints implementation (i.e., masking), (3) transforming spatial datasets to a standard suitability scale (i.e., value scaling), and (4) combining all criteria considering that not all aspects carry the same importance, hence should incorporate weights.

Defining procedures of weightage allocation for integrating the different layers is a key topic in GIS-planning. Examples of objective methods for weighting are the Order Preference by Similarity to Ideal Solution (TOPSIS) method (Wang *et al.*, 2017; Yang *et al.*, 2018), Shannon's Entropy method (Boroushaki, 2017; Perera *et al.*, 2019; Roodposhti *et al.*, 2016), Analytic Hierarchy Process (AHP) (Ahmadisharaf *et al.*, 2015; Garfi *et al.*, 2011; Ouma *et al.*, 2014) and artificial neural network (Kia *et al.*, 2011), between others. In these methods, alternatives (or indicators) can be evaluated with or without individuals (Boroushaki *et al.*, 2010; Malczewski, 1996, 2006; Malczewski *et al.*, 2015). Studies that combine GIS-MCDA tools with the involvement of decision-makers and interest groups for weightage allocation can be seen in Hazarika *et al.* (2018) de Brito *et al.* (2018), Wang *et al.* (2017), Frigerio *et al.* (2016b), Perera *et al.* (2019), Birgani *et al.* (2018), Boroushaki (2017), and Jiménez *et al.* (2019).

Although very powerful, the majority of GIS-MCDA mapping frameworks are not applicable for different areas and different disasters, due to geographical differences, human interactions and available data (Robinson *et al.*, 2019). Since each area will have a unique set of governance arrangements and legislations in place, it is essential to develop spatial methodologies for considering each case in context as well as their potential risks and impacts to society with the integration with management (Driessen *et al.*, 2018), the involvement of stakeholders and policymakers (Sultana *et al.*, 2019) and the dynamism of cities and the relationship between environmental disaster risk, vulnerabilities, and the built environment (Ciullo *et al.*, 2017).

2.3.5.2 Participatory approaches

Although public participation in science has existed for centuries, in the past few years citizen science projects have grown spectacularly in number, scale and scope (Brouwer *et al.*, 2018). There are different nomenclatures given for the involvement of people in research, such as Crowdsourcing and Crowdsourced Geographic Information, Volunteered Geographic Information (VGI), Participatory Modelling (PM), Collaborative Modelling (CM), Participatory Disaster Risk Reduction (PP-DRR), and Place-based Citizen Science (CS) (Baruch *et al.*, 2016; Basco-Carrera *et al.*, 2017; Brouwer *et al.*, 2019; Brouwer *et al.*, 2018; McEwen *et al.*, 2018).

The main differences between terminologies are the focus, strategies, and stakeholders' groups that collaborate. Brouwer *et al.* (2018) define CS as any form of active public participation in the process of research to generate science-based knowledge, from setting the research agenda by asking research questions to collect data and/or analysing the results. CS supports the integration of scientific and contextual knowledge leading to social learning and refers to the participation of the general public in the generation of scientific knowledge (Brouwer *et al.*, 2018). The instrumental rationale for CS is rooted in the idea that the process of participation will increase the legitimacy and or quality of the final product (Brouwer *et al.*, 2018). For Collins *et al.* (2019), it will also create inclusivity, give voice to the public's needs, and help to ensure that design meets their particular requirements. Some terminologies are more linked to increasing participation in the actual modelling process (i.e., crowdsourcing, VGI, PM, and CM). "Participatory and "collaborative modelling" emerged as possible solutions to address certain challenges in decision-support systems (Basco-Carrera *et al.*, 2017). Although stakeholder participation cannot be considered as the unique pre-requisite for guaranteeing the long term use of computer-based models, it can be a critical factor (Basco-Carrera *et al.*, 2017). For Nesshover *et al.* (2017), in general, participatory strategies can help understand the potential of alternatives, inform the design of new strategies, and improve the general understanding of environmental governance.

Traditional FRM and management has focused mostly on the application of technological measures (Marfai *et al.*, 2014; Peduzzi, 2019), however, in recent developments of risk management, risk perceptions, coping capacities, and adaptation are becoming recognised (Danso *et al.*, 2016; Fuchs *et al.*, 2017; Whitney *et al.*, 2017). Even with the ample recommendation for the involvement of stakeholders in the proposal of sustainable solutions (Hoang *et al.*, 2018), the number of studies that have meaningfully integrated collaboration based on a participatory framework is still low, especially in the field of FRM (Cheung *et al.*, 2019). Table 2.4 summarises studies in the water resources field that were served as the basis for this study, linking participatory approaches with modelling tools cited in the topic 2.3.5.1 (i.e., spatial modelling approaches).

The studies detailed in Table 2.4 shows different possibilities of incorporating participatory approaches, modelling and statistical tools, when studying FR, FRM and other climate extremes. Brito *et al.* (2018), Wang *et al.* (2018), René *et al.* (2013), and Cheung *et al.* (2018) point difficulties in the field of water resources, especially for modelling flood and vulnerability prone areas without the necessary data (i.e., physical conditions, land use, rain gauges, soil type). Similarly, the identification of susceptible and vulnerable areas (for now and future) through models is considered an important task to flood susceptibility mapping, being an essential tool for flood mitigation strategies and disaster preparedness (Hong *et al.,* 2017, Hazarika *et al.,* 2018, Owusu *et al.,* 2017).

Table 2.4 – Catalogue of studies focusing on participatory approaches, spatial modelling tools, and statistical methods in the water resources research field.

Authors	Year	Methods*	Main aim*
Birgani *et al.*	2018	MCDA, TOPSIS, Entropy Survey	Use of MCDA to evaluate plans to apply LID
Ajibade and McBean	2014	Surveys, in-depth interviews, focus group discussions	Investigate the link between housing rights and climate change extreme events
Hazarika *et al.*	2018	ArcMap, MCDA Survey	Mapping hazard, vulnerability, and risk with MCE
Song and Chung	2017	SWMM, TOPSIS Survey	MCDA to LID prioritizing catchments
René *et al.*	2013	Survey for scientific and consulting communities, Statistics	Assessing the potential for real-time urban flood forecasting based on a worldwide survey on data availability
Cheung *et al.*	2019	Literature review, household surveys, focus groups and training and outreach workshops	Development of a citizen science approach for flood risk management (FloodRISE project)
Khan *et al.*	2018	Urban growth, Hydraulic and damage assessment	Assess damages, impacts and uncertainties in the future
Ahmadisharaf *et al.*	2016	SWMM, AHP, TOPSIS Survey	Use of flood hazard and MCDA to detention basin positioning
Owusu *et al.*	2017	ArcMap, AHP, Weighted overlay, survey	Assess land suitability for aquifer and recharge with RS, GIS, and MCDA
Hong *et al.*	2018	Fuzzy, weighting process with experts	Flood susceptibility map with fuzzy and data mining techniques
Fuchs *et al.*	2017	Household surveys Statistics (SPSS), Mann-Whitney U test, Logistic Regression, etc.	Analysis of flood risk perception and adaptation capacity od residents of two sub-regional areas in Greece
Bryan *et al.*	2018	Theoretical framework Household's survey, Mann-Whitney U test	Investigation of perceptions and intentions of households towards drought and drought coping
McEwen *et al.*	2018	Semi-structured interviews with flood group members and flood risk management agencies	Evaluation of a participatory model for flood risk development involving horizontal support rather than top-down or bottom-up generation
Webber *et al.*	2020	CADDIES, ArcGIS, collaboration strategies with local government	Applying a cellular automata-based rapid scenario screening framework for evaluation of GI performance
Wang *et al.*	2018	CADDIES, LiDAR, Social media information	Investigate publicly available data (Twitter) to extract flood-related information for model calibration and validation.
O'Donnel *et al.*	2017	Semi-structured surveys with professional stakeholders	Barriers for the implementation of BGI in Newcastle, UK
De Brito *et al.*	2018	MCDA, Delphi, Survey, focus groups, workshops AHP and ANP	Participatory flood vulnerability assessment in Brazil

*MCDA refers to "Multi-Criteria Decision Making", SWMM to "Storm Water Management Model", AHP to "Analytical Hierarchy Process", ANP to "Analytical Network Process", TOPSIS to "Technique for Order of Preference by Similarity to Ideal Solution", CADDIES to "Cellular Automata Dual-DraInagE Simulation model", BGI to "Blue-Green Infrastructure", GI to "Green Infrastructure and LID to "Low Impact Development".

Others also point the difficulties of effectively applying participation and multi-criteria decision analysis in policymaking, especially in developing countries, due to issues with collaboration between researchers, government, and citizens (Brito *et al*. 2018, O'Donnel *et al.* 2017, McEwen *et al.* 2018, Everett *et al.,* 2018). From the different studies, the importance of **multi-stakeholders'** participation (i.e., experts, public authorities, and citizens) to develop an integrated mitigation framework in a long-term perspective is shown, however, rarely made with the three key groups simultaneously.

Another challenge is suggested in a review developed by de Brito *et al.* (2017). From 128 peer-reviewed articles, about half of the studies acknowledged the involvement of multiple stakeholders, however, participation was generally fragmented and restricted to consultation at specific stages of FR management frameworks. Since participatory decision-making is time-consuming and expensive, methodological and time constraints are suggested as a few reasons for the fragmented participation (de Brito *et al.*, 2017). Others highlight how the involvement of the public is often restricted to only collection of data with minor collaboration (Brouwer *et al.*, 2018).

However, authors suggest that incorporating bottom-up approaches bring the "socially oriented" characteristic for studies by enabling communities to participate of the entire process of FRM aiming for them to be better prepared for unexpected extreme events (i.e., see more details in Ciullo *et al.* (2017)). For Cheung *et al.* (2019), CS projects set expectations as to how projects outcome will be used in decision-making or research, by following a disaster-preparedness principle of which resilience is a key aspect. For Hicks *et al.* (2019), CS is a tool for "open-up discourse" that creates knowledge situated in the socio-cultural context that can help in early warning, can generate shared understandings of hazardous phenomena, improve communication, and help communities at risk to take actions.

In general, participatory studies tend to implement different collaboration strategies such as focus groups and workshops (de Brito *et al.*, 2018), interviews and questionnaires (de Brito *et al.*, 2017), web and phone applications (Del Grande *et al.*, 2016a), mappings, and mind maps (Hardoy *et al.*, 2019; Verweij *et al.*, 2020), and mixed-methods approaches linked with Delphi method (de Brito *et al.*, 2017). However, as suggested elsewhere (Heckert *et al.*, 2018; O'Donnell *et al.*, 2018; Ruangpan *et al.*, 2020; Wright *et al.*, 2020), only a few articles included stakeholders' participation for the proposal of solutions for FRM. These studies suggest the engaging with stakeholders should be incorporated as tool for understanding the current conditions of places supporting the "successful" adaptation for climate extreme. For Gimenez-Maranges *et al.* (2020), identifying the prevailing knowledge of stakeholders and governance structures, the role of the local community, and the discussion of barriers and enablers, remain receiving less attention in proposals, even though it is a requirement for understanding of current conditions.

Others authors such as Dagenais *et al.* (2016) and Morgan *et al.* (2019) also point to the importance of presenting the benefits that can be obtained with solutions for stakeholders, including modelling decisions and assumptions, in an attempt to increase social acceptability, understanding, and interest of beneficiaries and policy makers. The demonstration of benefits to communities may increase the support for flood management schemes (O'Donnell *et al.*, 2017). Therefore, engagement strategies can minimise the "maladaptation" to extremes by increasing communication with (1) communities who are supposed to adapt (so-called beneficiaries), that appears to have limited information leading to poor choices (Schipper, 2020), (2) with the ones that are responsible for managing the policies, governance and actions in the different levels of management. However, ensuring collaboration is not an easy task. The management of water resources for such different objectives and goals (i.e., sustainability, resilience, risk mitigation) for so many, and diverse, stakeholders groups always brings challenges and conflicts, including (A) to ensure the participation of all actors of the planning, (B) the awareness and training of stakeholders, (C) the provision of dialogue and participation spaces, (D) to enable effective communication, and (E) to create opportunities for the integration of sectors of planning (Hardoy *et al.*, 2019; Lund, 2015).

In this study, the multiple participatory and modelling studies cited in this literature review were used for building the spatial-participatory approach for pluvial flood risk reduction in Campina Grande, Brazil. More details are described from chapter 3 to 7.

2.4 Studies in the Brazilian context

Since the case study of application of this thesis is in Brazil, it is important to analyse the studies published in the Brazilian territory for characterising meaningful gaps. For this, a quantitative literature review was undertaken to analyse the country's current literature on sustainable flooding mitigation.

Articles in the Scopus, Web of Science, and Google Scholar databases, the three primary academic databases (Matsler *et al.*, 2021), and in the visual online platform "*Connected Papers*" (www.connectedpapers.com) were systematically searched. The Connected Papers tool arranges papers according to their similarity but does not necessarily act as a citation tree. Moreover, the tool connects papers that do not directly cite each other but are strongly connected and very closely positioned through co-citation and bibliographic coupling. To find eligible articles, the search strings "Flooding" (OR "Flood" OR "Inundation") AND "Nature-Based Solutions" (OR "Low Impact Development" OR "Sustainable Urban Drainage Systems" OR "Compensatory Techniques" OR "Green Infrastructure" or "Blue Green Infrastructure" or "Best Management Practices" OR "Sustainable Solutions" OR "Water Sensitive Urban Design") AND "Brazil" were used in the titles, abstracts, and keywords (Figure 2.7). Given that this section aims to identify current issues, the search was restricted to journal articles written mainly in English and in Portuguese published between January 2007 and May of 2021.

These queries found 45 papers in Scopus, and 25 papers in Web of Science, totalling 70 articles. After screening the abstracts, 31 articles were excluded as it were not about flooding mitigation with sustainable strategies with study cases in Brazil, or they were repeated in the databases. We checked the databases with the Connected Papers tool and Google Scholar and included other 06 papers, totalling 45 articles in this review. It is recognised that relevant articles may be missing from these databases because the main language used in strings differs from the language in the country and due to the other types of publications such as books, or conferences issues, and non-peer reviewed literature that were systematically excluded. The complete list of the 45 articles is in Appendix A, and their classification scheme is shown in Table 2.5.

Figure 2.7 – Combination of keywords used for literature research in Scopus, Web of Science and Google Scholar databases and Connected papers tool.

Table 2.5 – The summary of phases and topics for the classification of Brazilian papers in this review.

	Articles Classification	***Groups***
First phase	Year	
	Case study area	City, state, and region of Brazil
	Scale of analysis	City-wide, catchment, neighbourhoods/site, households, and prototype
Second phase	Type of solutions	Green roofs, rain gardens, permeable pavements, infiltration trenches, bioretention, floodable parks, retention and detention tanks or basins, swales, and rainwater harvesting.
	Modelling approach	Software, scenarios, spatial and temporal analyses
	Participatory approaches	Surveys, interviews, workshops, focus groups, collaborative mapping
	Stakeholders involved	Citizens, authorities, private companies, specialists

First, the articles were classified according to their publication year, case study area, and scale of analysis. The scale of analysis was distinguished into city-wide, catchment, neighbourhoods/site, households, and prototype (Table 2.5). The examination of scales aims to analyse the "way" the sustainable strategies are proposed and implemented in Brazil. The second phase aimed to investigate the types of sustainable solutions selected, the reasons for selecting it, and the tools used for assessing their effectiveness. The modelling tools used were also analysed, and if participatory approaches were included in the proposal. Specifically, this phase wanted to verify if participation and collaboration strategies were considered since it is one of the key elements of the proposal of sustainable solutions (Heckert *et al.*, 2018; O'Donnell *et al.*, 2018; Ruangpan *et al.*, 2020; Shah *et al.*, 2020).

The discussion of findings presented in this section combines studies in the Brazilian and the broader context presented beforehand. The previous literature was used to contextualise the proposal of mitigation solutions in the broader context from sections 2.1 to 2.3. Therefore, through the combination of Brazilian and wider contexts, the state-of-the-art of the proposal of sustainable solutions for flood risk mitigation is presented in this thesis.

2.4.1 Quantitative analysis of the Brazilian context

Most articles were published from 2018 to 2021 (69%, n = 31) reflecting an increasing and recent search for sustainable solutions for flood risk management in the country (Figure 2.8a). This may be due to the more frequent and intense hydro-meteorological extremes over the last decade in Brazil (Teston *et al.*, 2018; Young *et al.*, 2020). In fact, research carried out by the Brazilian Institute of Geography and Statistics (IBGE) showed that more than half of municipalities in Brazil experienced floods between 2008 and 2021 (IBGE, 2021). In 2019, 105,142 people were homeless or displaced because of hydrological events, of which 15,962 are from the Northeast region (BRASIL, 2020). Also, as shown in the timeline of sustainable strategies in Figure 2.2 (section 2.2.1), the last three decades were the period of a great advent of solutions' terminologies, which may indicate more scientific search for sustainable solutions worldwide (Eggermont *et al.*, 2015).

When looking to the areas of application (i.e., cities in which the sustainable solutions are being proposed), 69% of the articles are built for studying the Southeast region, followed by 10.7% in the South, 8.3% in the Northeast, 7.1% in the North and 4.8% in the Midwest. Rio de Janeiro and São Paulo states are studied in 20 articles, which can indicate a disproportional focus when compared to the other cities and regions of Brazil.

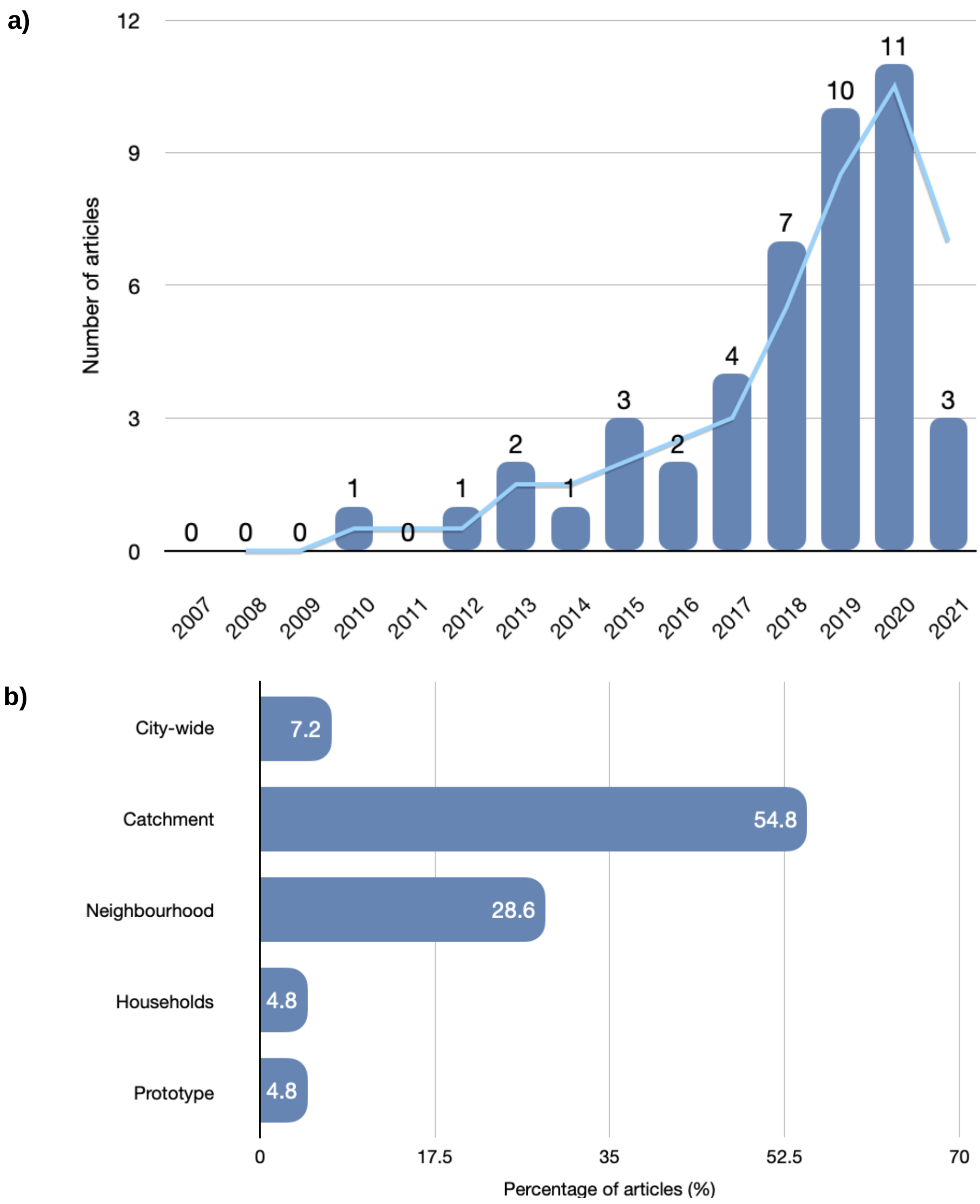


Figure 2.8 – a) The number of articles per year, b) Spatial scale of application of the reviewed papers (n = 42). The number of articles is 42 because 3 papers in the sample are reviews.

When analysing the scale of analysis, Figure 2.8b shows that only a minority of papers analyse the impacts (i.e., benefits and co-benefits) of solutions in the entire municipality (7.2%, n = 3). Most papers assessed the sustainable solutions within a catchment (54.8%, n = 23) or a neighbourhood (28.6%, n= 12) (Figure 8b). Evaluating the scale of analysis is particularly important because one of the gaps of proposals is that analyses of sustainable solutions are usually made for smaller scales and case studies (Ruangpan *et al.*, 2020). Since solutions will alter the water cycle, the impacts (i.e., positive or negative) can be generated for areas downstream (Buurman *et al.*, 2017).

Figure 2.9a shows that most studies propose the implementation of permeable pavements (33%), detention tanks (29%), green roofs (26%), rain gardens (19%), and swales (14%). The most common terminologies for sustainable solutions are LID and SUDS, with 38.1% and 29.6% of the papers, respectively (Figure 2.9b). NBS is ranked in 3rd place with 9.5% of papers. Interestingly, some papers use more than one nomenclature in their analysis, which corroborates findings that researchers may consider the strategies as synonyms (Matsler *et al.*, 2021; Mell, 2017; Ronchi *et al.*, 2018).

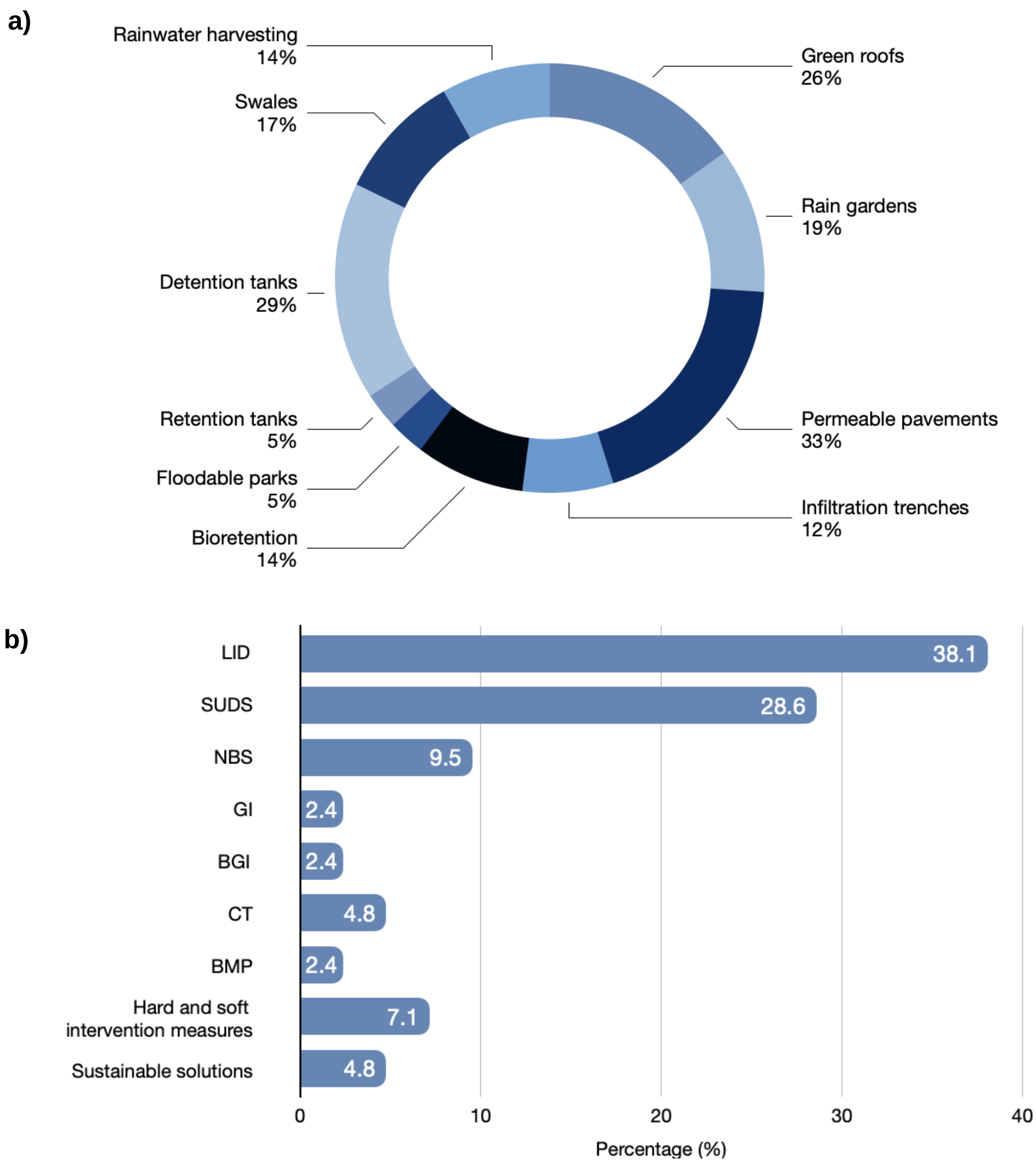


Figure 2.9 – a) The types of sustainable solutions analysed in each paper. Many articles evaluate more than one solution at a time, which makes the total more than 100%. b) The terminology of sustainable solutions used in the articles. LID refers to "Low Impact Development", SUDS to "Sustainable Urban Drainage Systems", NBS to "Nature-based Solutions", GI to "Green Infrastructure", BGI to "Blue-Green Infrastructure", CT to "Compensatory Techniques" and BMP to "Best Management Practices".

When considering the approaches used for assessing the effectiveness of solutions, Figure 2.10 shows a great focus on hydrologic modelling (59.6%). The main software used are SWMM (USEPA), the Urban Flood Cell Model - MODCEL (Federal University of Rio de Janeiro), the Rainfall-Runoff Model (Hydrologic Engineering Centre – Hydrologic Modelling System, HEC-HMS) and Hydraulic Model (HEC–RAS). GIS-based tools (10.6%) and other mathematical models (10.6%) are also used in the context of flood risk mitigation, with examples of ArcGIS Pro and ArcMap (ESRI). Participatory approaches were only used in five papers, applying interviews, surveys, and workshops. The low rate of application of subjective strategies may be the "search strings" used for finding the articles since it can reflect a "search" more focused on the engineering perspective of proposing sustainable solutions. The lower rate stands for article reviews that systematically analysed scientific literature (6.4%).

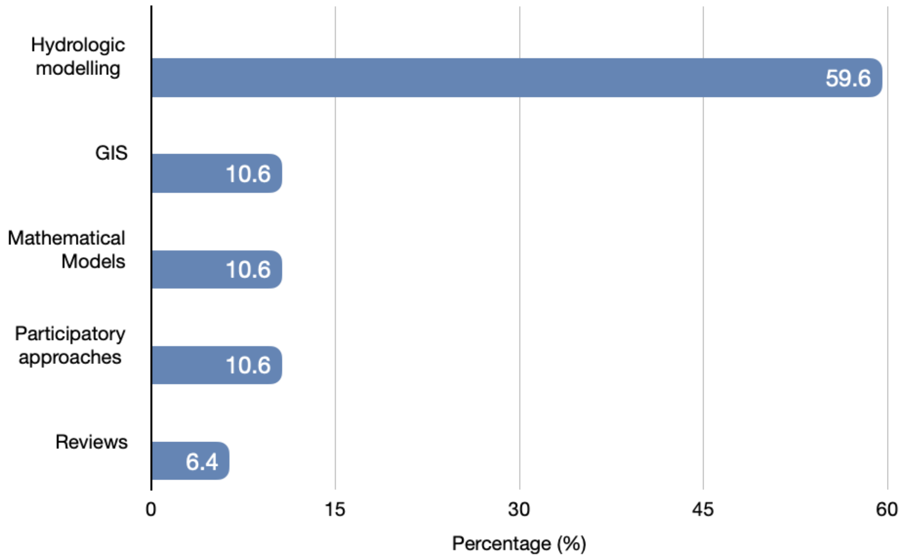


Figure 2.10 – Summary of approaches used for analysing sustainable solutions in the Brazilian study cases.

Lastly, the focus of articles is also analysed regarding the keywords used in each publication. Figure 2.11 reflects the detailed list of keywords organised in the four research areas and gaps suggested in Figure 2.1 (section 2.2) of this literature review. Figure 2.11 confirms the different nomenclature of sustainable solutions used in the country as indicated in Figure 2.9b, including the addition of the term "Ecosystem Services (ES)" (n = 2). SUDS and LID received more citations (n = 9), while NBS, CT, and GI were cited three times each, and BGI and BMP once each (Figure 2.11).

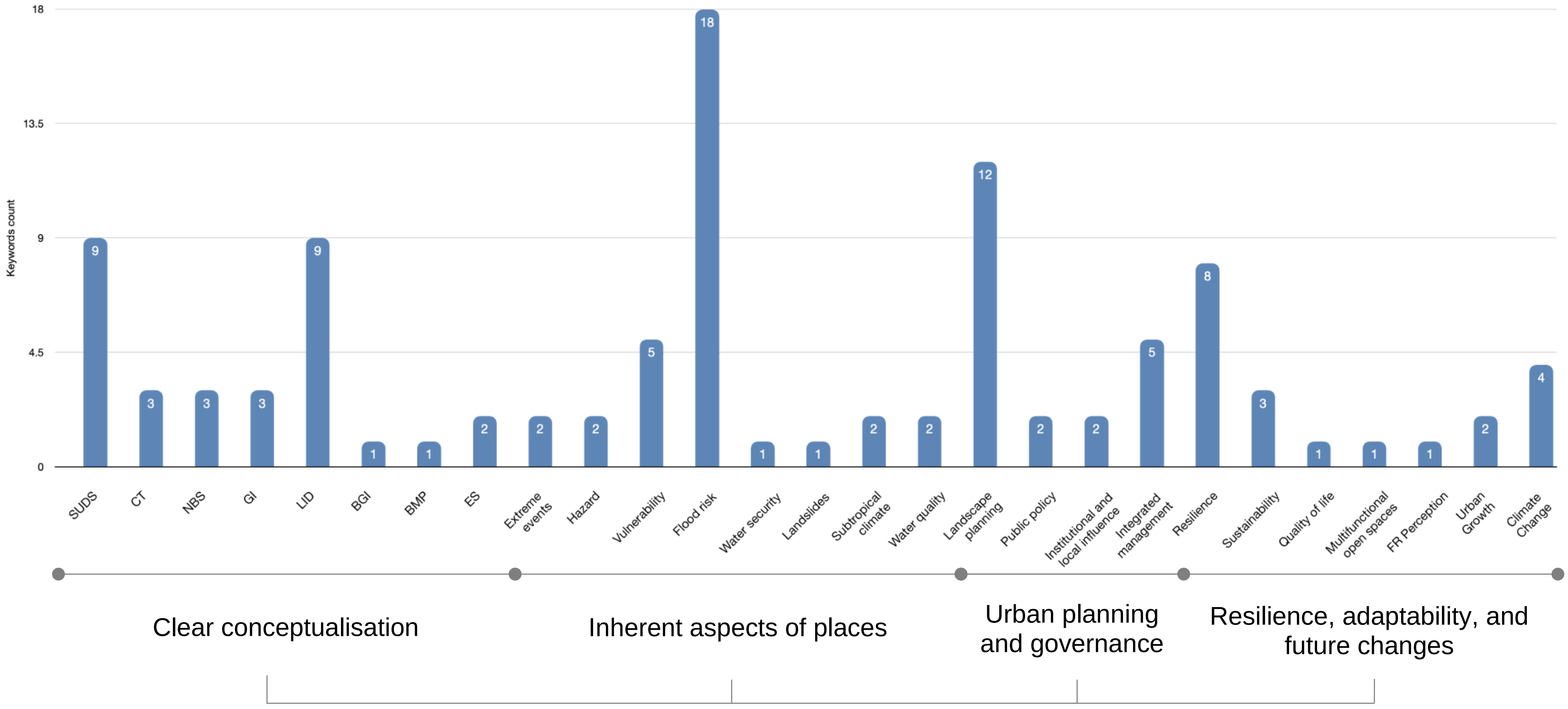


Figure 2.11 – Summary of keywords used for analysing sustainable solutions in the Brazilian study cases. The count indicates the sum of the number of times that each keyword was used in the different articles. Four key research areas are highlighted: “Clear conceptualisation”, “Inherent aspects of places”, “Urban planning and governance” and “Resilience, adaptability and future changes”. SUDS refers to “Sustainable Urban Drainage Systems”, CT to “Compensatory Techniques”, to NBS to “Nature-Based Solutions”, GI to “Green Infrastructure”, LID to “Low Impact Development”, BGI to “Blue-Green Infrastructure”, BMP to “Best Management Practices”, and ES to “Ecosystem Services”.

Regarding the *inherent* aspects of places (Figure 2.11), the keyword more used in the publications is “flood risk” (n = 18), which was expected because of the search strings used to find the articles in the databases. Regarding other societal challenges, “extreme events” and “hazard” are cited twice, but after carefully reading the articles, their content is more focused on flooding hazard as the extreme event.

Also, it is important to mention that only a few articles focused on the effectiveness of strategies concerning other hazards in place. For example, only one article cited “landslides,” and another used “water security”. “Subtropical climate” is cited twice (n = 2), indicating the analysis of climate constraints and FR solutions. “Water quality” is mentioned twice. Given Brazil's extensive and diversified territory, this finding is particularly important because of the climate, physical and social variations in the territory (Young et al., 2020), which may indicate the presence of compound hazards and other societal challenges in municipalities.

A similar conclusion is seen in the reflection of social aspects of disasters. Even though vulnerability and exposure form the roots causes of a disaster (i.e., see section 2.2.2 and Cutter *et al.* (2003), Sharma *et al.* (2019), Londe *et al.* (2015)) and are especially key for mitigating FR (Climent-Gil *et al.*, 2018; Klijn *et al.*, 2015), only five articles used “vulnerability” and no articles cited “exposure” or “adaptability” in the keywords list (Figure 2.11). Since the concepts of vulnerability, sustainability and resilience are interconnected (Cutter *et al.*, 2008; Rezende *et al.*, 2019), eight articles emphasize the analysis of “resilience” (n = 8), and three articles mention sustainability (n = 3). Other societal challenges such as climate change (n = 4) and urban growth (n = 2) are cited. Only one article cites “flood risk perception”, “multifunctionality”, and “quality of life”, which can indicate less focus in the search of social benefits with sustainable solutions.

Part of the articles focused on the analysis of governance and management for proposing solutions (de Macedo *et al.*, 2019; Gomes Calixto *et al.*, 2020; Miguez *et al.*, 2015a; Sanches Brito *et al.*, 2020). Some articles focus on “landscape planning” (n = 12) and integrated management (n = 5), which refer to the integration of water resources and land use planning. Both keywords “public policy” and “institutional and local influence” appear twice in the keywords (Figure 2.11).

2.4.2 The main barriers for the proposals of actions and solutions for flood risk mitigation in Brazil

Assuming that regions are not equally exposed to disasters (IPCC, 2012, 2014), and therefore, have different challenges (i.e., see the inherent aspects of places in section 2.2.2), the main barriers for the proposal of solutions in the Brazilian context are summarised below.

It is important to recognise that the results discussed here do not represent the majority of publications of Brazilian study cases. Instead, it indicates a sample of articles chosen using search strings in the three primary databases of science production (Matsler *et al.*, 2021). It is acknowledged that additional papers can be found in other databases, especially if the language used for strings is in Portuguese, since it can reveal articles used in national journals that tend to be more explored by scientists in early stages of career of Brazil. Yet, it is highlighted that results provide confidence for discussing concerns for the implementation of solutions in the country, mainly because the understanding of barriers can anticipate challenges for the implementation of solutions in practice (Eckart *et al.*, 2017; Elmqvist *et al.*, 2019; Santos *et al.*, 2021).

2.4.2.1 The urbanisation, vulnerability, and inequalities

Urbanisation is vastly analysed in many of the Brazilian articles (Gomes Calixto *et al.*, 2020; Lourenço *et al.*, 2020; Machado *et al.*, 2019; Miguez *et al.*, 2014; Miguez *et al.*, 2007; Sanches Brito *et al.*, 2020; Veról *et al.*, 2020). Brazilian cities have faced an astonishing demographic growth rate and urbanisation process since the 1970s (Ultramari, 2013). According to IBGE (2020), Brazil has approximately 212 million inhabitants, 84% of its population live in urban areas and 43% live in metropolitan areas with over 1 million inhabitants. The process of urbanisation has not been homogeneous in Brazil, and much of this growth was rapid but not really “planned” (i.e., referring to the reduced planning in municipalities) (Miranda, 2017). For Miguez *et al.* (2007), the most aggravating aspect of urbanisation in Brazil is the rapid growth in a short period, without adequate infrastructure and public policies (ARUP, 2018; Tassi *et al.*, 2014).

The rapid and unplanned growth creates heterogeneous social and structural conditions within municipalities. Brazilian urbanisation has specific dual characteristics: on the one hand, is the formal city, and on the other, the informal one, both of which result from the lack of territorial and ordering (Polidoro *et al.*, 2012). The formal city is one composed of areas equipped with infrastructure in which public investments are concentrated, while the "informal city" is characterised as the region where growth is disordered and unplanned, and there the lack of infrastructure and the socio-environmental differences are alarming (Polidoro *et al.*, 2012). Informal (or irregular) cities have been growing in the last years (dos Santos *et al.*, 2021). Also called slum areas or *favelas*, the informal cities are the emblematic expression of urbanisation in an underdeveloped country like Brazil (Fix *et al.*, 2021). For Fix *et al.* (2021), unlike the suburbs and peripheries, *favelas* are mostly located in central areas, side by side with wealthy neighbourhoods, which embody the direct contrast inherent within Brazilian society.

The context of these areas is worsened due to the issues with basic sanitation. Moreover, much is left to be accomplished in terms of basic services and infrastructures in Brazil (Ultramari, 2013). In 2016, a study from the National System of Sanitation Information of Brazil (SNS) found that 51.9% of the Brazilian population did not have access to appropriate sewage treatment. It is important to highlight that regions with less sanitation does not only refers to *favelas* but also to other poor areas such as suburbs or peripheries. In Brazil, it is common to use peripheries as the expansion of urban zones, for allocating spatial interest housing and middle and low-cost housing projects in locations far from the consolidated city centre (Polidoro *et al.*, 2012). These structural, social, and financial vulnerabilities directly impact flood management since the people with the lowest socioeconomic status can be the most vulnerable and live in the areas most at risk. For Miguez *et al.* (2013), the lack of basic structure in favelas and peripheries and the inadequate urban growth are some of the main causes of urban floods in the country.

Brazil's predominant conception of urban drainage system is still based on the "traditional and classical system" (Tavares *et al.*, 2018), a set of structural and non-structural measures. According to Tucci (2007), the structural measures in the country refer mainly to macro and micro drainage systems, while the non-structural refers to management and governance policies, such as sanitation and drainage plans. Due to urbanisation, streams and rivers are channelised and straightened, and large surface areas become impermeable exacerbating flood risk (Goncalves *et al.*, 2018). Separate drainage and sewage networks systems are enquired to be constructed in the built environment according to federal legislations such as the Water Law 9.433/1997 (i.e., "*Lei das Águas*"), and the Sanitation Laws 11.445/2007 and 14.026/2020. Still, it is very common to have a unique system with a combination of water and sewage. In 2019, the SNS reported that from 3,653 Brazilian municipalities investigated, 822 (22.5%) have the unique system, and 551 (15.1%) do not have any drainage system network (BRASIL, 2020). The maintenance of network systems is considered as one of the great problems in FRM in Brazil (BRASIL, 2020). In this regard, some articles present strong concerns about the proposal of solutions and effectiveness for environmental challenges such as sewage pollution, quality, and improvement of existing network structures (de Macedo *et al.*, 2019; dos Santos *et al.*, 2021; Fileni *et al.*, 2019; Londe *et al.*, 2015; Miguez *et al.*, 2016).

From the articles selected in this review, only five (n = 5) papers combined the analysis of sustainable solutions in favelas or poor geographical regions. Specifically, Ronchi *et al.* (2018) proposed green roofs and permeable pavements for the largest favela in South America, the *Rocinha*, located in Rio de Janeiro state. dos Santos *et al.* (2021) evaluated challenges for applying sustainable solutions in a low-income settlement located in São Carlos, São Paulo state. The study explores how social inequality, the raised density, reduced land sites, and socio-economic constraints affect LID strategies and resilience. Young *et al.* (2020) focuses on comprehending local processes to predict and reduce flooding disasters by considering the impacts of land use and land cover (LULC). The *Cabras* watershed located in Campinas, São Paulo state is studied in the article. Machado *et al.* (2019) consider the increase of vegetation in the fourth largest city of Brazil, Salvador - Bahia state. The municipality has a high social inequality and severe structural problems derived from the population growth observed in the last sixty years, with an increase of 1060%. The study by Rosa *et al.* (2020) considers there are *favelas* in Belo Horizonte, Minas Gerais state, however, the work focuses more on the hydrologic responses of LID strategies than on the specific barriers for application regarding the social and institutional perspectives of the area.

2.4.2.2 The geographical differences

The Brazilian territory has five distinct climatic regions categorised as equatorial, tropical, semiarid, highland tropical and subtropical zones (IBGE, 2010). Most of the territory is composed of tropical and subtropical climates. This may be why 84.5% of the articles in this review propose solutions in municipalities located within tropical and subtropical climate zones (i.e., in the Midwest, Southeast and South regions of Brazil). These studies are extremely valuable because the combination of these three regions, especially the Southeast, reflects areas with the highest flood risk in the country (Table 2.5). Only in 2019, more than 52 thousand people were impacted by hydrological events in the southeast region of Brazil, data from BRASIL (2020) shown in Table 2.6. Besides this, it is also pointed the important role of the articles in academia discourse since most studies of sustainable strategies have been analysed for temperate regions, while their performance in tropical and subtropical climates is yet to be well understood (Batalini de Macedo *et al.*, 2019). However, the findings of this review suggest that equatorial and semiarid climate remain less studied in the national perspective.

Table 2.6 – Hydrological impacts on population and households (properties), and percentage of municipalities with Drainage Plan and mappings of flood-risk zones in 2019 per region of Brazil (BRASIL, 2020).

	Population impacted during flood risk events in 2019*	Households in risk of flooding	Percentage of municipalities with Drainage Plan	Percentage of municipalities with mappings of flood-risk zones
North	18,362	108,800	14%	30%
Northeast	15,962	236,300	8.6%	24.5%
Midwest	785	162,700	14.9%	16.7%
South	17,895	312,700	17.4%	40.5%
Southeast	52,138	801,500	30.4%	40%
Total	105,142	1,600,000	----	----

**Population impacted refer to the number of homeless or displaced people in the urban area of the municipality due to the hydrological events in the reference year.*

The equatorial climate predominates in the country's northern region, having total precipitation that can reach more than 2500 mm per year (IBGE, 2005). The northern region of Brazil has been facing accelerated urban growth in the last decades. Only the region of Amazon Delta-Estuary (ADE) has increased approximately 300% during the previous 40 years (IBGE, 2010). The cities along ADE have experiences accelerated population growth, including an expansion of river margins and low-lying areas coupled with poor access to clean water and sanitation at the household level (Mansur *et al.*, 2017). In 2021, the *Negro* River (i.e., Rio Negro in Portuguese) reached the highest elevation (i.e., 29.98 metres) during the largest flood event in the history of the region, since records began in 1902 (CPRM). According to the region's Civil Defense, more than 400 thousand people were affected in the floods of 2021. As it can be seen in Table 2.6, this number has increased considerably in relation to the number of people affected by hydrological events (flooding and inundation) in 2019 in the region (BRASIL, 2020). Table 2.6 shows that more than 100 thousand households currently live on properties at risk of flooding in the region. Still, only 14% and 30% of the municipalities have the municipal Drainage Plan or the mappings of flood-risk zones in a municipal scale, respectively. Only three studies were developed for the region (Blanco *et al.*, 2013; Mansur *et al.*, 2017; Watrin *et al.*, 2020). For Mansur *et al.* (2017) and Watrin *et al.* (2020), flooding in the region is not only increasing in frequency, intensity and impact on people's displacement but also affects water quality and health. The articles were developed regarding how the population in the North region lives with poor or inexistent infrastructure and how solutions and technologies are needed to reduce impacts (Blanco *et al.*, 2013; Mansur *et al.*, 2017; Watrin *et al.*, 2020).

The semiarid climate is predominantly located in the Northeast region of Brazil. The region is considered the most densely populated dry region in the world (Alvala *et al.,* 2019). Approximately 22 million people reside with many environmental and socio-economic challenges in more than 1,000 counties (IBGE, 2010). Most of the drinking water supply for municipalities is obtained with surface reservoirs located in neighbouring cities (Cordão *et al.*, 2020; Del Grande *et al.*, 2016a; Marengo *et al.*, 2009). Rainfall is scarce with less than 600 mm per year and not reaching 400 mm in some areas (Braga *et al.*, 2015). In dry years, water supply can get minimal conditions for contribution and simultaneously create water shortage in many municipalities. For example, the National Institute of Semiarid Region (INSA) emitted an alert because 54% of the water surface supply reservoirs were in critical conditions for providing water in March of 2018.

In March of 2017, the *Epitácio Pessoa* (i.e., or “*Boqueirão*”) surface reservoir, located in Paraíba state, reached less than 5% of the volume, impacting more than 18 municipalities that were alleged to receive water (Rêgo *et al.*, 2017). In addition to being scarce, the rains are irregular and occur in a torrential manner.

Other studies show that even during one of the most challenging drought periods of the last decade (from 2012 to 2017), many flooding episodes and landslides took place in different municipalities, indicating that cities can face multiple hazards, sometimes simultaneously (Alves *et al.*, 2018b; Santos *et al.*, 2017c). In 2019, approximately 16 thousand people were affected by flooding, and more than 200 thousand properties were at risk of the region's hydrological events (Table 2.6). Only 8.6% of municipalities of the region have the Drainage Plan, the lowest rate in the country, and 24.5% have the mappings of flood risk zones (Table 2.6). Studies highlight that the region's hydrological deficit will continue to increase, either due to irregular rainfalls or increased evaporation, especially if average temperatures continue to rise due to climate change (Marengo *et al.*, 2009). Semiarid projects are challenged to search for living alternatives to extreme climate events and the creation of social improvements (Cunha *et al.*, 2015). Only four articles in the sample work with case studies in the northeast region Machado Machado *et al.* (2019), Silva *et al.* (2020), Londe *et al.* (2015), and Alves *et al.* (2020b), in which Alves *et al.* is one of the results of this thesis, fully described in chapter 6.

2.4.2.3 The assessment of sustainable strategies

The evaluation of sustainable strategies in the articles was made mostly through the attenuation of flood hazard itself, especially runoff reduction (Batalini de Macedo *et al.*, 2019; Fileni *et al.*, 2019; Gomes Calixto *et al.*, 2020). The “maximisation of benefits” is not commonly considered in the sample, with some exceptions (Londe *et al.*, 2015; Lourenço *et al.*, 2020; McClymont *et al.*, 2020). The study by Lourenço *et al.* (2020) recognise land as a valuable resource for reducing the gap for landscape and water resources integrated planning and as a tool for incorporating urbanism, landscaping, and engineering to obtain flood resilience. Similarly, Miguez *et al.* (2015b) also contribute to the integrated planning by considering land use for employing distributed solutions for flood reduction. Londe *et al.* (2015) focus on analysing the benefits for public health during disasters according to census track information (IBGE), and McClymont *et al.* (2020) proposes an improved quality of life index (iQoL) for delivering the amenity and biodiversity benefits with SUDS.

Even with the increase of publications in the last years (Figure 2.8a), there is still a low focus on analysing the strategies regarding compound hazards. Only eight papers (n = 8) evaluate the solutions according to flood and other hazards (i.e., landslides and drought). When dealing with climate specificities, the most common strategy for evaluation is the inclusion of extreme temperatures and rainfalls in the modelling (Alves *et al.*, 2020b; Batalini de Macedo *et al.*, 2019; de Macedo *et al.*, 2019; Fileni *et al.*, 2019; Goncalves *et al.*, 2018; Machado *et al.*, 2019; Moura *et al.*, 2016; Watrin *et al.*, 2020). Aspects related to the effectiveness of solutions in wet and dry seasons are discussed (Batalini de Macedo *et al.*, 2019; de Macedo *et al.*, 2019; Fileni *et al.*, 2019; Goncalves *et al.*, 2018; McClymont *et al.*, 2020).

Resilience appears to have an important role in the studies with many examples (Bertilsson *et al.*, 2019; Brasil *et al.*, 2021; Lourenço *et al.*, 2020; Miguez *et al.*, 2018; Miguez *et al.*, 2013; Ronchi *et al.*, 2018; Veról *et al.*, 2020; Young *et al.*, 2020). However, although participatory approaches are often suggested as key for generating more resilient proposals, only a few articles apply collaboration strategies (Mansur *et al.*, 2017; Tassi *et al.*, 2016; Young *et al.*, 2020). Tassi *et al.* (2016) analysed the social context by interviewing residents of 518 properties of Santa Maria (Rio Grande do Sul state). The residents were asked about their preferences for flood sustainable solutions, as an attempt to understand what are the information and knowledge that people have about sustainability and mitigation. Results indicate that residents have more preferences for infiltration and retention solutions, including rainwater harvesting. Young *et al.* (2019) developed a co-learning process using knowledge maps to identify flood practices of institutional actors in São Paulo state, Brazil. Workshop, meetings, and questionnaires were applied to 70 respondents from different public agencies including staff from civil defence and municipal departments engaged in spatial planning. Other papers (Bustillos Ardaya *et al.*, 2017; Mansur *et al.*, 2017) also applied questionnaires, grassroots, interviews, and workshops with citizens and authorities for improving the proposal of sustainable solutions.

Finally, findings suggest that sustainable strategies are becoming a strong research focus in Brazil, however, their application is still restricted (Tavares *et al.*, 2018). Although it can be considered that Brazilian literature has accomplished much in the last years (Figure 2.8a), very few cities in Brazil have either been studied or implemented sustainable strategies in reality. From the 3,653 municipalities analysed by BRASIL (2020), only 855 cities (23.4%) have parks or detention and retention basins, which can indicate a gap between proposal and application. Other forms of sustainable strategies are not covered in the SNS report. Cities of Porto Alegre and Curitiba are known as “green” municipalities in the country with many green initiatives in the built environment (Baptista *et al.*, 2011; Tucci, 2007). Although green spaces can also be seen in other cities, the studies show that most initiatives were not conceptualised aiming to flood risk reduction, even though there are disasters in place (Machado *et al.*, 2019; Silva *et al.*, 2020).

This reflection can indicate there is a gap from the science to the application of sustainable solutions, including a lack of trust and low perception of policymakers and citizens that nature-solutions can support the mitigation of risks (Lourenço *et al.*, 2020; Tassi *et al.*, 2016). In addition, it is argued that the current structure of Brazilian governance and urban planning can constrain solutions implementation, mainly due to misalliance of the responsibilities of the management of urban environment, water resources and disaster risk reduction (Caprario *et al.*, 2019a; Tassi *et al.*, 2016; Veról *et al.*, 2020). In other to cover limitations of proposals in urban planning and policies, articles are focused on suggesting strategies concerning the limitations of governance (Alves *et al.*, 2020b; Batalini de Macedo *et al.*, 2019; Gomes Calixto *et al.*, 2020; Miguez *et al.*, 2015a).

2.5 Chapter summary

This chapter aimed to discuss key research areas and gaps in the proposal of actions and solutions for flood risk management and mitigation. The main findings of this literature review are that current approaches of the proposal of actions still lack in considering social conditions and providing context-specific information to guide local decision-making and implementation of solutions in the built environment. The research gaps were discussed as the intersection of four groups: the improvement of conceptualisation of solutions, the consideration of the inherent aspects of places, the resilience, and adaptability, and the impacts of urban planning and governance (Figure 2.1) in the broader and Brazilian contexts. Moreover, this Ph.D. thesis suggests that three "recommendations" should be considered for the improvement of proposals of solutions for FRM in different contexts, especially in vulnerable regions with climate constraints:

Recommendation 1: Managing and mitigating risk and not only the hazard

The literature review presented how the debates between the terminologies of sustainable solutions, hazard, disasters, and resilience could influence how proposals are conceptualised (i.e., see sections 2.1 to 2.3). The differences between terminologies suggest the integrated and sustainable management of water (i.e., IUWM and SUWM) are central for considering the urban environment holistically, as it reflects the connection with many other systems (i.e., referring to the hydro-social contract on Brown *et al.* (2009)). Linking the multiple components of risk for suggesting solutions for risk reduction aims to provide benefits beyond hazard mitigation, including the reduction vulnerabilities and inequalities (Dagenais *et al.*, 2016; Heckert *et al.*, 2018; La Rosa *et al.*, 2020; Pappalardo *et al.*, 2017). However, it was shown that a vast amount of research still mainly focuses on the proposal of actions and solutions based on the "hazards-tradition" definition of FR (Equation 2.2), and less effort is made to recognising flooding, vulnerability and exposure separate risk constituents (Equation 2.3).

Specifically, in the Brazilian context, findings suggest there is a focus on analysing the benefits of solutions only with the environmental perspective (i.e., runoff reduction). The other disasters components (i.e., vulnerability and exposure) remain less analysed. Similarly, proposing solutions considering other hazards in place remain less analysed. As seen beforehand, there is a great value in considering the integration between the hazards for proposing solutions (i.e., see section 2.3.2 and Ruiter *et al.,* 2020; Ward *et al.,* 2020). In the Brazilian context, most articles are made for the tropical and subtropical climates, and less articles are made to the other climates, especially for the semiarid region with water shortage and flooding risks. In this sense, the association between different risks can provide guidance for mitigating the extreme events according to the inherent aspects of places.

With that said, there is a need for shifting the focus of the proposal of actions and solutions from not only considering the environmental and structural aspects as it usually is in the engineering field but also including the aspects inherent of the places, including the climate, other hazards in place and especially tackling vulnerability and the social conditions that form the roots causes of disasters (Cutter *et al.*, 2008; Norris *et al.*, 2008; Pescaroli *et al.*, 2019; Ross *et al.*, 2020). In this sense, it is highlighted that providing context-based information and evaluating the relationships between physical, structural, social, and institutional aspects is crucial for addressing vulnerability.

Recommendation 2: Addressing the social aspects of a disaster (i.e., the socially oriented water planning)

As designing actions to reduce disasters requires a better understanding of the conditions that influence the social and environmental aspects of risk (Kumar *et al.*, 2020; Shah *et al.*, 2020), the assessment of vulnerability, especially of how inequalities and social justice affects and is affected by efforts to build capacity, is crucial to reducing unintended outcomes (Cinner *et al.*, 2018). Moreover, the literature review revealed that the reflection about societal challenges, beyond the hazards (or multi-hazards) perspective, can indicate the resources needed by the community to reduce impacts during risk situations. For this, questions of "what are the social factors that influence this community?" and "what are the conditions that make people vulnerable and unequal in this territory?" should be clarified, especially regarding the adaptability, perception, and coping capacity of residents in risk territories (Buurman *et al.*, 2017; Fuchs *et al.*, 2017; Fuchs *et al.*, 2011; Lechowska, 2018).

In addition, this literature review also highlighted how public policies, government, and institutional vulnerabilities play an important role for risk mitigation (Albert *et al.*, 2020; Djordjević *et al.*, 2011; Hammond *et al.*, 2018; Marchezini *et al.*, 2017). This was shown in the general context, and in the Brazilian territory, since the low number of policies, the ineffective management, and the low perception of policymakers can constrain the proposal and application of solutions in urban planning, which will result in landscapes with less flood resilience.

The link between recommendations 1 and 2 is summarised in Figure 2.12. Figure 2.12 exemplifies how the risk is created when the "hazard" (i.e., step 1) occur in a "complex system" (i.e., step 2) with factors that form its "vulnerabilities" and the "exposure" of certain elements (i.e., steps 3 and 4). The integration of hazard, vulnerability, and exposure will help to identity and select solutions, including policy instruments, for risk reduction (i.e., step 5). Considering the different concepts aims to provide a broader perspective that considers the current conditions shaping the complex system, and how it will be developed into the future, to suggest solutions that not only reduces the flood depth or the probability of flooding, but also reducing their societal consequences.

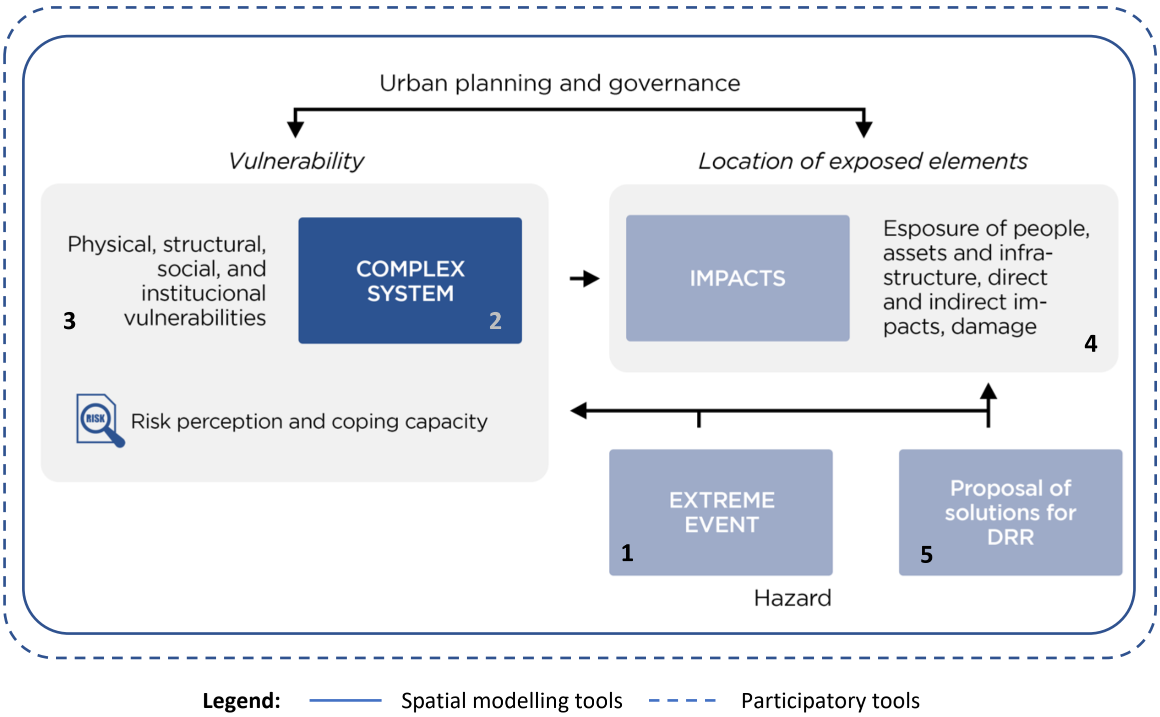


Figure 2.12 – Summary of the recommendations identified in the literature. The recommendations represent an integration of concepts of hazard, vulnerability, and exposure for Flood Risk Reduction (FRR) through the combination of spatial and participatory tools.

Recommendation 3: The combination of spatial and participatory approaches for FRR

The intrinsic characteristics of risk suggest there are two main standpoints of approaches for proposing solutions for FRR in an environment, the spatial and social aspects. The literature provided a review of a range of studies that developed and applied spatial and modelling tools for analysing the multiple benefits of solutions (i.e., section 2.5). Some of them involve selecting and preparing indicators in a GIS-MCDA approach, choosing appropriate hydraulic software for assessing flood hazard reduction, or acquiring data with quality for analysis and model validation (Malczewski, 1996).

In this regard, municipalities face many challenges for applying proposals in terms of modelling risk and assessing benefits (Dawson *et al.*, 2020; Eriksen *et al.*, 2021; Kuller *et al.*, 2019; Morgan *et al.*, 2019; Vercruysse *et al.*, 2019), especially when analysing not only the environmental but also social and economic benefits. Similarly, the inclusion of social conditions can be very challenging from the modelling perspective, which makes critical to involve stakeholders in the proposal as an attempt to include their perspectives in proposals (Di Baldassarre *et al.*, 2019; Lück *et al.*, 2017; Nesshover *et al.*, 2017; Renn, 2004; Šakić Trogrlić *et al.*, 2017).

The literature review provided a range of research examples that developed participatory projects; however, it was showed how the number of studies that effectively applied participation is still very low in water research, in both broader and Brazilian contexts (Ashley *et al.*, 2020; Bissonnette *et al.*, 2018; Cheung *et al.*, 2019; Cinner *et al.*, 2018; Coaffee *et al.*, 2018).

Therefore, this thesis suggests that an effective combination of GIS-based tools and participatory approaches can positively impact the proposal of sustainable solutions, with the inclusion of the current conditions that shape the *"complex system"* (Figure 2.12). However, as highlighted beforehand, not all participatory and GIS models are possible for all environments, because of available data, physical environments, social conditions, research challenges, between other factors. In this sense, while combining the spatial and participatory tools, this research also aims to show how the tools were applied in the study case, as well as showing how the limitations were considered, and how changes could be applied for the methodology for its application in other study cases.

CHAPTER 3
Materials and Methods

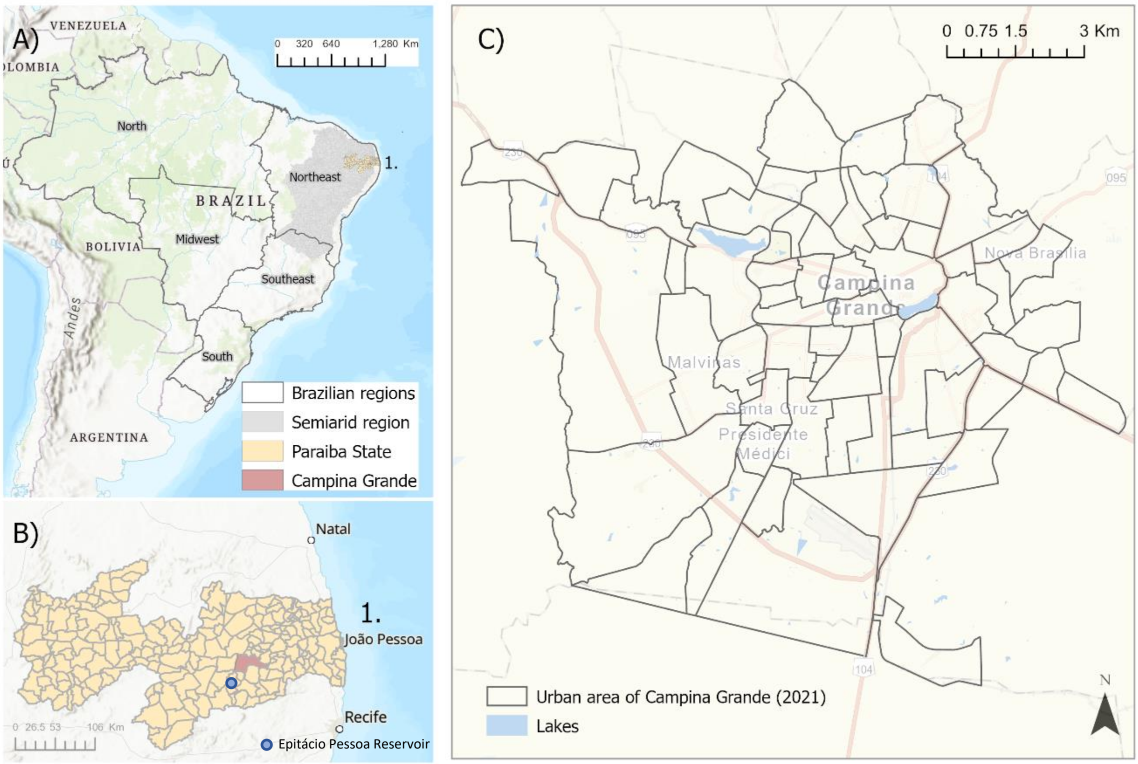
Chapter 3 focuses on presenting aspects of the study case and the methodology used in this research. Due to the style of this thesis, some information may be repeated in the chapters 4, 5, 6 and 7.

Chapter 3 - Materials and Methods

3.1 Study case

3.1.1 Climate, urbanisation, and disasters

The city of Campina Grande is the study case of this thesis. The municipality is in the Northeast region of Brazil (i.e., the semiarid region in Figure 3.1a), and as seen in section 2.4.2, the climate poses many challenges with water availability and water shortage periods in the region (ANA, 2017; Cunha *et al.*, 2015; Del Grande *et al.*, 2016b). Campina Grande is the second largest city of Paraiba State (Figure 3.1b) (IBGE, 2021).



Esri, FAO, NOAA, Esri, HERE, Garmin, METI/NASA, USGS, Esri, HERE, Garmin, FAO, NOAA, USGS, Esri, USGS

Figure 3.1 - Location of Campina Grande: a) Brazilian Northeast and Semiarid region, b) Paraiba state, c) Urban area of the city.

The most recent census data shows the city had 385,212 inhabitants in 2010 (IBGE, 2010). From 1991 to 2010, the urban population increased more than 20%, representing many changes, such as an increase of paved and asphalted streets, residential and commercial areas, and buildings (IBGE 2000, 2010). A new Brazilian census was due to be released in 2020; however, because of the Sar2-Cov-2 pandemic and the nature of collection surveys, the new census was postponed for 2022. In this regard, the IBGE only estimates the population of Campina Grande in 2021, being approximately 410,332 residents in 594,182 km² of territorial area (IBGE, 2021).

The lack of more recent information difficult the indication of places with new interventions in the built environment; however, data made available by the Campina Grande City Council (PMCG) shows that more neighbourhoods were included in the peripheries of the urban area in the last years. Figure 3.2 shows the changes on Campina Grande's urban area in the last years.

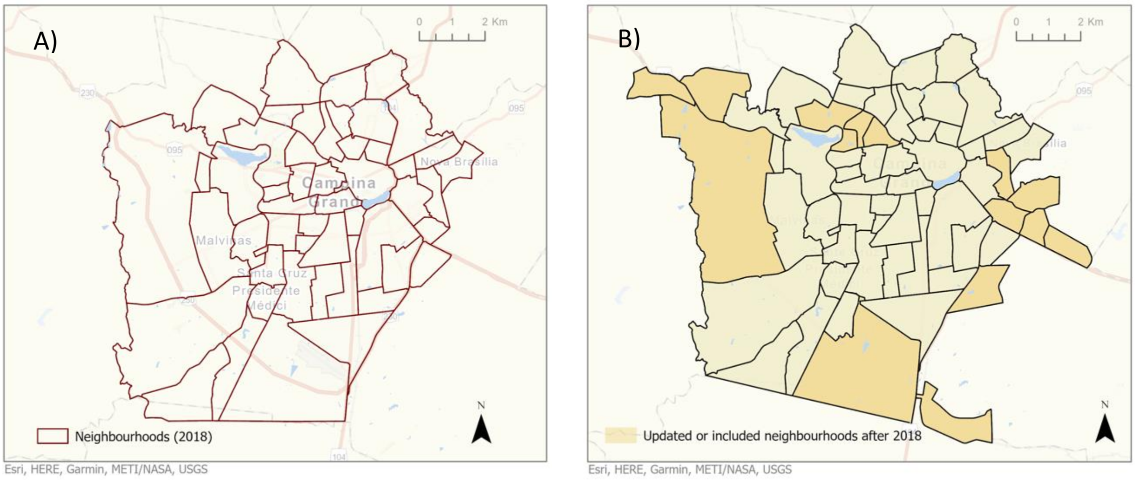


Figure 3.2 – Urban growth of Campina Grande: a) Neighbourhoods in 2018, and b) Neighbourhoods in 2021. Data from the Campina Grande City Council (PMCG)

The only water supply of Campina Grande is a surface reservoir named as *"Epitácio Pessoa" (i.e., known popularly as Boqueirão reservoir*) with a maximum capacity of 466,52 million m^3 and a surface area of 2,678.0 ha (AESA, 2019). The Epitácio Pessoa reservoir is located in the hydrographic basin of the Paraíba River, approximately 40 km from Campina Grande (Figure 3.1b). The reservoir plays a unique role in the local and state economies, especially for supplying Campina Grande, and 26 other surrounding locations, serving a total of more than half a million people.

The residents of Campina Grande face a dual water-related disasters context, water shortage (WSR) and pluvial flooding risks (FR). According to the National Water and Sanitation Agency (ANA), the Northeast region is the only in Brazil with arid desert and arid steppe (BWh and BSh from Köppen-Geiger Climate). To characterise the average precipitation in the urban area of Campina Grande, Figure 3.3a was prepared with rainfall data from 2000 to 2020.

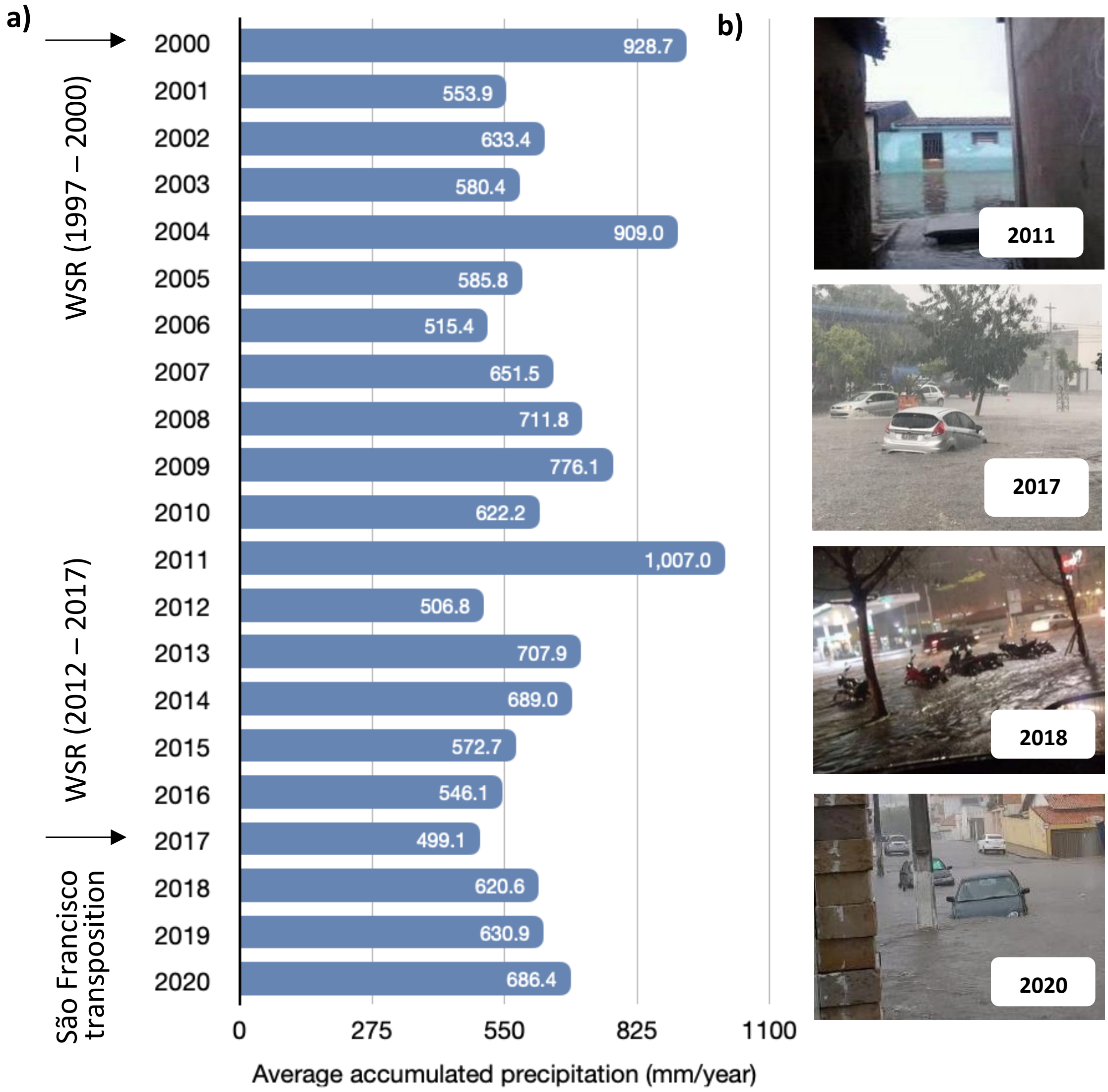


Figure 3.3 – a) Average accumulated precipitation data of Campina Grande from 2000 to 2020 (CHIRPS database). The indication of water shortage years is based on previous findings and reports (ANA, 2020; Cordão *et al.*, 2020; Del Grande *et al.*, 2016b; Rêgo *et al.*, 2017). b) Photos of flood cases in the city in different years.

The rainfall was calculated with the average sum of the rain in 5mx5m pixels of the urban area with the Climate Hazards Centre InfraRed Precipitation with Station (CHIRPS) dataset (Figure 3.3a). The average rainfall obtained with CHIRPS datasets is 663 mm per year, with a minimum of 506.8mm in 2012 and a maximum of 1007 mm in 2011 (Figure 3.3a).

The last two WSR periods in Campina Grande, from 1997 to 2000 and from 2012 to 2017 are indicated in Figure 3.3a (Del Grande *et al.*, 2016b; Rêgo *et al.*, 2017). From 2012 to 2017, residents experienced a severe water deficit with more than five days per week with no drinking water available (Rêgo *et al.*, 2017). The Water and Sanitation National Agency (ANA) and the Executive Agency of Water Management of Paraíba state (AESA) consider this period was the worst drought period in the last 50 years in the region (ANA, 2020), with the critical period from 2015 to 2017 (Cordão *et al.*, 2020). In 2017, the Epitácio Pessoa reservoir had only 5% of volume (AESA). In the same year, the transposition of the São Francisco River was concluded to the Paraíba River, which increased the surface volume of the Epitácio Pessoa reservoir and improved the supply for Campina Grande and the other neighbouring cities (Figure 3.3a). However, water researchers agree that this diversion will not solve water scarcity issues permanently if there is no improvement in the management (Cordão *et al.*, 2020; Grangeiro *et al.*, 2019; Rêgo *et al.*, 2017), especially because of the challenges posed by the arid climate (Figure 3.3a).

Despite the water supply issues, Campina Grande is also susceptible to pluvial flood risk (Alves *et al.*, 2018b; Santos *et al.*, 2017c; Sasaki *et al.*, 2021). The combination of population growth and interventions in the built environment impacted Campina Grande, especially increasing soil imperviousness and, consequently, surface runoff volume (Alves *et al.*, 2018b; Santos *et al.*, 2017c). In this context, studies have been focused on investigating pluvial flooding in the city (Alves *et al.*, 2018b; Nobrega, 2012; Santos *et al.*, 2017c). According to the municipal Civil Defence of the city (i.e., the sector responsible for supporting the communities at risk of disasters), the years 2000, 2004, 2008 and 2011 are known as four of the rainiest years in the last two decades (Figure 3.3).

To exemplify some of the pluvial flooding cases, photos gathered in the media and provided by the residents of Campina Grande were organised in a timeline to show that flooding does not occur only in wetter but also in dryer years (Figure 3.3b).

3.1.2 Flood risk and management

On the national scale, flood risk cases of Campina Grande are being monitored by the National Centre for Monitoring and Alert of Natural Disasters (CEMADEN, Ministry of Science, Technology, and Innovation), and the Geological Survey of Brazil (CPRM, Ministry of Mining and Energy of Brazil). In 2013, the CPRM visited the city, which mapped eleven areas at risk of floods and landslides in Campina Grande (Figure 3.4). Ten of the eleven areas were categorised as “potential” locations for flooding, indicated as susceptible zones with poor drainage systems, households located in the floodplain, high volume of garbage in the drainage system, and leakages in the sewage network.

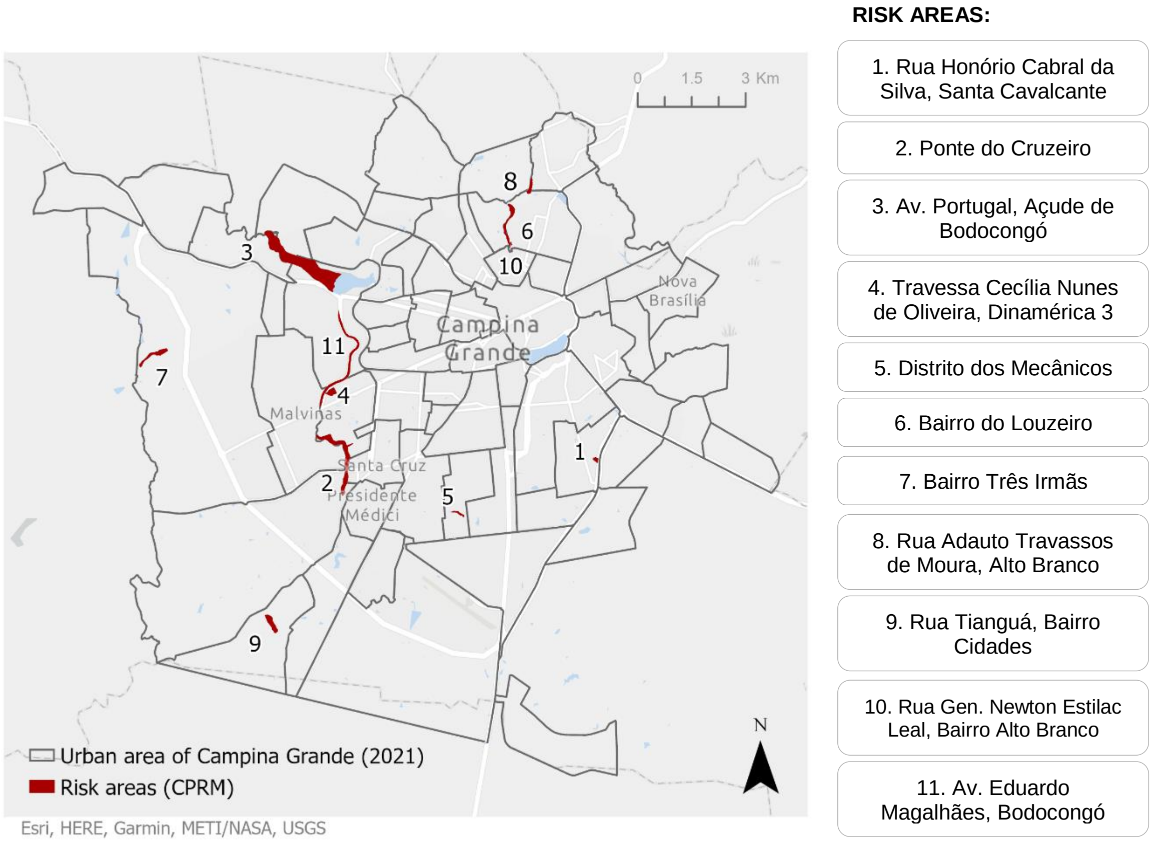


Figure 3.4 – The mapping of flood (and landslides) risk areas in Campina Grande according to CPRM. The boxes on the right describe the address of each risk area (1 – 11).

When analysing the current legislation of the municipality, according to the Brazilian National Policy of Civil Protection and Defence (12.608/2012), it is the duty of the union, states, federal district, and municipalities to adopt the necessary measures to reduce risk from disasters. At the local scale, civil defense and firefighting officers must support residents in case of flooding, including implementing early warning systems. The legislation 12.608/2012 also asks for states and municipalities to identify threats, susceptibilities, and vulnerabilities to disasters on the local scale. However, the national context indicates that many cities are not supported with such information (Londe *et al.*, 2015; Marchezini *et al.*, 2017; Young *et al.*, 2020; Young *et al.*, 2019), including Campina Grande

(Nobrega, 2012). In addition, the PMCG does not provide a municipal Drainage Plan for offering guidance to the management and mitigation of stormwater and flooding in the city (Alves *et al.*, 2018b; Miranda, 2017). Up to the writing of this thesis, neither the city council of Campina Grande nor the municipal Civil Defence has developed official and detailed mappings of flood-prone areas and most flood vulnerable regions of the city.

The decree Nº. 7.217/2010 (BRASIL, 2010) that regulates the legislation Nº. 11.445/2007 of Basic Sanitation in Brazil establishes that, as with other public sanitation services, drainage management must have an exclusive and independent infrastructure and must be carried out in a manner that is adequate for health and environmental protection in the cities. However, it is very common to see the release of sanitary sewage into drainage channels in many Brazilian cities (de Macedo *et al.*, 2019; McClymont *et al.*, 2020; Rosa *et al.*, 2020), including in Campina Grande (Camelo *et al.*, 2020). For Camelo *et al.* (2020), such releases compromise the quality of rainwaters in the drainage channels, generating a risk to the population's health and serious environmental impacts when in case of flooding. The legislation N° 11.445/2012 also asks for the elaboration of a Sanitation Plan to all municipalities with more than 100,000 inhabitants (BRASIL, 2010). The plan covers the development of the diagnosis and prognosis of the four components of the sanitation in the city, including water supply, wastewater, drainage, and solid waste. Even though the Sanitation Plan of Campina Grande was developed and finalised in 2015, until the writing of this thesis it has not been approved as a law yet.

Additionally, Brazil's National Federal Water Law (Nº 9.433/1997) and the Sanitation Law (Nº 11.445/2012) suggest approaching water resources with integrated and participative management. Current researchers discuss how Brazil is striving to apply these approaches, with issues from national to local scales (Libanio, 2018; Marchezini *et al.*, 2017). Recent studies highlight the integrated and participative management as barriers to managing water resources in Campina Grande (Grangeiro *et al.*, 2019; Miranda, 2017; Rêgo *et al.*, 2017).

In this context, the reasons for selecting Campina Grande as the study case of this thesis are summarised as:

(i) The city represents middle-sized municipalities with more than 400,000 inhabitants in developing countries facing urban growth.
(ii) The city has contrasting water-related hazards susceptibility, flooding, and water shortage, which poses complex challenges for their integration in management.
(iii) The city council does not have flooding (hazard) or vulnerability mappings to guide decision-making.
(iv) Pluvial flooding occurs at many locations in the city, not only restricted to the national delimitation of flood areas, which can indicate the insufficiency of mapping and that residents may be affected differently.
(v) The city should have a separator system of drainage and sewage, but the release of sewage can be observed into many of the drainage channels in the urban area, which suggests a unique drainage system.
(vi) The city has management and legislation issues, like the lack of public policies and public participation in water policies, which can create challenges in the institutional context.
(vii) Personal previous experiences with pluvial flooding in the city, including knowledge and access to policymakers for developing the engagement strategies.

Due to the style of this thesis, chapters 4, 5, 6, and 7 will also provide short summaries of the case study. In each chapter, the objective was to present new information about the city; however, it is acknowledged that some information may be repeated.

3.2 Methodology

3.2.1 Worldview

As the risk of disasters takes place in a geographical area, which can have the presence of people living in a certain built environment, the effects (i.e., impacts) of disasters are subject to multiple conditions. A combination of physical, anthropogenic, and institutional aspects acts as "pre-existing context conditions" that will form the context when the risk occur in an area. Disasters' impact will be a function of all contributing factors (i.e., hazard, vulnerability, and exposure) whether they arise from the hazard, the exposure, or the vulnerability, and regardless of whether the contributing factors are extreme (de Brito *et al.*, 2018; Leonard *et al.*, 2013; Scolobig *et al.*, 2017). The contributing factors have diverse intensities and are "interconnected" but are also differently distributed in the territory (de Brito *et al.*, 2018; Leonard *et al.*, 2013; Scolobig *et al.*, 2017). The "multiple" characteristics of a "complex system" (Figure 2.12) will have similarities and differences in both spatial and temporal scales, which makes imperative to fully analyse the area in which the disaster takes place (IPCC, 2014).

In this regard, as shown in section 2.5, this study considers the "complex system" as a geographical area characterised by various spatial attributes that form its own conditions when the risk takes place. On one hand, context-specific conditions can form the "vulnerabilities" present in this specific setting, defined as *the "inherent characteristics of the place that create the potential to harm"* (Cutter *et al.*, 2008). As shown in Section 2.2.2, the vulnerability will manifest itself in a series of categories that do not develop independently but interact on different time and space scales (Pescaroli *et al.*, 2019). In this regard, the combination of "pre-existing context-specific conditions" can also increase or decrease the vulnerability to a specific disaster risk (Cutter *et al.*, 2008; Frigerio *et al.*, 2016a; Norton *et al.*, 2015), which makes essential to understand the "context-specific conditions" as well "disasters' contributing factors", and their interactions, for addressing vulnerability and therefore risk mitigation.

On the other hand, although context specificities should be considered for suggesting actions and solutions for the DRR, it's possible to see a strong disconnection between strategies for risk reduction and the "context" when evaluating DRR approaches. This disconnection can lead to the suggestion of solutions that in fact amplify the risk and thus lead to disaster risk creation. Schipper (2020) suggest that poorly designed strategies can result in "*maladaptation"*, where exposure and sensitivity to climate change impacts are instead increased because of the actions taken. Therefore, "*maladaptation"* and vulnerability are intrinsic related. The "root-causes" of vulnerability can contribute to systemic inequalities, similarly as socio-economic factors such as poverty, gender, ethnicity, income and race can create conditions to turn into a disastrous risk event for those who are placed into these categories (Schipper, 2020; Hendricks *et al.* 2021), being fundamental to properly understand what are the factors that make a community more or less vulnerable to risk, and how *actions* can be adapted to reduce the risk of these communities.

For example, the manner that policymakers act towards risk mitigation, governance structure, and legislations in charge will dynamically change the built environment, including the risk conditions of poor and slum areas (Ajibade *et al.*, 2014; McMartin *et al.*, 2018; Mell, 2017; Young *et al.*, 2019). In this sense, the proposal of solutions for risk reduction should address not only the occurrence of the hazard itself but also tackle the reduction of vulnerability and exposure, with regards to the current governance and urban planning legislation and how local actors perceive and act towards FRR (Klijn *et al.*, 2015; UNDRR, 2019).

However, the disaster risk, and in the case of this thesis the FR, will only be generated if the extreme event (i.e., hazard) takes place in a vulnerable area with the exposition of a community, infrastructure, and/or assets (IPCC, 2014; UNDRR, 2019). Because of this, it is also argued that both system's vulnerable attributes and exposed elements are directly related to a specific event; hence they are called "hazard-specific components" (Sharma *et al.*, 2019). Their relationship shows an anticipatory state or "pre-existing state" concerning the hazard (Cutter *et al.*, 2008). Along with the hazard occurrence, both vulnerability and exposure will produce impacts, which can be increased or decreased by implementing solutions for DRR. Practically, this means that vulnerability and exposure are related to the hazard itself (Klijn *et al.*, 2015; Sharma *et al.*, 2019; UNDRR, 2019).

For example, due to the dual water-related hazards character of Campina Grande, the impacts of pluvial flooding and water shortage will be influenced by different vulnerabilities and social factors (i.e., the disposal of garbage in the streets may not directly influence the water shortage but are extremely important to flooding, as well it can affect people differently according to their social conditions). Similarly, communities can be exposed but not entirely vulnerable to flood if they are in a flooded area but have sufficient means to modify buildings structures and behaviour to mitigate potential loss (IPCC, 2012). Hence, the understanding of the complex system asks for the integration of all systems that may affect disasters mitigation, resilience, and adaptability, such as a better inclusion of social and environmental conditions, and how the community in risk perceive and cope with hazards (Ajibade *et al.*, 2014; Bryan *et al.*, 2009; Bryan *et al.*, 2019; Fuchs *et al.*, 2017; Liu *et al.*, 2018a; Nguimalet, 2018).

The suggestion of "*actions* and *solutions"* for risk mitigation is called to be "multiple" and not only "single" oriented (Figure 3.5). This is adapted from the work of Scolobig *et al.* (2017) and Ruangpan *et al.* (2020)*,* in which governance and mitigation solutions are called to provide multiple objectives, not only reducing the environmental aspects, and beyond of only comprehending the technical understanding of strategies (Schipper, 2020; Schipper *et al.*, 2021)*.*

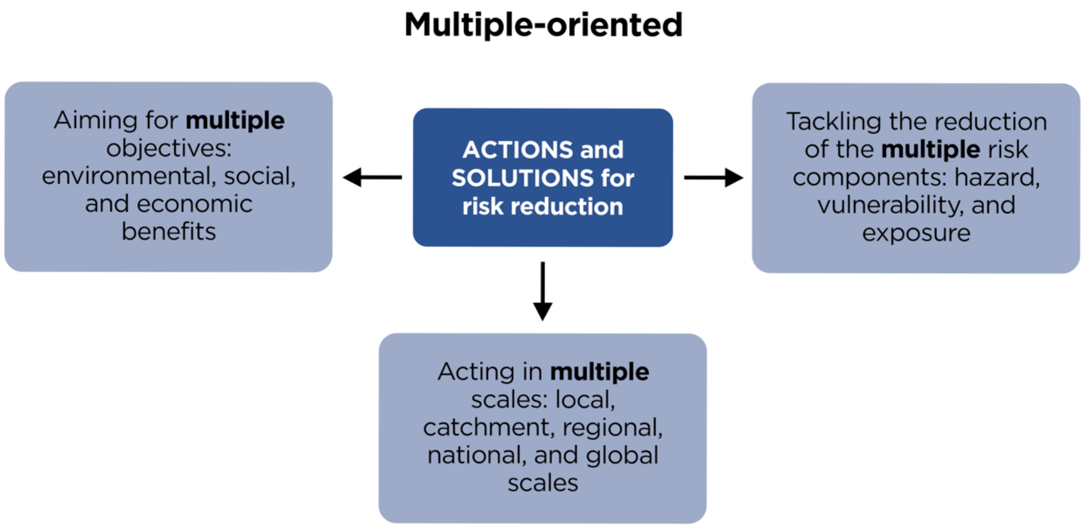


Figure 3.5 – The "multiple-oriented" actions and solutions for risk reduction: (i) solutions for multiple objectives, (ii) solutions for reducing multiple risk components, (iii) solutions acting in multiple scales.

Finally, there is also a need to examining the trade-offs (i.e., positive, and negative impacts) and synergies of solutions to the risk components. That is, the possibility of solutions in creating more (or less) vulnerabilities and exposure, for example. As shown in the literature review, designing actions for FRM will require (1) a better understanding of the conditions that influence the social and environmental aspects of risk (Kumar *et al.*, 2020; Shah *et al.*, 2020), (2) the assessment of vulnerability and exposure (Sharma *et al.*, 2019), and (3) how inequalities and social justice affects and is affected by efforts to build capacity, as an attempt to avoiding unintended outcomes (Cinner *et al.*, 2018). "*Actions* and *solutions"* can target the reduction of the impacts of the risk components, but many adaptation projects are contributing to increased vulnerability, due in part to poor understandings of local contexts where projects are being implemented. Lastly, *actions* and *solutions* should also act in multiple scales (Figure 3.5), from local to larger scales (Eckart *et al.* 2017), with a careful consideration of various factors and local contexts.

In summary, "*actions and solutions"* for risk reduction should incorporate:

(i) The pre-existing and hazard-specific attributes and factors that when combined generate the pre-state context before the hazard take place (Cutter *et al.*, 2008; Norris *et al.*, 2008; Sharma *et al.*, 2019),

(ii) The perception, decisions, and behaviours of local actors, especially policymakers and communities at risk, enables the understanding of existing vulnerabilities (Bryan *et al.*, 2019; Cutter *et al.*, 2008; Fuchs *et al.*, 2017),

(iii) The manner in which urban planning and governance are organised, the conditions of the built environment, and how policymakers act towards risk mitigation are essential for formulating and proposing appropriate solutions for DRR (López-Martínez *et al.*, 2019; Marchezini *et al.*, 2017; Mell, 2017),

(iv) The spatial distribution and patterns of the risk components, since the disaster risk is the result of the interaction of hazard, vulnerability, and exposure (i.e., chapter 2). The spatial understanding of risk can facilitate outlining the manner in which impacts can be reduced (Ward *et al.* 2020).

(v) "Multiple-oriented" characteristics: aiming for acquiring social, economic and environmental benefits (Ruangpan *et al.* 2020), as well as the reduction of the risk components (i.e., hazard, vulnerability and exposure), considering the inherent aspects of places, in multiple scales, and if and how the strategies provide multiple benefits for society (Dagenais *et al.*, 2016; Eckart *et al.*, 2017; Klijn *et al.*, 2015; O'Donnell *et al.*, 2018).

3.2.2 The integrated spatial-participatory framework

From the assumption that disasters are rooted in social and environmental aspects (Fuchs *et al.*, 2017; Fuchs *et al.*, 2011; Kunapo *et al.*, 2018; Lund, 2015), the detailed framework of this study is based mainly in three principles and goals (described in the Figure 3.6a). The first principle refers to assessing the context before any solutions are undertaken (Climent-Gil *et al.*, 2018). Principle A encompass the three "recommendations of focus" discussed in chapter 2 (i.e., details are seen in Section 2.5 of chapter 2). To comprehend the context-specific conditions, it is proposed to understand current levels of vulnerability and exposure in spatial and social scales at the complex system.

Principle A highlights that social and institutional vulnerabilities, including perception and attitudes of stakeholders, are crucial for reducing flood risk (Baruch *et al.*, 2016; Cinner *et al.*, 2018; Lechowska, 2018; Parker *et al.*, 2019; Pescaroli *et al.*, 2019; Sharma *et al.*, 2019). The principle refers to findings of McMartin *et al.* (2018), which discusses how the adoption of new environmental solutions is subject to social and institutional factors that can enhance and/or constrain the capacity of communities (i.e., the "planned adaptation") during the disaster. Understanding the context allows the assessment of what are the societal challenges and *needs* of the population, including constraints generated by the governance and urban planning in the development of local knowledge and current infrastructure (Albert *et al.*, 2020; Ashley *et al.*, 2020; Ashley *et al.*, 2018; O'Donnell *et al.*, 2018; Wright *et al.*, 2020).

Principle B refers to the characterisation of areas in *need* of changes (i.e., areas that face DR and need the implementation of solutions) before the proposal of actions and strategies (Caldas *et al.*, 2018; Climent-Gil *et al.*, 2018; McMartin *et al.*, 2018) (Figure 3.6). Principle B highlights the importance of evaluating the places with more susceptibility of hazard, vulnerability, and exposure, and what aspects increases flood vulnerability (Birkmann, 2007; Ciullo *et al.*, 2017; Cutter *et al.*, 2008; Cutter *et al.*, 2003; Dagenais *et al.*, 2016; de Loyola Hummell *et al.*, 2016; Frigerio *et al.*, 2016a; Hazarika *et al.*, 2018; Nguimalet, 2018) for subsequently defining the solutions to be applied (Climent-Gil *et al.*, 2018; Hong *et al.*, 2018). Principle B also objective to accomplish the three recommendations discussed in Section 2.5.

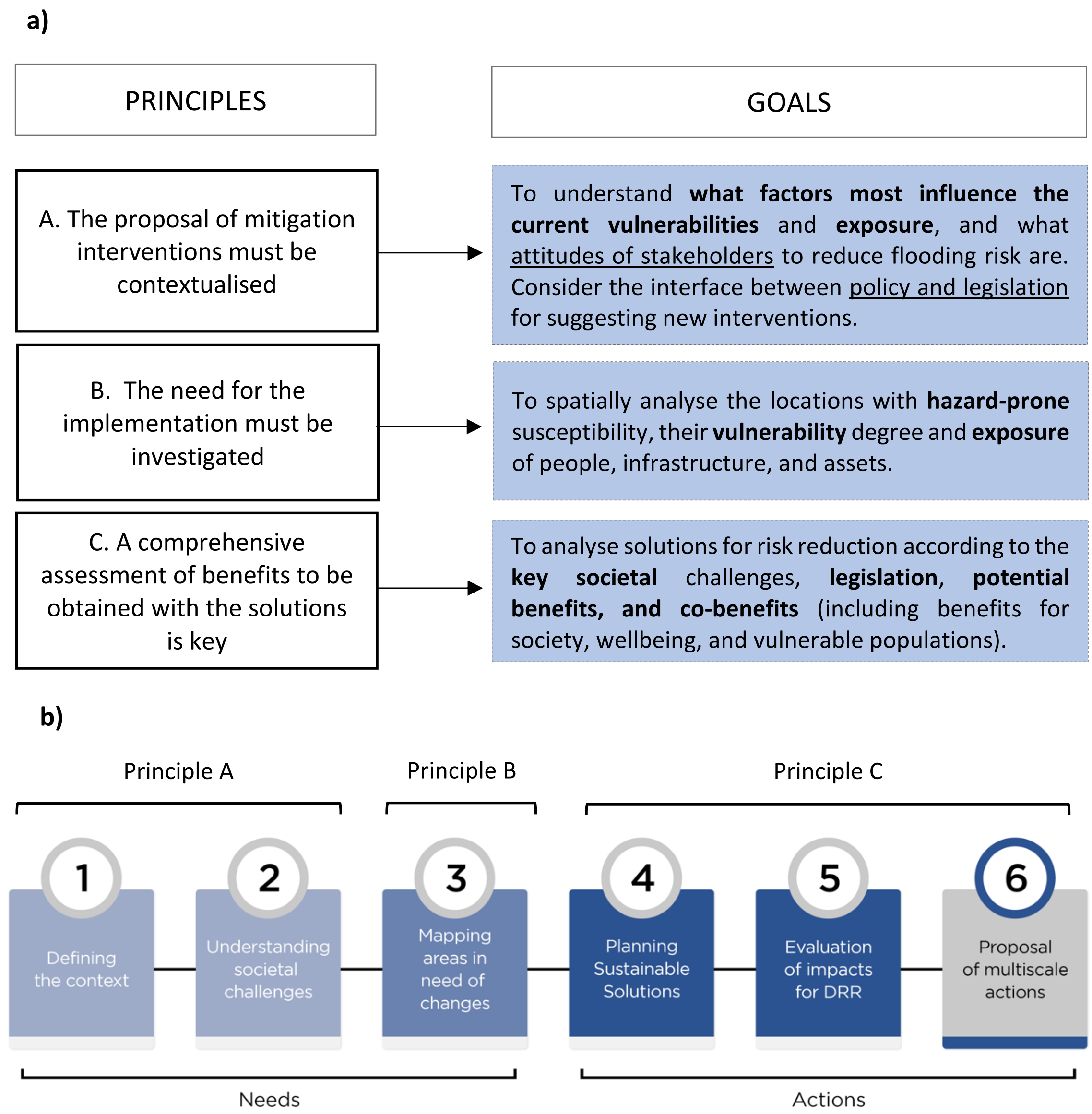


Figure 3.6 – a) Principles A, B, and C for building the spatial-participatory framework, b) Summary of the integrated spatial-participative framework. Phases cover the definition of the context and societal challenges (P1 and P2), mappings of hazard, vulnerability, and exposure (P3), the placement of solutions (P4), the evaluation of impacts and benefits (P5) and the proposal of actions for risk reduction (P6). Phases 1 to 6 are shown with the integration with the principles A, B and C.

Lastly, principle C considers that developing a comprehensive assessment of potential benefits is crucial for proposing solutions (Ashley *et al.*, 2020; Ashley *et al.*, 2018; Dawson *et al.*, 2020; Grace *et al.*, 2021; La Rosa *et al.*, 2020; Pappalardo *et al.*, 2017; Vercruysse *et al.*, 2019; Wright *et al.*, 2020). Traditionally, the selection of solutions to reduce FR is based on economic efficiency and suitability for local conditions but focusing mainly on traditional grey infrastructure (Alves *et al.*, 2018a). However, the pursuit for sustainability and resilience shows this process needs to incorporate other elements such as the provision of social, environmental, and economic benefits with a holistic approach (Alves *et al.*, 2019; Alves *et al.*, 2018a; Debele *et al.*, 2019; Eriksen *et al.*, 2021; Jarvie *et al.*, 2017; Kumar *et al.*, 2020; Liquete *et al.*, 2016). In this sense, the final principle considers that interventions must be suggested according to the societal challenges of the study area, considering the provision of benefits and co-benefits and the integration with urban planning. After formulating principles A, B, and C (Figure 3.6a), the steps of the spatial-participatory framework were articulated aiming for flood risk mitigation based on the study case of Campina Grande, Brazil (Figure 3.6b). Figure 3.6b aims to indicate the spatial-participatory phases, and their relationship with the principles discussed in Figure 3.6a.

The detailed spatial-participatory framework is shown in Figure 3.7. The framework was developed based on the current conditions of the study case, aiming to exemplify the conditions of vulnerable cities located in developing countries around the globe. Phases 1 to 6 were divided according to the definition of two main groups (i.e., the *NEEDs* and *ACTIONs*), which was built to replicate the primary assumption of this thesis (i.e., section 1.2). Phases 1 to 3 refer to the understanding of the *needs* of the area, especially the social and spatial contexts, while phases 4 to 6 focus on the analysis and proposal of sustainable solutions (i.e., *actions*). The integrated spatial-participatory framework (NEEDS for ACTION) was built with different methods summarised in Table 3.1.

Table 3.1 – Summary of methods applied in each phase of the spatial-participatory framework (i.e., NEEDS for ACTION). The reference of each chapter is also included.

	Phases	Description of methods	Chapter
NEEDS	Phase 1 (P1)	- Participatory tools: Surveys, workshop, focus groups (phase 1) - GIS tools: ArcGIS Pro (ESRI) - Statistics methods: Pearson correlation, Wilcoxon Z and Mann Whitney U test	Chapter 4
	Phase 2 (P2)	- Participatory tools: Surveys, workshop, focus groups (phase 1) - Statistics methods: Pearson correlation, Wilcoxon Z and Mann Whitney U test	Chapter 4
	Phase 3 (P3)	- Participatory tools: Surveys, workshop, focus groups (phases 1 and 2) - GIS tools: ArcGIS Pro (ESRI) - Statistics methods: Pearson Correlation	Chapter 5
ACTION	Phase 4 (P4)	- Participatory tools: Surveys, workshop, focus groups (phases 1 and 2) - Legislation analysis: Historical policy analysis - GIS tools: ArcGIS Pro (ESRI) - Hydraulic software: Stormwater Management Model (SWMM) (US EPA) and Cellular Automata Dual-DrainagE Simulation (CADDIES) (University of Exeter)	Chapter 6 and 7
	Phase 5 (P5)	- Participatory tools: Surveys, workshop, focus groups (phases 1 and 2) - GIS tools: ArcGIS Pro (ESRI) - Hydraulic software: Stormwater Management Model (SWMM) (US EPA) and Cellular Automata Dual-DrainagE Simulation (CADDIES) (University of Exeter)	Chapter 6 and 7
	Phase 6 (P6)	- Summary of phases 2, 3, 4 and 5	Chapter 4 to 7

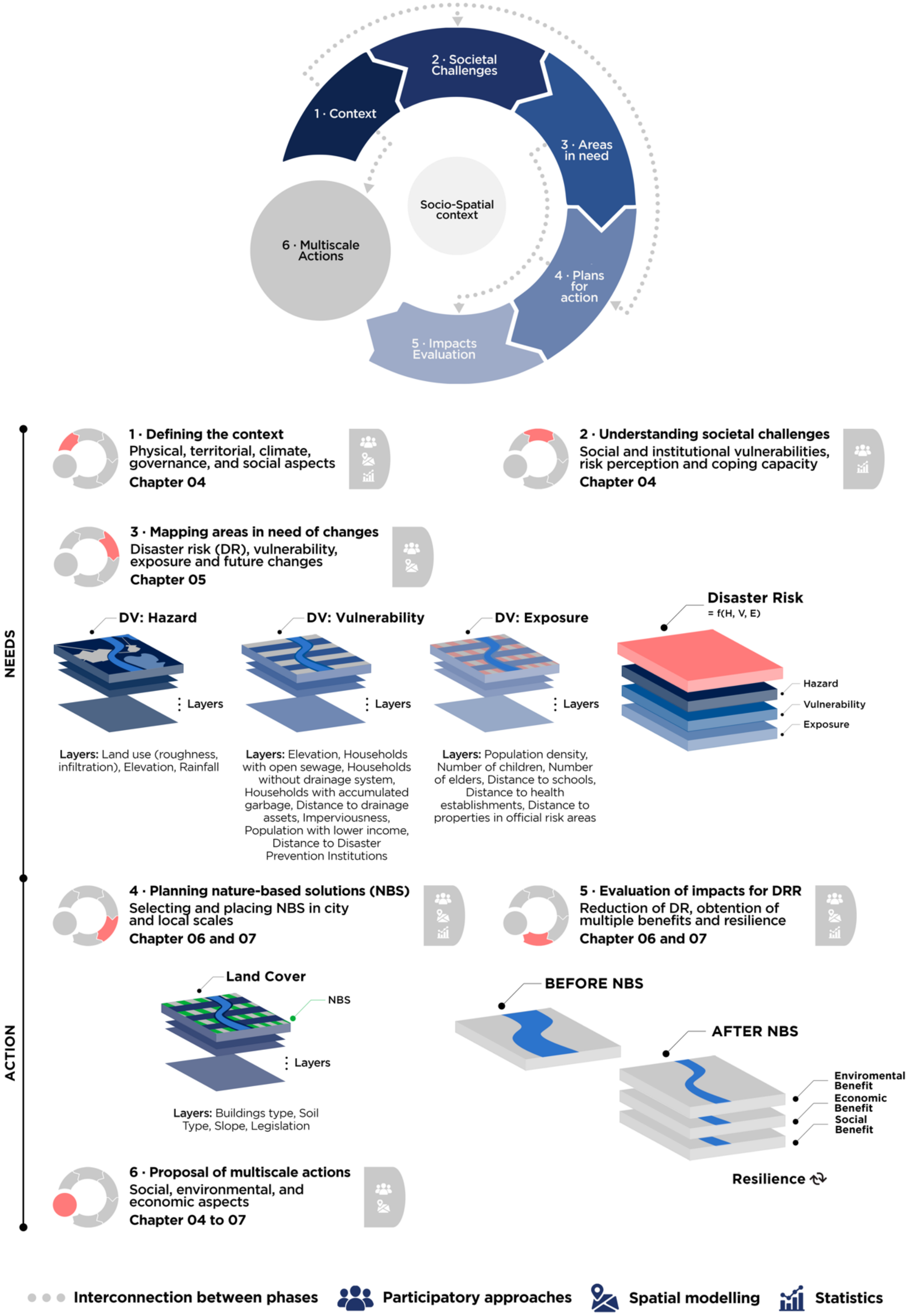


Figure 3.7 – The detailed spatial-participatory framework. The framework is based on the definition of the NEEDs (P1 to P3) for proposing ACTIONs (P4 to P6). P1 and P2 establishes the social context, and P3 to P5 analyse the socio-spatial context with spatial-participatory tools. Actions and solutions for FRR are summarised in P6.

Because of the style of this thesis, the methodological steps of the framework are separately detailed in chapters 4, 5, 6, and 7. In this section, only a summary of each phase is provided.

3.2.2.1 Phases 1 and 2: The context and societal challenges of the city

The main outcomes of phases 1 (P1) and 2 (P2) are to understand the current levels of vulnerability and exposure, and stakeholders' perceptions and attitudes to reduce flooding risk. Considering that governance and urban planning are closely merged (Albert *et al.*, 2020), P1 and P2 are linked, highlighting that local actors' context, legislation, perception, and behaviours should be integrated and comprehended for suggesting new interventions (e.g., goals in Figure 3.6). P1 and P2 are described in detail in chapter 4.

Since the disasters are extreme events (i.e., hazards) and their social consequence (Norris *et al.*, 2008; Pescaroli *et al.*, 2019), P1 and P2 gathered information from the participatory approach to define what are the key societal challenges faced by the population of Campina Grande, Brazil. Chapter 4 provides details about the formulation of the mixed-methods approach, with subjective and objective methods, with stakeholders of the Campina Grande, through the Project PLANEJEEE (To Plan Extreme Events).

The project was formulated to enable the participation of residents, policymakers, and local specialists of the city, considering "disasters risks" as an inherently social phenomenon, which can be better understood in the context of social change (Almoradie *et al.*, 2020; Cutter *et al.*, 2008; Danso *et al.*, 2016; Mondino *et al.*, 2020). The approach had five main objectives:

a) To promote collaboration opportunities with the different stakeholders for discussing the challenges and solutions of flood risk management,
b) To support stakeholders' communication and sharing about their previous experiences with flooding in the city,
c) To discuss possible sources of flood vulnerabilities and exposure, and flood causations in the city with the different stakeholders,
d) To investigate what are the solutions preferred by the different stakeholders, and
e) To obtain official datasets from the authorities in charge of flood risk management.

As seen in Figure 3.7, P1 and P2 focus on defining the NEEDS of the studied area. The "context" and "societal challenges" are expressed with the understanding of social and institutional vulnerabilities, risk perception and coping capacities of residents located in risk areas (i.e., chapter 4). All methods and datasets used for the development of P1 and P2 are shown in Table 3.1 and 3.2. Detailed approaches developed for P1 and P2 are seen in chapter 4.

Table 3.2 – Summary of datasets, their description, source, and type, for each phase of the spatial-participatory framework.

Phases*	Data source	Description	Data type
P1 to P6	Surveys for residents	Socio-economic, informational, geographical, and contextual factors, risk perception (awareness, worry, preparedness, and knowledge), coping capacity (responsiveness, adaptive measures, permanent measures). Flood causation, perceived effectiveness of solutions to flood and water shortage risk reduction	Yes/no, Likert scale (1 to 5), open questions
P1 to P6	Surveys and workshop (authorities, specialists)	Issues with flood risk management, flood risk legislation, and current vulnerabilities. Flood causation, solutions for flood risk mitigation	Yes/no, Likert scale (1 to 5) or open questions, discussion in the focus groups
P4, P5, P6	Surveys and workshop (authorities, specialists)	Preferred Nature-Based Solutions for Campina Grande, NBS‘ benefits preferences	Yes/no, Likert scale (1 to 5) or open questions, discussion in the focus groups
P1, P2, P4, P5	Legislation	Historical evaluation of current policy instruments	Written reports and laws
P1 to P6	CPRM (2013)	Official mapping of flood-prone areas of Campina Grande	Polygon shapefile
P1 to P6	Tsuyuguchi (2015)	Elevation of Campina Grande (Brazil)	Raster
P1, P2, P3	Census (IBGE, 2010)	Census blocks with presence of garbage	Polygon shapefile
P1, P2, P3	Census (IBGE, 2010)	Census blocks without the presence of drainage system	Polygon shapefile
P1, P2, P3	Census (IBGE, 2010)	Population density	Polygon shapefile
P1, P2, P3	Census (IBGE, 2010)	Number of elders and children	Polygon shapefile
P1, P2	Census (IBGE, 2010)	Location of wells	Point shapefile
P1, P2	Census (IBGE, 2010)	Rainwater harvesting	Polygon shapefile
P1, P2	Census (IBGE, 2010)	Census blocks with water supply	Polygon shapefile
P1, P2, P3, P5	City council (2014)	Imperviousness	Polygon shapefile
P1, P2, P3, P5	City council (2019)	Location of drainage assets	Point shapefile
P1, P2, P3	City council (2014)	Location of schools	Point shapefile
P1, P2, P3	City council (2014)	Location of health establishments	Point shapefile
P1 to P6	City council (2014)	Land use	Polygon shapefile
P1, P2, P3	City council (2014)	Rivers	Polyline shapefile
P1, P2, P3	City council (2014)	Lakes	Polygon shapefile
P5, P6	City council (2014)	Catchments of Campina Grande (Brazil)	Polygon shapefile
P4, P5, P6	Aragão *et al.* 2000	Rainfall: Intense, duration and frequency curves (IDF) for Campina Grande (Brazil)	Local parameters
P4, P5, P6	Paixão *et al.* 2009	Infiltration: Horton equation for Campina Grande (Brazil)	Local parameters
P4, P5, P6	Rufino *et al.* (2021)	Built-up information of Campina Grande (Brazil) in 2040	Raster

*P1, P2, P3, P4, P5 and P6 refers to phase 1, phase 2, phase 3, phase 4, phase 5 and phase 6, respectively.

3.2.2.2 Phase 3: Mapping hazard-specific vulnerability and exposure

Phase 3 (P3) corresponds to principle B with the formulation of the spatial framework for mapping "areas in need of changes" (i.e., referred to places that face the disaster risk, vulnerability, exposure, and hazard, as suggested on IPCC (2014)). P3 is detailed in chapter 5 with the formulation of a participatory-entropy-fuzzy framework for mapping hazard-specific vulnerability and exposure. The approach was developed through a GIS-Multi-Criteria Decision Analysis (GIS-MCDA) approach with ArcGIS (Pro) and Python. More details are shown in chapter 5.

The collaboration with stakeholders in the PLANEJEEE Project is used as input for the participatory-fuzzy-entropy methodology. Stakeholders participated of this phase in two stages:

a) For selecting the indicators to represent the vulnerability' attributes and the location of exposed elements,
b) With discussions for validating the flood vulnerability and exposure mappings.

The indicators shown in Figure 3.7 are examples of variables analysed in this thesis for mapping flood hazard, and flood vulnerability and exposure. The methods and datasets used for the formulation of P3 are shown in Table 3.1 and 3.2, respectively. Full details of the approach are shown in chapter 5.

3.2.2.3 Phases 4, 5, and 6: Planning, implementing, and evaluating sustainable solutions

Phases 4 (P4) and 5 (P5) refer to the analysis of the benefits acquired with sustainable strategies in the city. Chapter 6 assesses the environmental benefits of green roofs, permeable pavement, and rain gardens in three catchments of Campina Grande. At this stage, the goal of the assessment was only the environmental aspect of the solutions, and because of this, chapter 6 focuses mainly on the concepts of SUDS for flood risk reduction (Fletcher *et al.*, 2014; Ruangpan *et al.*, 2020). P4 integrates land-use and legislation for selecting the locations to apply sustainable solutions.

Besides this, it is evaluated if the flooding will increase if the current legislations of the city are fulfilled in the future. P5 is covered in the analysis of environmental benefits obtained with the solutions. For evaluating the flooding (hazard), SWMM (US EPA) was used to simulate flood-prone areas in three catchments of Campina Grande, according to 2 and 5 return periods' rainfalls. SWMM was selected as it is widely used and recommended for flood mapping (i.e., see section 2.3.5.1). More details are shown in chapter 6.

After that, chapter 7 extended the analysis of sustainable solutions for the entire city, and with the provision of environmental, social, and economic benefits. Chapter 7 analysed multiple nature-based solutions (NBS), such as green roofs, permeable pavement, green areas, rainwater harvesting, and the drainage system improvement (the integration of sustainable solutions and grey infrastructure) for Campina Grande. As shown in Figure 3.7, the analysis of benefits assesses the difference of flooding before and after incorporating solutions.

In chapter 7, as the entire urban area of Campina Grande was analysed, flood risk areas were simulated with CADDIES model (University of Exeter) with 10, 20, and 100 return periods' rainfalls. At this stage, CADDIES was selected because of data availability, and due to its successful application in other study cases previously (i.e., see section 2.3.5.1). Insights of land-use and legislation from chapter 6, and engagement strategies with stakeholders, are used to plan the location for applying solutions in chapter 7. Chapters 6 and 7 are built based on the principle C to maximise benefits according to the societal challenges established in phase 2.

Phase 6 is covered in the discussion of chapters 4, 5, 6, and 7. The "actions and solutions" discussed in these chapters are summarised in the chapter 8, based on:

a) Perceptions obtained with the collaboration of stakeholders during the PLANEJEEE Project (i.e., objective 1 of this thesis)
b) The influence of socio-economical, geographical, informational, and contextual factors in creating more flood vulnerabilities (i.e., objective 2)
c) The mappings of flood vulnerability and exposure based on social, institutional, and structural factors (i.e., objective 3)
d) The selection of different location for implementing solutions in the built environment (i.e., objective 4)
e) The analysis of the multiple benefits that can be obtained with the solutions, (i.e., objective 5)
f) The current legislation for water management of Brazil (i.e., objective 6)

3.2.2.4 The formulation and development of the participatory approach in Campina Grande, Brazil

The participatory approach was entitled the Project **PLANEJEEE**: To Plan Extreme Events, translated from Portuguese: "***PlanejE E****ventos* ***E****xtremos*". The project aimed to involve stakeholders in the formulation of the integrated spatial-participatory approach. For increasing participation, a social media (Instagram) account (@planejeee) and a website (www.planejeee.com) were built and disseminated within the community. The project had the participation of 255 stakeholders of Campina Grande distributed in two phases of collaboration, in 2019 and 2021 (Figure 3.8), described below.

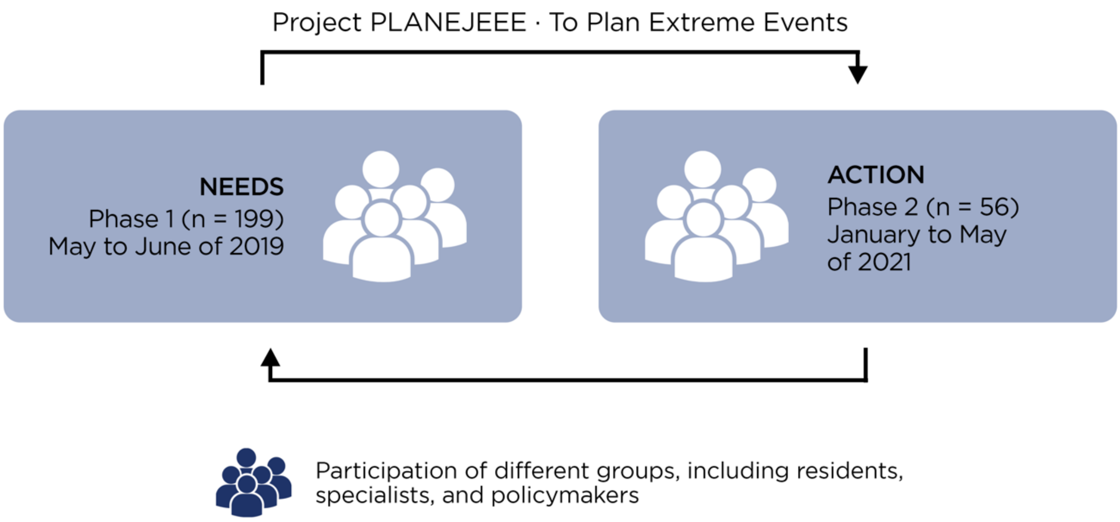


Figure 3.8 – The conceptualisation of the PLANEJEEE Project. The participatory approach was designed to provide understanding of the "NEEDS" of the city for then planning to "ACT" to reduce the flood risk.

The first phase of the participatory approach

The first phase of the project was from May to June of 2019. The 45-days fieldwork aimed to involve different stakeholders of Campina Grande for the definition of the context (i.e., Phase 1 of Figures 3.6b and 3.7), understanding of the main societal challenges faced by the community in risk (i.e., Phase 2), and for building and verifying the mappings of the areas in need of changes (i.e., Phase 3). The activities of the PLANEJEEE Project had the support of the Federal University of Campina Grande (UFCG), which contributed with materials, infrastructure, and transportation during the fieldwork in 2019. To accomplish the objectives, nine undergraduate and one postgraduate student from the College of Technology and Natural Resources and the Centre of Civil Engineering at the UFCG assisted in the project's activities, detailed below.

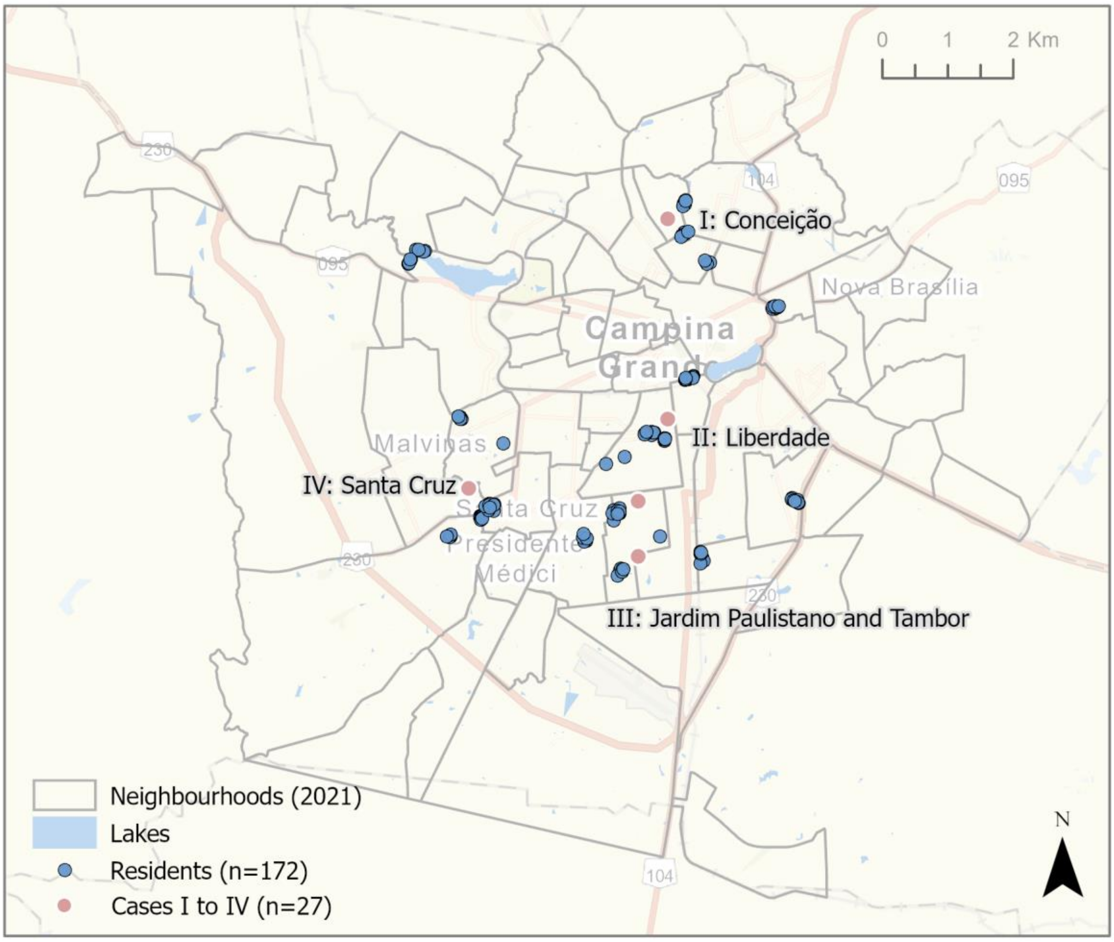
- *The participation of residents in risk of flooding and water shortage*

Initially, the PLANEJEEE team (n = 10) assisted with applying surveys with residents of the city. Before implementing the questionnaire, an online pilot questionnaire was applied from March to May 2019 with 48 individuals using the TypeForm online platform. The pilot group was formed with two main groups: (i) professionals selected based on their research field (i.e., flood risk, water research, water resources, sustainable solutions modelling and implementation) and (ii) residents of Campina Grande that had any experience with flooding or water shortage risk. The participants were asked to fill the survey and analyse the questions and the questionnaire's organization, as suggested by other participatory studies (Cheung *et al.*, 2019; Hardoy *et al.*, 2019; Rodríguez *et al.*, 2007; Verweij *et al.*, 2020). In this regard, pilot participants could recommend the improvement of questions and suggest new questionings if necessary. The final questions' description is shown in Appendix B. All questionnaires were built with a five-point Likert scale (from 1 – *less preference* to 5 – *more preference*) and in Portuguese (main Brazilian language).

The sample size for residents' participation was calculated through the Simplified Yamane's formula (Yamane, 1967). The data provided by CPRM was used to calculate the number of citizens that live in the eleven risk areas, a total of 2,156 people, according to the only official dataset available for Campina Grande (CPRM). From this, the sample size with a minimum of 96 people with an error acceptance of 10% was calculated with Equation 3.1, from which n is the sample size, N is the total number of citizens, and e is the error acceptance value.

$$Sample\ size\ (n) = \frac{N}{1 + Ne^2} \qquad \text{Equation (3.1)}$$

A total of 172 residents participated in the first phase of the project (Figure 3.10). Since Campina Grande has cases of flood and water shortage risks, the participation of residents aimed to evaluate how the community at risk perceive and cope with the two extreme events.



Esri, HERE, Garmin, METI/NASA, USGS

Figure 3.9 – The PLANEJEEE Project: Location of questionnaire application with residents of Campina Grande, and details of cases I (Conceição), II (Liberdade), III (Jardim Paulistano/Tambor) and IV (Santa Cruz/Três Irmãs).

(a) (b) (c)

Figure 3.10 – Examples of vulnerabilities seen in Campina Grande during the PLANEJEEE Project: a) Liberdade, b) Ponte do Cruzeiro and, c) Itararé neighbourhood.

The selection of areas for survey application was based on 1) official flood risk areas, and 2) previous locations with flood cases. As the flood risk cases are localised in many parts of the city, the first surveys applications were based mainly in the flood risk areas of CPRM (Figure 3.3). When applying the questionnaires, areas with previous flood risk cases were also assessed. For this, the information about flood location collected from official reports of the Civil Defence were used, as well, other areas indicated by the residents themselves. The Civil Defence team carried out the application of the surveys together with the PLANEJEEE team (Figure 3.10). Also, each PLANEJEEE team member received official vest of the Civil Defence for survey application (Figure 3.10), which helped the acceptance of residents to filling the survey.

The contact with the 172 residents was crucial for the first screening of potential sources of vulnerabilities of the city. Cases I, II, III and IV of Figure 3.9 refer to specific flood vulnerable neighbourhoods in the city (i.e., the pink circles in Figure 3.9). Photos shown in Figures 3.10a to 10c indicate some of the context seen in different locations, such as the situation of properties very near open channels (Figure 3.10b), garbage, vegetation, and sewage infiltration in the rain channels (Figures 3.10a and 3.10b), and the construction of flood barriers (Figure 3.10c). The participation of residents is detailed in Chapter 4 of this thesis.

- *The participation of policymakers and specialists*

The authorities and specialists of the city also participated in the PLANEJEEE Project in 2019. Informal meetings and a workshop were developed with different sectors of PMCG, with representatives of planning, urban services, engineering, health, education, traffic, GIS, science, and technology sectors of the city council. The informal meetings aimed to introduce the project and briefly discuss some of the goals and aims of the workshop to be held posteriorly. In addition to these sectors, stakeholders from the water management companies (AESA - Executive Agency of Water Management and CAGEPA – Water Company that manage the supply of Paraíba state) and representatives of the civil society (e.g., Civil Defence, NGOs and the CONCIDADE) were contacted to participate of the collaboration strategies. Professors and postgraduate students at the Federal University of Campina Grande (UFCG) were also contacted to participate of the workshop, according to their research field and interests. The workshop was held in 18th of June of 2019 in SEBRAE, with the attendance of 27 people attended and 22 survey answers.

The workshop followed the structure: (1) survey application, (2) general exposition of the PLANEJEEE Project, (3) the introduction of participants, (4) the division of the four focus groups, (5) the provision of guidance for underlining vulnerabilities, (6) discussion of the main challenges and solutions for water management in the city, (7) presentation of discussions to the bigger group, (8) summary and workshop finalisation. From this structure, it is important to highlight some details about the engagement strategies. First, the choice of administrating the survey initially aimed to evaluate the answers from stakeholders before the discussions, and without any external influence (de Brito *et al.*, 2018). Secondly, the division of stakeholders in the focus groups was made in order to generate a multidisciplinary discussion with a combination of different sectors of the city council and different specialists. The 27 participants were divided into four focus groups according to the delimitation of flood risk cases of Figure 3.10. Each group had a leader from the PLANEJEEE team who was responsible for facilitating and providing guidelines for discussion. Participants received a “baseline” material, with maps underlining structural vulnerabilities (i.e. garbage in the street, streets without drainage system) (IBGE, 2010), physical vulnerabilities (Alves *et al.*, 2018b; Tsuyuguchi, 2015) (i.e. elevation, slope, distance to rivers, lakes) and sources of exposure (i.e. population density, number of elders, children) of the study case. The maps were produced in the ArcGIS Pro (ESRI) with the most recent census track information (IBGE, 2010).

Maps with water shortage vulnerabilities (i.e., wells location, rainwater harvesting, and streets with water supply) were also provided. Participants were guided to use this information to analyse the challenges and solutions for water management in the study case. The groups also received a map with the delimitation of the urban area of Campina Grande, in which they could draw possible solutions and discuss key points of the area in study. Thirdly, after the discussion in the small groups, a representative was chosen to present the challenges and solutions of the small area (Cases I to IV of Figure 3.9) for the bigger group. This was made to enable the other groups to engage with the issues of the entire city. Participants were guided to present their opinion and previous experiences with flooding and water shortage in the city as desired in all the cases. Subsequently, the leading researcher of this thesis presented the overall findings and concluded the workshop. More details of this phase are described in chapters 4 and 5.

In the first phase of the project, the PLANEJEEE team had regular meetings for discussing the results obtained with the engagement strategies. Since the project had the support of PMCG and UFCG, informal meetings with the different sectors of PMCG and UFCG were also made regularly to discuss challenges faced, and to obtain their feedback about the participatory approach.

The second phase of the participatory approach

The second phase of Project PLANEJEEE was held from January to May of 2021 (Figure 3.8). Collaboration strategies were held online and in person, however, due to the SARS-CoV-2 pandemic, only smaller groups were allowed to collaborate, which generated reduced participation (n final = 56). Even though the project's objective was to involve residents in planning actions for risk mitigation (Figure 3.8), public participation was not possible at this phase because of the COVID-19 pandemic. Still, in smaller groups, the project promoted opportunities for involvement with policymakers to define an action plan to implement sustainable flood risk solutions in the city. The participation was through meetings and a workshop with the city's policymakers (n = 33) and survey application with specialists and authorities (n = 23).

Phase 2 of the PLANEJEEE Project occurred in parallel to the revision of the master plan of Campina Grande. The master plan is a set of principles and rules that guide the action of the construction agents in the built environment with the neighbourhood as the central unit of management (i.e., more details are provided in chapters 6 and 7). According to the Brazilian legislation Nº 10.257 of 2001, the “City Statue”, the master plan is compulsory for every city with more than 100,000 inhabitants and should be updated every ten years. However, the last version of the Master Plan of Campina Grande is from 2006, which indicates the updated version has been overdue since 2016. In this regard, Project PLANEJEEE was invited to participate in meetings of the revision of the plan and organized a workshop with the group focusing on implementing sustainable solutions for flood risk mitigation in the municipality.

The meetings were held on January 28th (n = 9) and February 4th (n = 10) and the workshop was held on February 2nd (n = 14) of 2021. The discussions took place in the urban planning sector building of the PMCG, however, representatives of other sectors also participated in the meetings and workshop such as civil defence, traffic mobility, and construction sectors. The workshop was outlined similarly to the previous one in 2019, however, in 2021 the analysis of the "needs" of Campina Grande were presented to participants. A material was provided for the discussions, covering the details of the challenges Campina Grande residents face in terms of multiple hazards, vulnerability, and exposure (i.e., DR). In this sense, discussions covered the social, structural, and institutional vulnerabilities (P1 and P2 of Figures 3.6b and 3.7), the mappings of hazard, vulnerability, and exposure (Phase 3 of Figures 3.6b and 3.7) and how sustainable solutions could be implemented in the city (Phases 4 to 5 of Figures 3.6b and 3.7). At this stage, the outputs with the implementation of sustainable solutions in the three catchments of the city was also discussed (Chapter 6).

To increase collaboration, specialists and authorities were invited to fill an in-person or online survey according to their research focus (n = 12) and to their roles in the sectors of the city council (PMCG) (n = 11). Before the questionnaire application, a pilot survey was applied with a small group for verification (n = 5). Similar to the first phase of the project, pilot respondents could suggest improvements in the questions and include new ones. The survey was prepared to cover: (1) consent and willingness to participate, (2) personal data, (3) preferences for mitigation sustainable solutions, (4) preferred multiple benefits to be acquired with solutions, (5) feedback and, (6) acknowledgments. The questionnaire was prepared with a five-point Likert scale (from 1 – *less preference* to 5 – *more preference*) and in Portuguese. The platform of *GoogleForms* was used to disseminate the online version for respondents. More details of this phase are presented in chapter 7.

- *Ethical clearance and specifications*

Phases 1 and 2 of the participatory approach were developed with ethical clearance with the host university of this thesis (University of Exeter), through the CEMPS Ethics Committee (application eEMPS000076). The Ethics application was prepared based on the guidance of the "Good Practice in the Conduct of Research" code of the University of Exeter. The application aimed to cover the "communication and consent" with the stakeholders, "possible harms", "vulnerable groups" and "data protection and storage". Additionally, risk assessments were prepared and applied for both participatory approaches, in 2019 and 2021.

The application was analysed by the supervisory team and the Ethics Committee of CEMPS (College of Engineering, Mathematics and Physics Sciences). As part of the funding for this research, other two applications were made for CAPES (*Coordenação de Aperfeiçoamento de Pessoal de Nível Superior* – Brasil) and Marie Sklodowska-Curie, which were approved. As the study case of this thesis is in Brazil, a formal authorisation of the Brazilian university collaborating with the research (i.e., Federal University of Campina Grande - UFCG) was attached to the application.

The PLANEJEEE Project was formulated to:

- Ensure that subjects are fully informed about the research,
- Ensure that subjects have the freedom to participate or not of the research,
- Ensure voluntariness:
    - The research subjects are free to participate or not, as they prefer,
    - Participants are free to end their participation for any reason, without consequences,
- Obtain an informed consent and provide a comprehensive description of the project, with the appropriate language understandable by the research subjects,
- Ensure that people are treated in an ethical manner, respecting their decisions, protecting them from harm, and securing their wellbeing,
- Ensure that the PLANEJEEE team are protected from undesired harms, including the support of the local authority responsible for managing flooding cases, and a team of the Federal University of Campina Grande (UFCG), including a driver to the risk areas,
- Promote weekly meetings with the PLANEJEEE team to listen their experience in the flood risk areas, to plan for further activities, and to minimise risks and unexpected harms,
- Ensure data security and privacy of respondents.

More details about the ethics process are provided in the chapters 4, 5 and 7. A summary of questionnaires applied in the Project PLANEJEEE is available in Appendix B.

CHAPTER 4
Understanding the
social context of
Campina Grande, Brazil

Chapter 4 - Understanding the social context of Campina Grande, Brazil

Chapter 4 focuses on discussing two journal papers that refer to results obtained with the engagement with stakeholders of Campina Grande in 2019. Article 1 is currently under review in the Journal of Flood Risk Management, and article 2 is published in the Sustainability Journal.

Research questions:

- RQ 3: *How can social and institutional vulnerabilities in the flood risk context be assessed with stakeholders' collaboration?*
- RQ 4: *How do local actors perceive the challenges and solutions for flood risk mitigation?*
- RQ 5: *In what way are the risk perception (RP) and coping capacity (CC) of residents similar (or different) when facing flooding and water shortage*?
- RQ 6: *What are the main preferences of stakeholders for strategies to mitigate flood and water shortage risks?*

4.1 Addressing social and institutional vulnerabilities in the context flood risk mitigation (article 01)

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Article currently under review in the Flood Risk Management Journal

Abstract
There are different perspectives of what constitutes disaster risk. Among the “hazards”-tradition research, greater focus is given to modelling hazards, and less effort is made to understand the *context* in which they occur. Considering the vulnerabilities are the “inherent characteristics of the place that create the potential to harm”, this paper highlights the importance of understanding the vulnerabilities of the place before defining actions for risk reduction. In this sense, a participatory approach, the Project PLANEJEEE, was developed to understand the social and institutional vulnerabilities of flood risk in Campina Grande, Brazil. Data was collected with the collaboration with 199 stakeholders through surveys, workshop and focus groups. The results reflect the analysis of the social context with the assessment of risk perception and coping capacity of communities at risk (n = 172), whereas the institutional context is discussed based on the collaboration with policymakers and local specialists (n = 27). Although results confirm that residents faced severe previous flood risk cases, findings show that risk communities need further resources and actions for increasing their coping capacity and their own protection in the future. Institutional vulnerabilities are shown with the view of stakeholders about flood risk challenges, especially with issues with management, legislation, society, and stakeholders’ collaboration. Findings show that multiple scale challenges and solutions in social and institutional contexts should be systematically addressed to propose solutions, reduce flood risk vulnerability, and increase resilience.

Keywords: flood risk mitigation, social and institutional vulnerabilities, participatory approach.

4.1.1 Introduction

The United Nations International Strategy for Disaster Risk Reduction (UNISDRR) defines vulnerability as “the conditions determined by physical, social, economic and environmental factors, or processes, which increase the susceptibility of an individual, a community, assets or systems, to the impacts of hazards (UNISDR, 2021). Different disciplines, in both social and environmental sciences, search for appropriate definitions of vulnerability with examples of urban planning, disaster management, engineering, economics, sociology and anthropology (Bergstrand *et al.*, 2015; Birkmann, 2007; Cutter *et al.*, 2003). For the Intergovernmental Panel on Climate Change (IPCC), defining what makes a system vulnerable is particularly key for Disaster Risk Reduction (DRR) approaches based on the assumption that hazards only become disasters if they occur in vulnerable contexts (IPCC, 2014). This is corroborated by other authors that consider the vulnerability as a series of categories in physical and structural, environmental, social, psychological, and institutional contexts (Pescaroli *et al.*, 2019) that, when combined with exposed elements, will determine whether the event will translate into a disaster (Hazarika *et al.*, 2018; Sharma *et al.*, 2019).

The understanding of vulnerability is essential for flood risk management. Flooding is a hazard widespread worldwide (Hammond *et al.*, 2018; Wang *et al.*, 2018), reaching both developed and developing countries (Danso *et al.*, 2016; Miguez *et al.*, 2018; Nguimalet, 2018). The uncontrolled expansion of urban areas makes cities more exposed to flooding and leads to economic losses and adverse social impacts (Thistlethwaite *et al.*, 2018), including human health and wellbeing (Raymond *et al.*, 2017). However, due to the dynamic nature of risk (Peduzzi, 2019; Pescaroli *et al.*, 2019; UNDRR, 2019), there is a debate of how flood risk (FR) should be contextualised. There are two main definitions of FR: (1) the “hazards”-tradition approach, more common among natural scientists and engineers, encompassing the probability of flooding and their consequences, and (2) “social”-tradition approach, among social scientists and planners, considering the hazard as a phenomenon with the potential to harm (i.e., detailed definitions can be seen in Klijn *et al.* (2015) and Gouldby *et al.* (2009)). For Cutter *et al.* (2003), the main barrier of the “hazards”-tradition approach lies in placing the origin of disasters in the hazard origin, instead of the vulnerability. In this sense, authors argues that studies in the hazards-research still have a great focus on hazards modelling (Lund, 2015; Peduzzi, 2019), whereas the underlying factors are not well addressed, focusing more on the hazard itself (Ajibade *et al.*, 2014).

This paper highlights how delineating actions for flood risk mitigation should be accompanied by the understanding of vulnerabilities, as they are the “inherent characteristics of the place that create the potential to harm” (Cutter *et al.*, 2008), including their underlying causes in both social and political contexts (Ajibade *et al.*, 2014). For Klijn *et al.* (2012), the proposal of solutions should equally consider (1) reducing flood probability, (2) reducing exposure to floods, (3) reducing the vulnerability of people and property. Specifically, the understanding of the three constituents of risk (i.e., hazard, vulnerability, exposure (IPCC, 2014)) may help to identify and select solutions and policy instruments aimed at influencing the development of each constituent (Klijn *et al.*, 2015; Shah *et al.*, 2020). When dealing with policies and urban planning in the context of DRR approaches, Marchezini *et al.* (2017) discuss how effective governance, institutional arrangements, warnings, and communication systems are essential to meet the needs of every group, in every vulnerable community, including the needs of young people. For the authors, the ineffectiveness of these measures can be regarded as "institutional vulnerabilities". Similarly, López-Martínez *et al.* (2019) argue that institutional vulnerabilities are the vulnerability root cause, involving all the dimensions of vulnerabilities (Birkmann, 2007; Fuchs *et al.*, 2011) and showing how the inefficiency of authorities in charge of hazard management could amplify exposure.

We argue the proposal of actions for FR reduction is also affected by social constraints. This is explicitly shown in the resilience conceptualisation, covering the "ability to respond to and recover from the impacts of hazards" (Cutter, 1996). However, like disaster and FR, resilience is acknowledged differently in the literature, which leads to several criticisms in the academic discourse (Coaffee *et al.*, 2018; Rezende *et al.*, 2019). In this article, the resilience definition of Cutter *et al.* (2008) is used, which considers the resilience of a community "as the ability of a social system to respond and recover from disasters, including the inherent conditions that allow the system to absorb impacts and cope with an event, as well as the post-event and adaptive processes that facilitate the ability of the social system to reorganise, change and learn in response to a threat". In other words, understanding *how* societies perceive, respond, recover, and cope with an event, in pre- and post-events, may help to answer how disaster resilience can be achieved (Cardoso *et al.*, 2020; Norris *et al.*, 2008; Räsänen *et al.*, 2020; Rezende *et al.*, 2019). As such, studies have been focused on comprehending risk perception and coping capacity of communities towards risk mitigation (Chowdhooree *et al.*, 2018; Houston *et al.*, 2017; Lechowska, 2018; Netzel *et al.*, 2021), leading to no consensus of how the measurement should be made (Liu *et al.*, 2018a), and what indicators should be used (Danso *et al.*, 2016; Lechowska, 2018).

The different social (i.e., risk perception and coping capacity of residents at risk) and institutional vulnerabilities (i.e., government, legislation, and institutions) characterise how disaster risks are not a random natural phenomenon but a consequence of human activities and decisions (Peduzzi, 2019). In this regard, this paper argues that suggesting risk reduction actions, especially in the context of FR, should simultaneously incorporate the comprehension of vulnerabilities. Findings investigate the social and institutional vulnerabilities with the collaboration with stakeholders, namely residents, policymakers, and specialists, including their view of challenges and actions for flood risk mitigation (O'Donnell *et al.*, 2017), as well as the risk perception (Lechowska, 2018) and coping capacity (Danso *et al.*, 2016) of flood risk communities in the city of Campina Grande, semiarid region of Brazil.

The PLANEJEEE Project, named in Portuguese as "*PLANEJE Eventos Extremos*" (i.e., English translation as "To Plan Extreme Events"), gathered information among citizens, policymakers (authorities), and local specialists of the municipality. This article shows how participatory planning can be embedded in the search for risk mitigation solutions in developing countries through this case study. The participatory approach was built with mixed objective and subjective methods, detailed further in this article. The social and institutional contexts are assessed by answering the two research questions:

1. How can social and institutional vulnerabilities in the flood risk context be assessed with stakeholders' collaboration?
2. How do local actors perceive the challenges and solutions for flood risk mitigation?

The paper is organised as follows. Section 4.1.2 present the study case, the conceptual framework, and aspects related to the participatory approach. Section 4.1.3 shows the analysis of social and institutional contexts with the participation of residents, policymakers, and local specialists, including the discussion of underlying causes of flood risk vulnerabilities. After that, conclusions are presented.

4.1.2 Case study

Campina Grande is in the Northeast (NE) region, also called as the "semiarid region" of Brazil (Figure 4.1a). The semiarid region encompasses 18% of the national territory, 1,262 municipalities (IBGE, 2021), and one-third of the country's population (Lemos *et al.*, 2016). According to the Brazilian Institute of Geography and Statistics (IBGE), the population of Campina Grande is estimated as above 400,000 inhabitants (IBGE, 2021). The city is an industrial, technological, and educational centre in Paraíba state (Figure 4.1b), attracting many visitors and residents from surrounding areas (Del Grande *et al.*, 2016a).

Because of the climate of the semiarid region, Campina Grande faces regular periods of water scarcity (Cordão *et al.*, 2020; Rêgo *et al.*, 2017). From 2012 to 2017, the city faced one of the harmful water shortage period in Campina Grande history (Rêgo *et al.*, 2017). However, the city is also susceptible to pluvial flooding risk (Alves *et al.*, 2020e). Flood risk areas are seen in different areas in the city (Figure 4.1c). Previous studies have been focused on delineating the relation of disordered land occupancy with flood risk (Santos *et al.*, 2017c), as well as the issues from the association of sewage inside drainage infrastructure, creating numerous health impacts in the city (Camelo *et al.*, 2020). Similarly, Campina Grande has management and legislation issues, such as the lack of public participation in water policies, which corroborates to challenges in the institutional context (Miranda, 2017).

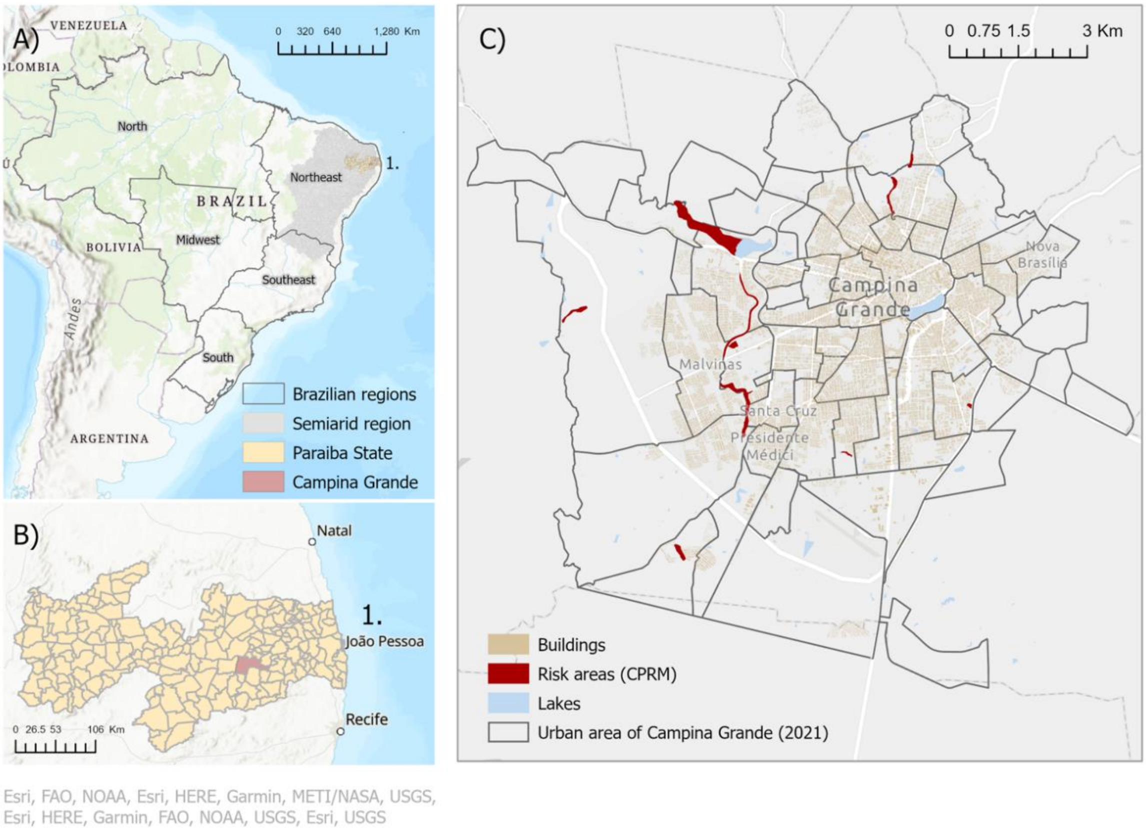

Figure 4.1 – Geography of Campina Grande - Brazil: a) Location on the semiarid region of Brazil; b) The location of Campina Grande in Paraíba state, c) Perimeter highlighting the urban area, neighbourhoods, buildings and flood risk areas according to CPRM.

4.1.3 Methodology

4.1.3.1 The conceptualisation of social and institutional vulnerabilities in the context of flood risk

Definitions of FR, as the relationship between hazard, vulnerability, and exposure (Gouldby *et al.*, 2009; Klijn *et al.*, 2015) and resilience (Cutter *et al.*, 2008) presented in Section 4.1.1 were integrated when defining the conceptual framework of the PLANEJEEE Project, detailed in Figure 4.2. In essence, Figure 4.2 assumes that understanding the perception of local actors can help comprehend some of the underlying causes of flood risk vulnerabilities (Mondino *et al.*, 2020). As vulnerabilities represent the inherent characteristics of the place and can express themselves in several categories (Cutter *et al.*, 2008; Pescaroli *et al.*, 2019), they are shown in terms of the institutional and social contexts (Figure 4.2). The framework shows that understanding the *decisions, interests, and varied perceptions* of local actors (Fernandez, 2021) can facilitate the comprehension about root causes of vulnerabilities, and therefore, can assist in the proposal of actions and solutions for flood risk mitigation (FRM) and resilience (UNDRR, 2019).

The social context of communities in risk is investigated through the concepts of risk perception (RP) and coping capacity (CC) (Figure 4.2). RP is considered a fundamental factor for understanding the population's responses to hazards, being defined as "an assessment of the probability of a hazard and the probability of the results, most often the negative consequences, perceived by the society" (Lechowska, 2018). For Renn (2004), RP must be seen as a mental or sociopsychological instrument that can enable the prediction of future actions and facilitate the decision of risk reduction solutions. In this study, RP is analysed through the selection of four indicators, which combine the residents' cognitive factors, **awareness (A) and worry (W)**, and behavioural factors, **preparedness (P) and knowledge (K**), showing how the citizen sees the probability of facing an extreme water event in the future (Figure 4.2). Whilst RP reflects how individuals and communities perceives risk, the CC is "the ability of people, organisations, and systems, using available skills and resources to manage the adverse conditions of risk or disasters" (UNISDR, 2021). CC represents the citizens' **responsiveness (R)** to cope with the hazard in the current scenario and the intention to use **adaptive (AM) and permanent measures (PM)** in the future (Figure 4.2). The seven indicators of RP and CC were selected through the surveying of indicators used in previous studies (Ajibade *et al.*, 2014; Bryan *et al.*, 2019; de Brito *et al.*, 2017; Fuchs *et al.*, 2017; Liu *et al.*, 2018a; Marfai *et al.*, 2014; Nguimalet, 2018; Thistlethwaite *et al.*, 2018).

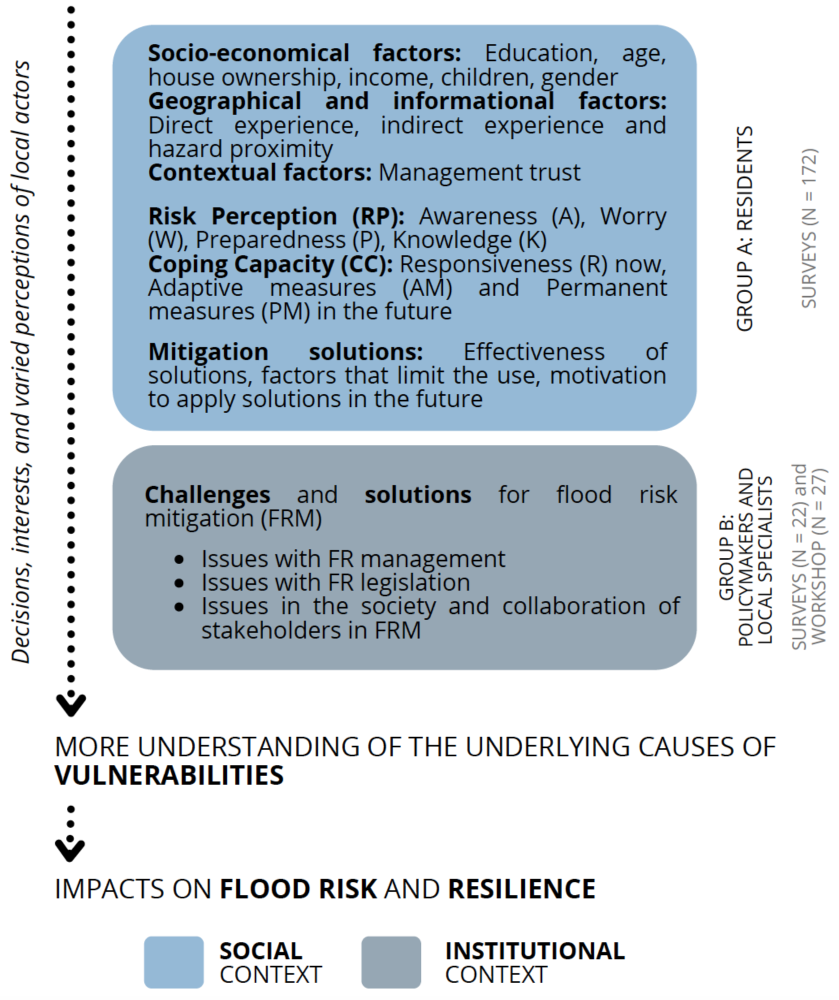

Figure 4.2 – The conceptual framework for assessing the social and institutional contexts as the "behaviours and attitudes of local actors" that can influence in the generation of vulnerabilities for flood risk mitigation (FRM). Surveys and workshop were used for the participation of groups A and B (i.e., referred to residents, and policymakers (authorities) and local specialists, respectively) during the Project PLANEJEEE in 2019.

The institutional context is assessed by understanding that it reflects both the context and the process by which governance, formal and informal institutions may be too weak to provide protection against DR (Lassa, 2010). In this regard, more institutional vulnerabilities can indicate the increase of risk, especially when solutions for dealing with the given risk are inadequate, not accepted, or not used by all actors within the territory (Fernandez, 2021). In this study, the institutional vulnerabilities were discussed during the collaboration strategies with stakeholders in the PLANEJEEE Project, described below.

4.1.3.2 The Participatory Project

The PLANEJEEE Project developed several engagement strategies with stakeholders, aiming to clarify the *social and institutional contexts* regarding the flood risk disaster in Campina Grande, Brazil (RQ1). From May to June of 2019, questionnaires were applied with residents, policymakers (authorities), and local city specialists. Informal meetings, a workshop and focus groups were developed with policymakers and local specialists (Figure 4.2).

Citizens' participation was mainly through door-to-door surveys. First, it is important to highlight that even the city facing flood and water shortage risks, the flood risk was the main goal of the project, and because of this, the location of residents' properties for questionnaire application was based on previous flood locations, the official mapping of flood-prone areas developed by the Geologic Survey of Brazil (CPRM, 2013) with the support of Civil Defence (Figure 4.3). A total of 172 residents participated in the project (Figure 4.2). To investigate the social aspects, questions regarding the socio-economical, geographical, and informational, and contextual questions were included in the questionnaire (Figure 4.2). Questionnaires were divided into sections to cover RP and CC of residents, as shown in Figure 4.2. The questions for obtaining the answers of residents for each RP and CC indicator are shown in Table 4.2, wherein citizens could answer in a scale from "very low" (score 1) to "very high" (score 5) or select the "I don't know" option. Other questions regarding the perception of solutions for FRM were also included. Pearson Correlation, Wilcoxon Z, and Mann Whitney U tests, within the 95% confidence interval were used to statistically analyse the answers with IBM SPSS Statistics 23 software and Python notebooks.

The second part of the PLANEJEEE Project aimed to analyse the institutional vulnerabilities (Figure 4.2). Initially, informal meetings with policymakers were held to present the project briefly. Later, policymakers and local specialists were invited to participate in a workshop on 18th of June 2019. The invitations were based on their research field (for specialists) or position in the city council (e.g., planning, urban services, engineering, health, education, traffic, GIS, science, and technology), including water companies (AESA - Executive Agency of Water Management and CAGEPA) and their role in the society (e.g., Civil Defence, Municipal Council – CONCIDADE and NGOs). Twenty-seven people attended the workshop. The workshop was developed with the following structure: (1) survey application, (2) general exposition of the PLANEJEEE Project, (3) the introduction of participants, (4) participants division in four focus groups, (5) the provision of guidance for underlining vulnerabilities, (6) discussion of the main challenges and solutions for water management in the city, (7) presentation of discussions to the bigger group, (8) summary and workshop finalisation.

It is important to highlight some details about the engagement strategies. First, the choice of administrating the survey initially aimed to evaluate the answers from stakeholders before the discussions and without any external influence (de Brito *et al.*, 2018). Twenty-two survey answers were collected. Secondly, the division of stakeholders in the focus groups was made to generate a multidisciplinary discussion with a combination of different sectors of the city council and specialists from various fields. The 27 participants were divided into four focus groups according to the delimitation of flood risk areas by CPRM (2013), Civil Defence, and the residents that participated in the questionnaires (Figure 4.3).

Each focus group had a leader from the PLANEJEEE team responsible for facilitating and providing guidelines for discussion. Participants received a "baseline" material with maps underlining structural vulnerabilities (i.e. garbage in the street, streets without drainage system) (IBGE, 2010), physical characteristics (Alves *et al.*, 2018b; Tsuyuguchi, 2015) (i.e. elevation, slope, distance to rivers, lakes) and exposure (i.e. population density, number of elders, children) of the study case. Maps with water shortage vulnerabilities (i.e., wells location, rainwater harvesting and streets with water supply) were also provided because of the dual-disasters context in the city. The mappings were produced with ArcGIS Pro (ESRI), representing the most recent census track information available for the city (IBGE, 2010). Participants were directed to use this information as input to discuss the main challenges and solutions for flood risk mitigation (RQ2).

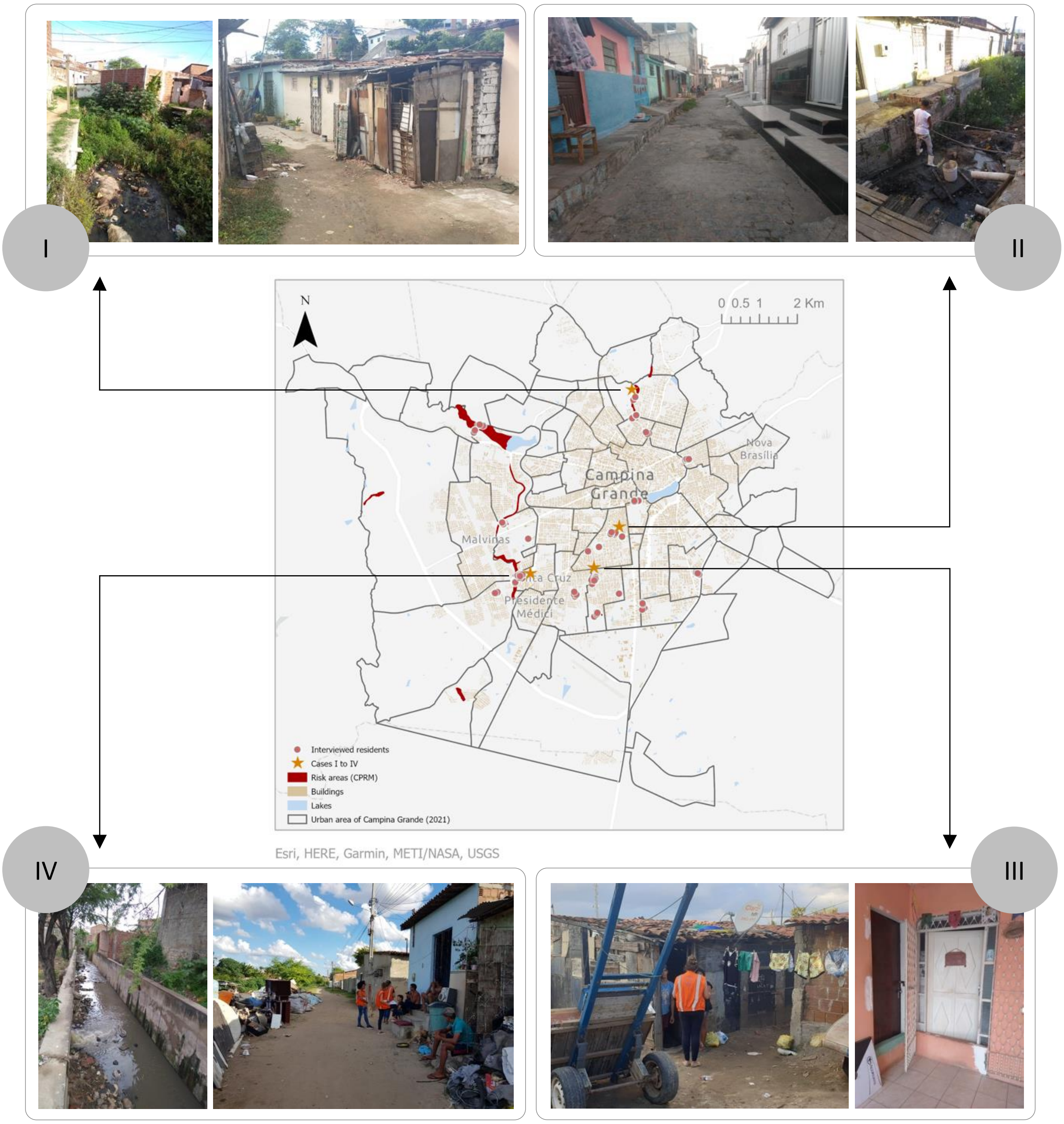

Figure 4.3 – The locations for survey implementation with 172 residents of Campina Grande – Brazil. The map highlights four specific flood cases discussed in the focus groups with policymakers and local specialists in the PLANEJEEE Project, referred as **I** (Conceição), **II** (Liberdade), **III** (Jardim Paulistano/Tambor) and **IV (**Santa Cruz/Três Irmãs).

After the discussions, a representative of each small group was chosen to present the challenges and solutions of the small area (i.e., Cases I to IV of Figure 4.3) for the bigger group. This was made to enable the other groups to engage with the issues of the entire city. At this point, the groups were able to complement the challenges and solutions of the other groups with their perspectives. Subsequently, the leading researcher of this article presented the overall findings and concluded the workshop. Ten postgraduate and undergraduate Civil

Engineering students at the Federal University of Campina Grande (UFCG) assisted in developing the PLANEJEEE Project. Ethical clearance was obtained through the University of Exeter, and an online pilot survey was applied from March to May 2019 with 48 participants.

4.1.4 Results and discussion

Results and discussions are shown with the analysis of the answers obtained in the PLANEJEEE Project. The results initially refer to the “challenges” according to the answers of stakeholders. At this point, the challenges discussed aims to clarify about the vulnerabilities in the social and institutional contexts. After that, “future actions” for FRM are examined based on the discussions of cases I to IV in the focus groups.

4.1.4.1 The challenges faced in the social context

Table 4.1 presents the summary of the results of RP and CC. The “awareness” and “worry” indicators had very similar results, which indicate that the citizens classify the severity of past flooding events from “high” to “very high” (Mean - M 4.4) and strongly expect the occurrence of other flooding cases in the next ten years (M 4.3). The consistency (SD) and variation of response (CV) of these two indicators show that residents overall agree in the high-very high severity of floods and that they will probably face another event in the next years (Table 4.1). The two indicators are fundamental in the risk perception analysis since they indicate how residents' experiences with the flood risk events are now and their concern for events in the future.

When asking about how likely they receive warnings before flood risk occurrence, the “preparedness” indicator, their answers show that overall, the residents do not receive many warnings (M 1.7). We asked the same question for specialists and policymakers (group B). The majority answered the residents do not have the necessary risk information (14.3% scored 1, and 47.6% scored 2) with M 2.43 and SD 0.98. Some of the residents (group A) also stated, in a further question, that the only warning they have of the flooding is the rainfall itself (quoting Resident A):

Resident A: *"When I realise that it is strong rainfall, I know it (the household) will be flooded".*

In comparison to the "knowledge" indicator, which asked if residents believe that they can handle flood better with adaptation measures in their homes, overall, the respondents affirmed to believe (M 4.2). However, there was less consistency and more variation in the answers, which can indicate different opinions amongst respondents (Table 4.1). The knowledge indicator had the objective to analyse their confidence for applying solutions, but not if solutions were already applied. To further analyse if residents had any solution in their households, the CC was evaluated.

Table 4.1 – Descriptive statistical analyses (Mean, SD and CV) for flood risk perception (RP) and coping capacity (CC).

	Key indicators	Specific questions	Mean	SD	CV (%)
RP	Awareness (A)	How do you classify the severity of the floods?	4.4	0.83	18.82
	Worry (W)	How likely is flooding going to occur within the next ten years?	4.3	0.96	22.35
	Preparedness or warnings (P)	How likely do you receive warnings before the flooding?	1.7	1.24	73.26
	Knowledge (K)	Do you think you can handle flood better with adaptation measures in your home?	4.2	1.35	32.30
CC	Responsiveness (R, taken adaptive measures)	Which of the following measures would you use in your home to prevent flooding? *Elevation of electrical installation, barriers, pumps, sewage valve, and change the elevation of furniture.*	1.34	1.23	91.94
	Adaptive measures (AM)	Would you make any investment in your home to reduce the risk of flooding?	4.5	1.15	25.40
	Permanent measures (PM)	If you had a chance to move home because of flooding, would you?	4.2	1.44	34.08

Residents were asked what measures they have in place to avoid flooding (i.e., referred to "R, responsiveness"), and their intentions to apply adaptive and permanent measures in the future (i.e., referred to "AM, adapt. future" and "PM, perm. future" in Table 4.1). "Responsiveness" was analysed by providing five options of solutions recurrent in Brazil (i.e., the elevation of electrical installation, barriers, water pumps, sewage valve, change the height of furniture, Table 4.1). Residents could select up to the five options provided or include other solutions later in the questionnaire. In this sense, the mean value of this question represents the average number of solutions used in the properties. Results show the mean of 1.34 for taken measures, which indicates that the residents do not have many measures to avoid flooding in place. In this regard, the most common solution seen in the properties was flood barrier, as shown in Figure 4.3. Residents were also asked what factors limit the application of measures for flooding mitigation in their properties. "*Money constraint*" received one of the highest scores with M 4.5 and SD 0.72. According to Table 4.1, the responses for AM and PM in the future had similar results with a high mean (M) from 4.5 to 4.2, respectively. Those answers indicate that although residents are open to applying adaptive and permanent measures in the future, many do not have measures in place.

Moreover, the Pearson correlation was analysed to understand the correlations between RP and CC indicators. Figure 4.4 presents the graphical correlations of RP and CC indicators expressing the positive (pink), negative (blue) or non-significant (grey) relationships. As seen, most of the relationships are positive; for example, responsiveness ("adaptation measures taken") is positively related to "awareness" and "worry", which indicates that the residents who have more solutions in place are more aware of flood severity and concerned with subsequent flooding events. Likewise, the correlation of "worry" and "awareness" shows that more worried citizens classified the past flood events as more severe. Adaptation and permanent measures in the future are positively related to almost all key indicators. The negative correlations are mainly related to warning (P) indicator. Pearson correlation shows that even though residents do not receive many warnings (P), they still have "adaptation measures in place" (R), indicating that residents apply some solutions to mitigate flood damages even with the lack of warnings from the authorities before the event. The directions of each influence are detailed in Table 4.2.

The second phase of the influence analysis evaluated relations of social factors of residents (Figure 4.1) with RP and CC indicators (Table 4.1), where p-values < 0.05 are considered as significant. The results in Table 4.2 indicate that awareness was influenced by direct (M 4.35 p 0.00) and indirect experiences (M 2.7 p 0.00). Residents with direct experiences of floods (i.e., inside their properties or streets) have higher awareness. Still, indirect experiences (i.e., passing through a flooded street when going to work) also influence the awareness factor. This is particularly important because of the positive Pearson correlation where more aware and worried residents have more adaptation measures in place and aim to apply in the future (Figure 4.4 and Table 4.2).

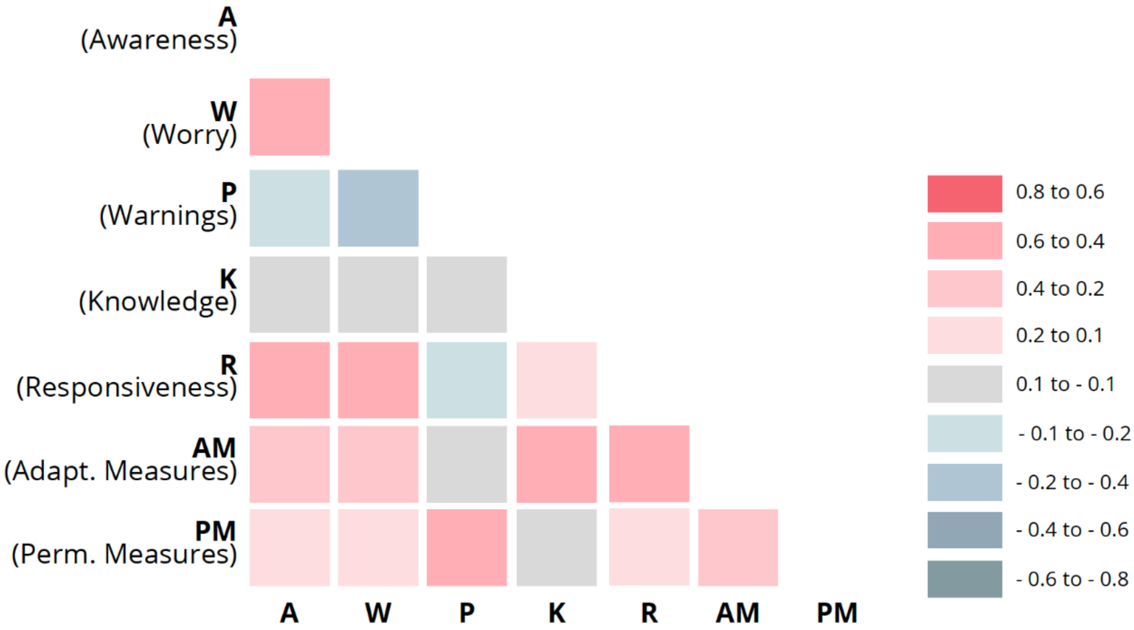

Figure 4.4 – Pearson correlations between risk perception and coping capacity indicators.

Other aspects related to geographical and contextual/cultural factors, such as living near the hazard (M 4.30 p 0.04) and owning the property (M 4.35 p 0.03), also influence awareness. Respondents are more aware when they live in a risk area and own the property, indicating more responsiveness to avoid flooding (Liu *et al.*, 2018a). The worry indicator also influenced “hazard proximity” (M 4.15 p 0.04) and “indirect experience” (M 3.69 p 0.00) factors. According to the Wilcoxon Z and Mann Whitney U tests, neither preparedness nor knowledge indicators received any substantial influence of social factors (Table 4.2).

For coping capacity, the adaptation measures taken are influenced by house ownership (p 0.003), age (p 0.009), and direct experience (p 0.000) factors. Answers from all social groups had low mean values for adaptive measures taken (M. 1.34), even the residents with direct experiences. This was clearly seen at the PLANEJEEE Project because only a few residents had flood barriers or altered the height of electrical fixtures on walls (Figure 4.3). Residents who own the property have more adaptation measures (M 1.12) than people that rent the place (M 0.79). Although this conclusion may seem logical, this result is not always evaluated since it depends directly on the residents that will be interviewed (Liu *et al.*, 2018a).

Table 4.2 – Final influencing factors of RP and CC. "p-value" was calculated with Wilcoxon Z and Mann Whitney U tests, and Pearson correlation was used to evaluate the influence between RP and CC indicators.

	Key indicator	Social factor with significant influence	p-value	Direction of influence in RP and CC (+,-)
RP	Awareness (A)	Direct experience Indirect experience House ownership Hazard proximity	0.000 0.000 0.028 0.037	Worry (+) Preparedness (-) Responsiveness (+) Adapt. Future (+) Perm. Future (+)
	Worry (W)	Indirect experience Hazard proximity	0.001 0.042	Awareness (+) Preparedness (-) Responsiveness (+) Adapt. Future (+) Perm. Future (+)
	Preparedness or warnings (P)	-	*Non-significant*	Awareness (+) Worry (+) Responsiveness (-) Perm. Future (+)
	Knowledge (K)	-	*Non-significant*	Responsiveness (-) Adapt. Future (+)
CC	Responsiveness (R, taken adaptive measures)	House ownership Age Direct experience	0.003 0.009 0.000	Awareness (+) Worry (+) Preparedness (-) Knowledge (+) Adapt. Future (+) Perm. Future (+)
	Adaptive measures (AM)	Management trust	0.010	Awareness (+) Worry (+) Knowledge (+) Responsiveness (+) Perm. Future (+)
	Permanent measures (PM)	Education	0.022	Awareness (+) Worry (+) Preparedness (+) Responsiveness (+) Adapt. Future (+)

Results significant at the p < 0.05 level; (+) indicates positive correlation and (-) indicates negative correlation

Similarly, age appeared to be an essential variable, where the respondents younger than twenty-five have more measures applied (M 1.73). To implement solutions in the future, people with less trust in management have fewer plans to use adaptive measures in the future (p 0.01), and literate residents are more willing to take permanent measures (M 4.23 p 0.02). Socio-economic factors, such as income, children, and gender, have not significantly influenced the risk perception and coping capacity indicators. In summary, the responses related to geographical factors (i.e., direct, and indirect experience and hazard proximity), contextual factors (i.e., management trust) and socio-economic factors (i.e., house ownership, age, and education) substantially influenced risk perception and coping capacity (Table 4.2).

4.1.4.2 The challenges faced in the institutional context

To fully comprehend how institutional vulnerabilities affect flooding risk mitigation, understanding the mitigation policy as an integral part of a broader development context is necessary (Cinner *et al.*, 2018). In this section, discussions of groups A and B were divided into multiple challenges, namely management, legislation, society, and collaboration, which are summarised in Table 4.3.

The main discussions of group B highlighted the challenges related to the "*location*" of properties. Location was also pointed in the RP and CC analysis, in which people who live in or near risk areas are more exposed to the hazards and have more awareness and worry (Table 4.3). Many of these properties are *illegal*, where the residents build or take ownership regardless of the area where it is located or the necessary legislation to properly construct. Part of these occupations refers to informal substandard occupations, mainly known as "*favelas*" or "slum areas", common areas on Brazilian municipalities (Fix *et al.*, 2021). Group B also highlighted the proximity of properties to the drainage channels also corroborates for the severe flooding cases.

Groups A and B suggested the "*social link between the residents and the place they live*" as one of the city's challenges for flood risk mitigation. When the residents were asked if their households are in a flood risk area, 65% answered "yes," and 22% answered "I don't know". To the respondents who confirmed, we asked the reasons they live in the area and the options "*I don't have money to move*", "*I don't have anywhere else to go*" and "*I got used to the situation*", were mainly selected with 27.1%, 25.2%, and 24.3% respectively. Residents also affirmed they live in the area because *"the flooding does not reach inside my property*", suggesting fewer damages in their houses. Other residents expressed to be financially and emotionally attached to the place where they live. This can be viewed in the answers from the residents B and C:

Resident B: *"I own this house; we like here, and my friends and family are here."*

Resident C: *"Here I have my family, but I live in a place that I can't sleep in peace anymore."*

Table 4.3 – Multiple challenges and solutions suggested by stakeholders for flood risk mitigation (FRM) in Campina Grande, Brazil.

Scales	Microscale	Challenges	Solutions/actions
MANAGEMENT	Location	Buildings located in risk areas[a,b,b+] Illegal properties in the flood risk areas[b+] Buildings near to channels[b+] Low income of residents[a,b,b+]	Relocate people from risk areas[a,b,b+] Map flood-prone vulnerable areas[b+] Create parks in flood risk regions to avoid urbanisation in the areas[b+] Develop strategies regarding the social context[b+]
	Maintenance	Lack of inspection by authorities[b+] Increase of urbanisation[a,b] Problems with design and maintenance of drainage network[a,b,b+]	Clearer maintenance and adoption arrangements[a,b] Effectively plan areas for urban growth in the city[b+]
	Government	Lack of interest of government[b]	Increase perception at developer and community level[a,b,b+]
LEGISLATION	Legislation implementation	Comply of legislation[a,b+] Uncertainty of legislation application[b+]	Comply of legislation[a,b,b+] Engagement with stakeholders[b+]
	Legislation improvement	Lack of monetary incentives[b+] Lack of space in legislation[b] Lack of funds/budget[b]	Development of mandatory standards[b,b+] Strengthen the Master Plan[b+] Ensure a participatory planning[b+] Proposal of mitigation measures in context with other hazards[a,b,b+]
SOCIETY AND COLLABORATION	Risk perception and coping capacity of citizens	Lack of knowledge and awareness of the population[a,b,b+] Low flexibility of population[a,b+] The social link between residents and the place[a,b+]	Improve communication with residents[a,b,b+] Raise perception and coping capacity[a,b,b+] Promote educational actions with residents[b+]
	Engagement and communication of stakeholders	Lack of appropriate risk communication[a,b,b+] Lack of public participation[b+] Lack of communication between stakeholders[b,b+]	Promote a "shared responsibility" campaign in the city council sectors and residents[b+] Promote "capacity-building" for stakeholders[b+] Promote collaboration between stakeholders[b+]

Challenges and solutions discussed in the PLANEJEEE Project: [a]= survey for group A (citizens), [b] = survey for group B (policymakers and local specialists), [b+] = workshop and focus groups

Groups A and B suggested to "*relocate the communities at risk*". Still, there is a need for finding an area where the citizens will be safer from flooding and making the necessary investment to make the citizens feel part of the area where they will live. At the same time, group B also suggested that solutions are not always beneficial for all population groups in the same way or to the same degree, which can intensify current inequalities. Concerns about the appropriate manner to relocate flood-vulnerable communities are discussed in other studies, affirming that rebuilding infrastructure can make vulnerable people even more vulnerable (Cinner *et al.*, 2018). Similarly, other studies highlight "environmental justice" and "equity" as a sensitive topic that can positively or negatively influence the current social conditions (Hendricks *et al.*, 2021), vulnerability (Vercruysse *et al.*, 2019) and exposure (Weis *et al.*, 2016). Hence, attention should be directed to the location (Eckart *et al.*, 2017) and to the dynamic character of vulnerability, which could make actions in one location undermine the efforts of other locations, people, and scales (Cinner *et al.*, 2018).

Group B demonstrated concerns about the uncertainty of legislation application, arguing that *legislation* is not clear. When asked about the critical challenges for applying mitigation strategies in management, the "*lack of space to apply mitigation strategies in policies*" was selected with 27.3% of the votes. Besides, stakeholders believed that if the legislation in place were applied, the number of flood risk issues would be smaller (Table 4.3). The key reasons for not implementing mitigation strategies when they are already predicted in the legislation were mainly "*costs/budget*", "*lack of awareness*" and "*lack of interest from local governments*". Other reasons like "*lack of understanding of what it is*" and "*maintenance*" were suggested for when the strategies are not yet in the legislation. In the focus groups, group B also emphasised challenges related to the "*weak inspection"* by authorities as well as problems with the "*design and maintenance of drainage structures"*.

Finally, the improvement of "*stakeholders' collaboration"* was expressly mentioned as a current challenge for FRM by Groups A and B. Literature classifies participation and cooperation as critical aspects of bridging the gap between science and policy (de Brito *et al.*, 2018). Engaging with local actors in management is considered essential to (i) defining risk mitigation actions and reducing *maladaptation* (i.e., or "bad" adaptation (Schipper, 2020; Schipper *et al.*, 2021)), (ii) to encouraging the adoption of actions by communities (Cheung *et al.*, 2019), and (iii) to improving the RP and CC of residents in the future (Danso *et al.*, 2016; Fuchs *et al.*, 2017). In this regard, the survey also assessed how residents would be keener to participate in flood management. They affirmed that would participate not only with monetary incentives (M 3.89 SD 1.80) but also if they knew their contribution "*was going to be listened*" (M 4.41 SD 0.68) and "*used in management*" (M 4.44 SD 0.72).

4.1.4.3 Future actions for flood risk mitigation

As the Project PLANEJEE also aimed to understand how the stakeholders identify actions for FRM in the city, Table 4.3 details stakeholders' suggestions according to the opinion of groups A and B. At this section, an overview of the solutions proposed to the cases I to IV is discussed (Figure 4.3).

The discussions of actions for "*Conceição*" (I) and "*Santa Cruz*" (IV) study cases (Figure 4.3) focused on the improvement of conditions in official risk areas (i.e., many times seen as "*favelas*"). Group B highlighted the need for *"transforming the place*" with sustainable solutions, such as SUDS (Sustainable Drainage Systems), Nature-Based Solutions (NBS) and Green Infrastructure (GI). This reflection was very important for analysing further actions since sustainable solutions are widely recommended in guidelines and legislations throughout the world, but their adoption in developing countries is still low (Almoradie *et al.*, 2020; Ronchi *et al.*, 2018). To understand stakeholders' perception of flood risk solutions, different options were provided to groups A and B. The highest efficiencies in this question were for management actions, such as maintenance of existing measures (M 4.47[a] and M 4.33[b]) and improvement of awareness and preparedness of citizens (M 4.47[a] and M 4.52[b]). Both groups scored green solutions with the lowest effectiveness, especially to green roofs (M 2.99[a] and M 3.30[b]), showing that even though local specialists and policymakers identified NBS as actions to be implemented in Campina Grande, they still consider these strategies as the least effective when compared to other options.

Suggestions were also proposed with regards to the multiple water-related hazards context in the area. The cases of "*Liberdade*" (II), "*Jardim Paulistano/Tambor*" (III) and "*Santa Cruz*" (IV) (Figure 4.3) considered the implementation of solutions that enabled to achieve benefits for both the water-related hazards. Rainwater harvesting (RWH) was suggested for cases I to IV, since the city also faces water shortage risk (Cordão *et al.*, 2020; Del Grande *et al.*, 2016a). This topic appears to have great importance for Brazil and other countries with opposite but simultaneous water-related hazards, such as flood and water shortage. In Brazil, drought and flood disasters have severely affected the country in recent decades (Ávila *et al.*, 2016; Lorentz *et al.*, 2016; Marengo *et al.*, 2009). Additionally, much is left to be accomplished in terms of basic services and infrastructures in the country (Ultramari, 2013). In 2016, a study from the National System of Sanitation Information of Brazil (SNS) found that 51.9% of the Brazilian population did not have access to appropriate sewage treatment (BRASIL, 2020). These structural, social, and financial vulnerabilities directly impact flood and water shortage mitigation, since the people with the lowest socioeconomic status can be the most vulnerable and live in the areas most at risk. For this, discussions in the PLANEJEEE Project also highlighted the need to only defining actions for FRM with the understanding of flood risk causations and vulnerabilities (Table 4.3).

The discussions made clear the expectation of obtaining *primary* (i.e., flood reduction) and *secondary* benefits (i.e., heat reduction, wellbeing, access to nature) with FRM actions and solutions. This is also shown in other studies, from which, O'Donnell *et al.* (2017), for example, recommend the promotion of "sustainable solutions" as strategies that can meet numerous policy and strategic objectives of different organisations and departments, in addition to providing benefits beyond the flood and water management function. Others consider that NBS and GI can assist in reducing vulnerabilities for areas facing flood risk (Dagenais *et al.,* 2016), as well as it can bring new social services that reduce the possibilities of citizens reoccupying the location and produce more spatial equity (Heckert *et al.*, 2018).

In summary, stakeholders of the workshop showed perception for proposing FRM actions and solutions within an urban planning approach, addressing multiple goals and benefits, while adopting adequate governance to tackle issues at city-scale (Table 4.3), such as the encouragement of "*shared-responsibility*" and "*educational ca*mpaigns" campaigns for implementing FRM actions, and the development of *collaborative strategies* for risk mitigation.

Finally, FRM actions also include increasing the perception at the developer and community levels, as an attempt to increase the uptake of mitigation strategies. According to group B, the responsibility to apply the mitigation measures must be shared by the community (34%), management companies (14%) and local authorities (46%). Details about the FRM actions proposed by groups A and B are fully described in Table 4.3. Discussions recognise how actions and solutions towards risk mitigation must be incorporated within a sustainable urban management, linking vulnerabilities, adaptability, inequalities, equity and risk.

4.1.5 Conclusions

The main objectives of this study were to present how social and institutional vulnerabilities could be integrated into the analysis of flood risk mitigation in a participatory approach (RQ1) and the analysis of how the stakeholders see the main challenges and solutions for flood risk mitigation (RQ2). The objectives were answered with the formulation of a participatory approach in Campina Grande – Brazil, which aimed to provide insights into the underlying causes of flood vulnerabilities, especially looking into social and institutional contexts that may generate vulnerabilities and worsen flood risk impacts and resilience (Figure 4.2).

The analysis of social vulnerabilities was made through RP and CC, which showed that residents faced severe previous flood risk events in the past (“A”, M 4.4) and have concerns about the future floods (“W”, M 4.3 of Table 4.2). Other social challenges were seen since residents affirmed to receive inappropriate warnings before the flood (“P”, M 1.7) and only have a few measures in place for reducing flood risk impacts (“R”, M 1.34). When asked about solutions, they agree that solutions in their households can mitigate the impacts from the flood event (“K”, M 4.2), and that they plan to make investments in their properties to reduce flood risk (“AM”, M 4.5). Also, residents would move to another least flood-risk area (“PM”, M 4.2).

Results have shown that social factors seemed to affect each RP and CC indicator differently (Table 4.2). The geographical and informational factors (i.e., direct, and indirect experience and hazard proximity) were correlated with “A”, “W”, “R” (Table 4.2). Socio-economic and geographical factors, especially age, house ownership, and direct experience, influenced the adaptive measures taken, in which young people, house owners, and people with previous cases of flooding inside their properties had more solutions applied. Contextual factors, such as management trust, influenced the knowledge indicator whereas the socio-economical factor (education) influenced the decision to move house permanently (Table 4.2). Future research will investigate how these social factors can be incorporated for improving the conditions of people at risk of flooding. Additionally, since the city faces flood and water shortage risks, the evaluation of RP and CC of residents towards the two water-related disasters should be assessed to propose collective actions that can benefit society towards the compound risks, as suggested in the participatory approach.

Through the investigation of institutional vulnerabilities, insights of reasons for the failure of the flooding risk management are provided, such as the issues with maintenance of current infrastructures, lack of interest of the government to mitigate FR, the number of properties located in risk areas, or near to channels, the lack of mappings of either vulnerability or flood-prone areas. For the legislation, stakeholders suggested the lack of clarity of current laws, the lack of monetary incentives, and the lack of appropriate risk communication and collaboration with residents as main challenges (Table 4.3). In this regard, stakeholders suggested multiple actions for FRM, which were discussed in relation to management, legislation, society, and collaboration challenges (Table 4.3). When looking specifically into the use of sustainable solutions for FRM, stakeholders appear to agree with their implementation in the future; however, results show they still consider grey infrastructure the more effective.

The results presented in this article enabled to discuss, through a study case in Brazil, how stakeholders can be involved for understanding social and institutional vulnerabilities in the context of flood risk mitigation. This article emphasises the need for tackling risk mitigation beyond the hazard and the technical aspects of solutions, focusing on the understanding of the specificities of the place and current vulnerabilities. Finally, we consider the discussions provided in this article can provide insights for the dialogue about actions to FRM in Campina Grande (Brazil), and other cities in similar contexts.

Acknowledgments

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4.2 Place-Based Citizen Science for Assessing Risk Perception and Coping Capacity of Households Affected by Multiple Hazards (article 02)

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Abstract
Since hazards act upon vulnerability and exposure to become disasters, the understanding of societal challenges is key for disaster risk reduction. This condition is even more critical when more than one hazard is in place. Taking the case of flooding and water shortage, this study is built upon the premise that disasters are a social phenomenon; therefore, it is essential to comprehend the social context in which they occur. Particularly, this study aims to evaluate the similarities and differences in risk perception and the coping capacity of residents in the multiple-hazard context. For this, a place-based citizen science approach was developed in this study in Campina Grande, a semiarid region of Brazil, with the collaboration of 199 participants. Risk perception and coping capacity were analysed through the citizens' participation, while combining subjective and objective methods. The results indicate that even though residents have experienced severe flooding and water shortages in the past, they still have low coping capacity. The findings highlight the need to combine a triad of societal challenges, namely information, trust, and incentives, to improve coping capacity in the future and increase resilience. This study underlines the need to understand multiple hazards according to social, spatial, and temporal scales in a socio-spatial perspective.

Keywords: disaster; multiple hazards; risk perception; coping capacity; flooding; water shortage

4.2.1 Introduction

Disasters are a social phenomenon (Cutter *et al.*, 2008). According to United Nations Office for Disaster Risk Reduction (UNDRR), disasters are a serious disruption to the functioning of a community or a society at any scale. Hazardous events interact with conditions of exposure, vulnerability, and capacity, leading to one or more of the following: human, material, economic and environmental losses, and impacts. People who are socially, economically, culturally, politically, institutionally, or otherwise marginalised are especially vulnerable to climate change and also to some adaptation and mitigation responses (IPCC, 2014). This intensified vulnerability is the product of intersecting social processes that result in inequalities in socioeconomic status and income, as well as exposure (Djoudi *et al.*, 2016; Kaijser *et al.*, 2013). Such social processes include, for example, discrimination based on gender, class, ethnicity, age, and (dis)ability (Gambe, 2018; Hoekstra, 2016). Other social configuration sources can also intensify vulnerabilities, such as the political and sociocultural context, and geographical location (Lechowska, 2018).

In the literature, concepts of perception, coping, adaptation, and mitigation have definitions that often appear concurrently and occur alongside discussions on vulnerability and resilience. Although these concepts together form a network of resources that at high levels create resilience and at low levels create vulnerabilities, they have been applied differently in disaster risk approaches. Risk perception is a fundamental factor in understanding the population's responses to hazards. In other words, it describes the level of preparedness for hazard occurrences (Daramola *et al.*, 2016). Therefore, the empirical knowledge about the risk that people acquire through the information communicated and their own experience are defining elements of risk perception. According to Renn (2004), perception of risk must be seen as a mental or sociopsychological instrument that allows for the prediction of future dangers and facilitates risk reduction measures.

The processes that contribute to disaster risk management and reduction comprise coping, adaptation, and mitigation measures. We distinguish between coping, adaptation, and mitigation following the terminology derived from the universal concepts. The term coping capacity is the ability of people, organisations, and systems, using available skills and resources, to manage adverse conditions of risk or disasters (UNISDR, 2021). Adaptation refers to the process of adjustment to actual or expected climate and its effects to moderate harm or exploit beneficial opportunities (IPCC, 2014). Lastly, mitigation is the lessening or minimising the adverse impacts of a hazardous event (UNISDR, 2021).

Despite the similarity and overlapping of these definitions, coping measures are emergency reactions to a specific event that often take the form of reactive, immediate, and informal schemes (Lund Schlamovitz *et al.*, 2020; Westoby *et al.*, 2020). Adaptive strategies, on the other hand, are actions before the disaster, typically medium and long term. In turn, mitigation involves strategies that reduce the severity of the impacts of disasters that cannot be avoided (for example, structures resistant to hazards). The three types of responses can transform and evolve on the temporal and spatial scales. Coping strategies can develop into adaptive strategies, which in turn can become mitigation strategies over time and as the scale changes. Coping strategies are more likely to occur at the local scale, at the individual and family level, and adaptive strategies are more likely to emerge at larger spatial scales, from a sector or neighbourhood, or the entire city (Jolly, 2001; Westoby *et al.*, 2020; Whitney *et al.*, 2017). For their part, mitigation strategies can involve even larger scales, up to municipalities and jurisdictions.

Daramola *et al.* (2016) argued that while coping strategies are needed in the aftermath of disasters, they may not always represent desirable options for households (for example, relocating furniture to upper floors and temporary migration). In contrast, strengthening adaptive capacity serves to reduce the establishing of the risks associated with disasters. Norris (Norris *et al.*, 2008) defined adaptive capacities as resources with dynamic attributes of (i) robustness, i.e., the resource strength in combination with a low probability of deterioration; (ii) redundancy, i.e., the extent to which elements are substitutable in the event of disruption or degradation; and (iii) rapid accessibility, i.e., how quickly the resource can be accessed and used. The interaction between these available resources and disaster risk factors produces different responses due to the social differences between individuals, families, and communities.

Due to the relationship between the risk of disasters and the existing social configurations, we agree that disasters are a social event. In this way, vulnerability is a dynamic factor that changes as the coping, adaptation, and mitigation arrangements develop. We argue that coping, adaptation, and mitigation are processes that, in this sequence, advance to generate risk reduction. As risk reduction strategies begin with coping strategies and move towards adaptation and mitigation strategies, the processes used evolve, reduce vulnerability, and increase resilience.

The reduction of vulnerability can be even more complex in regions with multiple hazards. Multi-hazards coexist when two or more disasters occur simultaneously or in succession (Kc *et al.*, 2020; Wang *et al.*, 2020). A study from Pagliacci *et al.* (2020) observed positive correlations between multi-hazards, exposure, vulnerability, and risk. The results express clear trends of interaction between the disasters' drivers which amplify the multiple hazards impacts. This means that due to the multiplicity of simultaneous risks, many citizens may already have a vulnerability (i.e., from another hazard) and at the same time may need multiple resources for preparation. This condition was highlighted by Aksha *et al.* (2020), whose work show the cumulative and cascading impacts produced using integrated hazard maps as a function of spatial information (e.g., Geographic Information System - GIS) and socioeconomic data. According to Kc *et al.* (2020), in the future, urban areas will be even more susceptible to multiple risks due to the increase in population and infrastructure concentration.

Even though the importance of integrating multiple hazards is recognised, especially floods and droughts, most research on hydrological risks tends to focus on either flood risk or drought risk (Ward *et al.*, 2020). Certain locations may suffer flooding and may also experience extreme drought in some years and extreme precipitation in others, even in dry periods; this means that these areas can be facing either water shortage or flooding or both in different times (temporal scale). Temporal and spatial dynamics of disasters are particularly important given that design and implementation of disaster risk strategies can reduce risk in the short term but may increase exposure and vulnerability in the long term (IPCC, 2014).

Therefore, this paper considers the importance of understanding the multiple hazards in both spatial and temporal scales (Ruiter *et al.*, 2020), by linking it with the concept of vulnerability and resilience, and considering the position and situation as elements that produce hazards, while also giving conditions to face them (Santos *et al.*, 2017b). With the premise that disaster risk is social, we acknowledge the importance of understanding vulnerabilities and human interactions to comprehend the social context in which the disasters occur (Kelman, 2020), and to evaluate ways to minimise the hazards with the implementation of mitigation strategies (Tassi *et al.*, 2016; Wright *et al.*, 2020).

For this, we developed a place-based citizen science methodology (Fraisl *et al.*, 2020; Mueller *et al.*, 2018) with the participation of stakeholders including residents, authorities, and specialists. A total of 199 participants collaborated in our project, plus 10 from the project team. The context in the study is Campina Grande, Brazil; it is a city with multiple-hazard occurrence (i.e., flooding and water shortage), which implies more complexity in management (Alves *et al.*, 2020e). The city has low public participation in the management and issues related to legislation and governance, such as integration between water resources and urban planning (Grangeiro *et al.*, 2019). This study is built upon answering this question: *"How can we improve the uptake of coping capacity strategies, in the* *future, when residents face multiple hazards?"* Particularly, our study aims to understand more deeply the social vulnerabilities in the multi-hazard context by answering two research questions:

1. In what way are the risk perception (RP) and coping capacity (CC) of residents similar (or different) when facing flooding and water shortage?
2. What are the main preferences of mitigation strategies to mitigate the hazards?

This paper is organised as follows. First, the case study is presented along with the socio-spatial context of floods and water shortage. Then, aspects of the place-based citizen science framework are explained. Thirdly, the differences and similarities of the risk perception and coping capacity (RQ1) and mitigation (RQ2) of each hazard are detailed. Afterwards, a discussion about the key societal challenges for improving coping capacity is offered by looking at the impacts into vulnerability and resilience. Finally, the study draws up some conclusions about the management of multiple hazards.

4.2.2 Case study

Campina Grande in Brazil is the second-most urbanised city in Paraíba state (PB), with more than 400,000 inhabitants (IBGE, 2021). The city is located in the countryside, but it is an urban area (Miranda, 2017), which makes it an important route of mobility between cities and states.

From the environmental point of view, the city faces two water-related hazards. On the one hand, the city lacks water due to the dry climate of the semiarid region (Figure 4.5), but on the other hand, when it rains (a concentrated rain), the city experiences flooding (Alves *et al.*, 2020e). Reports provided by the Civil Defence show flood cases at different scales (buildings and part of streets). At the other end of the spectrum, the Water Company Agency (CAGEPA) imposes water rationing periods on a city scale (Cordão *et al.*, 2020) by dividing the urban area into two operational zones and spreading the rationing period in the weekdays (for example, zone 1 will have water from Monday to Thursday, and zone 2 from Friday to Sunday). From this, we can infer that each hazard happens in a different spatial scale (Figure 4.5).

Due to the multiple-hazard character of the city, the population of Campina Grande is forced to adapt to two differing water-related hazards. In this sense, we believe that understanding the perceptions and behaviours of these residents can improve the proposal of mitigation strategies and achieve resilience from a long-term perspective.

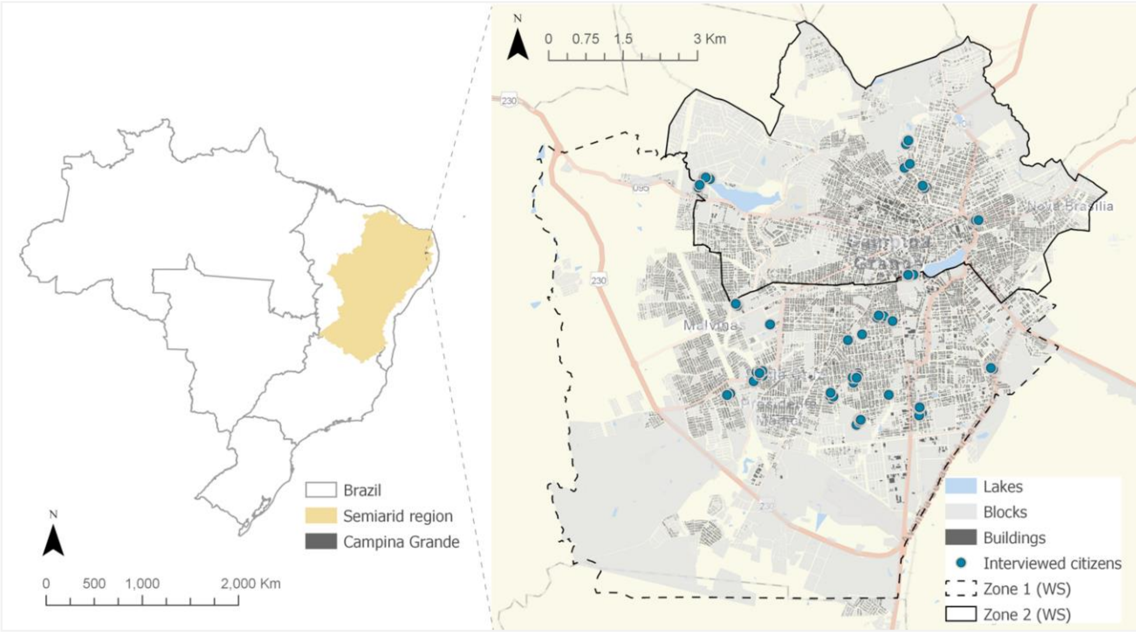

Figure 4.5 – Location of Campina Grande in the Brazilian semiarid region.

4.2.3 The socio-spatial context

Since each hazard has a spatial scale but only becomes a disaster with the component of social interaction (e.g., see the disaster risk definition from IPCC (2014)), we classified the complex system (i.e., the city) with a socio-spatial view (Figure 4.6). This analysis was inspired with the perspectives presented by Ruiter et al. (2020), in which temporal and spatial scales were discussed for consecutive hazards (more details are available in Ruiter *et al.* (2020)). Our approach presents an analysis for flooding and water shortage (WS) not only according to the temporal and spatial scales, but also concerning the social view (or exposure scale) as an attempt to better characterise the view from the residents who are forced to cope with hazards in different scales. The analysis can be applied to multiple hazards and different characteristics.

Figure 4.6 illustrates that flooding can take place in only a few minutes or hours (temporal scale). Moreover, flooding can create impacts to specific households (and streets) in the spatial scale. Damages can be indirect or direct, depending mainly on the vulnerabilities at the time of the hazard occurrence. On the other hand, water shortage can have two different behaviours. First, there are specific places (spatial scale) in the city that can have a lower water supply in normal days (i.e., not in the dry season) due to losses and problems in the network (Cordão *et al.*, 2020). This can last for hours, days, and weeks. However, in the dry season (i.e., rationing days), due to management choices, the whole city is exposed to the hazard, which can last for weeks, months, and years.

Citizens are expected to face and cope with hazards of different nature and spatial and temporal scales. On one side, the population located only in a part of the city is exposed to flooding and WS on normal days, but on other days (or months, years), the whole city can be exposed to the hazard of WS on rationing days. Due to the character of the hazards, flooding can happen in dry years or in a period of a lack of water on normal days, which makes the same population exposed to more than one hazard on the same temporal scale.

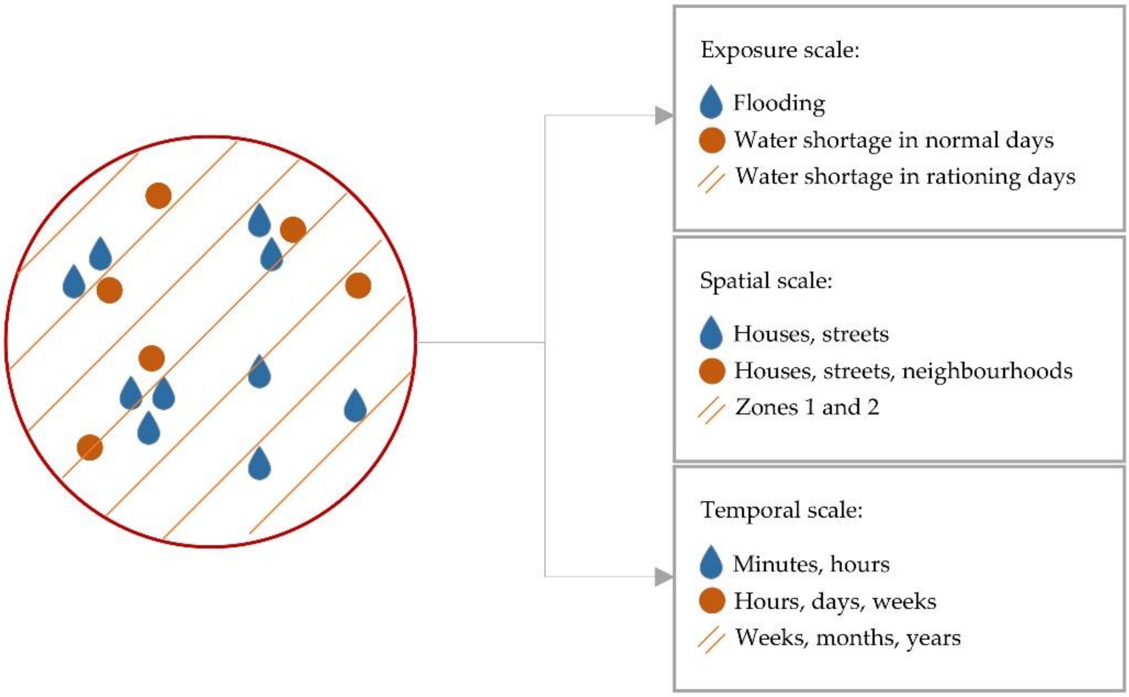

Figure 4.6 – The complex socio-spatial context of water shortage and flooding. Each disaster is described in three main scales: exposure (or social), spatial, and temporal.

Although WS and flooding generate direct and indirect impacts to the exposed population, we suggest that other factors are sources of vulnerabilities that may increase the damages. Particularly, we highlight that the way which citizens cope with the event can increase or decrease the vulnerabilities. If a community implements sufficient coping responses, the impact of the hazard event may be attenuated (Cutter *et al.*, 2008). For example, housing conditions (i.e., building materials) can increase the effects of flooding. On the other hand, rainwater harvesting can reduce the impacts for WS (and flooding). Vulnerabilities are considered as a combination of behaviours and attitudes that may influence the actions (or choices) for hazards mitigation in the socio-spatial context. Here, we analyse the vulnerabilities as “key societal challenges” faced by the exposed population that have a crucial role for increasing the resilience (Norris *et al.*, 2008).

4.2.4 Methodology

Citizen science terminologies are dynamic and change over time (Eitzel *et al.*, 2017). Throughout this study, the definition of citizen science (CS) provided by Lewentein (2016) is used. The author characterised CS as a science to society and also as participatory citizen science, where people mostly contribute observations or efforts for the scientific enterprise (a complete description is detailed in Eitzel *et al.* (2017)). In this paper, the place-based citizen science is used as a tool that provides more means to understand the social environment in which disasters take place (Hardoy *et al.*, 2019). Our method is based on three steps detailed below.

4.2.4.1 The Place-Based Citizen Science project

The citizen science was conceptualised in a participatory approach, i.e., Project PLANEJEEE (abbreviated from *Planeje Eventos Extremos* in Portuguese, translated as “to plan extreme events”*),* from May to June 2019. The project had the participation of 172 residents and 27 specialists and policymakers in different collaboration strategies, including surveys, informal meetings, workshops, and discussion groups. The sample size for residents’ participation was calculated through the simplified Yamane’s formula (Yamane, 1967). Data from the Geological Survey of Brazil (CPRM) show that 2156 citizens were in the risk areas of Campina Grande in 2014. From this, the sample size with a minimum of 96 people with an error acceptance of 10% was determined using Equation (4.1).

$$n = \frac{N}{1 + Ne^2} \quad \text{Equation (4.1)}$$

where *n* is the sample size, *N* is the total number of residents, and *e* is the error acceptance value. Data were obtained to cover other areas of this research, but only results related to the comparison of social vulnerabilities of residents are discussed here.

4.2.4.2 Questionnaire conceptualisation

The questionnaires were given to all stakeholders and intended to cover three main areas (Figure 4.7) from the definition of social factors to the proposal and evaluation of mitigation strategies. Residents participated according to their geographic location. Since water shortage occurs in the whole city and flooding occurs localised in the municipality (Figures 4.5 and 4.6), we applied the questionnaire to residents mainly in danger of flooding, with the premise that those areas will also be affected by water shortage.

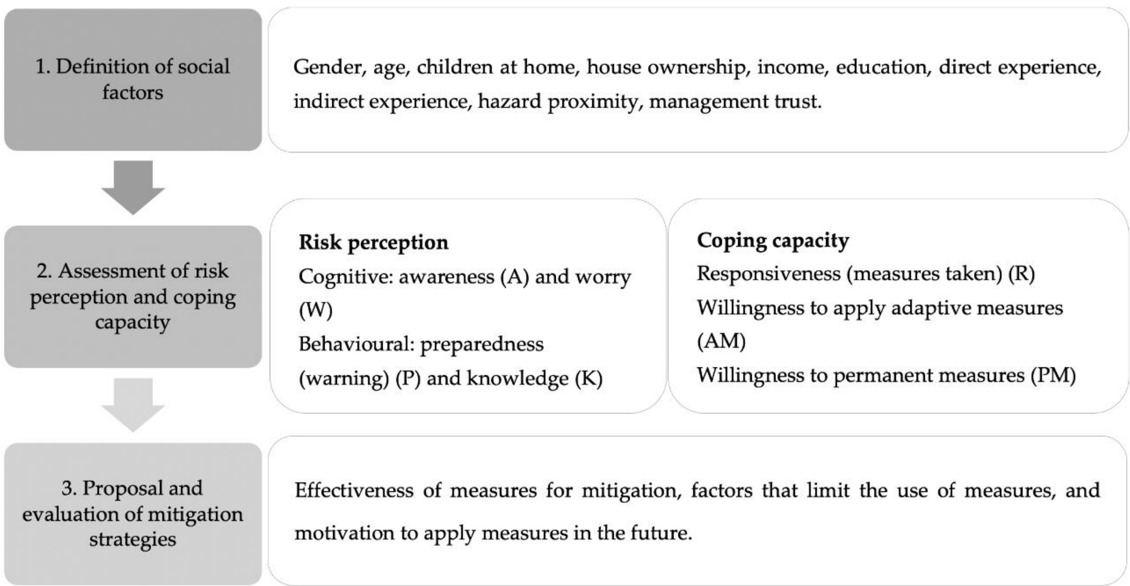

Figure 4.7 – Areas of analysis with the questionnaire application in the PLANEJEEE (Planeje Eventos Extremos) project.

From the 172 respondents, 95% experienced flooding before, and 96% experienced water shortage before. The questionnaire had two sections, i.e., flooding and water shortage, each with 30 questions that aimed to reflect the indicators spread in each area of analysis (Figure 4.6). During the participatory approach, the city was not facing rationing periods. However, due to the intermittent supply issues, many residents face a water supply reduction on “normal days” (see more details in the socio-spatial context in Section 4.2.3). The participatory approach and survey application had the support of undergraduate and postgraduate students at the Universidade Federal de Campina Grande (UFCG) and the Civil Defence.

4.2.4.3 The analysis of risk perception and coping capacity (RQ1), and preferences of mitigation measures (RQ2*)*

The risk perception (RP) and coping capacity (CC) were analysed with socio-psychological indicators. The indicators aimed to express how people perceive the risk before the occurrence (i.e., RP) and how they cope (i.e., CC) with adaptive and permanent measures in their household. Coping and adaptive capacity were analysed at the household level (i.e., measures that citizens can apply them in their home), and the mitigation capacity at the city scale (i.e., measures applied in the urban area). The third area of analysis (Figure 4.7) evaluated how likely the residents would agree with some measures to reduce the impacts of flooding and water shortage. Here, we aimed to understand how the residents see the effectiveness of mitigation measures.

Respondents could answer the questions with a 1–5 Likert scale, expressing how likely they agreed with the options (i.e., 5 as expressing strong agreement and 1 as least agreement). The answers were plotted in a RP and CC wheel that accounts for answers for both hazards and facilitate comparisons in the next section of this paper. The influence of each social factor (Figure 4.7) was analysed on the RP and CC indicators according to Wilcoxon Z and Mann–Whitney U tests, in which *p*-values lower than 0.05 are considered as significant (de Brito *et al.*, 2017).

4.2.5 Results

This section is divided into three main phases. First, the results obtained with the social factors are presented. Secondly, the analysis of risk perception and coping capacity and, thirdly, the perceived effectiveness of mitigation measures are presented and discussed.

4.2.5.1 The Social Factors

Social factors were divided in four groups: (i) socio-economical, (ii) informational, (iii) geographical, and (iv) contextual and cultural. The choice of social groups was based on studies of (2014; Bryan *et al.*, 2019; de Brito *et al.*, 2017; Fuchs *et al.*, 2017; Liu *et al.*, 2018a; Marfai *et al.*, 2014; Nguimalet, 2018); full details are presented in Table 4.4.

Socio-Economical Factors

The majority of respondents were female (65%). From the total, 38% of the respondents were over 55 years old, and 80% of the residents received fewer than 2 wages per month. In addition, 12.2% were illiterate, 48.3% completed only the first grade in school, and only 8.2% had a university degree.

Most respondents (75.3%) own property. Other questions were also asked that were intended to survey details about living conditions; it was found that 94% were houses and 69.8% of the residents lived in the same place for more than ten years. About the number of people in households, 48.2% had more than four people living in the property with at least one child in 47% of the properties. These questions were essential to further evaluate the previous experiences with the hazards and the choice of application of coping and adaptive measures at the household level.

Information and Geographical Factors

From the 172 residents, 94.8% confirmed having faced flooding before (i.e., indirect experience) and 75.46% affirmed the flooding reached inside their properties (i.e., direct experience). They were also asked whether they had any damage and whether they had to be removed from their households in any of the experiences, in which respectively 43.6% and 63% answered positively for these questions. Even though the selection of areas was mainly flooding based, 95.9% of the residents confirmed to also have issues with water shortage (i.e., direct experience).

Table 4.4 – Division of social factors into four groups covered in the PLANEJEE questionnaire: socio-economical, informational, geographical, and contextual

Social Groups	Social Factors	Classification	Percentage (%)		
			General	Water Shortage	Flooding
Socio-Economical	Education	Illiterate	12.2	-	-
		Literate	87.8	-	-
	Gender	Feminine	64.5	-	-
		Masculine	35.5	-	-
	Age	Less than 25 years	6.4	-	-
		25–35 years	16.4	-	-
		35–45 years	19.8	-	-
		45–55 years	19.8	-	-
		More than 55 years	37.8	-	-
	House Ownership	Own	75.3	-	-
		Rent	17.1	-	-
		Other	7.6	-	-
	Income	Less than 1 wage	23.6	-	-
		1–2 wages	56.4	-	-
		2–4 wages	10.3	-	-
		More than 4 wages	1.2	-	-
		Rather not to say	8.4	-	-
	Children	With children	47.1	-	-
		Without children	52.9	-	-
Informational	Indirect Experience	With ind. experience	-	-	94.8
		Without ind. experience	-	-	5.2
Geographical	Direct Experience	With d. experience	-	95.6	75.46
		Without d. experience	-	4.3	24.54
		I don't know			5.52
	Hazard Proximity	Living near hazard	-	-	64.7
		Not living near hazard	-	-	13.5
		I don't know	-	-	21.8
Contextual and Cultural	Management Trust	1 (very low trust)	-	37.8	51.2
		2 (low trust)	-	21.5	19.8
		3 (moderate trust)	-	12.2	11.0
		4 (high trust)	-	18.0	13.4
		5 (very high trust)	-	10.5	4.7

Contextual Factors

Another question was aimed to evaluate how the residents trusted in the management bodies to manage each hazard; the residents could answer with the

1 to 5 Likert scale. Responses showed that 51.2% and 37.8% have “very low” (score 1 of the Likert scale) trust in public authorities to manage flooding and water shortage, respectively. From this, it is possible to see that residents trust more in the management of water shortage than flooding.

4.2.5.2 Risk Perception and Coping Capacity

The risk perception analysis was based on four indicators that cover the cognitive and behavioural factors of residents (Figure 4.7). Each indicator was analysed with specific questions that are detailed in Table C1 (Appendix C). Figure 4.8 shows the mean answers of each indicator to the water-related hazards. Overall, two indicators, i.e., awareness and worry, had high mean values in both hazards (Figure 4.8), with slightly higher values for the flooding. This indicates that residents consider the flood and WS events as very severe and are very worried (from 4 to 5 on the Likert scale) about other similar events in the next 10 years.

In both hazards, the lower answers can be seen in the preparedness indicator (P). Preparedness generally refers to activities that improve the readiness to respond to a disaster, and we focus here on community preparedness and early warning systems. This is a broad concept, and many activities can fall under its umbrella, but it is distinct from hazard mitigation, which typically involves specific investments undertaken to lower damages from an event. For this question, we asked the respondents how likely they are to receive warnings before the extreme event. The mean answer for flooding was 1.7 (standard deviation (SD) = 1.24; variation (CV) = 73.26) and 3.32 for water shortage (SD = 1.60; CV = 48.09). Answers show that residents receive more warnings for water shortage than for flooding, which was expected due to the different temporal scales of the hazards.

Risk communication and warnings are considered as critical social problems in risk management (Ajibade *et al.*, 2014). Communication has uncountable benefits since it can better prepare the residents before, during, and after the hazard. According to Kelman (2020), in the case of a disaster, it is extremely important to provide enough information for residents to enable them to prepare and protect themselves before the disaster occurrence. Another study from Nguimalet (2018) emphasised the need for preparedness; this is not only restricted to “warnings” but also decentralised decision-making and effective engagement, especially in developing countries. To better understand the societal challenges, we asked how the residents are usually informed about extreme weather events; 49.6% and 16.8% affirmed that they use television and social media, respectively. Since the PLANEJEEE project had mixed age respondents (Table 4.4), these options can indicate ways to inform people about the hazards' occurrence effectively.

The answers of knowledge indicator show that people think that they can apply measures for protecting and reducing hazards impacts at home, with a slightly higher answer to water shortage (i.e., M 4.37^{WS}; M 4.19^{F}). This does not necessarily mean that they will apply measures, but it does show that residents know it is possible to protect themselves from the hazards.

Three questions analysed the coping capacity for the household level. First, residents were asked whether they have coping measures in place to avoid the extreme event (responsiveness indicator). The main answers showed 1.34 for flooding (SD 1.21 and CV 91.94) and 1.77 for water shortage (SD 1.11 and CV 62.62). This indicates that although people agree that they can apply measures at their homes (i.e., knowledge indicator), consider the hazard very severe (i.e., awareness indicator), and are very worried about other events in the future (i.e., worry indicator), they do not have many protection measures at the household level. In addition, we asked them what the main factors that can limit the use of measures by the population were. Money was considered as the main constraint, where 57% scored 1 (1 to 5 Likert scale). About the motivation to apply the measures in the future, the majority answered that they would be keen to use more measures with a tax relief (49.4% answered 4 and 43% answered 5 scales). Other motivations such as "if I knew it was really going to be effective" and "if a strong flooding or water shortage happened" also had high means (M = 4.33 and M = 4.30, respectively).

During the survey application in the PLANEJEEE project, some mitigation measures were seen in the households. Examples are water butts and tanks (Figure 4.8 A, B) for water shortage and barriers for flooding (Figure 4.8 C, D). Other questions asked about their willingness to apply adaptive measures (AM) or permanent measures (PM) in the future, and residents answered that they would be keen to do it in both hazards.

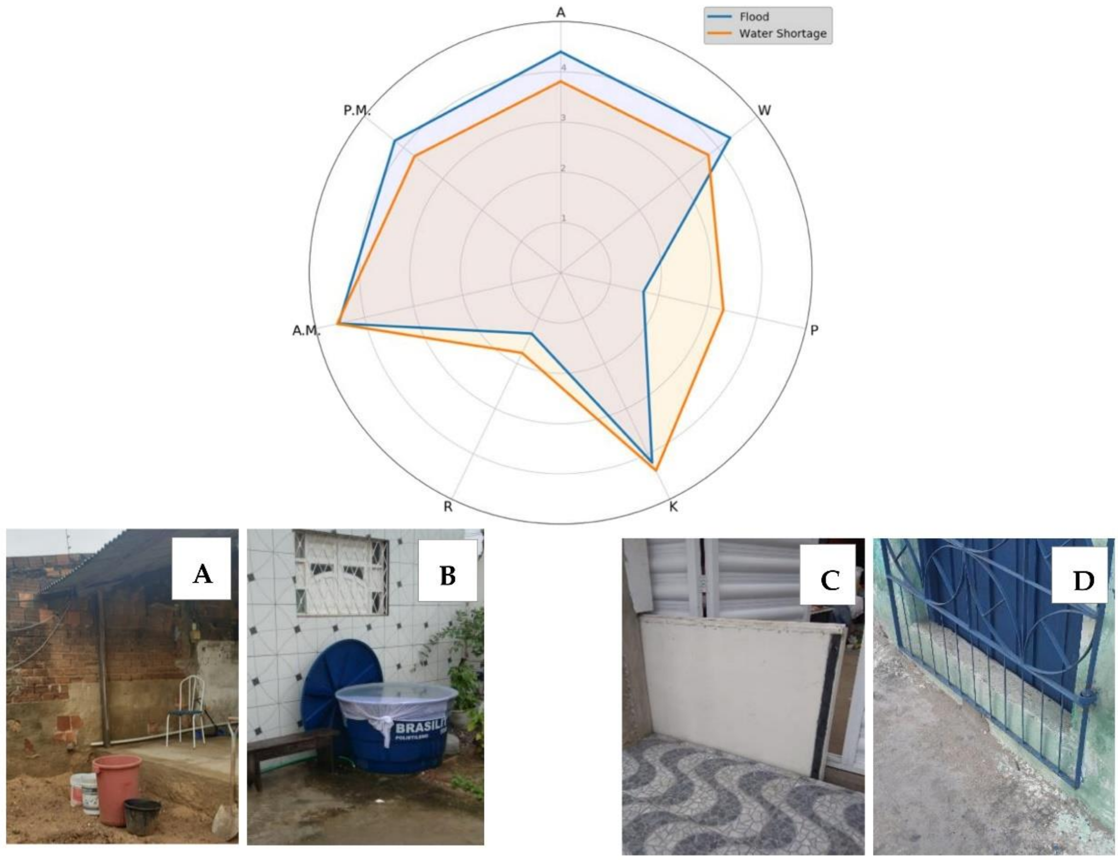

Figure 4.8 – Risk perception and coping capacity wheel to each hazard in study. Photos (**A**), (**B**), (**C**), and (**D**) were obtained in the PLANEJEEE project with authorisation of residents. (**A**) and (**B**) are water tanks and water butts to save water in the WS, and (**C**) and (**D**) are barriers to avoid the entrance of flooding waters.

The second phase of risk perception and coping capacity was the analysis of the influence of each social factor, according to Wilcoxon Z and Mann–Whitney U tests. In risk perception, for flooding, the residents with direct (p = 0.000^{F}) and indirect experience (p = 0.000^{F}), house ownership (p = 0.028^{F}), and hazard proximity (p = 0.037) presented more differences in the awareness indicator. For WS, the influence was given by direct experience (p = 0.000^{WS}), income (p = 0.041^{WS}) and age (p = 0.048^{WS}). Full details can be seen in Table F2 in Appendix F. Although this analysis shows that independent socio-economical, informational, geographical, and contextual groups have an influence on RP indicators, which express the importance of considering different social information, the analysis also indicates that a different type of social constraint influenced each cognitive and behaviour indicator. It mainly suggests the importance of analysing the influence of diverse social indicators to RP and CC.

Similar behaviour is seen in coping capacity. For responsiveness, house ownership (p = 0.003^F), age (p = 0.009^F), and direct experience (p = 0.000^F) were representative for flooding. However, no social group was influenced by the answers for WS responsiveness. For applying adaptive measures in the household, only management trust was representative (p = 0.010^F). Education (p = 0.022^F) was seen to influence permanent measures for flooding and age (p = 0.05^{WS}) for WS. In summary, the influence analysis shows that social groups are interrelated with RP and CC in different ways to each extreme event, which highlights the need to build more multi-disciplinary analyses to provide more understanding in how/what/why social factors influence the perception and adaptability.

4.2.5.3 Preferred of Strategies to Mitigate the Hazards

Residents were asked how they see the efficiency of structural and non-structural measures for reducing flooding and water shortage, including infiltration and retention, as well as grey and green strategies (Table 4.5). For flooding, the lowest efficiencies were found related to the green measures (items C–F), mainly to the use of green roofs (M = 2.99). In addition, the highest variances were also seen in these options (CV > 25%), which indicates that residents have less agreement in these options. The highest efficiencies are mainly related to management actions, such as the maintenance of existing measures (item B) and improvement of awareness and preparedness of residents (items H and I). This is an indication that residents prefer proven technologies (Leigh *et al.*, 2019). The analysis shows that green and infiltration measures are less supported as ways to reduce flooding in comparison with structural measures (item A). For water shortage, both management and structural measures (items J–O) are seen as effective with very low variance in answers (CV lower than 20%). The residents appreciate the high efficiency of rainwater harvesting to mitigate the effects of water shortage (M = 4.31), but they do not consider it as effective for flooding (M = 3.75).

These results can be an indication of the need for preparing the personnel and residents for the advantages of strategies such as green infrastructure (GI) and nature-based solutions (NbS) (Ruangpan *et al.*, 2020). In 2020, the IUCN defined

NbS as "actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges (e.g., climate change, food and water security or natural disasters) effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits". We argue that another critical point for implementing NbS in disaster planning is social participation. Exchange of information will be possible when individuals who experience risky situations report their experiences and solutions; on the other hand, policymakers can provide knowledge to citizens. The proposal of solutions must take social justice into account (Heckert *et al.*, 2018; M.B, 2012) and provide co-benefits (Albert *et al.*, 2020).

Table 4.5 – Perceived effectiveness of mitigation measures to each hazard.

	Flooding Mitigation Measures	**Mean**	**SD**	**CV (%)**
A	Design and implementation of new protection measures	4.25	0.71	16.7
B	Maintenance of existing protection measures (drainage system, channels)	4.47	0.61	13.6
C	Construction of green areas in the city	3.92	1.09	27.9
D	Use of green roofs in the buildings	2.99	1.23	41.1
E	Use of rainwater harvesting	3.75	1.08	28.9
F	Use of pavement permeable in the city	4.17	0.86	20.6
G	Ensure better land use management plans	4.33	0.59	13.7
H	Improve awareness of citizens	4.47	0.58	12.9
I	Improve preparedness of citizens	4.45	0.65	14.6
	Water Shortage Mitigation Measures	**Mean**	**SD**	**CV (%)**
J	Design and implementation of new protection measures	4.17	0.71	17.1
K	Use of rainwater harvesting	4.31	0.70	16.1
L	Maintenance of existing water supply system	4.37	0.64	14.7
M	Ensure better land use management plans	4.37	0.54	12.4
N	Improve awareness of citizens	4.51	0.55	12.1
O	Improve preparedness of citizens	4.51	0.52	11.6

4.2.6 Discussion

In general, the results show that residents had severe experiences with flooding and water shortage in the past. However, even though residents present high awareness and worry to both hazards (Figure 4.9), the number of coping measures in place (i.e., responsiveness) is low. Mondino *et al.* (2020), highlighted that previous experience influences risk awareness not only directly but also indirectly through the knowledge that was gained from that experience. Residents seem to have high knowledge on protecting themselves from hazards in the future, but they rarely effectively apply any measure, which makes us conclude that having previous experience (direct or indirect) is not enough for people to protect themselves from hazards.

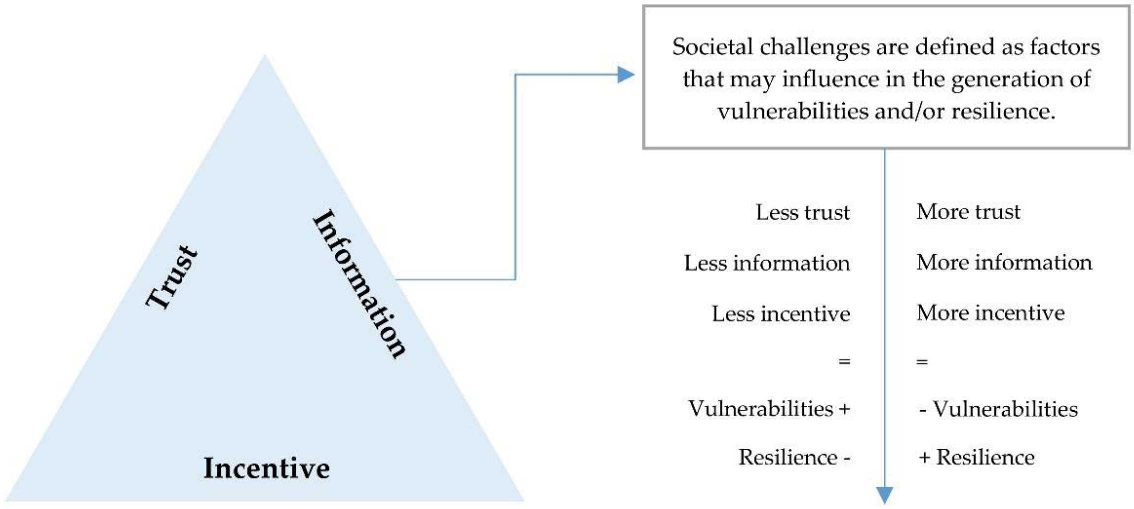

Figure 4.9 – The triad of societal challenges for increasing the uptake of measures in the multiple hazards' context.

The WS and flooding socio-spatial complex (Figure 4.6) pose even more complexity to the analysis since, depending on the nature of hazards, a person can contribute to reducing disasters' effects without having experienced them before. For example, flooding can be minimised with the implementation of adaptive measures in households located upstream, which means that people without experience may be asked to apply adaptive or mitigation measures in their houses to reduce flooding downstream.

In light of this discussion, we suggest that three main societal challenges, namely information, incentive, and trust, should be integrated to increase the uptake of measures for hazards mitigation (Figure 4.9). Here, we use the definition of societal challenges as resources that generate abilities for individuals to deal with disasters (Norris *et al.*, 2008). Therefore, those with greater resources are less vulnerable and more resilient (Figure 4.9). As said before, findings were produced in line with the integrated planning of water shortage and flooding but can also be applied to hazards of other nature.

4.2.6.1 The Role of Information

Although the knowledge obtained from the previous experience is essential (Mondino *et al.*, 2020), people need more information throughout the hazard. For this, some questions must be answered to provide information before (e.g., how can I know the hazard will occur?), during (e.g., how should I proceed?) and after the disaster (e.g., how can I prepare for the next event?). Due to the mixed spatial and temporal dynamics, specific challenges of the study case will be discussed, with an aim to enhance the disaster risk reduction.

The first issue is the access to climate-related information. Effective communication and appropriate choices based on information can create a difference in hazard impacts (Kelman, 2020). In the Campina Grande case, the availability of information in the pre-disaster phase is low in both WS (M = 3.2) and flooding (M = 1.8). Since 2014, the National Water Agency (ANA) of Brazil provides a Drought Monitor (*Monitor das Secas* in Portuguese) for critical regions in the territory. The monitor is a reference for the development and adoption of public policies to reduce drought in the country (ANA, 2020). Similarly, the National Centre of Alert and Monitoring of Natural Disasters (CEMADEN) provides mappings of drought and flooding in the Brazilian cities (CEMADEN, 2020). However, this information is more restricted to the academics and authorities, which means that more efforts should be made to deliver this information to residents. In addition, authorities must find appropriate ways to improve the accessibility and usefulness of information provided to facilitate their adaptation (Bryan *et al.*, 2009).

Another specific challenge is that, even though people are aware of flooding, approximately 65% of the respondents still live on risk-prone areas. When asked about the reasons for that, they mainly selected "I don't have money to move", "I don't have anywhere else to go", and "I got used to the situation". This context shows that there is a need not only to provide more information but also to consider other factors, such as the availability of other land, economic power, and personal desire to reduce the vulnerabilities. A study by Danso *et al.* (2016) investigated the reasons that residents continued to live in unsafe flood areas in Ghana. Although they were knowledgeable of the risk they faced, the main reasons cited were land affordability, easy land accessibility, and the quest to preserve ancestral lands. This is evidence that different social and cultural contexts can interfere with the ability to make choices, even when the level of information is high. In Campina Grande, temporary relocation was made to reduce risk of disasters in the past. While temporary or permanent relocation is a viable strategy, it is important to ask whether they will be moving to a place with sufficient access to water and other amenities (Nguimalet, 2018).

Moreover, an information and educational movement can foster the outdated idea that floods in arid and semiarid regions are very unlikely (Naima *et al.*, 2020). Since the flooding does not occur regularly, there is an underestimation of flood risks, as floods are a local disaster in some cities and therefore only affect specific social classes. The event takes place in a short time, and people can believe that the damage is not that great. Those that are affected have become familiar with the event and simply try to live with the impacts generated. Concerning WS, some studies have observed a naturalisation of water under-consumption by residents who have extensive experiences of living with water scarcity (i.e., these people think it is "normal" to have a lack of water) (Del Grande *et al.*, 2016b). In contrast, this behavioural change lasts only during periods of severe drought or until the following year (Wens *et al.*, 2019), meaning that information about WS may decline over the years after a severe drought, and people will only feel its impacts on the next drought disaster when the information will have little influence in the time.

The last societal challenge is the need to enhance the understanding of the effectiveness of green interventions. Although mitigation solutions can be suggested in different scales to the city, the process of adaptation involves more than only proposing new technologies (Bryan *et al.*, 2009). Ward et al. (2020) suggested that a critical problem is a lack of understanding of how the underlying technologies and mechanisms can influence overall flood and drought risk at local and regional scales. Wright et al. (2020) suggested that for resilience, citizens' attitudes and behaviours to flood and water infrastructure must change so that they can better understand and appreciate the multiple benefits of blue and green infrastructure. In terms of bridging the gap between science and decision-making, it is essential to construct a mutual dialogue and learning mechanism among stakeholders to facilitate the mission of adaptation to climate change by reducing disaster risks (2014).

4.2.6.2 The Role of Trust

The political and socio-cultural context is also a significant aspect in the research of risk perception and coping capacity, but it is often neglected (Fuchs *et al.*, 2017; Lechowska, 2018). There is a relationship between coping capacity and trust in the management, whereas there is a common belief that authorities are primarily responsible for the protection and thus obliged to release the residents from flood protection responsibility (Kazmierczak, 2012). A similar situation was characterised by Fuchs et al. (2017), in which respondents believe that authorities are the only responsible for managing floods. These conditions represent challenges that were already in place before the extreme event. For example, people have a level of trust before the extreme event (the lack of or abundance of rainfall) take place in the socio-spatial system (Cutter *et al.*, 2008). This means that high local confidence in climate-related information provides enough time for residents' preparation before the disaster (Ward *et al.*, 2020). On the other hand, mistrust in forecasting can delay the time for people to prepare.

In Campina Grande, trust is higher for management in WS than in flooding (Table 4.4). People have a high degree of confidence in the water supply systems, as they believe that the authorities will join efforts for solutions, regardless of the investments applied (for example, the transposition of flows from distant places) that may be linked to the universal right to water. As seen in Figure 4.8 A,B, people have water tanks and water butts in their homes, but this does not necessarily indicate a lack of confidence in management. In fact, it is an indicator that they know about the inefficiency of the service, regardless of drought disasters. People want to protect themselves against phenomena that generate intermittences in the water service (Galaitsi *et al.*, 2016), such as hydraulic oscillations and piping ruptures. In addition, we consider the spatial and temporal scales to influence the way people trust in management.

In floods, due to the low trust in the municipal management actions, coping measures are more easily seen (Figure 4.8 C,D), but mainly flood barriers. Residents are willing to accept greater responsibility for the risk of floods (i.e., to apply more measures), as they do not believe that the government will do so. For example, residents shared a lack of proper information and warning before the flooding, and also a lack of belief that changes will be made before the next events. This is particularly important because if residents are to be asked to take on greater responsibility concerning their local environments, then there is a need to build relationships based on two-way dialogue and mutual representation (Scott-Bottoms *et al.*, 2020). Trust will interfere directly with the way that people believe in each other in times of crisis or agree on coordinated action from management to confront threats (Cinner *et al.*, 2018).

4.2.6.2 The Role of Incentives

Addressing societal challenges requires strong leadership and involvement of the government in planning for adaptation and implementing measures to facilitate adaptation at the local level (Bryan *et al.*, 2009). Incentives are defined with two main applications: to provide means for more coping capacity and to encourage more collaboration. These issues are mainly related to the way the management, legislation, and stakeholder collaboration is performed.

The participation of stakeholders throughout environmental decision-making is an established principle (Maskrey *et al.*, 2016), and significant value is given in including stakeholders in the process from early on, all the way from problem structuring through to problem analysis and the interpretation of results. According to Cinner *et al.* (2018), the formal and informal relationship between individuals, communities, and organisations can help people deal with change by providing social support and access to knowledge and resources. The defining characteristic of institutions is their capacity for stability and resistance to changes, including thinking, which means that encouraging people to participate in planning can generate changes in the administrative routines and professional cultures of the institutions responsible for planning. For example, while recovering from water-related hazards, not only will residents be asked to take individual actions, but agencies will also be asked to coordinate short-term recovery and long-term resilience strategies (Cinner *et al.*, 2018).

In Campina Grande, 75.6% affirmed that they could support and collaborate with the planning of WS and flooding. To assess what residents think participation is, we asked them how they can participate in the planning. A different range of answers was collected, involving mainly “reporting the lawbreakers”, “keeping the city clean”, “sharing my opinion, ideas and experiences”, and “saving water”. In general, people feel more encouraged to support WS and flooding management. The main criticisms were given related to flooding, such as, “The city council forgot about us, and there is only monitoring when the flood is occurring”. We asked how some factors could facilitate their participation in management. The options with higher percentages were “if I received a monetary incentive”, “if I knew the authorities would listen to me", and "if I knew my help was being used in the planning", with the mean being at 3.89, 4.41, and 4.44, respectively.

Even though the city faces both hazards, the findings obtained in this study show that residents are subjected to different levels of societal challenges in the socio-spatial system. As an attempt to illustrate the current situation of both water-related hazards, the triad of challenges is plotted in Figure 4.10. Levels of information, trust, and incentive are expressed on an increasing scale, where "–" and "+" represent lower and higher levels, respectively, to the current (t_ι) and the future (t_f). The analysis is fundamental since each challenge performs specific functions, as detailed previously, that together must integrate a network of important resources to mitigate water scarcity and floods. Notably, the plot emphasises that there are differences in terms of social vulnerabilities to each extreme event.

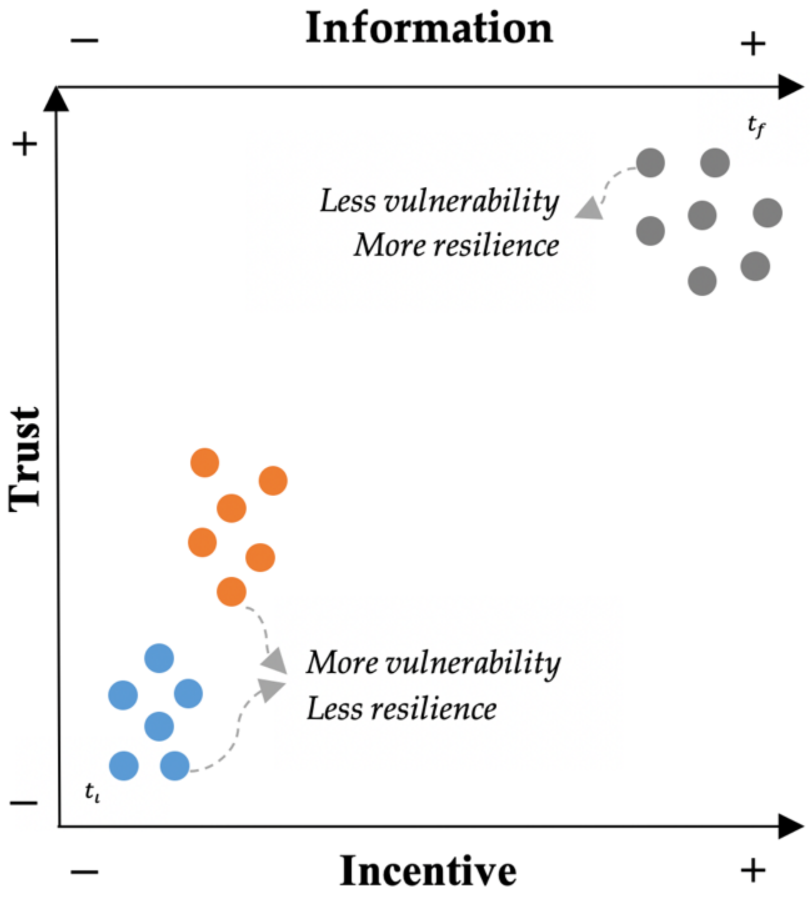

Figure 4.10 – Scheme of the triad of societal challenges in the socio-spatial context. Colours express the water shortage (orange) and flooding (blue) now (t_ι) and how it should be (grey) in the future (t_f).

For the current time (t_i), the residents appear to have more trust, information, and incentive to WS than to flooding, which makes the overall condition of flooding worse (indicated by the blue) than water shortage (orange). Consequently, we recommend that these specific challenges must be tackled to improve the services and reduce vulnerabilities in each water challenge. For the future (t_f), the grey dots illustrate how the reduction of social challenges may reduce the vulnerabilities and increase resilience.

In Brazil, drought and flood disasters have severely affected the country in recent decades (Ávila *et al.*, 2016; Lorentz *et al.*, 2016; Marengo *et al.*, 2009). Between 1991 and 2012, 39,000 natural disasters were recorded, 84% of which are associated with water, whether drought or flood (BRASIL, 2013). Between the years 2012 and 2017, the northeast region of the country that integrates the state of Paraíba passed through the worst drought period of the last 50 years (ANA, 2018). Between 2014 and 2016, major national metropolises, such as São Paulo, recorded the highest temperatures in the previous 70 years and a severe water crisis (Millington, 2018). In 2014, the Amazon region suffered one of the biggest floods in recent years (Espinoza *et al.*, 2014). On the other hand, studies confirmed that the process of facing risks in Brazil, in general, is still capable of delays or absence of actions by authorities or individuals (Giulio *et al.*, 2015). The human capacity to respond to and recover from disasters in Brazil lacks structures and indicators to assess the situation for the whole country (de Loyola Hummell *et al.*, 2016). In addition, the Brazilian society's lack of confidence in the agencies and bodies responsible for risk management and the absence of a plan to engage the public in the decision-making process are relevant points raised. In this way, our work contributes to the field by finding key societal challenges according to the residents' view. This is particularly important since public involvement is still limited in the Brazilian context, mainly due to the centralised access to information and low participation in decision-making consultation exercises (Giulio *et al.*, 2015).

4.2.7 Conclusions

The understanding of the social context in which disaster occurs provides conditions to face them, especially for less developed regions. Disasters act upon vulnerability and exposure to create risk; however, this context can be worsened when more than one hazard is in place. In that context, this study builds a place-based citizen science approach to more deeply comprehend the social context in which multiple water-related hazards take place. The study case is Campina Grande, a city located in the semiarid region of Brazil that suffers from water shortage and flooding. The methodology is based on a participatory approach, the PLANEJEEE project, which had the collaboration of 172 residents and 27 authorities and specialists.

Throughout the study, a combination of subjective (i.e., surveys, workshops) and objective (i.e., Wilcoxon and Mann–Whitney tests) methods were supported. The methodology was built upon the premise that vulnerabilities are influenced by actions and behaviours, which can increase or decrease resilience. The preliminary analysis indicated that hazards have differences in spatial, temporal, and social scales, which must be taken into account for a proper investigation into the perception and coping capacity of residents. For this, we presented an innovative perspective with a socio-spatial representation (Figure 4.6).

The findings show that residents have a high risk perception of flooding and water shortage. High levels of awareness and worry regarding both hazards were found (Figure 4.8), which indicates that residents had severe experiences in the past and fear new experiences in the future. However, even though they affirmed to believe that coping measures can reduce the risk, low coping and adaptive capacity were found.

In this sense, linking the relationship between risk perception and the social risk formula (Climent-Gil *et al.*, 2018), we consider that the way people perceive risk is more related to the social vulnerability experienced by the participants. Individuals become more interested in assuming environmental attitudes that transform their own space with the understanding of their own weaknesses to certain disasters, although coping is limited due to the number of resources available. However, the individuals' own location (i.e., territorial exposure) also characterises them as more or less vulnerable, that is, the vulnerability is specific to the site; for example, the poorest residents may occupy areas close to drainage channels, or their low standard housing limits the construction of water reservoirs. An approach to the social amplification of risk (Giulio *et al.*, 2015) assumes that the dangers and their material characteristics are real enough, but they interact with a series of psychological, social, and cultural processes. The interests of economic groups transform risk statements. This results in the intensification or attenuation of your perception. The low coping capacity of the present time shows that residents face strong economic and cultural barriers. However, for the future, economic and social incentives can provide motivations to increase adaptive capacity. In addition, other issues such as the inadequate early warning system, low communication, and low understanding of mitigation measures emerged in the analysis.

Finally, we conceptualised a triad of societal challenges that should be integrated to increase the coping capacity and to mitigate multiple hazards in the future. Looking at the triad of societal challenges that formed, findings suggest that previous experience alone (i.e., direct and indirect) is not enough to increase coping capacity. The social challenges are expressed in three areas, i.e., information, trust, and incentives that form a network of resources to reduce social vulnerability and increase resilience. It is essential to mention that measures to improve preparedness, risk perception, awareness, information, and trust can be beneficial for both extremes, but these do not always result in vulnerability-reducing actions (Ward *et al.*, 2020). Future studies must analyse deeply how each class of social factors influence the ability to cope and perceive risk for multiple hazards. Multidisciplinary analyses are suggested to account for the interdependencies between hazards (Ruiter *et al.*, 2020).

Since extreme weather events are very likely to become more common in the future (Ajibade *et al.*, 2014), we believe these findings can assist scientists and policy makers to establish societal challenges to improve risk perception and coping capacity through the analysis of different social, spatial, and temporal scales of multiple hazards, thereby increasing resilience.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study during the PLANEJEEE Project.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to ethical constraints.

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CHAPTER 5

Mapping hazard-
specific vulnerability
and exposure of
Campina Grande, Brazil

Chapter 5: Mapping hazard-specific vulnerability and exposure of Campina Grande, Brazil

Chapter 5 discusses the integration between social and environmental sciences for mapping flood vulnerability and exposure. The chapter refers to the article 3 published on the Urban Water Journal.

Research questions:

- RQ7: *How do social and environmental tools can be integrated towards vulnerability and exposure mapping assessments?*
- RQ8: *How can the relationship between vulnerability and exposure be tackled on a spatial scale?*

Chapter 5 - An integrated socio-environmental framework for mapping hazard-specific vulnerability and exposure in urban areas (article 03)

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Abstract
Hazards act upon vulnerability and exposure to create disaster risk. Despite the growth of disaster risk assessments, the number of approaches that develop vulnerability and exposure studies is still small when compared with hazards modelling. In fact, limited studies have considered the relationship between vulnerability and exposure variables and how this can change future management actions on a local scale. This paper addresses this gap by proposing an integrated framework with a combination of social and environmental sciences to map hazard-specific vulnerability and exposure in urban areas. Subjective (e.g., Participatory Approach) and objective methods (e.g., Shannon Entropy and Fuzzy Theory) were integrated into a pixel-by-pixel framework for enhancing the flooding management in Campina Grande, Brazil. The results express the spatial distribution of flood vulnerability and exposure and assess key issues for flood management in different vulnerability categories. Challenges for the integration of socio-environmental approaches in water resources studies are discussed.

Keywords: hazard-specific vulnerability, exposure, socio-environmental approach, urban flooding

5.1 Introduction

Through the rise of research in social and environmental sciences, there is a growing search for enhanced frameworks to mitigate disasters risk (Kunapo *et al.*, 2018) and to increase resilience (Ciullo *et al.*, 2017). Disasters are defined mainly in relation to its impacts (Kelman, 2020), however, those impacts can vary drastically depending on the local context (Frigerio *et al.*, 2016b).

In 2007, the Intergovernmental Panel on Climate Change (IPCC) used a definition in which the impact of a disaster is a relation between exposure, sensitivity and adaptive capacity (IPCC, 2007). In this report, the impact is defined as the "vulnerability" of the system, "sensitivity" is the effect of variations on the system, "adaptive capacity" as the ability of the system to adjust to climate related stimuli, and "exposure" is expressed with climatic variations (IPCC, 2007). In other words, reducing vulnerability was limited to addressing the impacts of the hazard, characterised as the interaction between exposure, sensitivity, and adaptive capacity (Kc *et al.*, 2015).

There is a significant interest in the concept of vulnerability in the literature. For Cutter *et al.* (2003), the concept of place vulnerabilities integrates biophysical and social vulnerabilities (i.e., social inequalities). According to Pescaroli *et al.* (2019) and Ghajari *et al.* (2017) vulnerability can be divided into multisectoral categories, namely physical, social, economic, environmental, psychological, structural, and institutional. In 2012, the IPCC replaced the vulnerability definition with the risk concept, as a function of hazard, exposure and vulnerability (IPCC, 2012). Vulnerability is described as the attributes of a system in danger of a hazard and the exposure as the location of elements that may be impacted by the hazard (Sharma *et al.*, 2019). In practice, this indicates those specific characteristics were already in place before the hazard occurrence. In other words, the new IPCC concept shows that the devastating effects of a disaster depend on the local vulnerability of an exposed society.

However, the overload and "similarity" between vulnerability assessment approaches are seen as barriers for application in a system (Sharma *et al.*, 2019). Even though there is a need to consider the vulnerability as one element of the disaster risk, which makes possible to reduce the vulnerability before and after the hazard's occurrence (IPCC, 2014) and as a strategy to increase resilience (Golz *et al.*, 2014), many applications still consider vulnerability only as the impacts of a disaster (Kc *et al.*, 2015; Weis *et al.*, 2016; Yang *et al.*, 2018) which can confuse the policymakers and reduce the applicability in real cases.

Challenges of vulnerability and exposure assessments

In recent years, there has been a search for identifying ways for a better representation of hazard, vulnerability, and exposure, along with spatial science (e.g., GIS: Geographic Information Systems). Recent studies include terms as "integrated" (Weis *et al.*, 2016), "hybrid" (Roodposhti *et al.*, 2016), "multicriteria decision analysis" (MCDA) and "system-thinking" approaches (Gomez Martin *et al.*, 2020). However, most frameworks are not applicable to different areas and different hazards. This is due to geographical differences, human interactions and lack of data (Robinson *et al.*, 2019), governance arrangements (Driessen *et al.*, 2018), the involvement of stakeholders and dynamism of cities (Ciullo *et al.*, 2017). For Cutter *et al.* (2008), since losses can vary geographically, over time, and among different social groups, the vulnerability also varies over time and space, which provide barriers for the assessment in different areas (Pescaroli *et al.*, 2019).

Despite the growth of mapping approaches, key uncertainties remain as challenges. First, the discussion of an appropriate method for indicators selection is still seen as a barrier (Malczewski *et al.*, 2015). The choice of indicators and the quality of available data requires a deep understanding of the complex system (Frigerio *et al.*, 2016b). For Boroushaki (2017), another challenge is the assignment of criteria weights. Due to the complexity of systems, all the criteria do not have equal influence in a disaster (Perera *et al.*, 2019). For vulnerability and exposure mapping assessments, many studies consider equal weighting (Hazarika *et al.*, 2018) or either subjective or objective (Birgani *et al.*, 2018) methods for weights calculation.

In the last few years, the subjective method has been gaining importance in mapping approaches. It can be practised as a way to engage different stakeholders in the decision-making process (Assumpção *et al.*, 2018). Also, collaboration strategies also enables stakeholders to select indicators (Song *et al.*, 2017) with consensus agreement (de Brito *et al.*, 2017). However, some authors argue that the decision-maker may be unable to quantify weights preferences (Roodposhti *et al.*, 2016), which can overestimate or underestimate the impacts. For those situations, other methods such as the entropy weighting (Boroushaki, 2017), artificial neural network (Kia *et al.*, 2011) and deterministic analysis can be used. To deal with the inherent uncertainty, the fuzzy theory (Kanani-Sadat *et al.*, 2019) is widely used as a value scaling procedure (e.g., standardisation) sensitive to the spatial and temporal extent of the data. In summary, both entropy and fuzzy theory handle the associated “vagueness” of data values using a statistical variation and represent weights and scale according to the information in the dataset (Hong *et al.*, 2018).

In this regard, this paper proposes a novel framework, here termed “integrated framework”, to obtain vulnerability and exposure mappings of urban areas in the context of flooding. The framework was built upon the paradigm change definition of (IPCC, 2007, 2014), in which the vulnerability can be assessed before, during and after the hazard, not as the impact (risk definition) but as a range of attributes that can contribute to the vulnerability of places (Cutter *et al.*, 2003). We suggest that vulnerability and exposure indicators must represent hazards-specific attributes (Sharma *et al.*, 2019), expressing the strengths and weaknesses in a temporal and spatial scale, but with both objective and subjective methods for assessment. Specifically, our paper aims to answer two specific questions:

1. How do social and environmental tools can be integrated towards vulnerability and exposure mapping assessments?
2. How can the relationship between vulnerability and exposure be tackled on a spatial scale?

An integrated framework was developed by combining tools for decision analysis in environmental science (e.g., Shannon Entropy and Fuzzy Theory) and social science (e.g., Participatory Approach) to map flood vulnerability and exposure. Flooding is considered the most frequent among natural disasters, driven mainly by climate change and rapid urbanisation inducing changes in watershed hydrology (Hammond *et al.*, 2018; Kunapo *et al.*, 2018). In this paper, the final flooding risk will not be obtained yet, since the paper's focus is to find reliable vulnerability and exposure assessments.

This paper begins by presenting the study case, the socio-environmental conceptualisation, and the integrated framework. After that, results express each disaster variable and the validation with a historical and participatory approach. Discussions highlight key aspects generating the flood vulnerability with interactions between social, institutional, and structural vulnerabilities. Finally, limitations and next steps of the socio-environmental framework are presented along with the conclusions of mapping flood vulnerability and exposure.

5.2 Study case

The study case for this research is Campina Grande – Paraíba, Brazil. According to the Brazilian Institute of Geography and Statistics (IBGE), the city's population was estimated as 409,731 inhabitants in 2019. The city is part of the Northeast region of Brazil, known as “semiarid region”(Figure 5.1a), with long water scarcity periods (ANA, 2018). Although the city has a dry climate, it also registers flooding cases. Campina Grande is currently monitored by the National Centre for Monitoring and Alert of Natural Disasters of Brazil (CEMADEN) and the Geological Survey of Brazil (CPRM).

Even though flooding episodes are seen quite frequently, the city does not clearly define flood-prone areas. Data from CPRM specify ten “risk areas” across the city, which refers not only to flooding but also to landslides and other disasters (Figure 5.1b). However, flooding cases are seen spatially dispersed in different areas of the city (Figure 5.1b), not only in the “risk areas”, which suggests there is a need for developing more accurate information for effective management (Alves *et al.*, 2018b). The middle-sized city (IBGE, 2021) lacks in having sufficient flooding preparedness strategies for the population (Alves *et al.*, 2020e; Santos *et al.*, 2017c) and has a weak integration of urban planning and water resources management (Grangeiro *et al.*, 2019).

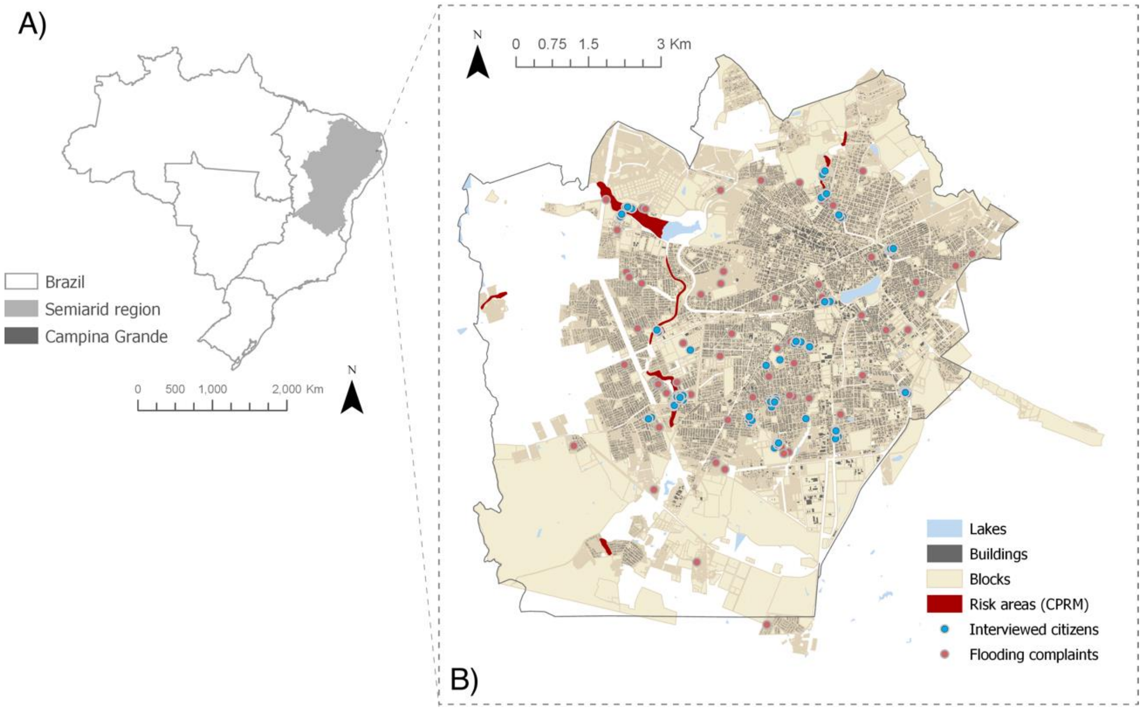


Figure 5.1 - Location of Campina Grande - Brazil: (a) Brazilian Semiarid; (b) Spatialisation of official risk areas (CPRM), flooding complaints (Civil Defence) and interviewed residents (PLANEJEEE Project).

5.3 The integrated socio-environmental approach

The methodology was constructed with basis in the disaster risk definition as the relationship between vulnerability, exposure and hazard (Figure 5.2). The vulnerability is considered as the *“manifestation in a series of categories that do not develop independently but interact on many different time and space scales*” (Pescaroli *et al.*, 2019). In other words, the vulnerability is expressed as a function of several criteria, which has weaknesses (e.g., sensitivity) and strengths (e.g., capacity) that influence the conditions and the abilities of a society respond to harm in both temporal and spatial scales (UNDRR, 2019).

Figure 5.2 shows that vulnerability is determined by attributes that affect the consequences of a hazard. In this study, the *sensitivity* represents the weaknesses that can worsen the impacts of the disaster in the analysis. *Capacity* refers to the ability of societies and communities to prepare for and respond to current and future climate impacts (IPCC, 2014). The system is also characterised by the elements located in hazard-prone areas, termed as “exposed elements”. According to IPCC (2012), *exposure* refers to the presence of a vulnerable system at a *location* that could be adversely affected and can be represented by people, livelihoods, and assets.

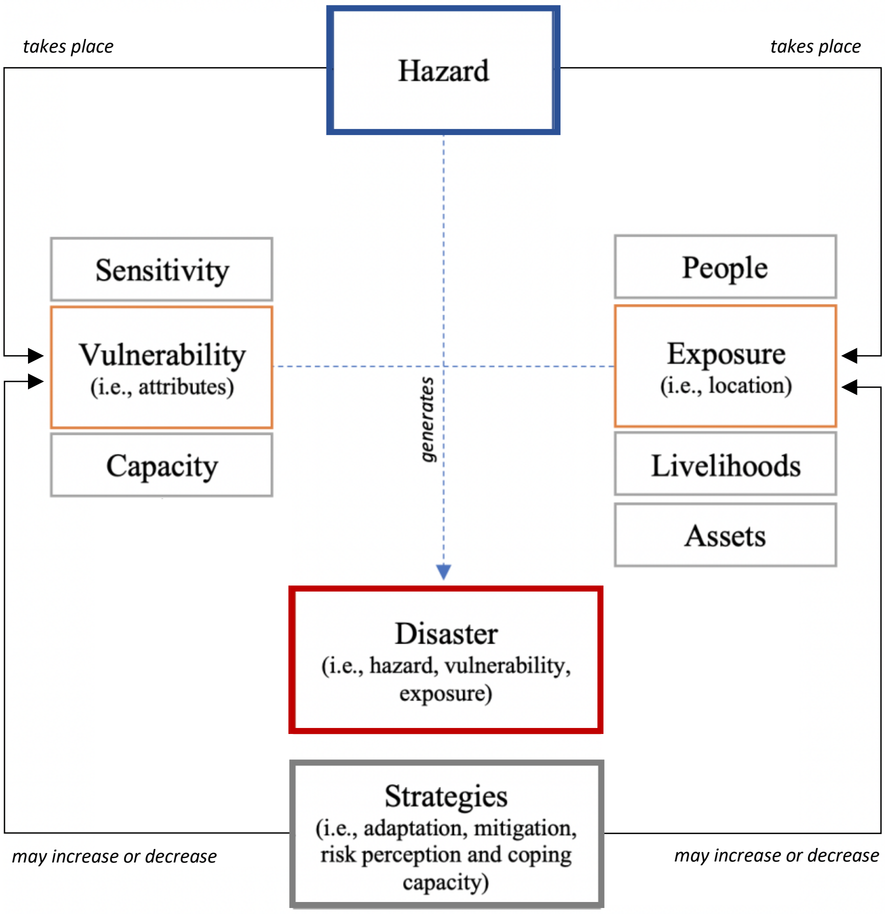


Figure 5.2 - Conceptualisation of vulnerability and exposure as “hazard-specific” components.

In this context, we argue that both system attributes and exposed elements are directly related to a specific event; hence we call them “hazard-specific components” (Sharma *et al.*, 2019). Due to the mixed temporal and spatial scales of hazards of different nature (i.e., drought, floods, landslides), several conditions can create vulnerability and exposure (Frigerio *et al.*, 2016b). In our approach, the vulnerability and exposure show an anticipatory state, or “pre-existing state”, concerning the hazard and will produce impacts, which can be increased or decreased by strategies, including coping capacity, risk perception, adaptation, and mitigation measures (Figure 5.2). Therefore, the concept of vulnerability is a starting situation of the affected population before any interventions are undertaken (Climent-Gil *et al.*, 2018), which means that mapping vulnerabilities is a pre-requisite for the proposition and implementation of strategies (Caldas *et al.*, 2018).

Considering the discussion of social and environmental impacts in the disaster risk reduction (DRR) (i.e., see more details in Fuchs *et al.* (2011)), we merged the definition of each disaster variable (Figure 5.2) in a socio-environmental framework detailed in Figure 5.3. The methodology reflects a combination of social and environmental phases (SS and ES), which are detailed below.

5.3.1 Data Collection:

Initially, we contacted policymakers and specialists from Campina Grande for data collection. At this stage, the Civil Defence Agency, responsible for managing flooding in the city, provided data to describe 101 flood cases across the city from 2004-2011. These points (Figure 5.1b) do not necessarily represent all the flooding areas of Campina Grande but show areas that experienced flooding and people reported officially to the Civil Defence.

Simultaneously, international, local research and official data sources of Brazil (e.g., IBGE, CEMADEN, CPRM) were considered for preparing a preliminary list of vulnerability and exposure indicators.

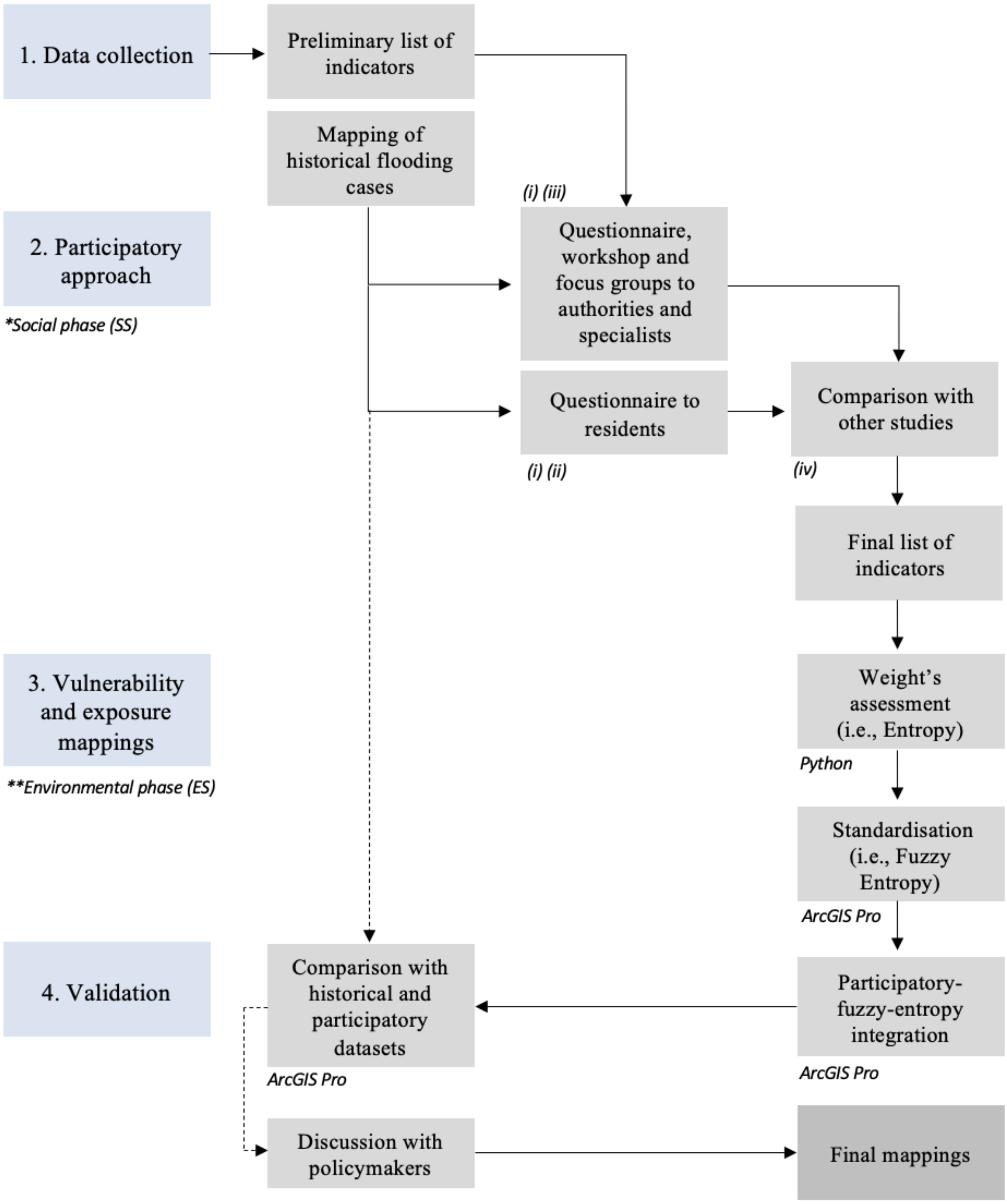


Figure 5.3 - The integrated methodology for mapping vulnerability and exposure with a combination of social (SS) and environmental sciences (ES).

5.3.2 The participatory approach:

Subsequently, we developed a place-based citizen science project, called as PLANEJEEE Project: To Plan Extreme Events ("*Planeje Eventos Extremos*" in Portuguese) from May – June of 2019 with specialists, policymakers, and citizens. The participatory approach was built upon the review of other citizen science studies (Ajibade *et al.*, 2014; Duan *et al.*, 2018; Eitzel *et al.*, 2017), GIS-MCDA approaches in similar fields, and the planning legislation of Campina

Grande. Mixed qualitative and quantitative methods namely focus groups, workshop and questionnaires were held with stakeholders. The engagement opportunities aimed to discuss current challenges and strategies to mitigate floods and water shortage, the promotion of critical reflection from the participants (Groulx *et al.*, 2017) and aspects to enhance risk communication (Cheung *et al.*, 2019). Details of the PLANEJEEE Project are detailed below.

Citizens were selected based in the Civil Defence flood dataset and by suggestions from the residents themselves with 172 households interviewed. Specialists and policymakers were asked to join a workshop and focus groups, according to their research field (for specialists) or position in the city council (e.g., planning, urban services, engineering, health, education, traffic, GIS, science and technology), water companies (e.g., AESA and CAGEPA) and to the society (e.g., Civil Defence, CONCIDADE, NGO). We aimed to engage with different individuals that support city management. In summary, 27 people attended the workshop and focus groups with 22 survey answers (n total = 199).

The selection of vulnerability and exposure mapping indicators:

Within this approach, the selection of the indicators was made in two phases, referred to as "social phase (SS)" and "environmental phase (ES)" in the framework (Figure 5.3). The indicators were selected into four stages: (i) selection according to the flooding causation (questionnaires to all stakeholders), (ii) selection according to the social context (survey with residents), (iii) discussion of key challenges and solutions (workshop with specialists and policymakers) and (iv) comparison with previous studies.

The preliminary list of indicators (i.e., referred in section 5.3.1) of vulnerability and exposure mappings was used to prepare the questionnaires for the stakeholders' collaboration. Surveys were developed with a 5-point Likert scale (i.e., 1- less importance to 5 – more importance). If the respondents were unsure, they could opt for the *"I don't know"* option. Empirical statistical analysis tools (mean – M and standard deviation - SD) were used to examine the questionnaire answers in Python. Although there is a consensus of indicators that may influence vulnerability to disasters, particularly in the social context (Cutter *et al.*, 2008), our intention with the PLANEJEEE Project was to find indicators that would characterise the city in the mappings according to the view of stakeholders. This is based upon on the assumption that they have knowledge by living experiences of the city exposed to floods (Hardoy *et al.*, 2019). Our intention with the indicator's choice is not to discard other criteria but to provide mappings according to the city's pre-existing context.

In this way, to investigate reasons for the vulnerability in the city, the stakeholders were asked what the flooding causations are (Table 5.1). The options encompassed four main categories of vulnerability suggested by Ghajari *et al.* (2017) and Pescaroli *et al.* (2019) regarding issues related to 1 – Households (social and structural vulnerability); 2 – Conditions of the drainage system (structural vulnerability); 3 – Interventions in the city (structural vulnerability); 4 – Legislation (institutional vulnerability). Table 5.1 shows that all stakeholders scored the options b, c and d with the highest scores (M: from 4 to 5). Also, the SDs of these options (b, c, and d) are smaller than 1, which represents a good consistency of answer. In general, stakeholders consider issues related to social, structural, and institutional vulnerabilities as the main causes of flooding.

To investigate the social context, we evaluated specific issues through citizens' participation. From the 172 respondents, 94.8% of the residents faced the previous flooding in the city, and 75.46% had flooding inside their property (direct experience). Approximately 38% of the respondents had more than 55 years old, and 53% of the households had children living in the property. About the income, preliminary results indicated that 80% of the interviewed citizens receive less than two minimum wages monthly. Residents were asked what the limitations for applying flood reduction measures are, in which "money" was considered the primary constraint. Approximately 36.6% and 57% scored the option as 4 (high) and 5 (very high), respectively. The mean for this question was 4.5 (between 4-5 Likert-scales) and SD 0.72.

Table 5.1 – Empirical statistical analysis (mean and standard deviation) of answers from stakeholders for the flooding causation options.

Flooding causation options	**Residents (n=172)**		**Specialists and policymakers (n=22)**	
	Mean	**SD**	**Mean**	**SD**
1 - Household's level				
a) Increase of urbanization (St. Vuln)	3.42	1.22	3.59	0.91*
b) Buildings in risk areas (S. Vuln)	4.22	0.80*	4.14	0.71*
2 – Drainage system level				
c) Problems with the design of the drainage network (St. Vuln)	4.30	0.74*	4.23	0.69*
d) Lack of maintenance of drainage network (St. Vuln)	4.35	0.72*	4.32	0.72*
3 – Intervention's level				
e) Interventions in the catchment (St. Vuln)	3.48	1.23	3.27	0.94*
f) Interventions on the channels (St. Vuln)	3.37	1.25	3.23	0.81*
4- Legislation's level				
g) Lack of appropriate legislation to deal with floods (Inst. Vuln)	2.97	1.34	3.14	1.08
h) There are laws, but they are neglected (Inst. Vuln)	3.91	1.14	3.86	0.83*
i) There are laws, but they are not implemented (Inst. Vuln)	3.91	1.12	3.82	0.85*

** Indicates answers with SD below 1.*
"St. Vuln" stands for "Structural Vulnerability", "S. Vuln" to "Social Vulnerability" and "Inst. Vuln" for "Institutional Vulnerability".

These multisectoral issues were also discussed in the PLANEJEEE workshop with specialists and policymakers. Participants were divided into four groups with severe flooding cases to discuss challenges and possible solutions for both flooding and water shortage. Maps with the vulnerability and exposure indicators were provided to facilitate the spatial visualisation of the "weaknesses" and "strengths" of the city. Stakeholders presented concerns about other indicators related to physical (i.e., elevation) and damages of important assets in case of flooding. A summary of discussions is expressed in the Table D1 in the Appendix D.

Lastly, the final choice of indicators took into consideration studies in similar fields (Table 5.2). The vulnerability indicators represent the "current state", which can vary according to time and space (IPCC, 2014). The exposure refers to the density of vulnerable residents and the distance to critical infrastructure, which will have considerable damages if they are exposed to the hazard. Table 2 provides a brief explanation of each indicator.

Table 5.2 – Summary of the final list of indicators to each disaster variable (sensitivity, capacity, and exposure).

Disaster variables		Indicator	Criterion	Description	Literature citation
Vulnerability	Sensitivity (weaknesses)	Physical (Phys. Vuln)	Elevation (m)	The higher elevation indicates the lesser risk of flooding	(Caldas *et al.*, 2018; Ouma *et al.*, 2014)
		Household characteristics (St. Vuln)	With open sewage (OS) (%)	Households with higher OS indicates more vulnerability to flooding	(de Brito *et al.*, 2018; de Brito *et al.*, 2017)
			Without drainage system (DS) (%)	Households without DS indicates more vulnerability	(de Brito *et al.*, 2018; de Brito *et al.*, 2017)
			With accumulated garbage (AG) (%)	Households with more AG indicates more vulnerability in a flood	(de Brito *et al.*, 2018; de Brito *et al.*, 2017)
		Drainage system structure (St. Vuln)	Distance to drainage assets (DA) (m)	The more distance to DA indicates less structure of DA, and therefore more vulnerability	(Tingsanchali *et al.*, 2019)
		Lack of urban planning (Inst. Vuln)	Imperviousness (%)	The more imperviousness indicates more vulnerability to flood	(Song *et al.*, 2017)
	Capacity (strengths)	Lack of financial resources (S. Vuln)	Lower income (%)	The more people with smaller financial resources, the less capacity to deal with flooding	(Ajibade *et al.*, 2014; Bryan *et al.*, 2019; Cunico *et al.*, 2017)
		Management (Inst. Vuln)	Distance to Disaster Prevention Institutions (DPI) (m)	The lesser distance to DPI, the more condition to receive support in case of a flooding	(de Brito *et al.*, 2018; de Brito *et al.*, 2017)
Exposure (location of elements)		Residents (S. Vuln)	Population density (%)	The more density of people (and children and elders) indicate more exposure to the flood event	(Cunico *et al.*, 2017; Santos *et al.*, 2017a)
			Number of children (%)		(Ghajari *et al.*, 2017; Santos *et al.*, 2017a)
			Number of elders (%)		(Santos *et al.*, 2017a)
		Critical infrastructure (S. and St. Vuln)	Distance to schools (m)	The lesser distance to critical infrastructure (schools, health, and flood risk areas) indicates more exposure to the flood event. A threshold of 200 m was inserted as a constraint.	(Parker *et al.*, 2019)
			Distance to health establishments (m)		(de Brito *et al.*, 2018; Parker *et al.*, 2019)
			Distance to properties in official flood risk areas (m)		(Caldas *et al.*, 2018; Ouma *et al.*, 2014)

"St. Vuln" stands for "Structural Vulnerability", "S. Vuln" to "Social Vulnerability" and "Inst. Vuln" for "Institutional Vulnerability".

5.3.3 Participatory-fuzzy-entropy integration:

The Shannon Entropy method was adopted to compute indicators' weights. This method starts by computing a decision-matrix for the set of indicators (step 1) where a certain quantity of information can be used to find appropriate weights to each indicator (Boroushaki, 2017). The data-driven method is considered as a measure of uncertainty (Birgani *et al.*, 2018).

In this paper, we developed a pixel-by-pixel analysis, by coupling GIS and Python, in which all the points of the surface are computed to find the weights. The final raster-matrix represents 670,364 cells with 10mx10m analysed in relation to the criteria to map vulnerability and exposure. Results show the diversity degree for each criterion, where larger values denote that more diverse information is contained in a set of criterion values (Boroushaki, 2017). The greater the entropy index; the greater the influence of the mapping criterion (Roodposhti *et al.*, 2016). A Python script was developed for the weight's calculation according to the following steps:

- Step 1: Calculate the normalised value (r_{ij}) of each cell (x_{ij}) to each j-th criterion in the decision-matrix:

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \quad \text{Equation (5.1)}$$

- Step 2: Entropy (E_j) is calculated as a set of values of j-th criterion for m pixels:

$$E_j = -k * \sum_{i=1}^{m} r_{ij} * \ln r_{ij} \quad \text{Equation (5.2)}$$

where the constant k ($k = 1 \frac{1}{\ln m}$) ensures that E_j remains between 0 and 1.

- Step 3: Diversification degree (d_j) implying uncertainty is calculated for each j-th criterion as:

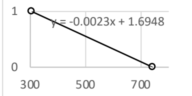
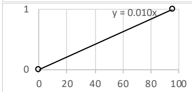
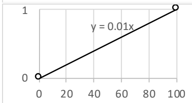
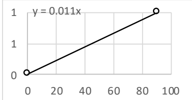
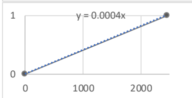
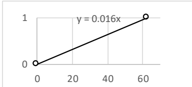
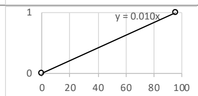
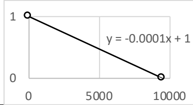
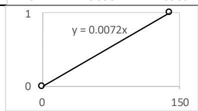
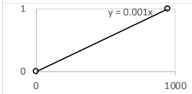
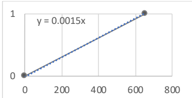
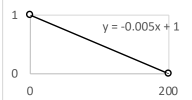
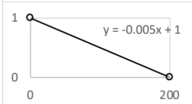
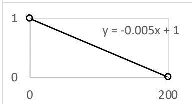
$$d_j = 1 - E_j \quad \text{Equation (5.3)}$$

- Step 4: The final weight of j-th criterion is calculated based on the following equation:

$$w_j = \frac{dj}{\sum_{i=1}^{n} dj} \quad \text{Equation (5.4)}$$

where w_j is the weight of j-th criterion without consideration of stakeholders' preferences. The final weights for each criterion can be seen in Table 5.3.

Table 5.3 – Description of the linear fuzzy functions and entropy weights to each criterion

Disaster variables		Criterion	Fuzzy linear functions	Weights	Sources
Vulnerability	Sensitivity (weaknesses)	a) Elevation (m)		-0.0013	Tsuyuguchi (2015)
		b) With open sewage (%)		+0.1513	IBGE (2010)
		c) Without drainage system (%)		+0.0146	IBGE (2010)
		d) With accumulated garbage (%)		+0.2402	IBGE (2010)
		e) Distance to drainage assets (nodes) (m)		+0.2487	City council (2014)
		f) Imperviousness (%)		+0.2861	City council (2014)
	Capacity (strengths)	g) Lower income (%)		+0.0165	IBGE (2010)
		h) Distance to Disaster Prevention Institutions (m)		-0.0422	City council (2014)
Exposure	Residents (Res)	i) Population density (%)		+0.0200	IBGE (2010)
		j) Number of children (%)		+0.2770	IBGE (2010)
		k) Number of elders (%)		+0.7031	IBGE (2010)
	Critical Infrastructure (CI)	l) Distance to schools (m)		-0.2326	City council (2014)
		m) Distance to health establishments (m)		-0.3484	City council (2014)
		n) Distance to properties in official flood risk areas (m)		-0.4190	CPRM (2014)

"+" indicates an increasing function, "-" indicates a decreasing function.

In mapping analyses, a major contribution can be seen with fuzzy set theory and fuzzy membership functions (FMFs) to deal with vague data, e.g., Roodposhti *et al.* (2016). FMFs represent the degree of membership value concerning a particular indicator of interest. The fuzzy theory is a method used to minimise inherent uncertainty from data and improve the results' reliability (Gheshlaghi *et al.*, 2017). There is no optimal method for choosing the types of fuzzy functions (Roodposhti *et al.*, 2016). This study used the linear FMFs, that transforms the input values linearly on the 0 and 1 scale, with 0 being assigned to the lowest input value and 1 to the largest input value. All in-between values received some membership value based on a linear scale, with the larger input values being assigned a greater possibility, closer to 1.

The linear FMFs were applied to express the direction of analysis to each indicator (Table 5.3) within the spatial tools of ArcGIS Pro (ESRI). For example, the pixels with more "imperviousness" increase the flood vulnerability. Each indicator was mapped with the "fuzzified" functions and represent layers for the vulnerability and exposure mapping (Figure D1a to Figure D1n in the Appendix D). Along with the participatory approach to select the indicators, the integration between fuzzy theory and entropy is made by proposing an equation to obtain the final vulnerability and exposure. The final map will be a sum of weighted and "fuzzified" indicators (Roodposhti *et al.*, 2016). The final maps follow the equation:

$$Disaster\ Variable\ (DV) = \sum_{j=1}^{n} w_j * f_j \qquad \text{Equation (5.5)}$$

where DV is the degree of the disaster variable (vulnerability and exposure) to the flood hazard, w_j stands for the weight of each criterion and f_j for the fuzzy standardised criterion. The final maps are presented in Figure 5.4 (a, b and c). Each disaster variable was classified in a five-range susceptibility according to geometric intervals and natural breaks of the dataset, from "very low" to "very high".

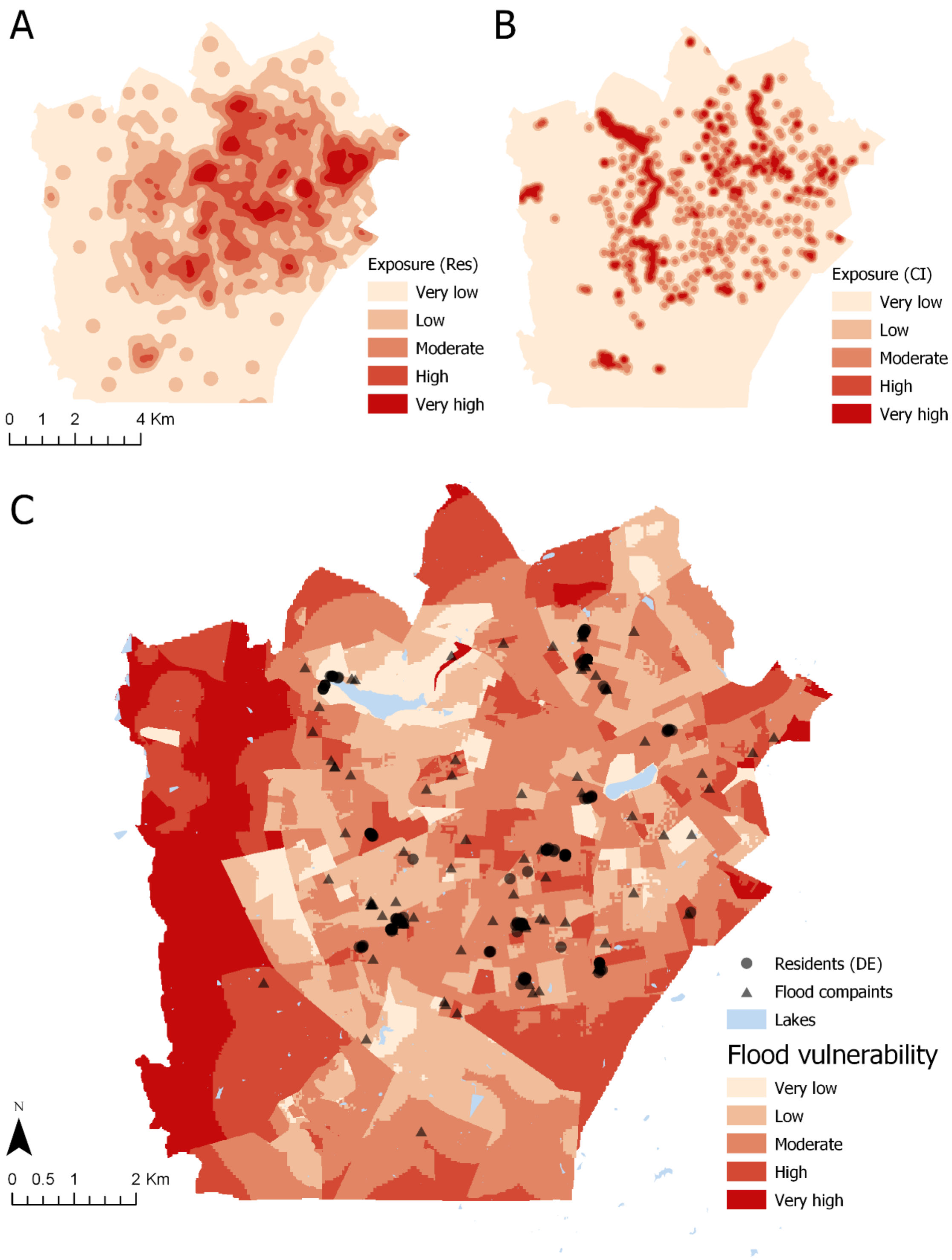


Figure 5.4 - Final mappings: (a) Exposure (Residents), (b) Exposure (Critical Infrastructure) and (c) Overall flood vulnerability.

5.3 Results

The flood vulnerability of Campina Grande is shown in Figure 5.4c. Overall, the final map reveals areas that are more susceptible to flood, according to a combination of physical, social, structural, environmental, and institutional vulnerabilities. The mapping expresses the different levels of flood vulnerability and highlights specific locations with fewer conditions to deal with the extreme rainfall event. The anticipatory strategy to deal with floods is following the "pre-existing" state detailed previously (see section 5.3). In summary, the "very high" and "high" vulnerabilities correspond to 15.85% and 25% of the city area, respectively. The "moderate" vulnerabilities are seen spread throughout the city (35.1% of the city area). The least vulnerable ("very low" and "low") areas represent approximately 25.05% of the city.

The vulnerability map was validated in two stages. First, we compared the flood vulnerability levels according to mixed-source information datasets. Datasets were built with the flooding complaints from 2004-2011 provided by the Civil Defence (n = 101) and with the residents (n = 123) that confirmed to have direct experience (DE) with flooding in the participatory approach. The 224 points represent "known" locations with flooding (Figure 5.4c).

The validation was performed by extracting the vulnerability mapping pixel values with the "Sample tool" within ArcGIS Pro (ESRI). Since the flooding in these locations were confirmed by residents and authorities, our assumption was that it represents areas with a relationship (strong or weak) between vulnerability and exposure that conveyed in the flooding occurrence (Hazarika *et al.*, 2018). This is based on the dynamic character of disaster, in which the characteristics in place on the instant the hazard takes place will define the intensity of the impacts (Pescaroli *et al.*, 2019). The sample analysis showed that 196 points with flood complaints and residents (DE) were classified with the "moderate and high" vulnerability to flooding, which validates the mapping in approximately 90% of the dataset. It is important to mention that the other 28 points represent areas with "very low" and "low" classifications of vulnerability, but still can turn into a disaster if in contact with exposure and extreme precipitation. Additionally, the mapping indicators (Tables 5.2 and 5.3) and final outputs (Figures 5.4a, 5.4b and 5.4c) were discussed and approved by authorities of Campina Grande in meetings held in January of 2021.

5.4 Discussion

Due to the nature of flood events and the relatively reduced time for preparation when the rainfall occurs, actions for flood management are mostly applied after it is transformed into impact (Pescaroli *et al.*, 2019). Although disasters are not preventable, we recognise the importance of analysing vulnerability assessments and hazards mitigation as essential for reducing impacts (Frigerio *et al.*, 2016b). In this study, we consider these issues as influences that need to be fully understood regarding their patterns of vulnerabilities and exposures to reduce the risk (Pescaroli *et al.*, 2019). In other words, we suggest that interactions between the multiple components of vulnerability provide insights on how to improve disaster management, including the amelioration of the structure of urban drainage system (Sivapalan *et al.*, 2012) and the reduction of social and institutional vulnerabilities (Cunico *et al.*, 2017; Marchezini *et al.*, 2017) before the hazard occurrence.

In this context, using the case of Campina Grande – Brazil, we discuss how the interactions between social, structural, and institutional vulnerabilities converge to generate the overall vulnerability and exposure. Since most research focuses only on vulnerability assessments as the disaster impacts, but pays less attention to the reasons behind vulnerabilities and approaches for alleviating these issues (Ghajari *et al.*, 2017), we consider these results contribute to the socio-environmental discussion of how to mitigate flooding with a vulnerability perspective.

5.4.1 Aspects generating the flood vulnerability

When analysing the vulnerability of the system, this approach considers the interrelationship between datasets characterised by the following situations: (i) *the increase of sensitivity and the decrease of capacity will generate more vulnerability, and (ii) the intersection of vulnerable, exposed and hazard-prone areas will culminate in the disaster occurrence.* The analysis is based on cross-tabulated pixel-by-pixel information of vulnerability indicators according to Pearson correlation. Figure 5.5 shows correlations from -1 to 1, indicating negative and positive correlations, respectively. At this phase, our intention was not to state causality between datasets but to evaluate how the indicators typically move together.

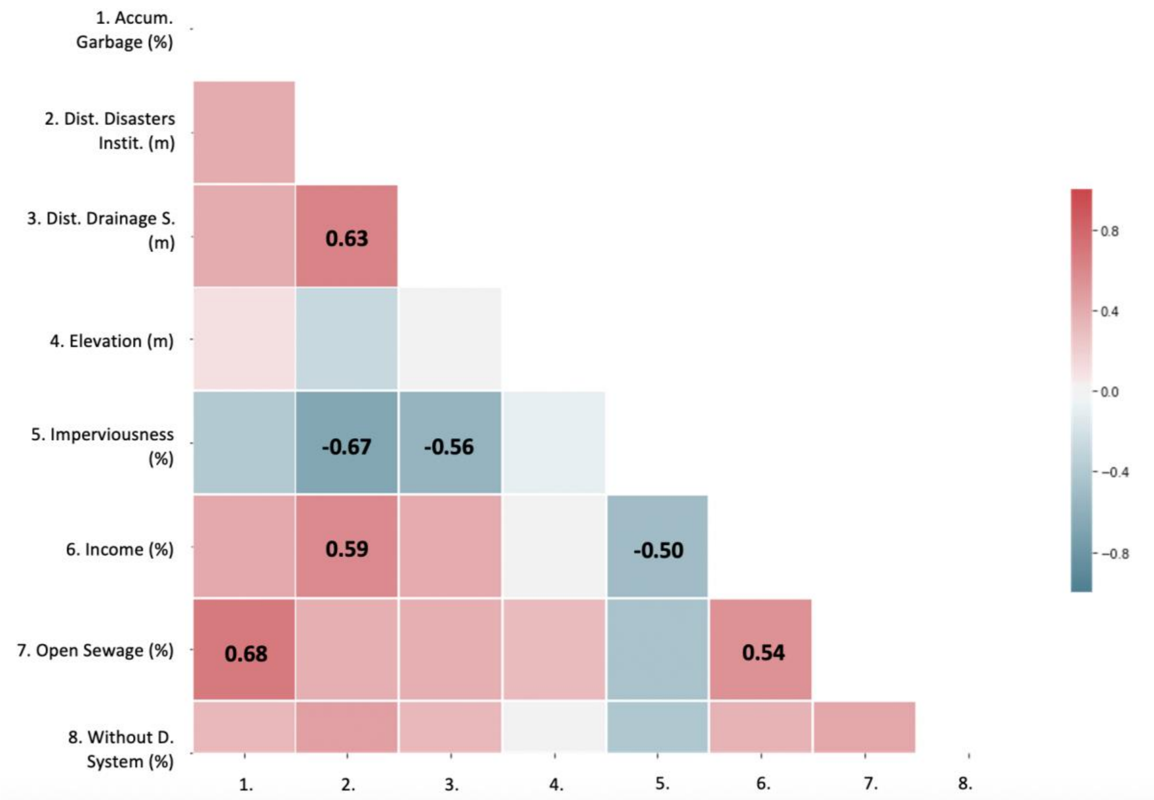


Figure 5.5 - Pearson correlation between the indicators of flood vulnerability (sensitivity and capacity mappings).

Pixels with "Open Sewage - OS" and "Accum. Garbage - AG" indicators are positively correlated (+0.68), which indicates that households have increasing and simultaneous issues with drainage capacity. This result was confirmed in the PLANEJEEE project, in which the low maintenance and design of network were underlined as the main causations to the flooding in Campina Grande (Table 5.1). Overall, structural vulnerabilities are suggested as flood causations in Brazil, particularly related to the drainage capacity (Goncalves *et al.*, 2018; Sarmento Buarque *et al.*, 2020). Cities with large geographical differences regarding urbanisation and climate are susceptible to floods, especially in areas with poor risk communication, social inequalities and lack of capacity (Marchezini *et al.*, 2017).

We suggest that not only structural aspects are inherently corroborating for flood vulnerability, but also institutional and social aspects. Since changes in land-uses contribute to a more significant frequency and intensity of floods by increasing surface runoff (Caldas *et al.*, 2018), it is essential to inspect the imperviousness land-use rates by management authorities. In the Brazilian context, a weak inspection of the legislation fulfilment is seen in different cities. The Master Plan of Campina Grande regulates the maximum imperviousness of 80% of the area in each lot, however, this threshold is often exceeded by residents without any consequence (Alves *et al.*, 2020e) (i.e., see Alves *et al.* (2020e) for a complete legislation analysis).

Stakeholders of the PLANEJEEE Project also highlighted other issues, like the low implementation of legislation, including urban planning (i.e., the Master Plan) and the lack of regulation specific to drainage as causes for vulnerability. For example, even though there is a requirement of updating the Master Plan in every ten years, the latest version of Campina Grande's Master Plan is from 2006. On the institutional level, other aspects like the poor collaboration between academia, citizens, and public/private administration were highlighted and reflects the disconnection of urban and water resources planning in the city (Grangeiro *et al.*, 2019).

In an attempt to identify the conditions that make people or a place more vulnerable (Cutter *et al.*, 2008), we emphasise the importance of analysing the social context of the city. This is based on the assumption that it reflects a "potential of loss" (Cutter, 1996) that in the context of disaster risk management is the most tangible manifestation of the social construction of risk (Hazarika *et al.*, 2018; IPCC, 2012). The blue boxes on Figure 5.5 indicate the negative correlation between datasets. For example, the comparison between "*Imperviousness*" ("institutional vulnerability") and "*Income*" ("social vulnerability") shows that when the imperviousness increases, the percentage of people with fewer income decreases (-0.50). This result suggests that more imperviousness is found in locations where more people with higher income live. This result corroborates with Cutter *et al.* (2003), where it is shown that social processes interact with natural processes and the built environments to redistribute the risks and the impacts of the hazards. Our analysis supports the conclusion that people with more income tend to reduce perviousness and create more flooding, which can indicate a low-risk perception of residents.

In addition, the participation of residents in the socio-environmental methodology allowed the conclusion that social aspects are also primary contributors for vulnerability since fewer individual and community resources for recovery are available in Campina Grande. Citizens detailed flood damages that are not only related to the duration of the flood event but also in the aftermath. Approximately 44% of the participants claimed to have lost assets in a flood event and 63% had to be temporarily moved to another location after the event. Besides, residents mentioned problems with mud, animals (e.g., mice, snakes, and cockroaches) and structural losses that appeared after the runoff of waters. This shows that income is not only needed to mitigate and to cope with flooding but also to recover from the hazard. For Birkmann (2007), difficulties in recovering from the negative impacts of hazardous events also generate vulnerability, which makes coping and recovering part of its assessment. Therefore, we suggest that a combination of institutional and social strategies to provide better financial conditions and generate enhanced risk perception and coping capacity must be implemented in the city as resources to decrease flood vulnerability and increase resilience (Nguimalet, 2018).

Finally, we suggest that reducing exposure of most affected groups is also crucial for minimising future risks. This factor is confirmed in the literature (Cutter *et al.*, 2008) where demographic groups like the percentage of elderly and children's presence impose more difficulties of the community to cope with flooding (de Brito *et al.*, 2017). For Fuchs *et al.* (2011), exposure can be seen as the relationship of elements at risk to the hazard. Therefore, defining exposure is a bridging element between the natural and social scientific part of the risk. In other words, the exposed elements detailed in this study (Figure 5.4A, B) are vital for management, since it shows the density of people and distance to assets, which will be impacted by the hazard and vulnerability indicators. Hence, the spatialisation of exposure enables the assessment of exposed areas with a social view that can help managers and policymakers for the flood management.

5.4.2 Limitations and next steps of the socio-environmental approach

As the vulnerability is a relationship between a series of categories that are not independent but interact on many different time and space scales (Pescaroli *et al.*, 2019), the dynamic aspect of vulnerability is key. In this context, the choice of indicators, including the assessment of weights and standardisation is still difficult. In this regard, out approach provided a pixel-by-pixel mapping, in which relationships were assessed and discussed between the indicators themselves and each disaster variable. We argue this strategy could be used to prioritise areas for reducing vulnerability before the flooding.

The integrated participatory-fuzzy-entropy approach considered uncertainty errors possibilities since the conception (Sharma *et al.*, 2019) until applying the framework (Malczewski *et al.*, 2015). We aimed to increase the collaboration of stakeholders, in all SES phases, from indicators to the mapping results and validation. This appears to have great importance in real-life applications since there is a need to select indicators that the stakeholders can understand for later use (Parker *et al.*, 2019). This is based on the conclusion presented by Fuchs *et al.* (2011) where the importance of clearly describing and defining the components of risk and/or vulnerability is considered essential for the management.

However, a limitation of our work is that the lack of datasets could constrain it. Without datasets, the objective phase of the framework would not be possible. So, it can only be applied in areas with representative data. Similarly to vulnerability, the risk is complex and dynamic, which requires regular re-assessment (Peduzzi, 2019). By using our framework, the re-assessment can be facilitated by the classes of indicators and by the pixel-by-pixel analysis, in which the stakeholder will have the complete analysis of the behaviour in each variable (sensitivity, capacity and exposure). Further research must apply this methodology considering future changes in the datasets.

The use of mixed-source information is being significantly used in flooding studies in the last years (Sarmento Buarque *et al.*, 2020), as a low-cost tool for low monitoring areas. In this context, we developed a validation approach based on the confirmation of flood cases in which approximately 90% of the points were validated. Besides, to evaluate the acceptability of policymakers, the indicators and mappings were presented and discussed with stakeholders. However, a more specific approach with the collection of more recent flooding cases and flood levels may be implemented in the future.

In this work, flooding hazard itself was not considered in the mapping. Future results will express the impacts generated by the interrelationship between hazard, vulnerability, and exposure. The risk areas will be analysed in the system to locate adaptation and mitigation strategies for enhancing the system and reducing flooding. For further steps, it is important to link the vulnerability and exposure maps with social and institutional vulnerabilities, in a broader context with integration with other elements of capacity, such as risk perception, to the proposal and placement of solutions for reducing the flooding in cities with context similar to Campina Grande.

5.5 Conclusions

Even though disaster risk reduction research tends to focus mostly on hazard modelling (Peduzzi, 2019) and in larger scales (Parker *et al.*, 2019), this work detailed and quantified vulnerability and exposure in local-scale. This work stands out in multidisciplinary research in water management since, until today, less effort has been made for addressing disaster risk variables beyond hazards modelling (Peduzzi, 2019).

Our work's novelty is also shown by approaching risk components with a more holistic framework, where GIS is used as a geographic bridge between social and physical sciences (Lund, 2015). Understanding vulnerability and exposure is extremely important for reducing the impacts of disasters in complex urban systems. In our work, vulnerability and exposure are expressed according to the new paradigm approach of IPCC (IPCC, 2012, 2014). The combination of sensitivity, capacity and exposure is expressed with multiple indicators according to vulnerability categories (physical, environmental, social, structural and institutional) that create overall flood vulnerabilities (Cinner *et al.*, 2018). Our results express the need to consider each multisectoral category of vulnerability as an important step for managing disaster risk reduction.

Our approach relies on inputs from households, policymakers, local experts, and pre-existing datasets, where it is possible to prioritise indicators and areas that require more intervention and support from the city administration. The involvement of relevant stakeholders from different levels and sectors provided valuable input and datasets for the assessment and can improve co-ownership and acceptance of the results (Hardoy *et al.*, 2019). The vulnerability and exposure are already conceptually complex, so, our objective was to characterise the system according to views from a multidisciplinary group of stakeholders (Hazarika *et al.*, 2018), including the residents.

The disaster variables maps are essential for managers and policymakers to manage disaster risk, including the selection and proposition of solutions strategies (Caldas *et al.*, 2018) and the selection of “hotspots” areas for DRR. In this sense, the integrated framework can be a tool where specific issues in both social and environmental perspectives can be directly tackled to generate a future reduction of sensitivity and exposure as well as the improvement of capacity rates. Finally, the hazard-specific approach provides an opportunity to produce in-depth knowledge of how disasters are created, in a local scale, and can be input for disaster risk management before, during and after the extreme event.

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CHAPTER 6
Evaluating sustainable solutions in a representative catchment of Campina Grande, Brazil

Chapter 6: Evaluating sustainable solutions in a representative catchment of Campina Grande, Brazil

This chapter refers to the analysis of environmental benefits with the implementation of sustainable solutions in a representative catchment of Campina Grande. Article 04 is currently published in the Sustainability Journal.

Research questions:

- RQ 9: *How can physical, climate, hydrological and governance factors be incorporated in the analysis of environmental benefits of sustainable solutions?*
- RQ 10: *How is the current context of legislation (and governance) in the study area for the proposal of sustainable solutions?*

Chapter 6 - Land-Use and Legislation-Based Methodology for the Implementation of Sustainable Drainage Systems in the Semi-Arid Region of Brazil (article 04)

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Abstract
In developing countries, the urbanisation process occurs with empirical urban management, a high increase of impermeable areas, and a lack of connection between water resource management and planning. In Brazil, concentrated rainfall and ineffective urban drainage systems add to this context and may impact the population with flash floods. Although sustainable drainage systems (SuDS) are widely used for flood mitigation, it is still not very well known how those strategies behave in semi-arid regions, where most of the time the weather is very dry. In Brazil, flood mitigation still mostly involves structural measures such as larger pipes or channels, with limited guidance for SuDS use due to the great resistance to change by citizens and managers. This study sought to analyse the efficacy of SuDS in Campina Grande, a semi-arid region of Brazil. A land-use and legislation-based methodology was developed with physical, climate, hydrological and governance data for three catchments and 312 sub-catchments in 30 applications and simulations. Simulations suggest that these strategies would be appropriate for semi-arid regions, with reductions in the flooded area, flooding volume, and impacts. This study is of relevance for cities with a similar climate to reach a sustainable level of urban drainage services, supporting the integration of urban planning and water resources management.

Keywords: sustainable drainage systems; semi-arid; flooding mitigation

6.1 Introduction

More than half of the world's population live in urban areas (Nations, 2010). Fast urban growth creates more impervious surfaces, high densification of neighbourhoods, and an inevitable reduction in the percentage of green areas. Currently, due to rapid changes in urbanisation patterns and major environmental concerns, there is increasing pressure on governments to provide improved and expanded urban water services in both developing and developed countries to face urbanisation challenges in environmental and socio-economic processes in a sustainable way (Poustie *et al.*, 2014).

Flooding is considered the most frequent among natural disasters, driven mainly by climate change and rapid urbanisation inducing changes in watershed hydrology (Ahiablame *et al.*, 2016; Xie *et al.*, 2017). The *World Research Institute Report* indicates the number of people affected by river flooding could triple to 50 million between 2015 to 2030, causing approximately US$500bn of damage (ARUP, 2018). For many years, the dominant approach in urban drainage was the use of canalised networks (Baptista *et al.*, 2011), also called “grey structure”. However, nowadays, flood risk management solutions promote the inclusion of sustainable concepts with different objectives, including the reduction of runoff volumes and flow rate (Qin *et al.*, 2016; Xu *et al.*, 2017), but also the achievement of long-term urban sustainability.

In the Australian context, the Water Sensitive Urban Design (WSUD) approach was an answer to improve the environment, create public spaces, and mitigate flood risk by considering the holistic management of the integrated water cycle. In other parts of the world, broadly speaking, similar solutions focusing on different scales and methods are acknowledged, such as "Low Impact Development" (LID), “Green Infrastructure” (GI), “Best Management Practices” (BMP), “Nature-Based Solutions” (NBS), and “Sustainable Drainage Systems” (SuDS), and well-known as sustainable alternatives for managing flood risk.

SuDS promotion via reports and guidelines has led to its rapid adoption in different regions and different countries (IPCC, 2012). Developed countries included SuDS in governance regulations, e.g., in the United States (Benton-Short *et al.*, 2017), Australia (Roy *et al.*, 2008), United Kingdom (Melville-Shreeve *et al.*, 2018), and across Europe (Eggermont *et al.*, 2015). The International Water Association (IWA) cited satisfactory implementations in Belfast (Northern Ireland), Vancouver (Canada), New York City and Portland (United States) in 2018 (ARUP, 2018).

Despite the growing number of research and case studies, experiences of sustainable strategies application in management still face many challenges to enhance urban flood reduction. SuDS effectiveness is not only analysed with regard to the ability to restore the pre-development characteristics of the area (Liu *et al.*, 2014), but should also respond successfully to climate variability analysis (e.g., adaptive capacity) with a reduction of impacts to specific populations (e.g., vulnerability assessment) (Ahmed *et al.*, 2017). Several variables can influence the SuDS performance on runoff control such as rainfall intensity (Qin *et al.*, 2013), area and placement (Passeport *et al.*, 2013), selection of techniques, and construction (Martin-Mikle *et al.*, 2015). Meanwhile, others (Leidel *et al.*, 2012; Webb *et al.*, 2018) argue that, beyond technical choices, for successful management, it is necessary to strengthen the governance. Some studies have focused on finding the best strategies (Xie *et al.*, 2017) and proposing different land uses (Emmanuel *et al.*, 2015; Norton *et al.*, 2015), however, many of them have difficulties in application due to climate and legislation restrictions.

Another barrier is related to differences between research focuses and their implication for policymakers. The high incidence of research conducted on temperate regions makes the applicability more difficult in subtropical regions with different geoclimatic, sanitary, and social conditions (de Macedo *et al.*, 2019). Recent studies have simulated the efficiency of flood compensatory strategies - a well-known research expression in the Brazilian context (from Portuguese: *"Medidas compensatórias de alagamentos"),* which refers to every strategy to mitigate flooding impacts, in urban and rural contexts, and returning to the pre-development state (before flood) - in Brazilian cities (Goncalves *et al.*, 2018), but mainly in highly developed urban watersheds (da Silva *et al.*, 2018) or regions with a high incidence of precipitation (Miguez *et al.*, 2015b; Moura *et al.*, 2016). This can be a problem in countries with huge regional, climate, and socio-economic differences (Goncalves *et al.*, 2018). Despite the efficiency of the compensatory measures, those approaches are not well-suited for other regions with only dry and rainy seasons (e.g., tropical countries), where often there is a great need for flooding reduction. In those countries and cities, decision-makers are supplied with information and parameters that require additional adaptation efforts.

The research presented in this paper aims to contribute to addressing those gaps by evaluating the efficiency of SuDS on mixed land-use catchments in the semi-arid region of Brazil, with the analysis of runoff reduction of severe flood-prone areas and the capacity of restoring the pre-development state, even with the climate constraint. For this, an approach linking water resources modelling and urban planning with land-use and legislation barriers was developed according to various types of data (physical, climate, hydrological, and governance) with applications in three catchments and 312 sub-catchments in Campina Grande, Brazil.

6.2 Brazilian Context

In Brazil, approximately 24 million people (corresponding to 12% of the population) live in the semi-arid region, located in 1189 counties (IBGE, 2010). The region is considered as the most densely populated dry region in the world (Alvala *et al.*, 2019), with challenges in environmental and socio-economic processes affecting the population. Miguez *et al.* (2007) emphasise that the most aggravating aspect of urbanisation is the rapid growth in a short period, without adequate infrastructure (Tassi *et al.*, 2014) and public policies. In Brazil, the lack of legal regulations causes further challenges and leads to a lack of synergy, resources, funding, and hope (ARUP, 2018).

Since the late 1980s, with the Water Resources Federal Law—Nº 9.433/1997, Brazil has been striving to implement aspects of integrated and participative water management into public policies (ANA, 2010). The water law reaches the local level and gives the municipal authorities the responsibilities of urban development, environmental protection, and provision of water supply and sanitation (Table 6.1).

Table 6.1 – Brazilian government levels and water legislation responsibilities.

Government Levels	Environmental Protection	Water Resources Management	Water Supply and Sanitation
Federal	Inter states impacts	Federal waters	
States	Inter municipalities impacts	State waters	Inter municipalities services
Municipalities	Local impacts		Local services

Source: Libanio (2014).

The Federal Law Nº 11.455, approved in 2007, established guidelines for basic sanitation in Brazil. This law asks for the elaboration of the sanitation plan to each municipality that has more than 20,000 inhabitants. This plan involves four areas of sanitation, including water supply and urban drainage. The law opened up new institutional perspectives for the design and management of urban rainwater, however it does not contain all the specificities of a drainage plan (Brasil, 2007). At present (late 2019), the drainage master plan still is not mandatory to municipalities. Metropolitan cities mainly present some developments (e.g., São Paulo, Curitiba, Recife, Porto Alegre, and Guarulhos), but it is often a local action of the municipal government. Recently, Libanio (2018) revealed aspects that consider Brazilian water policies very fragile, dysfunctional, and troublesome, especially concerning the participatory experience in legislation formulation and implementation. Water regulation has been basically restricted to the formalisation of entitlements, instead of reflecting priorities for water uses and policy goals (Libanio, 2018), and coordination across different planning scales has led to some non-effectiveness in management (RIBEIRO, 2017).

The Federal Law Nº 10.257, dated August 10, 2001, known as "the City Statute", provides for every municipality, the master plan, programs, and sectoral projects, as well as other urban planning instruments with the potential to control the impacts of urbanisation on the hydrological cycle and the environment. According to this statute, the urban master plan is a set of principles and rules that guide the action of the construction agents in an urban space with the neighbourhood (e.g., a set of blocks and lots) as the central unit of management. This aspect of the law was previously considered as another difficulty for linking water and urban policies since the water management unit is the catchment (Water Law 9.233/1997). So, the institutional efforts in integrating planning and water resources management are still a controversial topic among scholars and policymakers in Brazil (Miranda, 2017). For most of the municipalities, the master plan presents a land-use approach disconnected from environmental, drainage, and sustainability issues, which increases, even more, the lack of suitable legal tools towards water sensitive planning.

In Brazil, there are only a few legislations to control and mitigate floods with SuDs strategies, and most of them are not found in the semi-arid region. The number of regulatory tools is extremely low in comparison to the number of Brazilian cities, but there are some legal guidelines available in different governmental levels. The city of Porto Alegre, the capital of Rio Grande do Sul state, made the first initiative for the use of green roofs in Brazilian territory. The complementary law Nº 434/1999, promotes green roofs as a possibility to maintain green percentage on buildings. In 2013, the law Nº 54.423 was approved in São Paulo state to allow the use of green roofs and rain gardens as a measure to compensate constructed areas. There are green roof initiatives sprawled out in some of the main Brazilian cities, but it is still considered as a paradigm of the predominant and usual concepts of urban drainage management (Rangel *et al.*, 2015).

An interesting fact emerged from the analysis of the approved laws Nº 7.031 (2012) and Nº 10.047 (2013) for the city of Guarulhos (São Paulo state) and Paraíba state, respectively. In summary, these regulations made green roofs mandatory in all built condominiums, with more than three buildings, after the date of legislative approval. Although it can be effective, those areas have urban and geographic differences. Data from the Brazilian Institute of Geography and Statistics (IBGE) shows that Paraíba state, in the semi-arid region, has more than 200 municipalities, of which more than 60% have less than 10,000 inhabitants. However, the law Nº 10.047/2013 suggests the green roofs for all the cities. Guarulhos is part of the metropolitan area of São Paulo state, Southeast region, with more than 1.2 million residents. Cities from Paraiba are quite different from Guarulhos in too many aspects (weather, economy, size), which makes it hard to apply for the same urban permit in any way.

Other law projects are waiting to be evaluated by congress (e.g., Federal Law Nº 1.704/2011 and Nº 9.927/2018). However, the process of approval and implementation of legislation is slow and will possibly need many years to be finalised. Nevertheless, as the similarity between some policies is extremely high (in some cases, the laws are the same), and the areas of application (states and cities) are different, those laws are often developed without a previous study of local land use or downstream effects at the corresponding states and cities. Further, Miguez et al. (Miguez *et al.*, 2015b) suggest that low monitoring, fail control, and no penalties in Brazil often nullifies the application of such measures. The regular monitoring and evaluation of water policy and management systems have not yet been implemented in Brazil (RIBEIRO, 2017). Thus, there is still a need for a more comprehensive view of urban drainage sustainability.

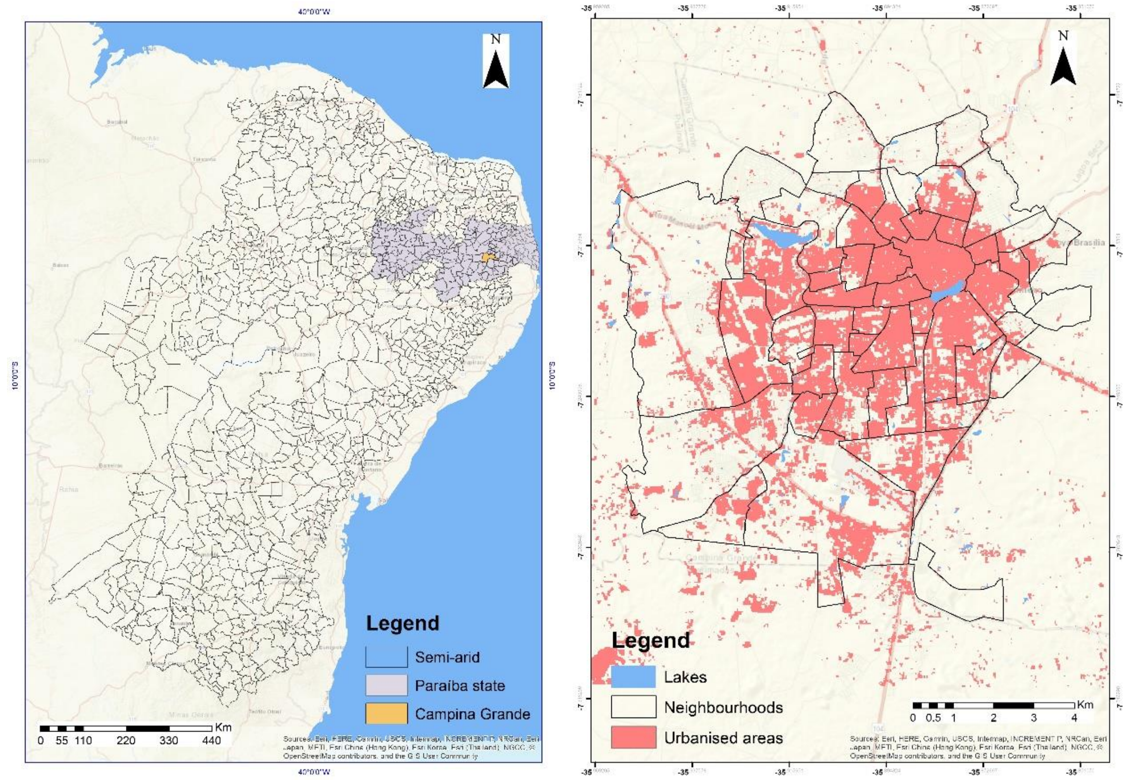
In this paper, the efficiency of three sustainable compensatory strategies, green roofs, permeable pavements, and rain gardens is evaluated in multiple semi-arid catchments of Campina Grande municipality, Brazil. These practices cannot wholly substitute conventional structures to control storm runoff, but integration between new and old structures is suggested (Xu *et al.*, 2017). To understand all interactions in the catchments, we developed a land-use and legislation-based methodology to identify possible strategies for a strategic planning tool with the integration of different structures. This will involve spatial analysis to select and characterise the area and also aspects of hydrological modelling and the proposal of legislation-based scenarios to implement and evaluate the suggested SuDS techniques. The results will help to understand which SuDS configuration is suitable for similar areas and can support the integration of urban planning and water resources.

6.3 Methodology

This paper seeks to address the case of the semi-arid region of Brazil. This region is one of the most populated semi-arid regions in the world (Figure 6.1a). The Brazilian semi-arid region is characterised by extreme weather conditions, highly irregular rainfall, and long and exhaustive periods of drought (Alvala *et al.*, 2019). These situations impose a significant increase in the vulnerability of human populations and social development. To investigate management issues that afflict Brazilian semi-arid cities, the city of Campina Grande (Paraíba state) was chosen as a study case. The city represents middle-sized municipalities with populated areas that experience a recurrence of drought and flooding hazards.

6.3.1 Study Case and Alternatives for SuDS Application

Located in Paraiba state, in the semi-arid region of Brazil (Figure 6.1a), Campina Grande is a city with 594 km^2 of total area and approximately 110 km^2 of the urbanised area. Data from IBGE, in 2016, estimated its population as 407,754 inhabitants, which had an increase of about 20% in the last two decades. This fact represents changes in the urban area, such as the number of buildings, paved streets, and impervious surfaces (Figure 6.1b).



(**a**) (**b**)

Figure 6.1 - Geographic and urban features: (a) Location of Campina Grande in the Brazilian semi-arid area; (b) Urbanised areas of Campina Grande; Source: Rufino *et al.* (2017).

In an attempt to find the best conditioning factors to represent the city, this work presents an analysis of legislation in different levels, available data, and previous literature. Data from the Campina Grande City Council (PMCG - Prefeitura Municipal de Campina Grande) classify the urban area according to different land uses (residential, commercial, institutional, and non-used areas). Although the municipality has a mandatory permeability rate (minimum of 20%) by the master plan, the basic sanitation plan indicates a different reality in the blocks, with impervious rates higher than the allowed rate in many places. The basic sanitation plan was developed in 2015 and only in 2019 was approved as a law. The master plan of the city was supposed to be updated since 2016, but up to 2019, the revision is still in process. Since 2013, the city council asphalted more than five hundred streets in the city, and more than 900 streets are expected to receive an asphalt paving before 2020.

As mentioned previously, the municipal authority has the responsibility for urban development, environmental protection, and provision of water supply and sanitation. In the municipality sphere, Campina Grande does not have a drainage plan or specific legislation for SuDS (or similar). The basic sanitation plan of the city characterises the drainage system with design and maintenance issues. In the plan, sustainable solutions were suggested in local-scale (Ramalho *et al.*, 2015) but, up to 2019, such plans were still not applied. As Campina Grande is located in Paraiba state, the State Law 10.047/2013 mentioned earlier is currently in force.

Despite the availability of these state and municipality policies, the city is exposed to flash floods during the rainy periods mainly due to concentrated and extreme rainfall events (Alves *et al.*, 2018b; Santos *et al.*, 2017c). The ill-planned urban growth brings several impacts to the hydrological cycle in urban environments such as an increased surface runoff volume. Research studies (Alves *et al.*, 2018b; Nobrega, 2012; Santos *et al.*, 2017c; Tsuyuguchi, 2015) have described the current urban drainage situation of Campina Grande, which includes issues of design, cleaning, and maintenance of drainage elements such as channels and manholes, as well as high urbanisation rates and a lack of planning. These facts make some areas often susceptible to flooding and also corroborate the need for implementing measures to mitigate the flooding effects.

According to the National Water Agency (ANA) (ANA, 2018), the Northeast region is the only one in Brazil with arid desert and arid steppe (BWh and BSh from Köppen-Geiger Climate). During the last period of water scarcity faced by the region (2012 to 2017), the city experienced a severe water shortage with more than five days per week with no water supply (Rêgo *et al.*, 2017). Recently, the city received waters from São Francisco River (e. g., referred to as "*transposição*": "a diversion of river waters to cities with water scarcity in the semi-arid region"). Some water researchers (Rêgo *et al.*, 2017) agree that this diversion will not solve water scarcity issues permanently if there is no improvement in the management. Up to May 2019, the Campina Grande water reservoir (Boqueirão) still has less than 25% of full capacity. In this paper, dry climate data were used to model SuDS in the city. Meteorological data were obtained from the weather station of the Brazilian Agricultural Research Corporation (EMBRAPA) in Campina Grande. EMBRAPA monitors climatic parameters in many Brazilian cities, which are mainly used for climate studies (de Macedo *et al.*, 2019). Köppen–Geiger climate classification and brazilian bioclimatic zones (Table 6.2) were also applied to provide more detail for the climate input data in the modelling. Although the integrated analysis of floods and drought is largely supported by literature, this paper will only deal with mitigation of flooding episodes. Based on this analysis, three conditioning factors were chosen to locally represent the city and are considered crucial to urban and water resources planning (Table 6.2).

Table 6.2 – Conditioning factors selected to the application of SuDS legislation in scenarios.

Conditioning Factors	Description	Sources
Urban development (land-use input)	Residential, commercial, institutional and no use areas.	Obtained from PMCG (2010)
Physical specificities (hydrological and climate inputs)	Rainfall[1], soil type and infiltration[2]	Aragão *et al.* (2000) Paixão *et al.* (2009)
	Drainage system assets	Obtained from PMCG (2019)
	Climate	Köppen-Geiger Climate Brazilian Guidelines for Buildings 15.220 of 2003 (Brazilian Bioclimatic Zones)
Alternatives for SuDS application (governance input)	Suggests sustainable measures for flooding mitigation in the city	Federal level: Basic Sanitation Plan (Federal Law 11.445/2007)
	Mandatory use of green roofs in condominiums with more than three buildings.	State level: Law 10.047/2013 (for Paraíba state)
	Rate of imperviousness granted according to uses and areas. Max imperviousness: 80%/ Min permeability: 20%	Municipal level: Master Plan (Complementary Law 003/2006)

Sources: [1]Aragão *et al.* (2000) and [2]Paixão *et al.* (2009)

6.3.2 Sustainable Measures Modelling

As already mentioned, permeable pavement, green roofs, and rain gardens are promising measures to reduce flood cases with different rainfall rates (Ishimatsu *et al.*, 2017; Lin *et al.*, 2015; Matheus *et al.*, 2016). On the other hand, merely increasing the number of measures is not enough. Recent papers (Ahmadisharaf *et al.*, 2015; Martin-Mikle *et al.*, 2015) have shown the importance of finding the best position and size to insert measures in the catchment. Versini *et al.* (2016) showed that green roofs could reduce the frequency and magnitude of floods, but the efficiency depends on their covered roof surface. Elmqvist *et al.* (2015) relate aspects of sustainability and flood mitigation to the provision of various man-made and natural green infrastructure. From a climate perspective, it is also necessary to determine the vegetation type and distribution to achieve the best outcomes (Benton-Short *et al.*, 2017). The effectiveness of each choice is influenced by the installation location (Song *et al.*, 2017), type, and the percentage of area occupied with one (or more) of these practices (Versini *et al.*, 2016).

Considering the above factors, we opted to apply each type of strategy in different scales, with the measures alone and in a combination strategy (Xie *et al.*, 2017) in which their performance can be evaluated by the capacity of restoring, totally or partially, the pre-development runoff regime (condition before growth). This research evaluated SuDS performance through SWMM (Storm Water Management Model) developed by the US Environmental Protection Agency (USEPA). SWMM enables the the assessment of urban drainage systems, which is widely applied and free of cost (Ahiablame *et al.*, 2016; Xu *et al.*, 2017).

Scenarios

The scenarios were selected according to imperviousness rates allowed by the Master Plan. For the "baseline scenario" (S1), it is the current occupation of the city. The model uses land built-up data from 2010 (PMCG). Land-use was updated through on-site visits and Google Street View from 2015 and 2016. The "future occupation" or "legislation upper limit scenario" (S2) uses the maximum rate allowed by legislation for impermeable areas (80%), indicating "a limit situation". SWMM used the Horton method and IDF equations for flow separation and rainfall intensities (Table 6.3). Two storm events representing two and five years of return periods were selected for model running, with values of 43.99 mm and 54.16 mm, over 2h of accumulated rainfalls respectively. The simulation runs at a 6-min time step based on rainfall inputs.

Table 6.3 – Input in SWMM.

Input	Parameters	Description	Values
Sub-catchments or blocks (312 blocks)	Area	Area of the sub-catchment	-
	Width	The maximum length that surface runoff will course inside the sub-catchment	-
	Slope	The slope of the sub-catchment	-
	IA	Impermeable area	-
	NI	Surface roughness (Manning's n) for the overland flow of impervious portion in a sub-catchment	0.011
	NP	Surface roughness (Manning's n) for the overland flow of pervious portion in a sub-catchment	0.04
	DI	Depression storage depth of impervious portion of the sub-catchment	1.01 mm
	DP	Depression storage depth of pervious portion of the sub-catchment	5.08 mm
	AINC	The fraction of the impervious area without depression storage	10%
Rain gauges from real events (IDF: Intense, duration and frequency equation) $i = \frac{K.Tr^m}{(b+t)^n}$ Source: (Aragão *et al.*, 2000)	K	Local parameter	334
	B	Local parameter	5
	n	Local parameter	0.596
	m	Local parameter	0.227
	t	Rainfall duration	120 minutes
	RT	Return period	2 and 5 years
Infiltration (Horton equation) $f_t = f_c + (f_0 - f_c)e^{-kt}$ Source: (Paixão *et al.*, 2009)	Initial infiltration capacity (f0)	Maximum infiltration rate	396.10 mm/h
	Final infiltration capacity (fc)	Minimum infiltration rate	7.10 mm/h
	Decay constant (k)	Decay constant specific to the soil	2.677 l/h

Sensitivity Analysis

To address the gap of sustainable strategies in the semi-arid area, the model considers climate aspects according to the "Brazilian Guidelines for Buildings" 15.220 of 2003 (Thermal performance in buildings and Brazilian Bioclimatic Zones) combined with urban development and the threshold permeability rates and regulations (Table 6.2). Some parameter adjustments were needed with the basis on this regulation and values suggested by the SWMM user manual. Final values (Table 6.4) were those with more efficiency considering the threshold bioclimatic zone and intervals from the SWMM user manual.

Table 6.4 – Final SuDS parameters input in SWMM.

Input	Parameters	Value	Source
Green Roof (GR)	Surface depth (mm)	15	Adapted from (Leite *et al.*, 2016) and (Palla *et al.*, 2012)
	Surface vegetable cover	0.11	
	Surface Roughness	0.15	
	Surface slope (%)	2.5	
	Drainage thickness (mm)	3	
	Drainage voids index	0.6	
	Drainage roughness	0.1	
Permeable pavement (PP)	Surface depth (mm)	10	Adapted from (Korkealaakso *et al.*, 2014) and (Silveira *et al.*, 2007)
	Surface Roughness	0.05	
	Surface slope (%)	6	
	Pavement thickness (mm)	100	
	Pavement voids index	0.2	
	Pavement impermeable surface fraction	0	
	Pavement permeability (mm/h)	5.4	
	Pavement clogging	180	
	Storage thickness (mm)	350	
	Storage voids index	0,6	
	Storage filtration index	7	
	Storage clogging	180	
Rain garden (RG)	Surface depth (mm)	15	Adapted from (Rosa *et al.*, 2015) and (Matlock, 2010)
	Surface vegetable cover	0.11	
	Surface Roughness	0.1	
	Surface slope (%)	1.0	

Analysis

Since the analysis aims to provide findings at the local-scale, land-use and governance data are crucial to ensure the reliability of the model. As mentioned previously, scenarios 1 and 2 represent the current and future occupation of the city, respectively. In total, 30 cases were simulated (Table 6.5 and Figure 6.2).

Table 6.5 – SuDS alternatives modelled with SWMM.

SuDS	Cases	**SuDS Location:** Defined by Legislation in Charge and Land-Use Development	**Scenarios:** Defined by Legislation in Charge	Return Period
No measures	1–4	-	1 and 2	2 and 5 years
GR	5–8	Condominiums, with more than three constructed buildings (Law 10.047/ 2013)	1 and 2	2 and 5 years
	9–12	Institutional/public buildings	1 and 2	2 and 5 years
	13–16	Free spaces/no use	1 and 2	2 and 5 years
PP	17–20	Sidewalks of free spaces	1 and 2	2 and 5 years
	21–24	Every sidewalk	1 and 2	2 and 5 years
RG	25–28	Free spaces/no use	1 and 2	2 and 5 years
ALL	29–30	GR in institutional/public buildings PP in every sidewalk RG in free spaces/no use	2	2 and 5 years

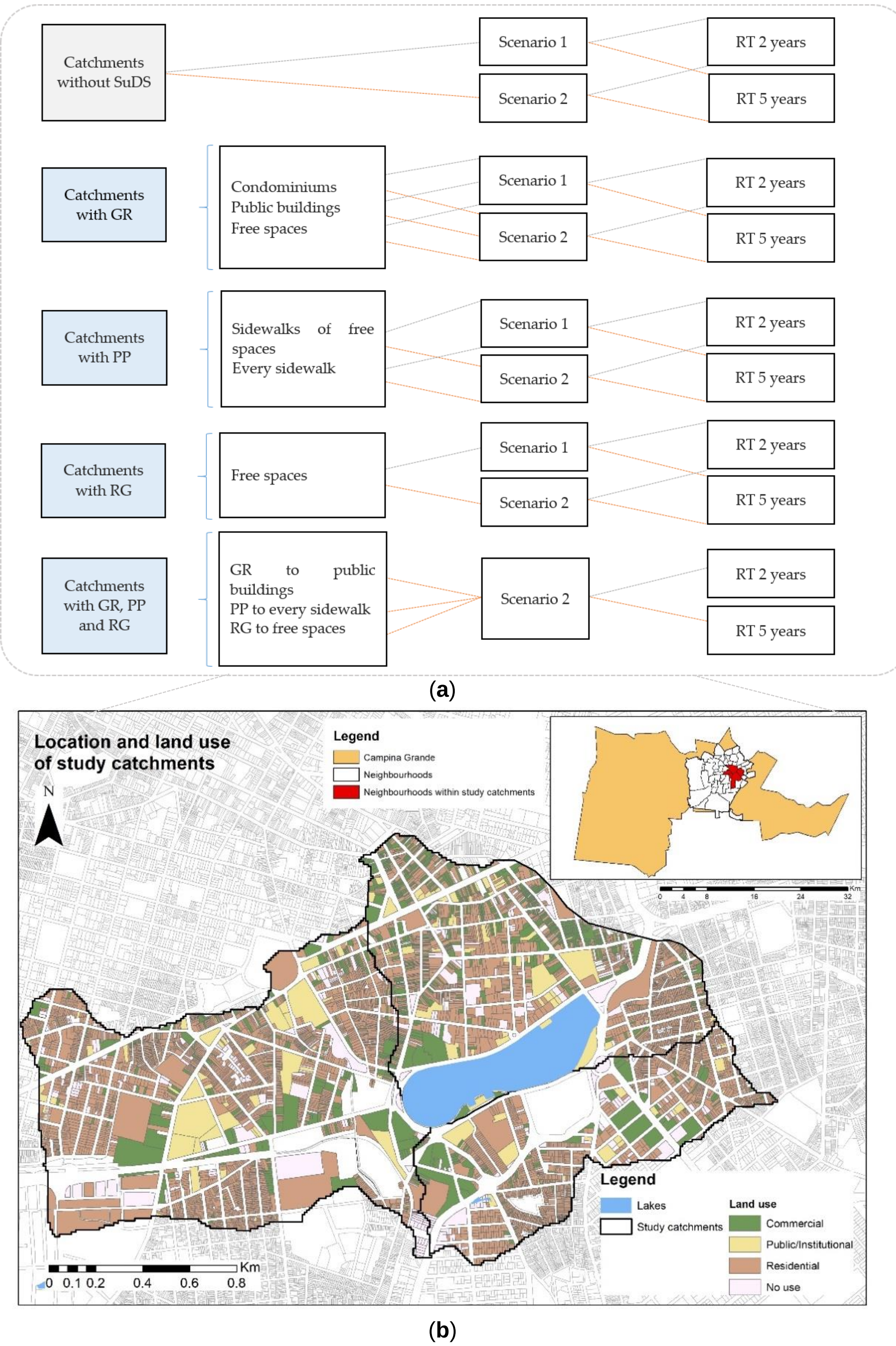


Figure 6.2 - Land-use and legislation- based methodology: (a) Description of the modelling framework; (b) Land-use data for each catchment.

Land-use mixed-catchments of Campina Grande were chosen as the application of the described methodology (Figure 6.2). This area was described as mostly urbanised and as highly susceptible to floods according to multi-criteria analysis in previous research (Alves *et al.*, 2018b). The findings are described by flood volume and percentage of blocks that returned to the previous condition (before the rain event).

Calibration and Validation

Due to the unavailable discharge and water level data, the calibration of the parameters was not possible in this study. However, all input data were carefully chosen and allowed for the conclusion of this research. For this, previous research in the area, on-site field visits, and meetings with stakeholders allowed to obtain the input data. For the validation of flooding maps, known flooding events were used as the basis for comparison. Flooding historical data were delivered by the Civil Defence Agency, which is responsible for checking flooding cases and drainage systems assets in the municipality. The validation evaluated similarities of flooding locations between the model and historical data from 2005 to 2011.

6.4 Results

The results are divided into two analyses: without SuDS strategies (cases 1 to 4) and with SuDS strategies (cases 5 to 30).

6.4.1. Without SuDS Strategies:

The first simulations were performed for the baseline scenario (S1) with no SuDS practices and using rainfall return periods of two and five years. All previous input data were loaded to each sub-catchment/block, totalling 312 blocks. Figure 6.3a,b shows the hydrologic behaviour of the area in S1. Maps generated by SWMM show 29 sub-catchments with a severe chance of floods (red colour) in both return periods. Future occupation scenario (S2) was modelled to complement the simulations with no SuDS practices (Figures 6.3c,d). In this scenario, 49 blocks (RT of two and five years) are in severe condition, which indicates that the drainage system supports neither the current nor the future rate of imperviousness.

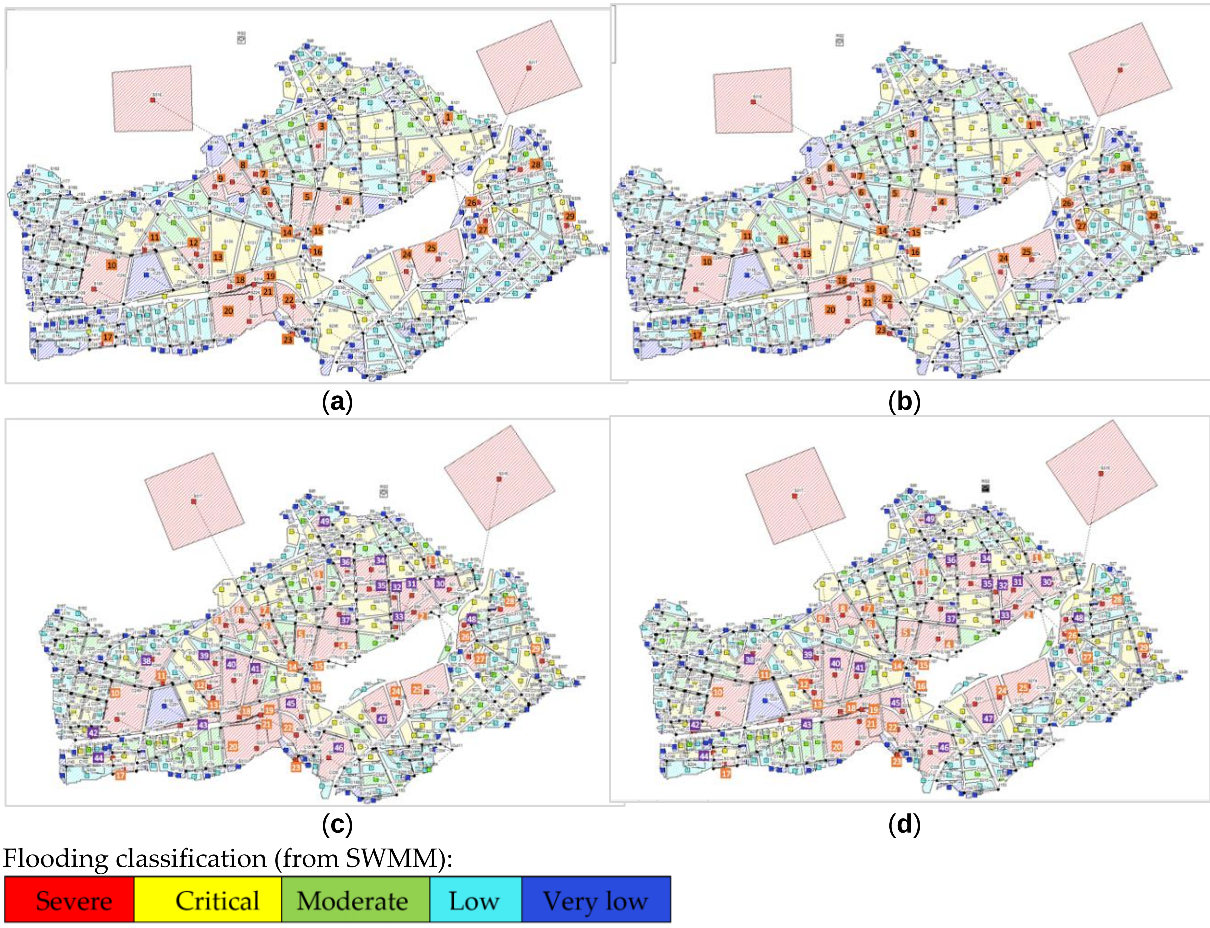
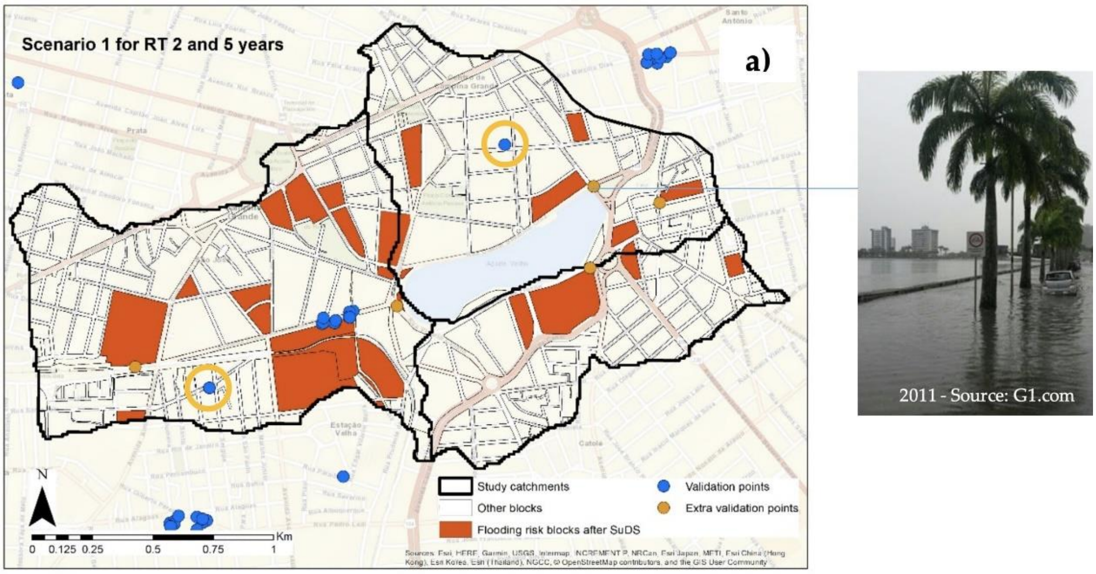


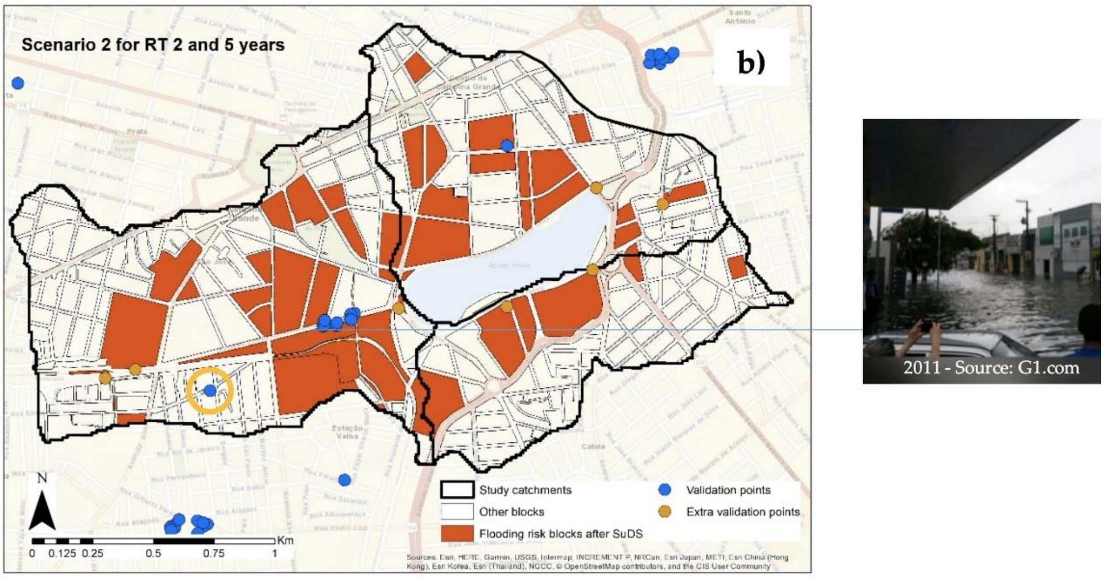
Figure 6.3 - Flooding risk classification for each block in the catchments. (**a**) S1 for RT 2 years; (**b**) S1 for RT 5 years; (**c**) S2 for RT 2 years; (**d**) S2 for RT 5 years.

In S2, the number of severe flood blocks increased by more than 70% in comparison with S1. This also indicates that the drainage system of the city is not sufficient for the current or future occupation. Since the legal instruments are not regularly reviewed, probably floods will keep occurring very often and increase disaster risk. These initial results also suggest that changes in S1 may probably prevent flood disasters occurring in this area in the future since all the severe blocks in S1 also are severe in S2, but with higher runoff volume. This is a significant result because it shows how urgent the adjustments to the current land-use regulation are. If managers keep attending the upper limit threshold, the city may have more severe problems in future than the current ones. It is therefore suggested that compensatory strategies in the present may help to mitigate or attenuate disasters in the future.

For validation, approximately 190 points in the city were reported as flooded. Those points do not necessarily represent all the flooding areas of Campina Grande but show areas that experienced flooding and people reported officially to civil defence (responsible for managing flooding disasters with citizens). Those reported cases are from 2005 to 2011 and were provided by the agency. This number of critical events allows questioning if the urban infrastructure is capable of minimising the negative effects on the citizens as well as their preparedness, awareness, and response (Figure 6.4).



(**a**)



(**b**)

Figure 6.4 - Validation points for: a) S1 in RT 2 and 5 years and; b) S2 in RT 2 and 5 years.

In this paper, since we are only working in three catchments of the city, only points inside this area were considered. According to the data, 11 points are located inside the catchments and, in scenario 1, only two of those points do not match with the map (Figure 6.4a). Still, one of these points is considered as “yellow” in SWMM (Figure 6.3a,b), which represents the “critical flooding classification”. For scenario 2, only one point does not correspond with the threshold classification (figure 4b), but, as before, it is considered as critical on SWMM (Figure 6.3c,d). This point can represent a rainfall with return period greater than five years in the area.

In addition, research in local newspapers, television websites, several web videos, and social media (mainly Facebook and Instagram accounts) allowed finding other locations with flooding within the area. Another seven points were added (Figure 6.4a,b) which also validate SWMM maps. This approach is suggested as a way to manage the lack of validation data in studies (Caldas *et al.*, 2018). However, an in-depth study is suggested for further research to collect more information about flooding episodes in different return periods.

After the simulation of S1 and S2 without any compensatory measures, each SuDS strategy was implemented on the severe (more flooded) blocks inside the basins (29 in S1 and 49 in S2), according to SWMM classification.

6.4.2. With SuDS Strategies:

The application of SuDS structures presents effects concerning each strategy separately and with a combination of all of them. In each analysis, a set of maps show the corresponding runoff volume reductions. Each sustainable measure was included in the catchment considering the equivalent built-up area based on land-use and occupation data (Table 6.2 and Figure 6.2) as well as vacant areas (free areas), where in the future, legislation could enforce the use of SuDS in new buildings. The threshold area for this condition is also based on the minimum and maximum imperviousness rates established in the Master Plan of the city (Table 6.2). This aimed to analyse if the runoff would be reduced with the application of SuDS in vacant areas, with the threshold imperviousness rates.

First, the simulation implemented green roofs (GR) in different urban configurations. As previously mentioned, the land-use in the study catchments area is mixed, mainly residential, commercial, and public, with the presence of buildings in its territory (Figure 6.2). This made the application of green roofs possible in many severe flooding blocks. This choice used guidelines of the Basic

Sanitation Plan and on the Law 10.047/2013. Those regulations suggest GR but without any modelling results of how efficient these measures are or what placement configuration is more effective. So, GR was applied in: (1) condominiums with more than three buildings (cases 5 to 8); (2) institutional/public buildings (cases 9 to 12) and; (3) free spaces/no use (cases 13 to 16).

The results made clear the relation between the three options of green roof and the equivalent area of application, but also the interference of reductions of volume in downstream blocks (Table 6.6). This case can be seen for GR application in condominiums with more than three buildings, where rates of reductions are observed in 100% of the blocks (Figure 6.5 and Table 6.6), although only 12 blocks have this type of land use. This indicates that the reduction is not conditioned only by the presence of buildings on the blocks. Therefore, it is understood that when the flow of a block upstream is reduced then the flow downstream will be automatically reduced. This is evident by analysing the blocks where GR have more area of application (15, 16, 17, 23 and 28) with reductions between 79% and 100%, in cases 5 to 8, and also other blocks without GR directly implemented that have great runoff reduction (case of block 14 with 77.28% of reduction).

The implementation of the measures in scenario 2 also provided reductions in runoff volumes. However, these reductions are more evident in S1 than in S2. With the increase of paving imperviousness of the blocks, the percentage of areas with three buildings became low (considering the current availability) to compensate the values of the flow volumes. But, even in S2, the coverings brought the reduction of the flow. This may indicate advantages in the application of GR in the current land use scenario to generate risk reduction in the future. As in S1, Figure 6.6 indicates that blocks with greater areas of buildings changed their severe condition (blocks 44 and 49, in scenario 2). The highest rates of reduction occurred in blocks 9, 18, and 44, with values between 32% and 44% for cases 5 to 8. Although the application of GR on condominiums with three buildings appears to have good reduction of runoff volume in this case, the effectiveness cannot be generalised to other catchments where this type of land-use is not representative.

Table 6.6 - Blocks with SuDS applied and blocks with reduced runoff after SuDS.

Cases	Number of Blocks with SuDS Applied	Percentage of Blocks with SuDS Applied (%)	Number of Blocks with Reduced Runoff	Percentage of Blocks with Reduced Runoff (%)
Scenario 1 - Current occupation				
GR on condominums	12	41.4	29	100.0
GR on public buildings	15	51.7	21	72.4
GR on free/no use areas	15	51.7	28	96.6
PP on sidewalks of free/no use areas	17	58.6	26	89.7
PP on every sidewalk	29	100.0	29	100.0
RG on free/no use areas	15	51.7	28	96.6
Scenario 2 - Legislation upper limit scenario				
GR on condominums	22	44.9	33	67.3
GR on public buildings	25	51.0	38	77.6
GR on free/no use areas	30	61.2	39	79.6
PP on sidewalks of free/ no use areas	32	65.3	48	98.0
PP on every sidewalk	49	100.0	48	98.0
RG on free/no use areas	30	61.2	40	81.6

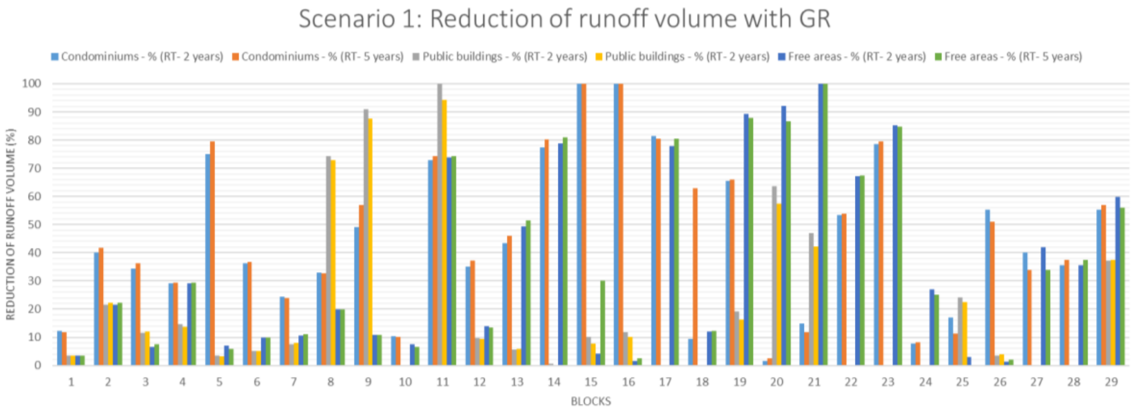


Figure 6.5 - Percentage of runoff volume reductions with GR application in scenario 1 for the 29 severe sub-catchments.

For GR in public buildings on S1 (Figure 6.5), the largest reductions occurred in blocks 8, 9, and 11 (respectively 74.23%, 90.91% and 100%). With the insertion, these blocks became non-critical. As before, Table 6.6 shows that, even without

SuDS strategies, other blocks also had changes in volume values. In S2, greater flow differences can be seen because the critical blocks have institutional areas available for the implantation of the green roofs. Regarding GR on free areas, changes are seen in both S1 and S2. For example, in S1, block 21 had 100% of the flow reduced (best situation) after the implementation of GR in approximately 42.5 % of the total area.

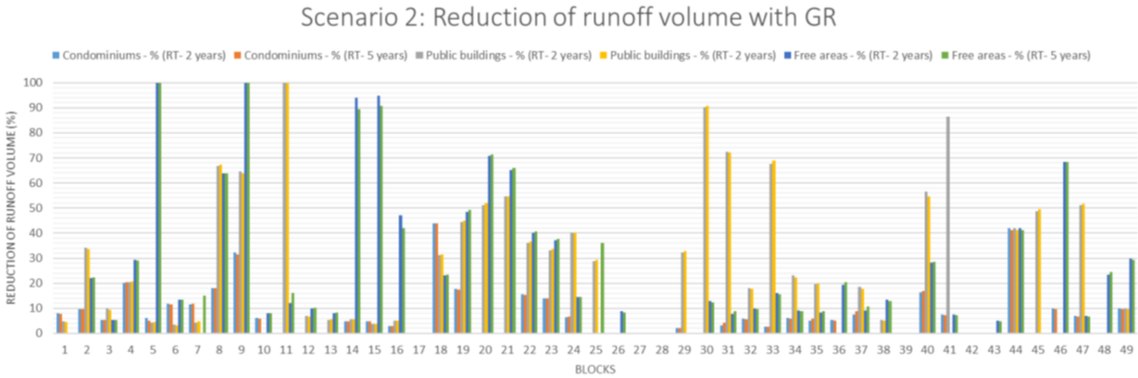


Figure 6.6 - Percentage of runoff volume reductions with GR application in scenario 2 for the 49 severe sub-catchments.

The second simulation analyses the performance of permeable pavement in two configurations: (1) sidewalks of free spaces (cases 17 to 20) and (2) sidewalks of the severely flooded blocks (cases 21 to 24). Free spaces (or no use) blocks represent the involvement of public actors to support this practice in future legislations since they can use laws to encourage this paving use. The last simulation is the use of rain gardens in non-built spaces (cases 25 to 28), where compensatory strategies are suggested for non-built spaces and, depending on the results, construction is encouraged in future buildings. Since each analysis has a significant number of blocks and findings, a summary of effectiveness related to the reduction of severe blocks after the implementation of SuDS was produced (Figure 6.7). This graph intends to show the efficiency of each strategy in each case and each scenario. The research data supporting this publication are provided within this paper, and all graphs related to the other simulations can be found in Appendix E.

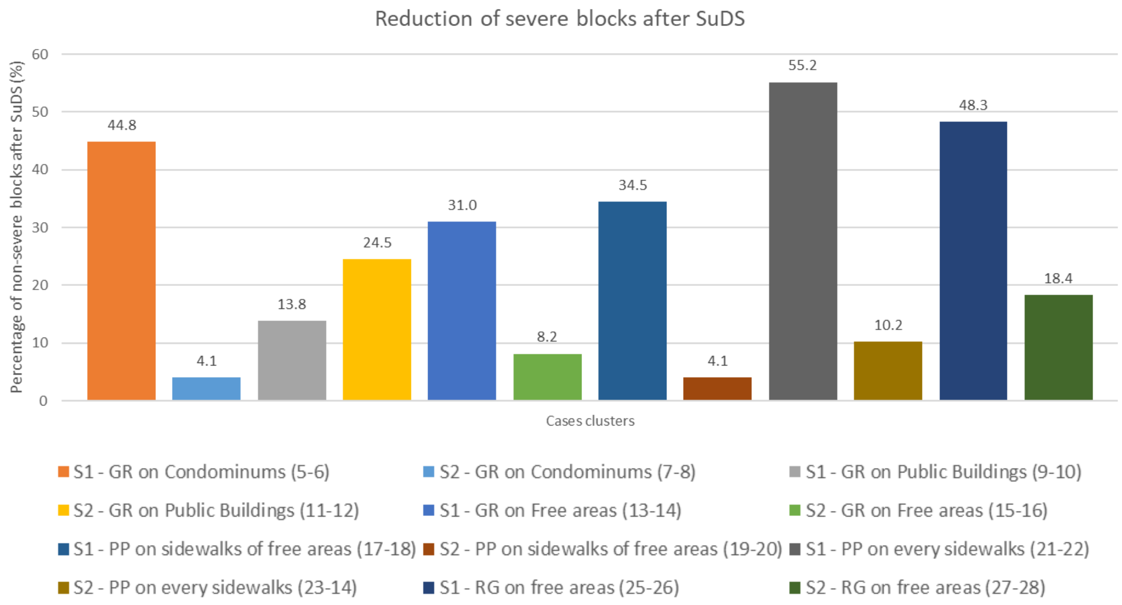


Figure 6.7 - Reduction of severe flooding blocks after the implementation of green roofs (GR), permeable pavements (PP) and rain gardens (RG).

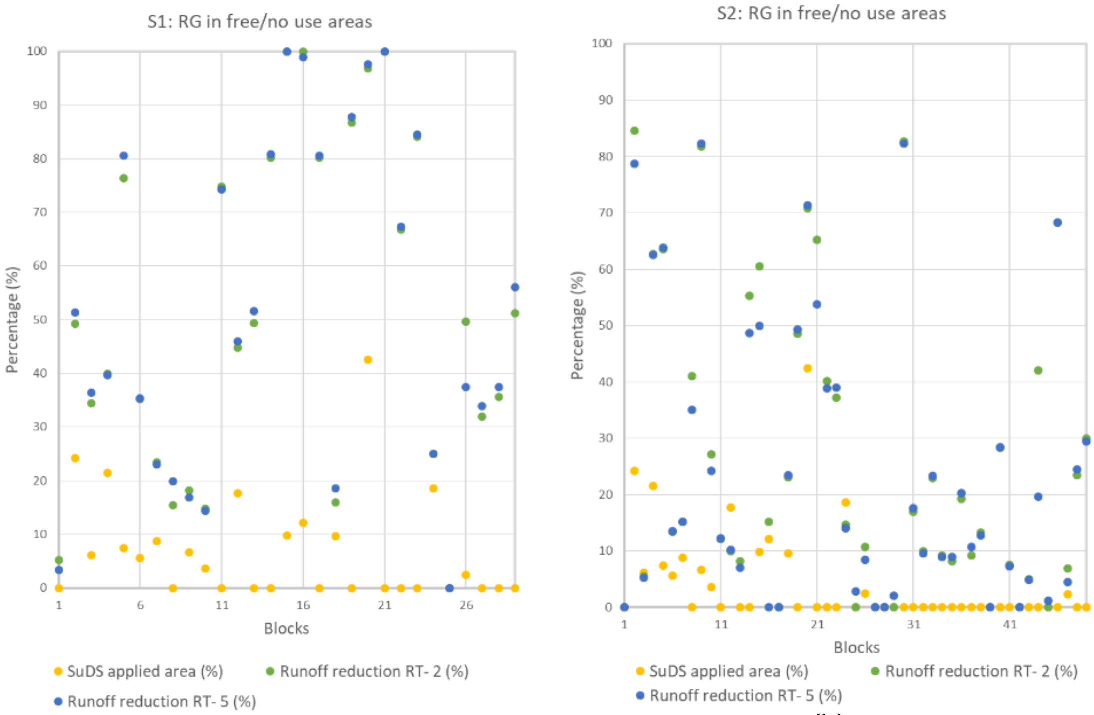
6.5 Discussion

The results confirm that the efficiency or SuDS varies directly according to the size of the area (Eckart *et al.*, 2017) and the placement of SuDS (Martin-Mikle *et al.*, 2015). The effectiveness of each choice of SuDS is more significant in the current scenario (S1) to almost all measures possibilities, except for GR on public buildings. Figure 6.7, shows that, for S1, applying green roofs to built-in public spaces is not the best choice (reduction of 13.8%), however, if the imperviousness achieves the suggested limits on master plan (scenario 2), this alternative provides a reduction of 24.5%. This happens because the percentage of these areas in S1 (Figure 6.2) is not enough for changing the “severe flooding susceptibility classification” of the analysed blocks. In agreement with other studies (Jiménez *et al.*, 2019; Versini *et al.*, 2016), our results confirm that SuDS effectiveness will depend on the basin land-use configuration and corresponding positioning choice. Regarding the future scenario (S2), the number of public spaces is more significant than in S1 which means that if green roofs will be applied in more areas, then, results will be better for this case. Andrés-Doménech *et al.* (2018) modelled GR in Spain, and also found reductions in runoff volumes despite the dry climate conditions. As stated previously, for most of the Brazilian cities, using SuDS is still a changing paradigm. Their application in public buildings represents an option for a good government example of sustainable actions.

In all other cases, SuDS strategies have more reductions in S1, which indicates that actions by managers are better suggested now. The best reduction is with the application of permeable pavement in every sidewalk, which had 55.2% of reduction on S1 (Figure 6.7). Despite this, when the urbanisation achieves its higher rate (80% of imperviousness in each block), the reduction rate falls to only 10.2%. According to this analysis, applying measures on non-built areas (free spaces/no use) would produce reductions of 31%, 34.5%, and 48.3% for green roofs, permeable pavements, and rain gardens, respectively, with the current occupation of the area. This choice represents good possibilities to enhance current legislation and change guidelines for the future (Moura *et al.*, 2016). Developed countries, such as UK, use this strategy for SuDS installation (Lashford *et al.*, 2019). This finding is even more important due to the lack of clear guidance in the city and the current master plan review in process in Campina Grande.

The use of rain gardens in free/no use areas enables 48.3% and 18.4% of blocks to change the "severe risk" of flooding in S1 and S2, respectively (Figure 6.7). Despite the quantity of fewer blocks in severe flooding condition on the catchment after RG, the runoff of others flooded blocks was also reduced, but not enough to change the "severe condition" classification in the model. Figures 6.8a,b show this land-use type made possible by the application on 15 blocks on S1 and 30 blocks on S2, but runoff reductions are distributed on almost all the other blocks (except for 1 on S1 and 9 on S2). This analysis suggests the reduction of flooding volumes is more related to imperviousness and location than with the respective area of SuDS application, which highlights the importance of determining an optimal location for SuDS. Also, there is a great similarity between values from return periods of two and five years, which justifies the same quantity of blocks that changed the severe state in Figure 6.7.

In order to assess what would be the reduction with the combination of different SuDS practices, the last situation evaluates all three compensatory techniques together in the S2 with both two- and five-year return periods (Figure 6.9). In this simulation, every strategy was applied to previously defined areas (Figure 6.2 and Table 6.2). The intention was to evaluate if the combination of compensatory strategies can provide better results than each one applied separately. Simulation referred to the worse condition, with the upper limit of occupancy allowed by legislation. This choice enabled the application of the three SuDS in 100% of blocks in the catchments.



(a) (b)

Figure 6.8 - The relation between RG applied area and runoff reductions for RT 2 and 5 years, on: a) scenario 1 and; b) scenario 2.

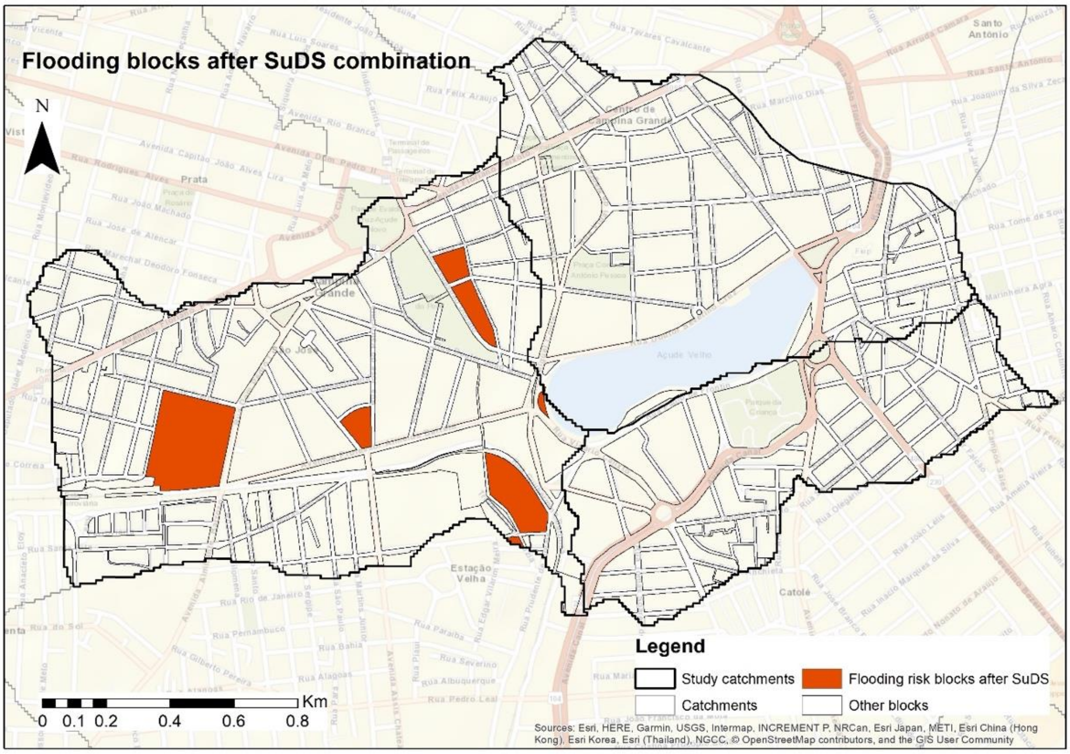


Figure 6.9 - Flooding blocks after SuDS combination implementation.

A comparison between Figures 6.3c,d and Figure 6.9 shows a significant difference in the behaviour of the catchments. After the SuDS practices were combined, the basins reduced the number of "severe flooding susceptibility" blocks substantially. This corroborates with other studies, where the combination of different SuDS, in conjunction, demonstrated the best effectiveness in reducing the runoff volume (Xie *et al.*, 2017). The reduction of 85.72% confirms that the best approach for the study area is to apply the combination of the three proposed compensatory techniques (Siekmann *et al.*, 2015). Only seven blocks with severe flood risk kept showing high runoff rates, even after the implementation with climatic conditions of drought regions (de Macedo *et al.*, 2019). In those blocks, it is strongly recommended that a more in-depth study and the implementation of SuDS in lots located upstream of the basin should be carried out in order to bring greater benefits.

In this approach, land-use development, and legislation (development, implementation, and monitoring) are drivers for flood mitigation and/or disaster risk attenuation. Good information related to legislation analysis and definition of land-use and catchment boundaries are ways to approximate the management of urban drainage to urban planning and sustainability. For this, a rank of effectiveness was produced in relation to each SuDS, threshold location and reductions (Table 6.7). This aims to encourage policymakers to invest in SuDS as a way to mitigate flooding episodes with different options.

Table 6.7 - Rank of SuDS alternatives in each scenario according to this methodology.

Scenario 1—Current Occupation		
Rank	**SuDS and location**	**Reduction of severe flooding blocks (%)**
1	PP on every sidewalk	55.2
2	RG on free/no use areas	48.3
3	GR on condominiums	44.8
4	PP on sidewalks of free/no use areas	34.5
5	GR on free/no use areas	31.0
6	GR on public buildings	13.8
Scenario 2—Legislation upper limit occupation area		
Rank	**SuDS and location**	**Reduction of severe flooding blocks (%)**
1	Combination of GR, PP and RG	85.7
2	GR on public buildings	24.5
3	RG on free/no use areas	18.4
4	PP on every sidewalk	10.2
5	GR on free/no use areas	8.2
6	GR on condominiums	4.1
7	PP on sidewalks of free/no use areas	4.1

Therefore, this analysis highlights the importance of the application of SuDS in the current scenario where the imperviousness of buildings is not yet the maximum allowed. Some examples in S1 include changes up to 55.2% of the number of “severe” flooding blocks with PP in every sidewalk and reductions in all the blocks (Table 6.6). Although GR in condominiums also generated reductions in 100% of the block, only 44.8% changed the severe classification. RG were applied in 15 blocks with vacant areas with reductions in 96.7% of the blocks, and 48.3% changed to a non-severe state.

Although reductions are still seen in most of the blocks (Table 6.6), rates reduced significantly with SuDS alone in the future scenario (Table 6.7), which was also the case in other studies (Miguez *et al.*, 2015b). The best results are with the application of GR in public buildings and RG in free areas, with 24.5% and 18.4% of reduction in severe blocks. In S2, the best reduction is with the combination of GR, PP and RG, with 85.7% in the severe flooding blocks. Both analyses emphasise the importance of implementing SuDS strategies in free areas, which is corroborated by other research (Moura *et al.*, 2016). This generates fewer investments with the retrofitting of structures and increase of their longevity (Eckart *et al.*, 2017). These results show that linking urban planning with water resources in advance will generate less flooding produced with imperviousness (Jiménez *et al.*, 2019). It is shown that SuDS should be introduced in the city, as a way to compensate current and future imperviousness rates.

Since the area has dry weather (semi-arid), even though all three SuDS (green roofs, permeable pavements and rain gardens) are designed for flooding purposes, they are also alternatives for storing water, as well as quality improvement and pollution control (de Macedo *et al.*, 2019). This is very important due to climate change (da Silva *et al.*, 2018), mainly increasing flooding and water stress cases, which raises the necessity of promoting adaptation measures to make more resilient cities. This study corroborates the promotion of an innovative solution for stormwater management (Qin *et al.*, 2013) as an alternative for drought adaptation (Coutts *et al.*, 2012) and integrated management across the entire water cycle (Roy *et al.*, 2008) and with applications in developing countries (Huang *et al.*, 2014; Roy *et al.*, 2008; Xu *et al.*, 2017).

6.6 Conclusions

The city of Campina Grande is a sample of middle size Brazilian cities with gaps between urban planning and water drainage planning. The current urban legal instruments (e.g., master plan, built-in codes) do not consider sustainable solutions for stormwater management and runoff problems. The city has initiatives of flooding reduction measures but still with no specificities of where or how to apply within the city. Although there has been a lot of research on integrated water resources management in Brazil (Bressiani *et al.*, 2015; Montenegro *et al.*, 2010), the effective actions remain fragmented in urban areas, showing a clear institutional frailty for handling the issue. The concepts are known but normally are not incorporated into practice by technicians, decision-makers, and local policymakers.

The methodology identified priority blocks with severe cases of floods for current and future legislation upper-limit scenarios, which emphasises the need for SuDS use to mitigate the impacts. However, the results revealed the inadequacy of imperviousness rates recommended by the law (land-use master plan), which works against the drainage infrastructure. Actually, this potentiates flood problems. This is further aggravated by the fact that there is no urban drainage plan for the municipality, meaning that the urbanisation expansion is not guided or supported by an urban water analysis including water supply and stormwater drainage. It is necessary to establish changes in local legislation and drainage systems to mitigate high rates of surface runoff.

The results can be used as guidelines for building new local legislation related to urban planning, which is extremely important since the master plan is being reviewed in 2019, and to guide decisions to implement such legislation as the basic sanitation plan of the city. There is a need to consider the development of city and drainage systems to maximise the effectiveness and efficiency in drainage systems (Parkinson *et al.*, 2007). A better planning of the drainage control measures plus better monitoring of built channels, drainage structures, and projects are vital for updating and revising legislation that deals with urban planning.

The proposed framework presents satisfactory and coherent results regarding the reduction of flow volumes, which can be a solution for flooding mitigation of study area and applied throughout the municipality. On the basis of results shown in this paper, each SuDS has reduced severe flooding in different percentages (Table 6.7), but the combination of all proved to be the most efficient mean of reducing flood impacts in the city. This research encourages the application of the present methodology to cities with similar problems, to produce pre-urban conditions and ensure the greater longevity of drainage systems. The benefits brought by the use of SuDS techniques are not only for the selected catchments but also for the neighbouring regions (Table 6.6).

The use of compensatory strategies is not capable of minimising all hydrological impacts of any mismanagement of land use. The efficiency of SuDS is substantially affected by their quantity, dimensions, properties, and adequate maintenance. These infrastructures are discussed as a method for flooding control, but this study highlights the importance of applying it along with land use management, governance, and climate considerations (Lashford *et al.*, 2019), acting as a long-term urban planning strategy. Further studies should take into consideration the optimal site location of measures, quantity, and dimensions along with runoff reductions in the total area to make a better decision. Further, as a management strategy, a "multi-hazards" approach, with drought and flooding considerations, with stakeholder participation and cost-effectiveness analysis will be added to the decision-making process.

The use of such an integrated approach as this, with water resources following environmental and sustainable objectives, helps to avoid conflicts related to urban management (Ako *et al.*, 2010) and is essential for achieving sustainable development, including social and economic development, poverty reduction and equity, and sustainable environmental services (Kalbus *et al.*, 2012).

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Conflicts of Interest: The authors declare no conflict of interest.

CHAPTER 7
Evaluating sustainable
solutions in the urban area
of Campina Grande, Brazil

Chapter 7: Evaluating sustainable solutions in the urban area of Campina Grande, Brazil

Chapter 7 discusses applying the risk-based integrated framework for evaluating the environmental, social, and economic benefits of sustainable solutions. The chapter refers to article 5 currently in review in Water Science & Technology.

Research questions:

- RQ 11: *How can the disaster risk be integrated into the Nature-Based Solutions (NBS) proposal?*
- RQ 12: *How can the vulnerability, exposure, and future changes be incorporated to evaluate the multiple benefits and resilience obtained by implementing NBS?*

Chapter 7 - Understanding the NEEDS for ACTING: An integrated framework for applying Nature-Based Solutions in Brazil (article 05)

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Abstract
Nature-Based Solutions (NBS) support the provision of multiple benefits for the environment and society. First idealised in 2008, NBS are recommended by worldwide reports and guidelines as strategies to protect, sustainably manage and restore ecosystems. However, their operationalisation is still in the early stages, especially in developing countries, and only a few studies consider their full potential. This article contributes to this context by developing an integrated framework, with spatial and participatory tools, for analysing flood risk mitigation in Brazil. The approach enables a deep understanding of the societal challenges and vulnerabilities of the area (i.e., NEEDS) for subsequently planning the appropriate NBS (i.e., ACTIONS), with the participation of 255 stakeholders of Campina Grande municipality. Results show mappings of flood-prone areas, in which approximately 52% of the flooded areas will see an increase in the future. Hotspots (i.e., hazard, vulnerability, and exposure) are shown and discussed with four application cases. Finally, multiple benefits of seven NBS alternatives are analysed in 53 scenarios of application, in which the higher rates of reductions are found to combined alternatives. The discussion emphasizes the importance of spatially assessing the 'needs' and 'multiple benefits' of NBS, including reducing vulnerabilities and increment of resilience.

Keywords: Multiple benefits, Nature-Based Solutions, participatory approach, resilience, spatial analysis, vulnerability.

7.1 Introduction

In the last few years, there has been a great search for tools for Nature-Based Solutions (NBS) operationalisation in the context of hydro-meteorological risks (Kumar *et al.*, 2020; Nesshover *et al.*, 2017; Sahani *et al.*, 2019). Conceptually, NBS refers to "*actions to protect, sustainably manage and restore natural or modified ecosystems, which address societal challenges (e.g., climate change, food, and water security) effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits*" (IUCN, 2020). Hence, the main difference from NBS and other terminologies such as Low Impact Development (LID), Sustainable Urban Drainage Systems (SUDS), Water Sensitive Urban Design (WSUD), and Blue-Green Infrastructure (BGI) is the focus on providing benefits and co-benefits for society in a *broader* scale and beyond water-related hazards (Ahmed *et al.*, 2017; Martin-Mikle *et al.*, 2015; Qin *et al.*, 2013; Wright *et al.*, 2020). Initiatives of these sustainable strategies can be seen in the UK, USA, New Zealand, Spain, Italy, and Canada (Fletcher *et al.*, 2014; Matsler *et al.*, 2021), as well as in China (Akter *et al.*, 2020), Bangkok (Majidi *et al.*, 2019), and Brazil (Momm-Schult *et al.*, 2013), despite others

The context will generate specific challenges that will need to be managed effectively to implement NBS (Raymond *et al.,* 2017). The first barrier for applying NBS is based on the understanding that context affects performance directly since they are significantly influenced by hazards intensities (Qin *et al.*, 2013), placement (Ahmed *et al.*, 2017; Passeport *et al.*, 2013), climate (Alves *et al.*, 2020e), land use (Martin-Mikle *et al.*, 2015) and social inequalities (Heckert *et al.*, 2018). The context will generate specific challenges that will need to be managed to effectively implement NBS (Raymond *et al.*, 2017). This suggests there is no "one-size-fits-all" approach that can be applied everywhere (Colléony *et al.*, 2019) and that the lack of "locally-oriented" information can harm NBS proposal (Nesshover *et al.*, 2017).

Recent studies have developed spatial tools for analysing sustainable solutions on local scale. For example, Kuller *et al.* (2019) built the GIS-MCDA Spatial Suitability ANalysis TOol (SSANTO) tool for the application of WSUD solutions as a relationship between the current context and the spatial opportunities (i.e., land use) offered by Melborne, Australia. The tool enables the assessment of the settings of the city concerning the goals (or benefits) of the sustainable solutions (Kuller *et al.*, 2019), which emphasizes the importance of locally developing the appropriate solutions. Similarly, Vercruysse *et al.* (2019) developed the "interoperability" concept, which analyse the context and built environment to indicate the priority sites for BGI in the city of Newcastle (UK) (Dawson *et al.*, 2020). Other tools for NBS proposal can be seen in Colléony *et al.* (2019). Cortinovis *et al.* (2020) and Grace *et al.* (2021).

However, approaches for NBS proposals are rarely developed with the reflection about risk and its constituents. Disaster Risk (DR) is a function of hazard, vulnerability, and exposure (i.e., the DR definition by (UNISDR, 2021)), which indicates that an extreme event will become a disaster when it causes disruption and overwhelms the capacity to cope of a community. In this context, previous studies (Morgan *et al.*, 2019; Vercruysse *et al.*, 2019) have pointed how part of the literature analyses mitigation strategies without the full consideration of risk. Similarly, for Albert *et al.* (2020) and Shah *et al.* (2020), existing approaches of NBS placement usually make less effort to understand the interlinked relation of societies (vulnerability and exposure) and environment (hazard) before recommending the final set of solutions.

While proposals inserted in the "hazards-tradition" approaches (Klijn *et al.*, 2015) focuses more on reducing the flood depth and extent when proposing solutions (i.e., environmental benefit), others suggest looking for solutions with more regards to the social context in which disasters are inserted (Cutter *et al.*, 2008). Actually, integrating social and environmental aspects appears to be particularly important for DRR, since the distribution of NBS might influence the generation of cascading effects or even differently affect people and create more inequalities (Hendricks *et al.*, 2021). Other studies are being developed for applying sustainable solutions according to the maximisation of benefits and the highest degree of spatial and environmental justice (Dagenais *et al.*, 2016; Heckert *et al.*, 2018; Pappalardo *et al.*, 2017; Wen *et al.*, 2020). However, La Rosa *et al.* (2020), approaches linking the proposal of solutions and spatial justice barriers are still reduced in literature. Current evidence shows that NBS proposals do not necessarily target social and environmental benefits in the same intensity (Debele *et al.*, 2019; Kumar *et al.*, 2020; Raymond, 2017), focusing more on "environmental" aspects. Others suggest deficits in managing trade-offs and synergies for obtaining multiple benefits (Colléony *et al.*, 2019), and integrating the complete understanding of risk and the interlink between vulnerability and resilience (Shah *et al.*, 2020).

Finally, another barrier of current NBS proposals refers to the development of approaches with stakeholders' collaboration. A range of literature highlights how nature solutions work best where local governments collaborate with local communities to manage trade-offs in full consultation (Bissonnette *et al.*, 2018; UNDRR, 2019). For example, Albert *et al.* (2020) provide a detailed approach of how NBS are actions that alleviate a well-defined societal challenge and employ ecosystem processes but must be embedded within viable governance models for having practical viability. NBS implementation requires social, political, economic and scientific challenges to be addressed simultaneously by several actor groups (Norton *et al.*, 2015), considering every situation with individuality and in context (Debele *et al.*, 2019). For Grace *et al.* (2021) and Cortinovis *et al.* (2020), however, the insights of NBS uptake in policy and planning are limited, and stakeholder perspectives are lacking from current research. Results of

Kumar *et al.* (2020) include that NBS are rarely considered a first choice by relevant stakeholders compared to other traditional approaches to reduce hydro-meteorological hazards. This is very common in developing countries such as Brazil, in which studies show a gap from the proposal to the application of NBS, since structural measures are usually considered for flood risk reduction (McClymont *et al.*, 2020). Simultaneously, others highlight how the recurring incidence of hydrological disasters demonstrate the fragility of traditional and structural drainage systems of the country (Jacob *et al.*, 2019).

In this sense, this paper addresses to these barriers with the development of an integrated framework that focuses on proposing NBS for flood risk mitigation, combining aspects of the built environment while also targeting the social aspects of the area. The integrated framework was formulated based on three assumptions: (i) NBS must be planned through the complete understanding of risk, (ii) Tools that enable the spatial representation of risk (i.e., Geographic Information Systems, GIS) are essential for proposing NBS and analysing their multiple benefits, and (iii) The lack of stakeholder's engagement and public participation can limit the adoption of NBS in realistic and practical applications. The framework is divided in the definition of the *needs* of the area, and in the discussion of which *actions* (i.e., or NBS) should be proposed according to these needs. The NEEDS for ACTION framework answers two research questions:

1. How can the disaster risk be integrated into the Nature-Based Solutions (NBS) proposal?
2. How can the vulnerability, exposure, and future changes be incorporated to evaluate the multiple benefits and resilience obtained by implementing NBS?

This paper focuses on presenting the risk-based framework, including the case study, the development of the participatory approach, and the provision of benefits, resilience, and vulnerability reduction to the flood risk context of Campina Grande municipality, Brazil.

This article is organised as it follows. Firstly, the general elements of the NEEDS for ACTION framework are presented. After that, the specific elements of the application are presented based on the case of Campina Grande municipality. Findings discuss the city's needs, including the occurrence of DR, and evaluate 53 planning scenarios, with and without NBS application, with the quantification of multiple benefits and resilience. After that, the framework's advantages, limitations, and next steps are discussed, and lastly, conclusions are presented.

7.2 Methodology

The NEEDS for ACTION framework assumes that it is essential to comprehend the *needs* of the place for proposing the uptake of mitigation *actions* (Albert *et al.*, 2020; Climent-Gil *et al.*, 2018). The tool is divided into six phases that combine spatial and participatory approaches (Figure 7.1).

7.2.1 The socio-spatial context:

The tool starts by defining the socio-spatial context wherein disasters take place. The social-spatial context refers to understanding disasters with social, spatial, and temporal views (Alves *et al.*, 2020a). This is from the assumption that the location in which the hazard will occur may change according to its' nature (Ruiter *et al.*, 2020). For example, floods might occur in specific areas of the city (buildings or streets) at some day in a year (or weeks, months, years), but the entire city will rarely be exposed at once. However, in case of a water shortage, entire neighbourhoods and catchments are frequently exposed for many days, weeks and even years (i.e., see more details in Alves *et al.* (2020a)). When hazards reach the most vulnerable areas, the impact produced will likely be exacerbated. This transforms the vulnerability and resilience assessments as key for mapping out the starting situation of an affected population before any intervention is undertaken (Climent-Gil *et al.*, 2018). In this sense, the framework initially evaluate the *needs* (P1 to P3) for proposing *actions* (P4 to P6).

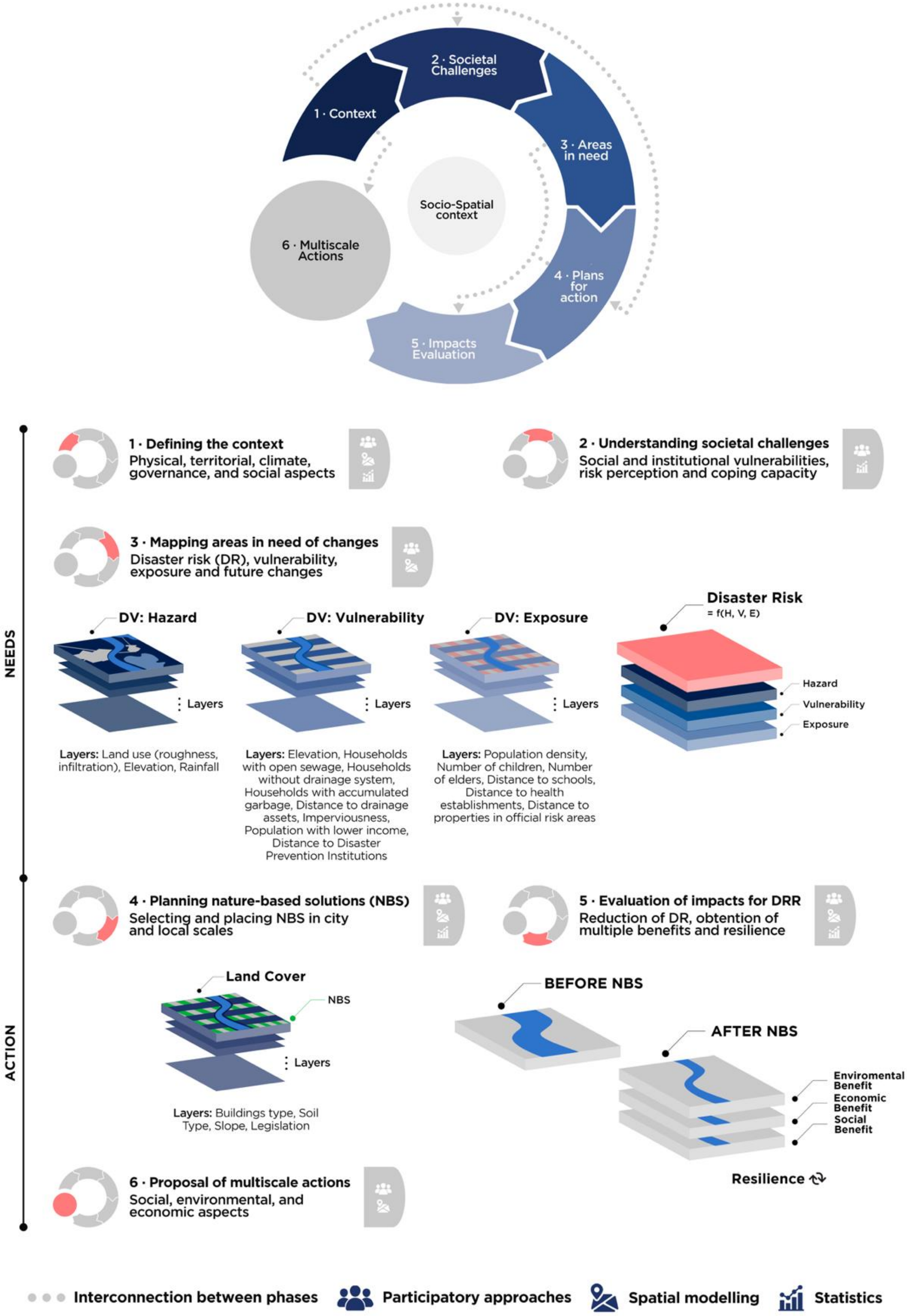


Figure 7.1 – The NEEDS for ACTION framework. Phases 1, 2, and 3 corresponds to the understanding of the “NEEDS” of the place, and phases 4, 5 and 6 refer to the planning of “ACTIONs”. Each phase is analysed with a combination of spatial and participatory approaches. The “layers” for analysing each phase are suggested in the context of flooding mitigation and adaptation.

7.2.2 Defining the context and societal challenges:

Phases 1 to 3 (Figure 7.1) cover the city's needs as the intersection of the natural and built environments and the residents that live in the region (as well as their backgrounds, perceptions, and previous experiences) (Fuchs *et al.*, 2017). In this sense, the context (P1) is described with the geographical region's physical, territorial, climate, governance, and social aspects (i.e., spatial scale). Phase 2 (P2) discusses the main societal challenges the population faces to *perceive* and *adapt* to the hazards. Spatial and social-science research tools (i.e., surveys, interviews, focus groups) are used to review and gain insights into the barriers and motivations for implementing NBS as well as understanding the community's resilience and stakeholders risk perception (Ruangpan *et al.*, 2020; Verweij *et al.*, 2020).

The development of P1 and P2 includes the identification and contact with stakeholders, historical analysis of legislation, and the definition of factors influencing societal challenges such as risk perception and coping capacity with objective tools (i.e., more details in Alves *et al.* (2020a)) (Figure 7.1). At these phases, citizens, specialists, and authorities are listened to define the critical societal challenges, especially for discussing which resources society needs to *adapt* to the extreme events.

7.2.3 Mapping areas at risk of disasters:

Disasters result from hazard, vulnerability, and exposure interactions (UNISDR, 2021), creating risks in different regions (Equation 7.1). Phase 3 (P3) defines the "areas at risk of disasters" in two sub-phases. Initially, the individual mappings of hazard, vulnerability, and exposure (i.e., disaster variables - DVs) are obtained with objective and subjective tools (Alves *et al.*, 2021). In this study, the DVs are a combination of indicators (i.e., Multi-Criteria Decision Analysis, MCDA) represented as layers in the GIS environment. The layers exemplified in Figure 7.1 are in the context of flooding.

Secondly, the DVs mappings are combined with the application of Equations 7.1 and 7.2, for mapping DR. Outputs of this phase are called "hotspots", referred to as "geographical areas with high vulnerability and exposure" (IPCC, 2014) (Figure 7.1). The individual DVs mappings are reclassified from very-low (VL) to very-high (VH) categories, with 1 to 5 scores (i.e., one corresponds to VL, and five to VH risk). Subsequently, the reclassified DVs are combined using the *Cell Statistics Tool* in ArcGIS Pro (ESRI), to obtain the final mapping of the hotspots.

$$Disaster\ Risk\ (DR) = f(Hazard, Vulnerability, Exposure) \qquad \text{Equation (7.1)}$$

The hazard, vulnerability, and exposure mappings were validated with the location of historical flooding cases and discussion with stakeholders. In this study, flooding risk (FR) is analysed for the current and future context. The FR in the future is analysed with a prediction of urbanisation, which is detailed together with the validation process in the next section. Areas with an increase of FR in the future are obtained with Equation 7.2. Flood increase is a subtraction of the flooding after urbanisation ($FR_{Urb(future)}$) with the flooding in the current situation ($FR_{Urb(now)}$).

$$Flood\ increase = FR_{Urb(future)} - FR_{Urb(now)} \qquad \text{Equation (7.2)}$$

7.2.4 Planning and evaluating solutions for DRR:

NBS are implemented in phases 4 and 5 of the integrated framework. Phase 4 corresponds to two sub-phases. First, the selection of NBS is made according to stakeholders' opinion (Bissonnette *et al.*, 2018; Ruangpan *et al.*, 2020) through meetings, workshops, and surveys. This phase also enables the verification of trade-offs of the previous stages of the framework, wherein stakeholders can stress discrepancies and propose modifications of the mappings.

Secondly, GIS and hydrologic tools are used to assess various types of NBS, alone and in combination and in large and smaller scales. This step is particularly important regarding the type of NBS chosen; for example, if "rain gardens" are proposed, datasets like "free areas" and "soil type" can be incorporated to represent the current land use of the area. This also answers the state-of-art by expanding the use of NBS from local to catchment scale as recommended by Eckart *et al.* (2017). In addition, we suggest the placement choice for NBS can be based on the spatial distribution of disaster variables. Since NBS offers an "umbrella" concept, it can be concluded that vulnerable and exposed areas and areas with urbanisation and other disasters can be used as input for analysing the solutions.

After that, phase 5 evaluates the impacts after NBS employment (Figure 7.1). The evaluation is based on the concept of “disaster resilience” (Cutter *et al.*, 2008) that indicates the ability to prepare and plan for, absorb, recover from, or more successfully adapt to actual or potential adverse events. In this sense, it is considered that when communities obtain the social, environmental, and economic benefits of NBS, risk can be reduced and their ability to adapt to extreme events will be improved. If there are more areas without the interaction of hazard, vulnerability, and exposure, it indicates more system resilience. Hence, we translated resilience and benefits in a metric by comparing the cells after ($DR_{afterNBS}$) and before ($DR_{beforeNBS}$) NBS implementation (Wang *et al.*, 2019), whilst the number of recovered areas indicates the system is increasing its resilience after NBS use (Equation 7.3).

$$Res = DR_{afterNBS} - DR_{beforeNBS} \qquad \text{Equation (7.3)}$$

7.2.5 The proposal of multiscale actions:

Phase 6 summarise the results of the NEEDs and ACTIONs phases with the proposal of actions for flood risk reduction (FRR). Multiple actions are suggested by addressing the territorial needs with a combination of NBS with social, environmental, and economic benefits (i.e., the sustainability pillars).

7.3 Case study: Campina Grande, Brazil.

Campina Grande is localised in the Northeast of Brazil, also called the Brazilian “semiarid region” (Figure 7.2a). Data from the last census shows that from 1991 to 2010 the city had a population growth of 20% (IBGE 1991, 2000 and 2010). Even though there is not a more recent census to evaluate population increase, the Brazilian Institute of Geography and Statistics (IBGE) estimates that 411,807 inhabitants reside in the city in 2021 (IBGE, 2021). A spatial analysis of the territorial boundaries of the city shows that in recent years the city has been increasing their neighbourhoods (in number and boundaries limits), which can indicate more built-up surfaces, paved streets, and imperviousness (Figure 7.2b). In fact, beyond the neighbourhoods shown in Figure 7.2b, two other neighbourhoods are being analysed by the city council for inclusion in the following months of 2021.

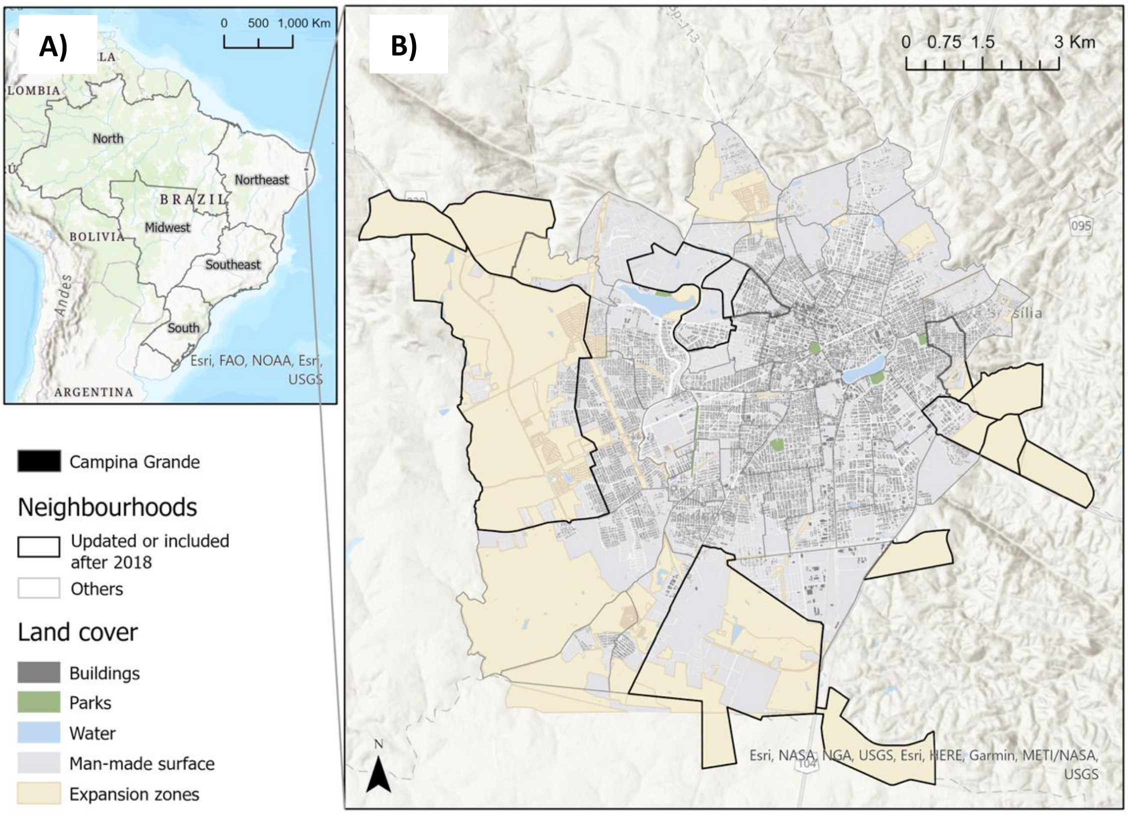


Figure 7.2 – The context of Campina Grande, Brazil. (a) Location in the Northeast region of Brazil, (b) City growth and land cover of the urban area.

Due to the climate constraints of the semiarid region, Campina Grande faces the occurrence of constant events of drought (Cordão *et al.*, 2020; Del Grande *et al.*, 2016a). For Rêgo *et al.* (2017), the region's last water shortage period (2012-2017) was one of the more damaging of the century. According to the State Water Agency of Paraíba, in 2017, the surface reservoir that provides water for consumption in the city (i.e., *"Açude Epitácio Pessoa – Boqueirão"*, in Portuguese), had less than 3% of its capacity (AESA) which posed a challenging context for Campina Grande and other bordering cities. In addition, the population of Campina Grande is also exposed to several flooding episodes. Flooding events occur in varied return periods and create damages in many parts of the city (Alves *et al.*, 2018b; Santos *et al.*, 2017c).

The city associates flooding and water shortage risk with existing social, physical, structural, and institutional vulnerabilities (Del Grande *et al.*, 2016a; Grangeiro *et al.*, 2019). Since applying sustainable strategies can be especially challenging in developing countries because of the social inequality and vulnerabilities (dos Santos *et al.*, 2021) and compound events (Shah *et al.*, 2020), Campina Grande was selected as the case study of this article.

7.3.1 The participatory approach

The NEEDS for ACTION framework was applied through the development of a participatory approach in Campina Grande. The Project PLANEJEEE: To Plan Extreme Events (from Portuguese "**PLANEJE E**ventos **E**xtremos) was held in 2019 and 2021 to cover phases 1 to 6 (Figure 7.1). The project had the objective to involve stakeholders in the definition of needs and for planning actions for FRR, in a sense that it can increase the understanding of NBS and facilitate the application of solutions in the real-life (Hardoy *et al.*, 2019; Lund, 2015). Two participatory processes were developed:

- In 2019, 199 stakeholders (i.e., 172 citizens and 27 policymakers and specialists) participated in the project. Collaboration strategies such as surveys, interviews, workshops, and meetings were developed to define the context, societal challenges and for mapping the needs of the city (i.e., more details in Alves *et al.* (2020a), and Alves *et al.* (2021)).
- In 2021, the project promoted several opportunities for defining an action plan to implement NBS on city and local scales. Participation was held with meetings with city authorities (n = 33) and survey applications with specialists and authorities (n = 23). Collaboration strategies were held online and in person (n final = 56). Due to the Sars-CoV-2 pandemic context, we opted not to involve the community participation at this phase.

In total, 255 people participated in the two participatory activities of the PLANEJEEE Project. Ethical clearance was obtained with the Host University (University of Exeter).

7.3.2 GIS input for mapping of hazard, vulnerability, and exposure

From the FR definition, the mappings of hazards, vulnerability, and exposure are a pre-requisite for the definition of “areas in risk of disaster” (i.e., phase 3, Figure 7.1). Each mapping was built with a range of indicators (i.e., MCDA) that act as spatial layers in the GIS environment, following the sub-phases described in Figure 7.1.

Present flooding situation

The Cellular Automata Dual-DraInagE Simulation (CADDIES) (University of Exeter) was used to model the flood-prone areas in Campina Grande. CADDIES is a 2D fast cellular-automata-based surface-water modelling developed at the Centre for Water Systems (CWS) - University of Exeter (Guidolin *et al.*, 2016; Vamvakeridou-Lyroudia *et al.*, 2020). The input data of CADDIES are land use (infiltration and roughness), elevation (DEM), and rainfall (Table 7.1 and Figure 7.1).

The land-use datasets supplied by Campina Grande City Council (*PMCG – Prefeitura Municipal de Campina Grande*), with the delimitation of buildings, blocks, and streets were used to map flooding in the current context (Figure 7.2b). Land-use and DEM (Tsuyuguchi, 2015) were inserted as 10x10m raster files in the model. In CADDIES, the infiltration represents the soil infiltration and the roughness of the drainage capacity (Wang *et al.*, 2019) for each land use. For example, CADDIES recognises “buildings” because of the related infiltration, roughness, and elevation height (i.e., pixel elevation plus 15 cm for buildings, and minus 15 cm for streets) (Liu *et al.,* 2018; Webber *et al*., 2019). Since the city council did not provide detailed data on the drainage system, the “constant infiltration approach” was considered for mapping the drainage system in the city's streets (Wang *et al.*, 2018).

To ensure a greater consistency of the flood model, the calibration of the input data was made with 24 test “scenarios” with 1h rainfall events that occurred in 2011 and 2020, with intensities of 81.7 mm h^{-1} and 41.7 mm h^{-1}, respectively. Each test was conceptualised to indicate a different soil infiltration based on the corresponding land cover. The calibration points were based on historical events and reports (i.e., Table A1 in the Supplementary Material). Rainfall data was provided from the Executive Water Agency of Paraíba (AESA) and INMET (Brazil). The final values of the input data are detailed in Table 1. The time step of 0.01s was undertaken in the simulations.

After calibration, design rainfalls were calculated using the intensity-duration-frequency equations of the gauge in the city (Paixão *et al.*, 2009). Initially, the rainfalls with 10 and 25 years return period (RT) were used in the flood simulations, especially the RT 25 as it is recommended as a standard RT by the Ministry of the Cities in Brazil (Miguez *et al.*, 2016). In addition, we also analysed the flooding with a design rainfall of RT 100 years. The rains were assumed to be uniformly distributed in space and constant in time. The total rainfall levels calculated for each return period were 46.80 mm for a RT 10, 57.62 mm for RT 25, and 78.93 mm for RT 100 years.

Future flooding situation

In addition, the increment of flooding in the future was analysed. The analysis is exemplified with the flooding in 2040, according to a methodology developed by Rufino *et al.* (2021). Authors characterised the urban sprawl of six Brazilian-cities, including Campina Grande, with the use of a cellular automata algorithm (SIMLANDER). The application of the methodology generates a raster dataset which indicates built-up areas in the city, based on six indicators: (1) distance to city centre, (2) distance to main roads, (3) distance to belt highways, (4) distances to other cities, (5) population density, and (6) inherent changes of pixels. More details can be seen in Rufino *et al.* (2021). ArcGIS (Pro) (ESRI) was used for modelling. The built-up dataset of 2040 was used as the “land use” input for modelling the flooding in 2040 with CADDIES software. The rainfalls with return periods of 10, 25 and 100 years were also used for simulations. Pixels with more than 10 cm of water depth were considered as flooded.

Mapping vulnerability and exposure

Flood vulnerability and exposure maps were obtained with a participatory-entropy-fuzzy framework (Alves *et al.*, 2021). The approach applied a participatory-MCDA with ArcGIS Pro (ESRI) and Python. In these mappings, vulnerability refers to the city's attributes such as physical, structural, social, and institutional indicators that can increase (or decrease) the flood susceptibility. Each variable was rescaled with linear fuzzy functions and then combined with a weighted-Entropy approach (Equation 7.4). Exposure refers to the location of people and assets that would have many impacts if they were exposed to a hazard (IPCC, 2014). The mappings considered census tracks with more elders, children, and population, and the locations of schools, health establishments and official risk areas.

$$Disaster\ Variable\ (DV) = \sum_{j=1}^{n} w_j * f_j \qquad \text{Equation (7.4)}$$

where DV is the degree of the disaster variable (vulnerability and exposure) to the flood hazard, w_j stands for the weight of each criterion and f_j for the fuzzy standardised criterion. The summary of indicators used are exemplified in Figure 7.1.

Verification of mappings with a historical-participatory dataset

Due to the lack of official information about the previous events of flood in Campina Grande, the validation of mappings was developed in four stages:

1. Application of a survey with residents to evaluate the previous experiences with flooding. Interviews were held from May to June of 2019 in the PLANEJEEE Project. The location of residents that confirmed flooding in their properties were transformed in a point-shapefile (ESRI).
2. Survey of flood cases in the news and civil defence reports. These points were converted in a point-shapefile (ESRI) with historical flood events from 2004 to 2020 in the city (Alves *et al.*, 2020c).
3. Verification and inclusion of "control-points" of flooding events to verify flood simulations. "Flood control points" express key areas that flood under different precipitations (varied return periods) that are known by the population. Control-points were discussed with the Civil Defence of the city in 2019 as one of the activities of the PLANEJEEE Project.
4. Combination of the previous datasets in a points shapefile that express areas with more probability of flooding in the city.

The verification compared the points with each of the 24 simulations described previously, until at least 70% of the flood points were confirmed in the simulations. More details are discussed further in the results and in Alves *et al.* (2020d).

7.3.3 The placement of NBS in local and city scales

NBS were implemented with the adjustment of infiltration, roughness, and rainfall values (Wang *et al.*, 2018) in CADDIES software (Table 7.1).

Table 7.1 – Input values of the land use and NBS in CADDIES model.

Land cover	Infiltration (mm/h)	Roughness (Manning's)	Rainfall (mm/h)	Sources
Buildings	0	0.012	-	McCuen *et al.,* (1996)
Streets	10	0.013	-	Chow (1959)
Man-made surface	12	0.025	-	Environment Agency (2013)
Expansion zone	12	0.040	-	Arcement Jr (1989), Chow (1959)
Green areas	15	0.100	-	Chow (1959)
Green roofs (GR)	12	0.060	-	Liu *et al.* (2018b); Vamvakeridou-Lyroudia *et al.* (2020); Wang *et al.* (2019); Webber *et al.* (2019b)
Permeable pavement (PP)	8 (+10)	0.015	-	
Rainwater harvesting (RWH)	-	-	20	
Green areas (GA) with minimal vegetation	15	0.065	-	
Drainage System Improvement (DSI)	10 (+10)	0.020	-	

For selecting the NBS types, specialists and authorities were invited to fill a survey according to their research focus (n = 12), and to their roles in the sectors of the city council (PMCG) (n = 11). The urban planning, civil defence, mobility, and construction sectors of the PMCG participated of the meetings. Before implementation, the questionnaire was evaluated by a pilot group (n = 5). A list of NBS was provided to each participant, in which they could select up to three measures that would be adequate for implementation in Campina Grande. Stakeholders' answers showed more preferences with rainwater harvesting (92.7%), permeable pavement (82.6%), and green areas (30.4% for rain gardens and 43.5% for infiltration trenches, respectively). Green roofs only had 21.7% of stakeholders' preferences; however, we also opted to analyse GR effectiveness since it is recommended by the state legislation 10.047/2013 currently in charge in the city.

Scenarios

The meetings with stakeholders in 2021 (n = 33) examined the appropriate scales for applying NBS. A summary of scenarios is seen in Table 7.2. Initially, the Business-As-Usual (BAU) flooding scenarios are modelled with CADDIES software for the current (CFS) and future flooding situations (FFS) without NBS. These initial simulations refer to the cases 1 to 32, since it reflects the calibration (n = 24) and modelling CFS and FFS with RT 10, 25 and 100 years. Cases 33 to 53 refer to simulations of seven NBS alternatives implemented in all city areas according to the placement described in Table 7.2. The NBS are applied in the "city-scale", according to the land-use, legislation requirements and stakeholder's opinions, but also considers the "local-scales" for application (i.e., for example, PP are applied in the streets).

Alternative 1 refer to green roofs (GR) in buildings. GR are considered as extensive, with soil thickness from 30 to 150 mm (Webber *et al.*, 2019b). In this study, we opted to increase the infiltration by 12 mm/h for each building with GR to represent the infiltration (Liu *et al.*, 2018b). For alternative 2, permeable pavements (PP) are implemented in the streets with an increase of 8 mm/h for each cell plus 10 mm/h of areas that already contributes for drainage capacity (i.e., roads). Increasing infiltration of streets was highlighted as a "key solution" for managing flooding in the PLANEJEEE Project, because the city is progressively asphalting its roads in the last years (Alves *et al.*, 2020e). Since PP will also affect surface roughness, we used a Manning's n coefficient of 0.015 to represent the concrete block based permeable paving.

The improvement of the drainage system (DSI) is also simulated even though it is not a green infrastructure. This was included while in the PLANEJEEE Project, since stakeholders highlighted many issues of the drainage system in the city (Alves *et al.*, 2021). Since the city council have not provided the full design of the drainage system, we represented the measures by increasing 10mm/h of infiltration in the streets of the city (i.e., n final = 10 + 10) (Webber *et al.*, 2019b) and adapting the surface roughness. Also, green areas (GA) are suggested for the front and backyards of properties, as in Brazil it is very common for residents to waterproof the area in the interior of their lot. Infiltration and roughness were adjusted to represent minimal vegetation (Table 7.1). For proposing rainwater capture tanks (RWH), local merchants of water tanks were surveyed, and we opted to use a 2000 litre capacity. The contributing area is considered as buildings of 100m^2. The rainfall capture of these measures is obtained by dividing the total storage volume with the size of the area situated (i.e., more details of this approach can be seen in Webber *et al.* (2019b) (Table 7.1).

NBS were also combined with a sum of GR and RWH in alternative 6 and all solutions in alternative 7. In this sense, the action plan considers a combination of green and grey infrastructure in a total of 53 simulations in multiple rainfall events (Table 7.2).

Table 7.2 – Description of scenarios for implementing NBS. NBS were modelled in the city and local scales. NBS placement was defined according to the city's current land use under stakeholders' opinions in the PLANEJEEE Project.

Scenarios		**Description**	**NBS placement**	**Design rainfall**	**Cases**
Business-as-usual (BAU)	Current Flood Situation (CFS)	Modelling flood in the existing situation	Without NBS	As in 2011 and 2020 (validation) 10, 25 and 100 years	1-27
	Future Flooding Situation (FFS)	Modelling flood in 2040	Without NBS	As in 2011 and 2020 (validation) 10, 25 and 100 years	28-32
Individual solutions	Alternative 1	Green Roofs (GR)	Buildings	10, 25 and 100 years	33-35
	Alternative 2	Permeable Pavements (PP)	Streets	10, 25 and 100 years	36-38
	Alternative 3	Drainage System Improvement (DSI)	Streets	10, 25 and 100 years	48-50
	Alternative 4	Green Areas (GA)	Front and back yards	10, 25 and 100 years	39-41
	Alternative 5	Rainwater Harvesting (RWH).	Buildings	10, 25 and 100 years	42-44
Combined solutions	Alternative 6	Green Roofs and Rainwater Harvesting (RWH + GR)	Buildings	10, 25 and 100 years	45-47
	Alternative 7	DSI and Nature-Based Solutions (NBS + DSI)	Buildings, streets, and front and back yards	10, 25 and 100 years	51-53

7.3.4 NBS evaluation and multiple benefits

The multiple benefits of NBS were discussed with specialists and authorities in the PLANEJEEE Project (2021). A survey was applied to assess what were the preferred NBS benefits expected by stakeholders. Participants were guided to specify their preferences to 23 options of benefits according to a 5-point Likert scale (i.e., 1 - less preference and 5 - more preference), concerning the *needs* of Campina Grande. The benefits list was prepared by scanning literature (Albert *et al.*, 2020; Eggermont *et al.*, 2015; O'Donnell *et al.*, 2018; Raymond *et al.*, 2017; Ruangpan *et al.*, 2020). Participants could opt with a “I do not know” option and suggest other benefits if desired. The online survey was disseminated through *Google Forms* platform.

Benefits are quantified with the difference of the condition before and after using NBS, using Equation (7.6). Benefits’ “effectiveness” is expressed as percentages or rates in this study; however, we highlight that it cannot be defined as “good” or “bad”, but rather is considered as a “desirable” or “undesirable” characteristic of a system according to the view of stakeholders. To enable the comparison of simulations, benefits are ranked in a high to low order in which the rank number 1 corresponds to the NBS with the higher benefit reduction. Finally, the benefits are summed and combined in a “disaster resilience metric” (Cutter *et al.*, 2008) to investigate how benefits can generate water resilience in the city.

7.4 Results

The results cover the NEEDS and ACTION phases (Figure 7.1) by answering: (1) *What* are the city's needs? (2) *What* are the benefits preferred by the stakeholders? And (3) *Which* benefits can be acquired with NBS?

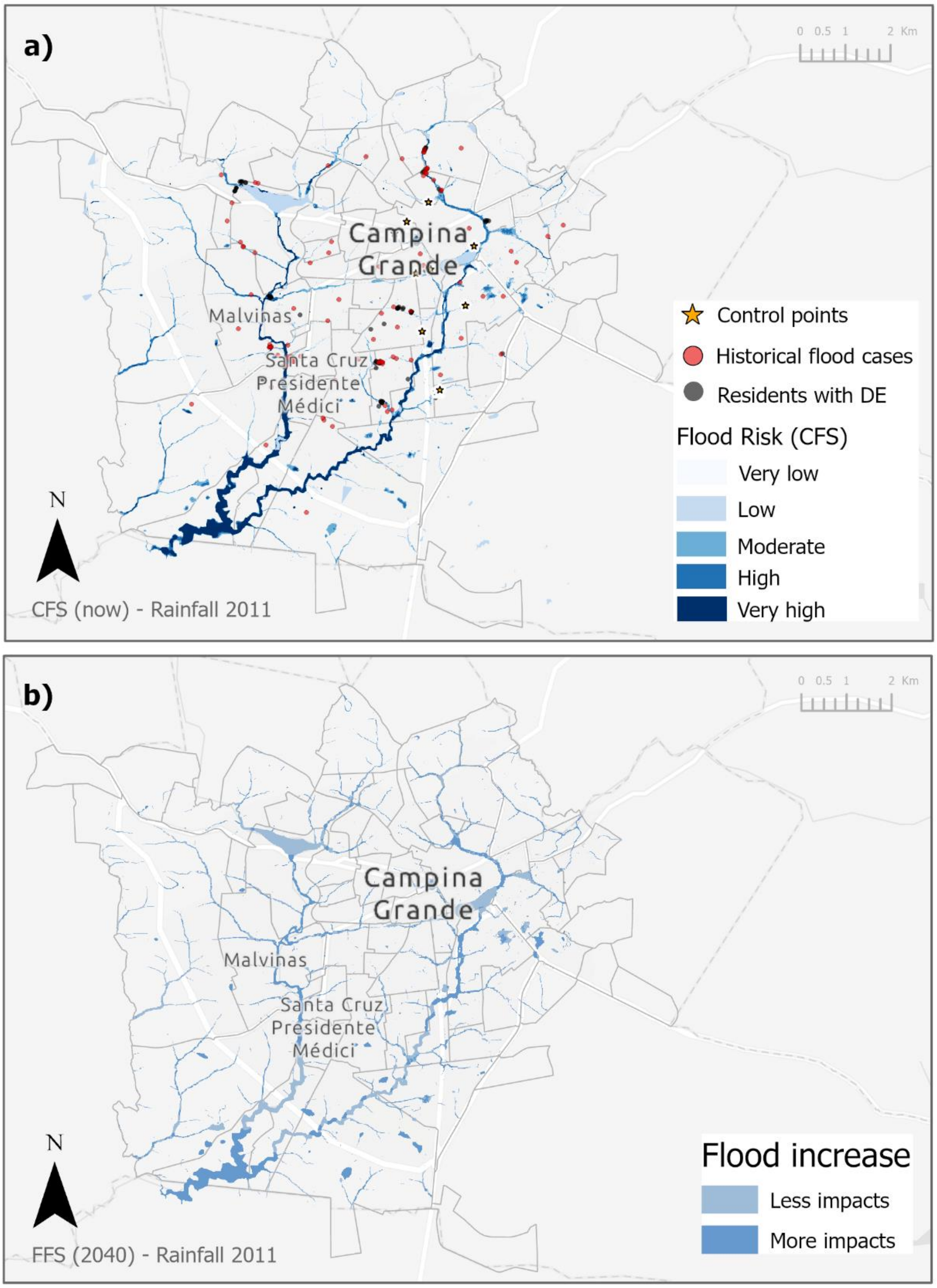
7.4.1 What are the location needs?

The needs of Campina Grande are discussed in the context of FR now and in the future. Figure 7.3a shows the final modelling of the Current Flooding Situation (CFS) of Campina Grande with CADDIES model. The scenarios 1 to 24 were built by assigning different values of infiltration and roughness for each land use, in a try-and-error approach, and simulating with historical rainfalls that occurred in 2011 and 2020 (i.e., see more details in Table F1 of Appendix F). Figure 7.3a represents scenario 22 with the rainfall of 2011, which was considered as one of the biggest rainfalls in the last decade (Sena *et al.*, 2019).

Since Campina Grande does not have an official definition of flood-prone areas, the verification of the 24 flood simulations was developed with participatory input datasets obtained through the PLANEJEEE Project (i.e., see the "verification of mappings" step-by-step detailed previously). Residents were interviewed about their previous experience with flooding in Campina Grande. From 172 residents, 94.8% faced flooding in the city in which 71.51% (n = 123) of the flood events occurred inside their households. Residents shared the location of these properties for the construction of the first flooding dataset (Figure 7.3a). Along with interviews, we built a historical flood map with other 247 cases of flooding that happened in the city from the period of 2004 to 2020 (Alves *et al.* 2020). We obtained the coordinates of the flood locations with the support of social media (i.e., Instagram @planejeee), news websites, Civil Defence reports, and informal meetings with authorities in 2019. The two datasets were combined in a 360-points shapefile representing areas in the city with a probability of flooding (Figure 7.3a).

Using the "*Sample tool*" in ArcGIS (Pro) (ESRI), the 360 flood points were compared in each of the 24 scenarios until more than 70% of the points were verified in the flood simulations. In addition, the location of other 15 severe control-flood points of the city were compared separately with the 24 CADDIES scenarios (Figure 7.3a). This was made to confirm if these flood severe locations were indicated as *flooded* in the modelling. Results show that 71.43% of the 360 flood-points and 86.60% of the control points were verified as "flooded" in scenario 22, which enabled the final selection of infiltration and roughness values in CADDIES. Full results of the verification of flood points are detailed in Table F1 of Appendix F.

Despite the model uncertainties relating to the input data, especially the lack of detailed data of the drainage system, the results suggest the proposed cellular-automata model (CADDIES) serves as a valuable tool to quantify the impacts of rainfall events in the city. The model can be adapted to other areas with similar information and data availability issues.



Esri, HERE, Garmin, METI/NASA, USGS

Figure 7.3 – Validation of the flood risk mappings: (a) In the current situation, (b) In the future situation (2040). Both simulations considered the rainfall as in May of 2011.

Right after mapping CFS, the Future Flooding Situation (FFS) was calculated with the built-up grid of 2040 according to the methodology presented in Rufino *et al.* (2021). The scenarios considered the prediction of urbanisation of 2040 with the rainfall as in 2011 and 2020. The analysis of FFS shows that if the urbanisation is as predicted but no progress to reduce flooding is made in the city, there will be an increase of FR in different areas mainly located near to the channels (Figure 7.3b). FR outputs from after and before urbanisation were analysed with Equation 7.3 (i.e., section 7.2.3), which shows that in 2040 there will be an increment of flooding in approximately 52% of the pixels (Figure 7.3b). In other words, if the rain event of 2011 were to occur in 2040, findings show that more flood damage would likely be seen in the city.

The city's needs are also analysed by considering the interactions between vulnerability, exposure, and hazard to evaluate if it will generate unequal flood impacts for the population (Hicks *et al.*, 2019). Risk interactions were represented through queries described in Box 7.1 with the "*Cell Statistics*" tool in ArcGIS (Pro). Figure 7.4 shows which *places need* more attention of management, named here as "hotspots". Mapping hotspots allow visualising aspects that make people vulnerable to flooding to inform the risk management process, as suggested by Mondino *et al.* (2020). The hotspots were mapped and divided into three categories, "caution", "warning", and "urgent", that mimic the intensity of DR impacts according to the interactions of DVs (Equation 7.2).

Box 7.1- Description of hotspots categories according to the level of impact that a disaster may generate.

The spatial analysis associate three queries* that together generate the risk in different intensities**:

1- The hazard-prone areas.
2- The vulnerability of the place.
3- The exposed assets, people, and infrastructure.

"Caution" hotspots

Express locations with VL to L susceptibility to the disaster risk, with VL to L hazard, exposure, and vulnerability. Represents geographical areas with smaller DR that can be managed in the long-term perspective.

"Warning" hotspots

Reflect areas with M to VH probability of hazard and/or exposure but with VL to L vulnerability, which indicates areas already in risk, but overall good capacity of systems (i.e., vulnerability) and less people and assets exposed. This hotspot also express areas with VL to L susceptibility of hazards and/or exposure but M to VH vulnerability, which are areas that must be observed since strong disruptions can be caused in case of a hazard because of vulnerability. Represents areas that can have more impacts and must be managed in the medium-term perspective.

"Urgent" hotspots

Express priority areas with M to VH probability of hazard and/or exposure and M to VH vulnerability. Represent areas with high probability of disaster risk and "*severe*" impacts, and therefore, the worse condition for population. The urgent hotspots must be managed in the short-term perspective.

** The spatial queries for mapping hotspots were discussed with stakeholders in the PLANEJEEE Project.*
***"VL" refer to Very Low, "L" to Low, "M" to Moderate, "H" to High, and "VH" to Very High classification (see more details in Appendix F).*

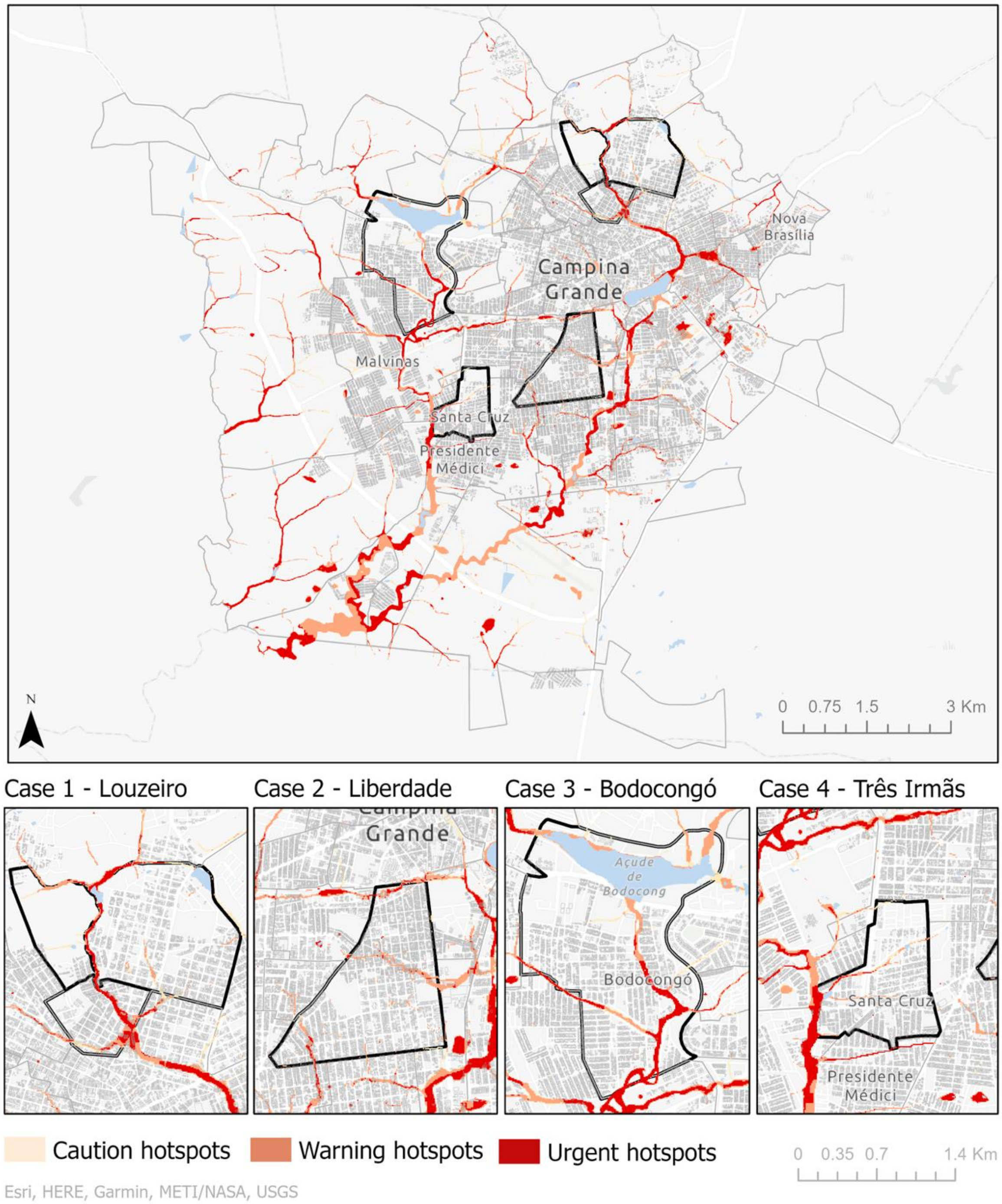


Figure 7.4 – Spatial analysis of interactions between hazard (flooding), vulnerability and exposure that generate DR. The hotspots represent areas that, according to level of impacts created with DR, need more attention in stormwater management. Four case studies are highlighted: (1) Louzeiro, (2) Liberdade, (3) Bodocongó, (4) Três irmãs.

7.4.2 What benefits can be obtained with NBS?

Selection of multiple benefits with the engagement of stakeholders

In 2021, the meetings and questionnaire application with policymakers and specialists had the goal of understanding, according to the city context, which

NBS benefits are the most preferred by stakeholders. Table 7.3 provides the complete list of the 23 benefits provided in the survey for stakeholders. The benefits were ranked in a "preference order" according to the answers' mean value (M).

The benefit with more preference was "rainwater harvesting" with M 4.45, which is linked to the city's simultaneous occurrence of water shortage risk (WSR) (Table 7.3). We attribute the higher M because most stakeholders have had a previous water shortage experience in Campina Grande since one of the strategies used by the policymakers to allocate water supply during WSR is to divide the urban area into two zones (Cordão *et al.*, 2020; Del Grande *et al.*, 2016a). Each zone has water available on different days, which makes the entire city exposed to the hazard (Del Grande *et al.*, 2016a). The context is different from FR since only parts of the city are exposed in a stormwater event that might reduce the preference for acquiring the flood reduction benefit (i.e., see more details about the socio-spatial context in Alves *et al.* (2020a)).

Table 7.3 – The multiple benefits' preferences of stakeholders in the PLANEJEEE Project (n = 23)

	Multiple benefits	**Mean value (n = 23)**	**Preference rank order**
1	*Reduction of flood zones*	4.30	5
2	Creation of green areas	4.41	2
3	Improvement of the socioeconomic context	4.09	11
4	*Wellbein*g	4.36	4
5	Tourism	3.68	17
6	*Reduce costs with flood management*	3.82	15
7	Heat alleviation	4.05	12
8	Air quality improvement	4.04	13
9	Access to nature	4.45	1
10	Improvement of risk perception	3.96	14
11	Improvement of coping capacity	4.23	8
12	Reduction of crime rates	3.73	16
13	Urban development	4.13	10
14	Environmentally oriented education	4.27	6
15	Rainwater harvesting (drought)	4.45	1
16	Groundwater recharge	3.55	18
17	Water quality	4.23	8
18	CO^2 reduction	4.26	7
19	Reduction of buildings' temperature	4.13	10
20	Noise reduction	3.55	18
21	Sewage treatment	4.22	9
22	Participative governance	4.36	4
23	Participative monitoring	4.39	3

The benefit “access to nature” is also ranked as 1st with M 4.45. Similarly, “creation of green areas”, “participative monitoring”, “wellbeing” and “participative governance” had M 4.41, 4.39, 4.36 and 4.36, respectively, sitting in the 2nd-4th ranks positions. The “reduction of flooding zones” occupies the 5th preference with M 4.30. Stakeholders' preferences showed the awareness of focusing on benefits for people and the environment itself in different scales (Eggermont *et al.*, 2015). Results indicate that stakeholders do not present a higher preference for “groundwater recharge”, “noise reduction”, “reduction of crime” and “tourism” (M 3.55, 3.55, 3.73 and 3.68 respectively), which are sited in the lower preference order (Table 7.3). This does not necessarily indicate stakeholders do not desire these benefits for Campina Grande but can instead denote less understanding that NBS can provide these benefits, as suggested by other studies (Bissonnette *et al.*, 2018; O'Donnell *et al.*, 2017; Ruangpan *et al.*, 2020). Therefore, it can be concluded there is a need to properly screening all benefits that can be obtained with NBS with stakeholders, being extremely important to provide opportunities for increasing engagement with stakeholders in participatory-NBS management.

After evaluating preferences, the NBS are analysed for multipurpose benefits assuming that strategies aimed at FRR and adaptation will deliver environmental, economic, and social benefits (Raymond *et al.*, 2017). The integrated framework is exemplified with the calculation of benefits 1, 4, and 6; however, as this article evaluates the effectiveness of NBS, benefits 2 and 9 are also indirectly characterised.

The provision of environmental, economic, and social benefits

The reduction of flood zones (i.e., benefit 1) is assessed with the mean flood depth (MD) decrease. The MDs of the RT 10, 25 and 100 years BAU CFS scenarios were 0.37m, 0.64m and 0.80m, respectively. This result shows an increasing flood depth when comparing the least to the most intense rainfall events (Table 7.4). NBS alternatives were applied separately and then in combination to evaluate the MDs reduction in each rainfall event, totalling 24 simulations. Table 7.4 shows that NBS are more effective for the 10-year rainfall event, which agrees with other studies that affirm that NBS are less effective when the rainfall return period increases (Majidi *et al.*, 2019).

When applied alone, the higher reduction rates are seen with GA (alternative 4) with 16.22%, GR (alternative 1), and RWH (alternative 5) with 10.81% in the RT 10-years. It is important to see that even applying the solutions within the same area (e.g., streets), the improvement of the drainage system (DSI) (alternative 3) offer a slightly higher reduction than permeable pavements (8.11%). We attribute this to the different roughness of each solution (Table 7.2). When combining GR and RWH (alternative 6), the MD reduction arises for 18.92%, which is seen as a good option due to the city's simultaneous occurrence of water shortage hazard.

Table 7.4 – Summary of environmental, social, and economic benefits obtained with the implementation of NBS. "SC" refers to Scenarios, "R" to Reduction, and "DRes" to "Disaster Resilience".

		Environmental: *Mean Depth (MD)*			**Social:** *Areas in VH flood risk*		**Economic:** *Properties in VH flood risk*		**DRes**
SC	*Rain event*	*MD*	*R (%)*	*Rank Order*	*R (%)*	*Rank Order*	*R (%)*	*Rank Order*	
1: **GR**	RT 10	0.33m	10.81	4	43.35	5	50	3	12
	RT 25	0.6m	6.25	4	7.27	4	16.67	1	9
	RT 100	0.77m	3.75	4	18.53	4	16.22	5	13
2: **PP**	RT 10	0.34m	8.11	5	32.53	7	50	3	15
	RT 25	0.62m	3.13	6	2.94	6	16.67	1	13
	RT 100	0.79m	1.25	6	15.41	7	21.62	3	16
3: **DSI**	RT 10	0.33m	10.81	4	44.90	4	50	3	11
	RT 25	0.61m	4.69	5	4.16	6	16.67	1	12
	RT 100	0.78m	2.51	5	16.49	5	18.92	4	14
4: **GA**	RT 10	0.31m	16.22	3	55.54	3	50	3	9
	RT 25	0.55m	14.06	2	13.78	2	0	3	7
	RT 100	0.7m	12.50	2	21.96	2	10.81	6	10
5: **RWH**	RT 10	0.33m	10.81	4	43.07	6	66.67	2	12
	RT 25	0.61m	4.68	5	4.56	5	8.33	2	12
	RT 100	0.78m	2.50	5	16.00	6	21.62	3	14
6: **RWH + GR**	RT 10	0.3m	18.92	2	63.09	2	66.67	2	6
	RT 25	0.58m	9.38	3	11.79	3	16.67	1	7
	RT 100	0.75m	6.25	3	20.80	3	24.32	2	8
7: **NBS + DSI**	RT 10	0.24m	35.14	1	92.19	1	100	1	3
	RT 25	0.45m	29.69	1	43.44	1	16.67	1	3
	RT 100	0.61m	23.75	1	33.35	1	32.43	1	3

"GR" stands for Green Roofs, "PP" to Permeable Pavements, "DSI" to Drainage System Improvement, "GA" to Green Areas, "RWH" to Rainwater Harvesting, and "NBS" to Nature-Based Solutions.

The combination of DSI and NBS (alternative 7) offers the best reduction rate (35.14%) in the smaller rainfall event. When looking into RT 25 and 100 years, alternative 7 still reduces MD by 29.69% and 23.75%, respectively, which are the higher reductions when compared to the other alternatives of NBS in the same rainfall event. For example, in RT 25 and RT100, GA have the best efficiency after alternative 7 (2^{nd} higher reduction overall). The effectiveness of NBS during each rain indicates the use of solutions will have a positive effect not only in the smaller return events but also in the more extreme ones.

For analysing the wellbeing (i.e., benefit 4), the reduction of areas with very high (VH) risk of flooding (i.e., the “urgent” hotspots in Figure 7.4, flood depth > 1m) was calculated by subtracting the pixels within the VH flood risk after and before the use of NBS (i.e., Equation 7.4 in Section 7.2). Table 7.4 shows the reduction of the percentage of VH risk area in all rainfall events. Before NBS, 5.57%, 18.24%, and 26.80% of the flooded pixels of RT 10, 25, and 100 were classified in the VH risk of flooding. Similar to the environmental benefit, alternative 7 also presented the best reduction rates of approximately 92%, 43%, and 33% of the VH-pixels in the RT 10-year, RT 25-year, and RT 100-year, respectively (Table 7.4). Alternatives 6 and 4 also presented high reduction rates in all rainfall events with the second and third rank orders of effectiveness.

After that, the “reduction of flood damage” (i.e., benefit 6) was calculated by considering the number of properties within the VH risk areas. The “*zonal statistics as table*” tool in ArcGIS (Pro) analysed the flood zone situation of residential, commercial, and institutional buildings of the urban area (Figure 7.4). Table 7.4 expresses the reduction of properties with each alternative and rainfall events. Compared to the number of properties before solutions, every NBS alternative reduces the number of properties, except alternative 4 in RT 25. Alternatives 6 and 7 provided a higher reduction in all the rainfall events (table 4). Results stress that NBS will reduce the damage of the residents located in the critical flood areas, being particularly important since not always the reduction of flood depth will reduce the number of properties exposed to the risk, which brings the robustness into the proposal of NBS (Ashley *et al.*, 2020).

Finally, the relationship between the multiple benefits and resilience is characterised. The “resilience” (Cutter *et al.*, 2008) is measured with the sum of rank orders of each benefit; hence the smaller rank of resilience value indicates the best scenario since it is the sum of the first ranked types of benefits reduction (Table 7.4). The metric demonstrates that when NBS are applied in combination (alternatives 6 and 7), the resilience increases in each return period investigated (Table 7.4). When applied alone, GA will provide more resilience, followed by GR, RWH, DSI, and PP - in this order (Table 7.4).

7.5 Discussion

Findings stress how FR mitigation should be understood beyond extreme events, in the current and future situation, incorporating the social aspects of the area (Pescaroli *et al.*, 2019). The city's needs are characterised in Figures 7.3a,b and 7.4.

Figure 7.3a shows that Campina Grande currently faces FR in different parts of the city, especially near channels. When analysing the FR in the future, Figure 7.3b shows how urbanisation will lead to more risk, in which approximately 50% of the flooded pixels will have flood increase. Additionally, the mapping in Figure 7.4 represents how the interaction between hazard, vulnerability, and exposure generates the risk and affects city's population on the local scale.

The spatialisation of "areas at risk" indicates how people can be differently affected by the disaster and support the distribution of sustainable solutions in a "equitable" manner in the city (Heckert *et al*., 2018). FR represents a process inherently unfair, since water occupy very different spaces in cities after flooding events (La Rosa *et al.,* 2020, Johnson *et al.,* 2007). The link between FR and "equity" is from the principles of environmental and spatial justice, underlining how all people have a right to be protected from specific environmental issues (Hendricks *et al.*, 2021), and should have access to the same level of services in the urban environment (La Rosa *et al.,* 2020). In this sense, the mappings produced in Figures 7.3 and 7.4 can be used as a tool to evaluate how the intersection between flood (hazard), vulnerability and exposure will impact the city on local scale, in the current and future situations.

For example, case 1 of Figure 7.4 refers to three neighbourhoods (*"Louzeiro", "Alto Branco"* and *"Conceição")* that are in the upper part of Campina Grande (Figure 7.4). With exception of "Alto Branco", case 1 refer to neighbourhoods with flood vulnerability, especially *Louzeiro*, being one of the poorest areas of Campina Grande (IBGE, 2010). For simplicity, the area is referred as the *Louzeiro* case. Louzeiro is monitored as a "flooding risk-zone" in a federal perspective by the Mines and Energy Ministry of Brazil through the Geological Survey of Brazil (CPRM). Case 2 corresponds to the *Liberdade* neighbourhood (located in the "Prado" catchment), which is considered an important economic area of Campina Grande, with many residential and commercial areas. The neighbourhood has mixed-income residents (IBGE, 2010), but even though some residents have more means to obtain flood adaptation strategies than the residents of *Louzeiro* case, this does not mean they will not also experience flood. Cases 3 and 4 are located on the Bodocongó catchment with flooding areas, however, only part of the flooded zones are monitored as an "official flood risk area" by the CPRM. The neighbourhoods have more residential properties than commercial establishments; however, both are exposed in the "urgent" and "warning" flood hotspots.

In other words, considering the connection between risk variables and the built environment enables to see how risk impacts must be evaluated with an understanding of the area and their vulnerabilities (Kumar *et al.*, 2020). Besides, it is also argued that if vulnerabilities and societal challenges (urbanisation, vulnerability, and exposure) are not adequately alleviated and considered before proposing risk reduction solutions, risk impacts' can be aggravated in the future, allied with other changes such as climate change and human-induced activities (Albert *et al.*, 2020; IUCN, 2020; UNISDR, 2021).

Additionally, findings show the multiple benefits which can be obtained using NBS; however, these are seen in different scales and rates (Table 7.4 and Figure 7.5). NBS's effectiveness will vary according to the land-use area and the rainfall return periods (Majidi *et al.*, 2019), with better reductions of flood depth when the solution has more area and is analysed in smaller rainfall return events (alternatives 4, 6 and 7). Therefore, this result demonstrates how the distribution of the built environment, and current "available land" are valuable resources for FRR and resilience, especially in urbanised areas (Lourenço *et al.*, 2020; Miguez *et al.*, 2015b; Versini *et al.*, 2016).

However, findings also indicate that NBS *can* simultaneously provide environmental, social, and economic benefits, but this will not occur in every case, as highlighted by O'Donnel *et al.* (2018) and Morgan *et al.* (2019). This can be seen when analysing the different NBS alternatives, in which strategies will not always provide multiple benefits.

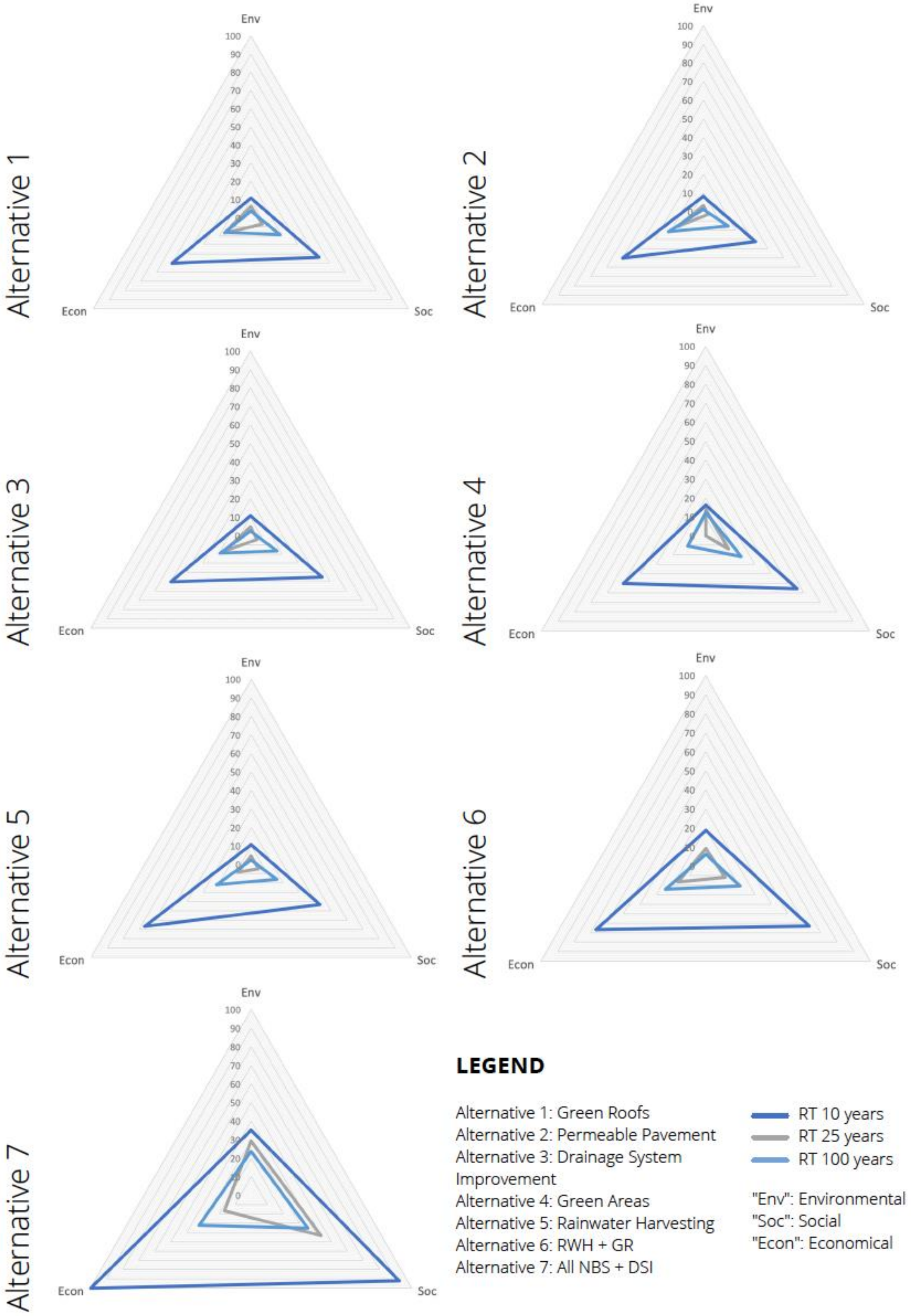


Figure 7.5 – The multiple actions diagram for DRR: Alternatives 1 to 7 are organised in quantitative approach highlighting the environmental, social, and economic benefits in each of the 10, 25 and 100 years return periods ("*Env*" refers to environmental, "*Soc*" to social and "*Econ*" to economic benefits).

Table 7.4 and Figure 7.5 emphasises that obtaining environmental benefits (i.e., the reduction of MD) is not an assurance that social (i.e., the reduction of VH-risk areas) and economic benefits (i.e., properties of the built environment) will be either acquired or acquired with high reduction rates. This is the case of properties located in pixels (i.e., or geographical areas) that reduced flood depth but are still vulnerable and exposed to flooding at some rate. In this sense, the characterisation of “how” the benefits are “distributed” in the spatial context is an indication of how the solutions differently reduce the risk condition of the area (Dagenais *et al.,* 2016; Heckert *et al.,* 2018; La Rosa *et al.,* 2020).

In this regard, reducing areas and properties with VH risk of flood used in this study enables the inclusion of social and spatial justice perspectives to evaluate benefits and resilience. Infrastructure is widely used for delimiting the impacts, especially for environmental science studies. However, less effort is made to link infrastructure and social systems when analysing DRR solutions (Cutter *et al.*, 2008), and environmental justice and flood risk (La Rosa *et al.*, 2020). The participation of local actors in the PLANEJEEE Project assisted the inclusion of social and economic benefits (i.e., corresponding to vulnerability and exposure respectively) in the analysis because several residents were seen living in risk-prone areas with poor social, institutional, and structural conditions, which are likely to increase the risk impacts (Alves *et al.*, 2020a). In other words, obtaining social and economic benefits of NBS can improve the conditions of those citizens by modifying the current risk conditions of the area and strengthening their capacity for the subsequent risk events (Dagenais *et al.*, 2016; Pappalardo *et al.*, 2017).

In this context, the spatial integration of “needs” and “benefits” analyses is recommended for managing FR with NBS. Since FR is influenced by hazard, vulnerability, and exposure, this analysis enables the evaluation of vulnerability and the unequal distribution of risk in hazard-prone areas (Hicks *et al.*, 2019), the multiple benefits (Raymond *et al.*, 2017) and the resilience (Ashley *et al.*, 2020) which can acquired with NBS. Therefore, vulnerability, risk, multiple benefits and resilience should be linked to the proposal of solutions (Dagenais *et al.*, 2016; Pappalardo *et al.*, 2017). In summary, the developed assessment for mapping and understanding the areas in need of changes, as well as the quantification of benefits, shows that NBS can deliver beyond the flood depth reduction, as it is routinely restricted in the hazards-tradition studies (Cutter *et al.*, 2008), and has the potential to strengthen environmental, social, and economic aspects of cities (Snep *et al.*, 2020).

Finally, this paper has demonstrated that applying NBS is beneficial for Campina Grande. Findings obtained with this study provide insights for city planning, with direct impacts on policy and management. Since the integrated framework was built with the active participation of stakeholders (i.e., policymakers, local citizens, and local specialists), the framework enables to thorough analyse of the current situation (needs) for proposing changes in the future (actions). However, we also highlight there is a need to reduce the "implementation gap" when proposing these sustainable solutions in climate change research, focusing mainly on ample communication and rethinking interdisciplinarity, as suggested by Schipper *et al.* (2021). Other findings related to the social, policy, and legislation constraints and flood risk reduction solutions can be found on Alves *et al.* (2020a), Alves *et al.* (2020d), and Alves *et al.* (2021).

7.6 Advantages, limitations, and next steps of the tool

The NEEDS for ACTION framework was built to promote an understanding of disaster risk reduction not only restricted to the hazard itself but including vulnerability, exposure, and future changes. GIS, modelling tools, and a continuous participatory approach were developed, tested, and applied for: (i) mapping and understanding the FR, (ii) selecting and locating NBS on a city-scale and, (iii) assessing multiple benefits and resilience. The results demonstrate how the combination of spatial-participatory tools can enhance the proposal and analysis of NBS and its multiple benefits.

However, a few limitations of the study need to be underlined. First, the land cover dataset used was provided by the city council of Campina Grande (PMCG), but due to the rapid dynamicity of cities, it is stressed it might have divergences from reality. When preparing the land cover dataset for inserting in the CADDIES model, a revision was made using Google Street View; however, we consider that a deep revision can provide more consistent results. A similar limitation is related to the availability of the drainage network data. We adapted this limitation by increasing the infiltration on the streets and considering the "constant infiltration approach" (Wang *et al.*, 2018; Wang *et al.*, 2019; Webber *et al.*, 2019b) since the streets are the land cover that should have the drainage structure.

Similarly, due to the limitation of official datasets availability, the calibration procedure was performed according to local experiences, news, and Civil Defence reports from several years (from 2004 to 2020). Even though the detailed *historical-participatory dataset* indicates areas with flood probability in the city, it is acknowledged that the flood-prone areas can be overvalued by this method. In this regard, it is recommended to strengthen the flood verification dataset to validate flood simulations in the subsequent phases of the study.

From the scenarios perspective, we acknowledge that NBS can also tackle climate change adaptation (EbA) (UNDRR, 2019; UNISDR, 2021). Hence, climate change scenarios should be incorporated in the modelling to evaluate the effectiveness of the measures in unique circumstances. In this regard, it is also acknowledged that more detailed rainfall information should be integrated for the subsequent phases of the study. Only block rainfalls were used in the CADDIES model, mainly because more detailed information was not available for the city. In this sense, it is recognised that more specified datasets may provide different percentages of benefits. However, it is also considered that this study still produces meaningful insights and results for the application of NBS and the successful application of the proposed integrated framework in the study case.

Next steps of the integrated framework include the quantitative and spatial analyses of other benefits based on stakeholders' preferences. This study provided the quantitative analysis of one indicator to each sustainability pillar (i.e., environmental, economic, and social). However, it is considered that NBS will generate additional benefits which need to be quantified accordingly (Dagenais *et al.*, 2016). Other benefits such as access to green spaces, green job creation, increased property values, biodiversity, and heat alleviation are suggested by literature with the inclusion of nature solutions (Heckert *et al.*, 2018). Similarly, it is also recommended to analyse other scenarios with half-empty tanks for rainwater harvesting, mainly because the application is in Brazilian territory (Jacob *et al.*, 2019). Finally, the results highlight how the participation of all kinds of local actors in defining the actions is critical, especially the local community because they live with the risk on a day-by-day basis (Groulx *et al.*, 2017; Hardoy *et al.*, 2019). Also, they may need to share responsibility for the NBS maintenance to provide more sustainable infrastructure (Ashley *et al.*, 2020). Therefore, the next steps of the study include the involvement of citizens in specific activities using mappings for finding relationships between multiple benefits and resilience (Snep *et al.*, 2020; Verweij *et al.*, 2020) and for increasing their understanding and connection with NBS (Buurman *et al.*, 2017).

Finally, next studies of the integrated framework can also include the analysis of the negative cascade effects with NBS implementation, as it is considered as a challenge of current proposals of solutions for DRR (Pescaroli *et al.*, 2019; Ruiter *et al.*, 2020; Ward *et al.*, 2020). In this study, only GA in RT 25 years generated negative benefits (i.e., also called “disservices” by Morgan *et al.* (2019)).

7.7 Conclusions

As disasters have a complex and unique setting (Ward *et al.*, 2020) as a function of hazard, vulnerability, and exposure (UNISDR, 2021), it is impracticable and unrealistic to apply the same approach for reducing DR in every situation (Colléony *et al.*, 2019). In this sense, this study does not aim to develop an approach that can be applied worldwide. Instead, it sought to integrate the concept of disaster risk, vulnerability, exposure, and resilience when planning the implementation of NBS in areas with multiple social and institutional vulnerabilities (Kelman, 2020). This study answer this gap with the development of an integrated framework that assesses the effectiveness of NBS according to the understanding of the needs of the area and the provision of multiple benefits (Albert *et al.*, 2020; Bissonnette *et al.*, 2018; Dagenais *et al.*, 2016; Kuller *et al.*, 2017).

The framework was applied with a combination of spatial and participatory tools in Campina Grande (Brazil). Needs’ analysis shows how the city faces many societal challenges such as flood risk in the current and future context, allied with the complex task of living in vulnerable and urbanised areas, societal challenges very common in developing countries (de Loyola Hummell *et al.*, 2016; dos Santos *et al.*, 2021; Khan *et al.*, 2018). In this sense, the findings show the spatial distribution of flooding in the current and future contexts, in which approximately 52% of the flooded areas in the CFS will have a flood increase in the FFS (2040) (Figure 7.3a and 7.3b). Additionally, the interactions of risk components (i.e., hazard, vulnerability, and exposure) create specific hotspots, which can be used by city planning and management as "preliminary" indications for concentrating efforts for risk mitigation (Figure 7.4).

Based on the environmental and social needs, seven alternatives of NBS were discussed with stakeholders to be implemented in the city. The results stress that applying NBS in combination provides higher environmental, economic, and social benefits in all return periods studied (10, 25, and 100 years). When alone, NBS alternatives still offer a reduction in all scenarios examined, which supports that NBS should be incorporated as a strategy for strengthening DR governance, management, and resilience (UNDRR, 2019; Young *et al.*, 2019). However, the findings highlight how NBS can offer both environmental, social, and economic benefits, even though at different scales, which emphasises the need for and the importance of considering spatial "needs" and "benefits" for analysing the context and effectiveness of NBS.

From the "social" and "collaboration" perspectives, the integrated framework is underlined as a valuable tool for engaging with stakeholders, assessing the current needs regarding the environment, spatial justice, and equity, and for analysing the multiple benefits of NBS. The NEEDS for ACTION approach offer insights about the spatial distributions of risk (RQ1) and answers to the implications of NBS according to environmental, social, and economic benefits, including vulnerability and resilience (RQ2). Finally, the study provides specific directions for the city planning and management, which can be adapted for Campina Grande and other cities with similar contexts.

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CHAPTER 8
Conclusions and recommendations

The chapter provides a general view of what are the innovations and contributions to knowledge of the thesis, the main recommendations for the Brazilian context and limitations and suggestions for next studies. However, since the results of this thesis were presented with the journal publications, it is highlighted that some of the conclusions discussed may have been described beforehand.

Chapter 8 - Conclusions and recommendations

8.1 Thesis' summary and contribution to knowledge

This Ph.D. thesis contributes to the engineering science by providing evidence of spatial and participatory methodologies for including hazard, vulnerability, and exposure assessments, and their understandings, for flood risk mitigation. In the five articles produced, this thesis provides insights for the integration of social and environmental aspects for flood risk mitigation, through the study of Campina Grande, Brazil.

Results shows how the proposal of actions and solutions for flood risk reduction is an interdisciplinary decision, which asks for the interaction of multiple research fields focused on the environmental, physical, institutional, and social aspects of cities. In summary, findings obtained in this study discusses disasters as a social condition, underlying that a combination of spatial and participatory approaches can provide more understanding about several phases of the risk mitigation process. Detailed discussions about the research questions are described in the research papers on chapters 4, 5, 6, and 7, but general conclusions can be seen below:

- Reflections about the spatial-participatory approach

(i) The spatial and participatory processes were successfully combined in the integrated framework. The selection of the two processes were based on the understanding that spatial and social characteristics of a geographical area is essential for risk mitigation. The framework aimed to initially engender context-specific aspects (i.e., the *NEEDS*, phases 1 to 3) for subsequently planning actions for flood risk reduction (i.e., the *ACTIONS*, phases 4 to 6, Figure 3.3). The framework is applied in the city of Campina Grande, semiarid region of Brazil.

(ii) Through the case of Brazil, the challenging context for FRR in developing countries is provided. Brazil is a diverse country, with many geographical, physical, territorial, and social differences, which can converge in creating institutional, structural, and social inequalities, particularly when dealing with flood risk. Findings of chapters 4, 5, 6 and 7 highlights how the social context of Campina Grande, allied with management and legislation constraints, also interfere in the process of flood risk mitigation.

(iii) The integrated approach provided more clarity about the multiple root-causes of vulnerability and risk and their influence for finding appropriate manners for risk reduction. The analysis discussed the way that the social, institutional and structural factors corroborate to creating more vulnerability and exposure in the city (chapter 5).

(iv) The analysis of areas with flood vulnerability and exposure showed that the spatial distribution of hazard, vulnerability and exposure create inequalities in the city (Figure 7.4). Caution, warning and urgent hotspots were mapped for the city through the application of spatial tools in ArcGIS Pro (ESRI). The description of the process is shown in article 5 (chapter 7).

(v) Results shows the estimation of the several benefits that sustainable strategies can provide for the city. Hydraulic and spatial tools, as well as scenarios testing of the appropriate placements of solutions, are used to analyse the effectiveness of green roofs, rain gardens, rainwater harvesting, permeable pavements, the improvement of the drainage system and green areas. The analysis was developed for a representative catchment (chapter 6) and for the entire city (chapter 7). Results shows the green solutions not always will provide benefits, which indicates that each case need to be analysed in context (chapter 7). The combination of strategies was the most effective for flood depth reduction in all scenarios analysed (chapter 6 and 7).

(vi) The main gaps for the proposal of sustainable solutions for risk mitigation are discussed. The proposal of nature-based solutions, especially with the advent of sustainability, is considered as the intersection of four research areas, entitled as the clear conceptualisation of solutions, the inherent aspects of places, the urban planning and management, and resilience, adaptability, and future changes (i.e., details seen in chapter 2).

- Reflections about the participatory approach

As the planning of built environments has been built mainly with expert focused groups, without community involvement, the development of the PLANEJEEE

Project stands out as an illustration of how different stakeholders can be engaged for flood risk mitigation. PLANEJEEE Project was built upon the premise that flood vulnerabilities are influenced by actions and behaviours of local actors, which can increase or decrease resilience to the extreme event (chapter 4). The Project aimed to understand how the extreme events will have differences in spatial, temporal, and social scales, causing impacts for perception and coping capacity of residents, and perceptions of local authorities and experts. The conclusions of each phase of the participatory approach are detailed in chapters 4, 5, 6 and 7, however, some concluding remarks are below:

(i) The discussion between experts and local stakeholders is a key characteristic of this study. What differentiates it from other frameworks is the fact that citizens and policymakers play a unique role by providing a range of information about many of the root causes for flood vulnerabilities. The engagement strategies provided space for stakeholders to share their own previous experiences. Results of chapter 4 (articles 1 and 2) shows how the flood impacts are linked with the location and type of properties in the built environment, social constraints, population growth, the lack of appropriate legislation and the reduced engagement and communication with citizens (Table 4.3).

(ii) The approach enabled the analysis of actions and solutions proposed according to the different stakeholders' perspectives. Group A (citizens) proposed solutions more focused on structural works, such as the relocation of communities at risk, as well as the maintenance of current drainage networks. Policymakers and experts (group B) suggested actions that enable the combination of policy arrangements, structural works as well as providing communication and educational campaigns for reducing the impacts of flood risk in the area (Table 4.3).

(iii) Findings show that residents have a high-risk perception for flooding and water shortage (chapter 4 – articles 1 and 2). High levels of awareness and worry regarding both hazards were found (Figure 4.8), which indicates that residents had severe experiences in the past and fear new experiences in the future. However, even though they affirmed to believe that coping measures can reduce the risk, low coping and adaptive capacity were found.

Residents' overall perception and coping capacity were influences by direct and indirect experiences, house ownership, hazard proximity, age, management trust and education (Table 4.2 – article 1).

(iv) Findings shows the way that people perceive risk is related to the social vulnerability experienced by the participants, although coping is limited due to the number of resources available. The individuals' own location (i.e., territorial exposure) also characterises them as more or less vulnerable, which enables the reflection that vulnerability is specific to the site. For example, the poorest residents may occupy areas close to drainage channels, or their low standard housing limits the construction of water reservoirs, which will increase their risk (Chapter 4, articles 1 and 2).

(v) Results highlight how social vulnerability and risk interact with a series of psychological, social, and cultural processes that interfere in the perception and coping capacity of residents. The low coping capacity of the present time is linked to the strong economic and cultural barriers of the developing country (chapter 4 – article 2). However, for the future, economic and social incentives can provide motivations to increase adaptive capacity. In addition, other issues such as the inadequate early warning system, low communication, and low understanding of mitigation measures emerged in the analysis.

(vi) The social challenges are expressed in three areas, i.e., information, trust, and incentives, that form a network of resources to reduce social vulnerability and increase resilience (Figure 4.9). It is essential to mention that measures to improve preparedness, risk perception, awareness, information, and trust can be beneficial for both extremes, but these do not always result in vulnerability-reducing actions. Looking at the triad of societal challenges that formed, findings suggest that having experienced flooding before (i.e., direct and indirect) is not an assurance that coping capacity is high.

(vii) Working in conjunction with local community groups of Campina Grande, the Project PLANEJEEE also enabled to involve stakeholders to define the flood vulnerability and exposure mappings, as well as their preferences for SUDS, GI and LID types, and their placement in the local scale. The approach was divided into two main phases (i.e., the NEEDS and the

ACTIONS) for covering the analysis of the current conditions of the city for subsequently defining actions to reduce flood risk. The final mappings of flood vulnerability and exposure are shown in Figure 5.4 (article 3), and flood hazard in figures 6.4, 6.4 and 7.3 (articles 4 and 5). Each mapping was validated through the discussion with local authorities and datasets provided by the Civil Defence (articles 3, 4 and 5).

(viii) The participatory approach was an opportunity to increase engagement, communication and trust within the community and local actors in the different phases of flood risk mitigation. The strategies were chosen as door-to-door or online surveys, informal meetings, workshops and focus groups. In each strategy, it was highlighted the role that all the stakeholders have for flood risk mitigation. Besides, stakeholders recognised the project as a valuable approach linking academics, local population and policymakers during the workshops, focus groups and informal meetings. However, because of the COVID-19 pandemic, it was not possible to ensure the participation of all stakeholders in the second phase of the project.

8.2 Contributions for each objective of the thesis

Considering the fulfilment of the main goal of this thesis, several other objectives were established, as shown in chapter 1. In this sense, the innovation and contribution to knowledge are also presented with the provision of the main conclusions of the outlined objectives.

a. To develop a participatory process with collaboration between specialists, authorities, and citizens to engender a context-specific knowledge of water management in Brazil.

Initially, the literature review of this thesis discussed how participatory approaches can provide a range of benefits for flood risk mitigation. However, while presenting the current context of Brazilian approaches, it was discussed the low number of studies that consider participatory planning while analysing sustainable solutions for flood risk mitigation in the country. In this regard, the participatory approach was formulated to engage with residents, policymakers (authorities), and local specialists to improve flood risk mitigation in the study area.

The project entitled as "*Projeto **PLANEJEEE**: **PLANEJE E**ventos **E**xtremos*" occurred in two phases, in 2019 and 2021. Results indicated the need for assessing the socio-spatial context, expressing how city residents can face more than one disaster risk, sometimes simultaneously, represented as flood and water shortage risks in the study case (chapter 4, article 2). The analysis of the exposure (social), spatial and temporal scales of disasters exemplified how some residents may be exposed but not vulnerable to the hazards, or sometimes exposed to more than one hazard at the same time.

The results share the findings obtained with the participation of 255 stakeholders in the different phases of the study. The specific goal was accomplished with formulation of the phase 1 (i.e., in 2019) which refers to the understanding of social (i.e., for flooding and water shortage) and institutional vulnerabilities of the study area, as well as the data collection for mapping the spatial distribution of vulnerabilities and exposure in the city, including legislation (chapter 4). The phase 2 (i.e., in 2021) enabled the validation of the mappings developed, and the discussion of how the planning and positioning of sustainable solutions could be developed in the city. In the project, stakeholders were able to engage through different strategies, including questionnaire (online and in person), meetings, workshops, focus groups, website, and social media (i.e., Instagram). The chapters 3, 4, 5, and 7 provides details of the experiences, and challenges, of the engagement strategies in the different phases of the participatory approach, including during COVID-19 pandemic.

b. Evaluate the factors that most influence the social vulnerabilities, including the risk perception and coping capacity of residents, considering the multiple hazards in place and the institutional vulnerabilities of the region.

Chapter 4 focuses on conceptualising the collaboration of stakeholders as a tool for assessing social and institutional vulnerabilities for flood risk mitigation. Since the city faces flooding and water shortage, the social vulnerabilities were assessed with the formulation of risk perception and coping capacity of residents facing the two extreme events. After screening the literature, risk perception (RP) was evaluated with indicators representing the awareness (A) and worry (W), and preparedness (warning) (P) and knowledge (K), while coping capacity (CC) was obtained with responsiveness (R), willingness to apply adaptive measures (AM) and permanent measures (PM).

Socio-economical, informational, geographical, contextual, and cultural factors of were collected through the application of questionnaires with residents located in flood risk areas. The findings express that most residents had previous experience with flooding (94.8%), multiple times inside their properties (75.46%), but also faced water shortage risk (95.9%). 94% of respondents lived in houses, 38% have over 55 years old, and 48.2% had more than four people living in the property. When asked about their trust in management, 51.2% have very low trust in flood risk management, and 37.8% in water shortage. In summary, according to Wilcoxon Z and Mann-Whitney U tests, the influence analysis showed that different factors influence RP and CC in each extreme event, highlighting the influences of information, geographical and contextual factors. The results relate territorial and social vulnerabilities, presenting how the economic and cultural barriers as well as the individual's own location (exposure) are specific to the site. The chapter discusses the need to build more multi and interdisciplinary analyses to evaluate the influence of social factors in perception and adaptability.

Chapter 4 also evaluates how the indicators of RP and CC influence each other with Pearson correlation. Results indicates the residents that have more flood coping strategies in place (AM) are more aware (A) and concerned (W) with the disaster. The analysis showed that most residents confirmed the lack of official warnings (P) before the hazard; however, they still apply coping strategies in their households (AM). Residents' answers showed low awareness of the efficiency of sustainable strategies for flood risk mitigation, which shows there is a need to improve the understanding of what are the solutions, and communication with population. In this sense, the chapter discusses how a triad of resources (i.e., named as trust, information, and incentive) can support the residents and provide abilities for individuals to deal with disasters (Norris *et al.*, 2008).

Institutional vulnerabilities were analysed with the support of residents, policymakers, and local specialists. Chapter 4 details the challenges and solutions debated with stakeholders in the Project PLANEJEEE considering three perspectives: (1) *how* the risk management is made in the city, (2) *which* legislations are in place, and (3) the impacts of society and *if* there is collaboration among stakeholders, especially public participation, in management and governance. Besides, as suggested in chapter 2, the analysis provides insights of what are the social challenges faced in the Brazilian context, especially the low income, the residents that live in suburbs, favelas and risk areas, the understanding of communities in risk of how to minimise the impacts of hazards, and the lack of trust in management.

In this regard, the objective is fulfilled with the analysis of what social factors (i.e., socio-economical, geographical, information and contextual) most influence RP and CC of residents, if there is any relationship between RP and CC of flooding and water shortage, and what are the challenges and suggestions of stakeholders to mitigate the flood risk in the city.

c. Select spatial criteria to model vulnerability and exposure areas with physical, urban, and social aspects, using pre-existing data, participatory and field surveys, mainly in GIS environment.

The criteria to model hazard-specific vulnerability and exposure were obtained through the development of a socioenvironmental approach, detailed in chapter 5. The methodology was constructed with basis in the disaster risk definition as the relationship between vulnerability, exposure, and hazard (IPCC, 2012, 2014; UNDRR, 2019). The vulnerability was modelled through the definition of *attributes* of the city, indicating that vulnerability is formed with a relation between weaknesses (e.g., sensitivity) and strengths (e.g., capacity) in the human-environmental system. The exposure was mapped through the understanding of what are the locations that can have more people, assets or infrastructure exposed on a flood event, following the concept of UNISDR (2021).

Entitled as a participatory-fuzzy-entropy methodology, the analysis combined physical, structural, institutional, and social indicators to map the flood vulnerability in the city. The indicators selected were elevation, households with open sewage, without drainage system and with accumulated garbage, the drainage structure of the city, the imperviousness, the residents with lower income, and the distance to disaster prevention institutions. When analysing the exposure, the mappings aimed to evaluate what are the places with more population density, with more children and elders. Similarly, the places nearer to schools, health establishments and properties in official flood risk areas were also considered. The vulnerability and exposure indicators correspond to different datasets that were inserted and integrated in the GIS environment, using ArcGIS (Pro) and linear fuzzy membership functions. The entropy method was used to objectively compute the weights for mapping the final vulnerability and exposure.

Indicators were chosen with the involvement of stakeholders in the PLANEJEEE Project. The selection was made through the results of the questionnaires with residents, policymakers, and local specialists (phase 1 of the PLANEJEEE Project), discussions about the main challenges for flood risk (i.e., the analysis of vulnerabilities), and comparisons with previous studies. Stakeholders' participation aimed to improve co-ownership and acceptance of the results in real-life applications (Hardoy *et al.*, 2019; Verweij *et al.*, 2020). The mappings express the different levels of flood vulnerability and highlights specific locations with fewer conditions to deal with the extreme rainfall event. In addition, the vulnerability and exposure mappings were validated with the comparison of previous flood cases in the city, and with the discussion of mappings outputs in the phase 2 of the participatory approach. The importance of the physical, structural, institutional, and social vulnerabilities is discussed (chapter 5).

d. Develop the most appropriate method for positioning sustainable solutions for flood risk mitigation, inside a representative basin, with the inclusion of aspects of the built environment, climate, and governance.

Aiming to include aspects not only related to the technical aspects of sustainable solutions but also to the context specificities, a land-use and legislation-based methodology was formulated. The approach built with ArcGIS (Pro) and SWMM (US EPA) assessed the environmental benefits (i.e., flood depth reduction) of green roofs, permeable pavements, and rain gardens in three catchments and 312 sub-catchments of Campina Grande, Brazil. At this point, the main goal was to evaluate the environmental aspects with SUDS.

The sustainable strategies were inserted considering the semiarid climate of Brazil, as well as the characteristics the built environment, using the existing land use dataset, and the current legislations of the city. The analysis of current legislations aimed evaluated three main contexts: (i) if sustainable solutions are already suggested in the regulations, (ii) what would be the impact if the legislation was fulfilled, and (iii) what would be the environmental benefits of solutions in the catchments. Findings of chapter 6 continues to discuss the impacts of various sources of institutional vulnerabilities in Brazil and Campina Grande, focused on analysing the legislation and governance, as suggested in chapter 2 and 4, respectively.

The built environment and the limitations of current legislations were used to build 30 scenarios for inserting the solutions, with return periods of 2 and 5 years, in the current and future context. Findings confirm the environmental benefits will vary according to the size of the application area and the location of strategies' placement. When applied alone or in combination, the effectiveness is more significant if the solutions are implemented in the current context (before urbanisation). When considering the urbanisation as allowed in the legislation, the flooding in the city will increase, which shows the ineffectiveness of the law and the increase of risk. This scenario is an indication of the gap between urban planning and water resources planning in the city. When solutions are applied in combination, the methodology shows 85.7% of flood reduction in the future imperviousness scenario. The objective refers to the phases 3, 4, 5 and 6 of the risk-based spatial-participatory framework.

e. Model the effectiveness of solutions in the study area, under normal and extreme conditions, aiming for the provision of environmental, social, and economic benefits.

Going further in the analysis of sustainable solutions, chapter 7 focuses on (i) the evaluation of environmental, social, and economic benefits that can be obtained and, (ii) the construction of an assessment in the entire urban area of Campina Grande. The approach was developed with a summary of the six phases of the risk-based spatial participatory framework, by establishing the *needs* and *actions* of the city. Chapter 7 provides the integration of vulnerability, exposure and hazard as the disaster risk, as shown in the chapter 2. For this, the mappings obtained in chapter 5 (i.e., specific objective c, referring to vulnerability and exposure), were combined with the flood hazard mapping, which was modelled with CADDIES software (University of Exeter). The integration is enabled with the use of spatial tools in ArcGIS Pro (ESRI). The analysis goes beyond the proposal of placement of chapter 6, since the selection, placement, and benefits to be acquired with solutions were chosen with policymakers and local specialists during the second phase of the PLANEJEEE Project in 2021. Because of the COVID-19 pandemic, the engagement approaches had to be limited to the participation of policymakers and specialists at this phase. Informal meetings and a workshop were made in the city council buildings with policymakers; however, participants were oriented to indicate if they wanted to take part even due to the unexpected circumstances. Online and in person surveys were distributed for policymakers and specialists. Since most residents that participated in the first phase of the PLANEJEEE Project lived in risk conditions with low access to internet, they were not involved in the 2021.

NBS terminology is used in chapter 7 because of the many benefits that can be obtained with the solutions. The results shows the assessment of flooding hazard with CADDIES model in the current and future urbanisation scenarios (Rufino *et al.*, 2021). At this chapter, the built-up grid developed by Rufino *et al.* (2021) was used to simulate the flood risk in Campina Grande in 2040. The analysis showed an increment of flooding on 52% of the pixels of the urban area. Results show the combination of flooding hazard, vulnerability, and flooding will create "hotspots", which refer to places that need more management attention due to the interactions between the disaster risk variables. The mappings of "caution", "warning" and "urgent" hotspots were specified in the urban area, characterising how neighbourhoods are differently impacted by the flood risk.

In this chapter, green roofs, permeable pavement, rainwater harvesting, green areas and the improvement of drainage system were analysed in 53 scenarios of application. The percentage of benefits acquired was ranked according to each benefit type (environmental, social, and economic) to analyse the solutions that provided more reduction rates. When alone, green areas and roofs provided more reduction and therefore more environmental, economic and social benefits. However, similar to chapter 6, the most effective sets of solutions are found to the combination of solutions for all types of benefits.

The chapter is concluded with the application of the "disaster resilience" concept (Cutter *et al.*, 2008), which evaluates resilience in terms of the type and rank of benefits which are obtained, according to the triad of sustainability pillars (WCED, 1987). The approach is discussed by analysing the city's needs and the provision of multiple benefits with the solutions. The objective refers to phases 1 to 6 of the risk-based spatial-participatory framework.

f. Formulate recommendations for the integrated and sustainable water management for the Brazilian context.

The recommendations for the Brazilian context, and specifically for Campina Grande – Brazil, were detailed in Chapters 2, 4, 5, 6 and 7 of this study. At this section, the summary is presented in groups A, B and C below:

Group A: The proposal of sustainable solutions in Brazil (chapter 2)

Findings:

1. The examination of the 45 Brazilian articles in chapter 2 shows most case studies are in the Southeast and South regions of Brazil. Case studies represent highly developed urban watersheds, cities, or regions with a high incidence of precipitation, such as Rio de Janeiro and São Paulo. Study cases in Midwest (4.8%), Northeast (8.3%) and North (7.1%) regions remain less analysed.
2. The number of studies that analyse sustainable solutions in the Brazilian context increased considerably from 2018 to 2021. The solutions are entitled differently in the studies with more examples of LID (38.1%) and SUDS (29.6%), although sometimes studies consider them as synonyms.
3. Most papers analyse the sustainable solutions only in terms of environmental benefits, especially the reduction of flood depth (n = 18), and mostly within a catchment (54.8%). Cities were only analysed in 7.2% of the articles. 59.6% of approaches applied hydraulic modelling, and 10.6% used GIS-based tools for assessing benefits. Only 10.6% of studies linked the proposal of solutions with participatory approaches.
4. In general, articles make less consideration to the social context in which the flood risk occur. "Vulnerability" is used as keyword in only five articles, and no articles cited either "exposure" or "adaptability". More emphasis is given to "resilience" (n = 8), "landscape planning" (n = 12) and "integrated management" (n = 5), which may indicate more concerns in linking the proposal of solutions and resilience with the integration in legislation, than to the vulnerabilities.

Recommendations:

1. Screening the journal articles in Scopus, Web of Science, Google Scholar, and Connected Papers databases showed the search for sustainable solutions in Brazil is very recent, but it also is an indication there is a growing motivation on the topic within Brazilian community.
2. Most studies are mainly focused on the analysis of environmental benefits of the solutions, with study cases mostly based on Sao Paulo and Rio de Janeiro states. Likewise, social factors such as sources of vulnerabilities, inequalities, and exposure, are rarely considered in the studies. When looking into methodological approaches, findings suggest a search for modelling tools, especially hydraulic models, and the analysis of legislation instruments, but a low inclusion of participatory approaches.
3. There is a need, therefore, to expand the analysis not only to include more cases in the other regions of Brazil, but also to enable the understanding of the societal factors of the area, in light that this will facilitate the comprehension of the barriers and challenges for flood risk mitigation, especially because Brazil is a country with great geographical differences. Participatory approaches are suggested to be used as a tool for understanding the human-environmental systems.

Group B: Considering social, structural, and institutional vulnerabilities for the proposal of risk reduction approaches (chapters 4, 5 and 6)

Findings:

1. The participatory approach enabled the interaction of different stakeholders for the FRR. During the two phases of the fieldwork, sources of vulnerabilities were verified, such as the low condition of properties and streets, the sewage discharge in the rain channels, the number of people that were living in risk areas, the difference of elevation in flood and no flood risk zones, and the number of flood cases in areas not officially considered as a flood risk zone, between others.
2. When residents were asked how likely they received warnings before the disaster occurrence, their answer indicated “very low” to “low” to FR (M 1.7), and “moderate” to “high” to WSR (M 3.3), which shows they receive more warnings before WSR than FR. Policymakers and specialists affirmed that residents have “low to moderate” necessary risk information before the disaster’s occurrence (M 2.43). This can indicate that risk mitigation strategies are not focused on “before” but mainly on “after” the event, especially in the context of FR.
3. When asked about the solutions for reducing the FR, all stakeholders affirmed the grey solutions are most effective than green infrastructure. Residents opted to apply more permanent solutions such as barriers (for FR) and water tanks (for WSR) on their households. Money was considered as the main issue for applying more solutions in their households, which can be an indication of the need to incentivising residents to apply solutions.
4. The lack of collaboration between the sectors of the city council and other stakeholders, including and especially with the public participation, was also highlighted as a key concern, and shows the gap between proposals and society. The residents affirmed to have a reduced trust in the management of FR and WS, which can interfere directly in management and the uptake of solutions.
5. The legislation in Brazil usually does not link urban planning with water resources or environmental concerns (i.e., results of chapters 4 and 6). Specifically, the chapter 6 shows that when the urban legislation (i.e., Master Plan) of Campina Grande is fulfilled, in terms of the urbanisation allowed in each lot, there is likely to have more flooding cases in Campina Grande.
6. Chapter 6 provided evidence of legislations, including the Law 10.047/2013 in Campina Grande, that request the use sustainable solutions in condominiums with more than three buildings in all the cities of Paraiba state. It was seen that similar laws are being suggested for other cities, even though cities have different built conditions and environments (for example, the law request the use in condominiums, but cities may not have any building with more than three floors). This can indicate that sustainable solutions are being recommended without the analysis of specificities of the city, which can undermine their effectiveness.
7. The FR and urban management are recurrent concerns in the country. Compulsory urban legislation such as the Master Plan should be updated in each 10 years, aiming to consider changes such as urbanisation in the proposal of actions in the city. The last version of Campina Grande’s master plan is from 2006. The plan has been in the process of review since 2019. However, it was not completed yet, being 15 years late in 2021.
8. Finally, there is also a concern about the lack of specific guidance for FR mitigation in Campina Grande, and in other cities of Brazil (i.e., discussed in chapters 2, 4, 5, 6 and 7). The “Sanitation Plan” and the “Drainage Master Plan” are very commonly either outdated or were not developed for the city. This is the case of Campina Grande, which does not provide any mappings of local flood hazard or vulnerability-prone areas, beyond the CPRM map. Furthermore, the city does not have clear guidance for mitigating the FR beyond the support of the Civil Defence.

Recommendations:

1. The analysis confirms there are different barriers for FRM in the city, including low communication with residents, low trust in government for mitigating disasters, and low financial incentive for residents implementing solutions in the property-level. Resources involving communication, trust and incentive are suggested for improving the coping capacity of residents during the extreme events.
2. The analyses showed that residents do not feel the warnings are sufficiently emitted before FR and WSR. The preparedness of WSR appears to be better than FR, mainly because of the socio-spatial context of the disasters (i.e., described in chapter 4). The improvement of early warning systems in Campina Grande is recommended, especially considered that it is one of the main strategies for DRR (i.e., see more details of Marchezini *et al.* (2017). Similarly, it should be noted the importance of dialoguing with residents for understanding the most appropriate approach for applying the warning systems.
3. Considering the issues with management and governance in the city, it is recommended to build stronger legislations that can link urban planning and water resources in Campina Grande. Legislation must be reviewed for analysing if it has any effect for generating more FR. Similarly, new legislations must be created according to the specificities of the city, especially targeting the sustainable mitigation of FR.
4. It is highlighted the collaboration amongst stakeholders must be improved, and how the participatory approach enabled a direct contact with residents, policymakers, and local specialists of the city. The review of current legislations and the proposal of specific regulations for FR, with inter and multidisciplinary perspectives, are likely to support the reduction of FR impacts if are combined with actions of management. It is considered that legislation, management, society, and stakeholders must work together for improving the challenges and solutions with DR in the city (i.e., chapter 4).

Group C: The implication of flood hazard, vulnerable and exposed mappings, and the effectiveness of sustainable solutions (chapters 5, 6 and 7)

Findings:

1. Mapping hazards, vulnerabilities, and exposure showed there are places in Campina Grande with susceptibility for FR. The mappings show that the delimitation of flood areas by CPRM (2013) does not reflect local areas with flood susceptibility. The city has many flood cases in specific streets (i.e., chapters 5, 6 and 7).
2. The analysis of flood-prone areas shows it is likely that Campina Grande will increase FR zones in the future, either by urbanising with the allowed in legislation (Complementary Law 003/2006), or if it urbanises as predicted by Rufino *et al.,* (2021).
3. The simulations showed that sustainable solutions provide environmental, social, and economic benefits, in the representative and wider area, in current and future conditions. The benefits were analysed by reducing flood depth, areas with VH flood risk areas, and properties located in those VH risk areas (i.e., chapters 6 and 7). After the collaboration with stakeholders, the list of preferred benefits to be acquired with the solutions was provided in chapter 7. The list can be used as a start-point in the analysis of other solutions for Campina Grande.
4. Results in chapters 6 and 7 show that each solution has provided benefits, but the combination of all strategies proved to be the most efficient result in this study.

It is acknowledged that sustainable solutions are a tool for acquiring water resilience for extreme events, allied with the reduction of vulnerability.

5. Since the beginning of the study, the PLANEJEEE Project enabled the involvement of stakeholders, which can improve the applicability of solutions in the future. In any way, the approach helped to discuss many water-related challenges and solutions with different f groups, which was told as very “valuable” for management. The results show that sustainable solutions need to become a "normal routine" in urban water management, especially in flood and scarcity scenarios, as seen in the Brazilian semiarid region.

Recommendations:

1. The separate analysis of disasters constituents enables the analysis of different strategies for FR, such as the increase of perviousness in the city scale, the improvement of drainage systems (i.e., grey infrastructure), the improvement of sanitation in the city (sewage, drainage, and garbage) with the participatory-entropy-fuzzy methodology of chapter 5, and in relation to the direct implementation of sustainable solutions on chapters 6 and 7.
2. The effectiveness rates with sustainable solutions demonstrated that using the existing “land” is as a valuable resource for urban planning (Lourenço *et al.*, 2020; Miguez *et al.*, 2015b). The insertion of sustainable solutions in the existing land covers enabled the reduction of FR and vulnerability in the city. Proposals according to the land use should be used as the link between urban and water resources planning, especially during the review of the master plan. The results presented in this study can be used as guidance for replicating the model with adequate land uses for implementing the solutions in the city.
3. The perception of stakeholders (engineers, architects, policymakers, population) towards sustainable solutions should be improved for believing and starting to apply the SUDS/NBS not only as "a green idea", or "environmental approach", but to assure a better life quality for future generations and, to make possible a continuous developing in urban areas.

8.3 Limitations and next studies

Limitations of the study are explained throughout the thesis, especially in the journal articles. In this section, a summary of limitations is presented with the indication of next studies related to aspects of the participatory approach, the spatial-participative analyses, the mappings produced, and the benefits of sustainable solutions.

8.2.1 Widening the participatory approach

The participatory approach developed in this study aimed to involve the three stakeholders (i.e., residents, policymakers, and specialists) in all the phases of the integrated framework. However, mainly because of the distance between the host university (University of Exeter) and the research study case, the fieldwork had to be limited to two opportunities. It is acknowledged that engagement strategies could have been developed differently, with other forms of collaboration, especially with the residents of Campina Grande. The engagement with residents can be made through the development of regular reunions in the neighbourhood centre buildings, where citizens can plan solutions to be implemented. For this, stakeholders can be engaged in a way to see "flood management as an opportunity" for improving the city, as well as their built environment. Therefore, increasing dialogue with communities in risk is suggested.

Additionally, while in the workshops, the policymakers of Campina Grande showed interest in applying the sustainable solutions in a pilot study area in the city. In this sense, the interest and collaboration between the local actors could be used as a tool for applying the proposed solutions in the city, for increasing their perception, and evaluating the benefits in local scale.

Besides, it is acknowledged the great value of discussing the challenges and solutions of the city with stakeholders. This step was crucial for the development of the risk-based methodology, especially because it could provide more comprehension of the current state of vulnerabilities by visualising possible underlying causes, as well as, through the engagement with stakeholders. In this sense, next studies could continue the search for enhanced strategies, with stakeholder engagement, and use the topics highlighted in this thesis as an "initial set of challenges" before proposing solutions for FR.

8.2.2 Integrating vulnerability and inequalities, a mapping approach.

Since the last census available for the Brazilian territory is from 2010, it is highlighted the datasets used are a limitation of the study. The new census was due to be distributed in 2020, however, because of the COVID-19 pandemic, it was postponed for 2022. As a manner to overcome this barrier, while engaging with policymakers, the most recent datasets of the city council were used in the mappings developed. Similarly, the datasets used to validate the mappings correspond to previous flood risk cases, showing the distribution of FR cases in the region, indicating their risk susceptibility. However, the 2010 census is considered one barrier in the flood vulnerability and exposure mappings, and therefore, it should be updated when the dataset is available. Similarly, other weighting methods can be analysed in future mappings, especially with a comparison of subjective and objective methods.

Since mappings provided evidence of the disproportional distribution of vulnerabilities and exposure in the city (chapter 5 and 7), it is suggested to evaluate how the flood vulnerabilities overlap with other social factors, such as low income, type of infrastructure, criminality and race with mapping approaches. Next studies should seek to develop methodologies for the correlation between the distribution of vulnerabilities and inequalities in city-scale (Hendricks *et al.*, 2021; Pescaroli *et al.*, 2019; Ross *et al.*, 2020). In addition, the vulnerability-inequalities mapping can contribute to incorporating decentralised solutions in the city, supporting the risk mitigation in more appropriate manners, according to specific needs of the population and region.

8.2.3 Assessing the multiple benefits of sustainable solutions with "time" and "spatial equity" lenses

The results of this thesis showed how FR benefits of sustainable solutions will vary between options. Aspects of each solution, such as its size, the area of application and of the property, and technical characteristics can significantly influence their effectiveness. Besides this, climate and legislation regulations influence in the final effectiveness of the solutions.

Next studies should also consider the analysis of how benefits may change with time in a flexible manner. This is considered as a great barrier for incorporating sustainable solutions in the city scale, since their effectiveness may change with time constraints. In this thesis, the "time" was considered according to "urbanisation" and "return periods" of rainfalls, however, it is acknowledged that other variables, such as the conditions of the climate change variations, built environment, periods of water shortage, direct interferences with climate and vegetation type can be inserted.

The collaboration with stakeholders that will receive these benefits also appeared to the crucial for the management. This thesis provided the analysis of three benefits in environmental, social, and economic pillars of sustainability (Chapter 7). For Campina Grande, the preferred options by stakeholders can be used for selecting other benefits to be analysed in the future (Table 7.3, chapter 7).

Due to the COVID-19 pandemic, it was not possible to engage with residents located in risk-zone areas at the final phase of the PLANEJEEE Project. Next studies should also be focused on discussing these benefits with people from areas that are not currently in flood risk areas but are zones where interventions should be designed to protect areas downstream (O'Donnell *et al.*, 2018). In this sense, the following studies should consider the interdependence between people and solutions to identify the local community's role in the transition process for sustainable development (Gimenez-Maranges *et al.*, 2020).In addition, benefits can be suggested as a strategy for promoting more equity in the built environment. For this, understanding the social factors, such as low income, elders, children, and areas with more schools, can be used as variables for selecting the most appropriate locations for solutions. Studies such as Heckert *et al.* (2018), La Rosa *et al.* (2020), and Pappalardo *et al.* (2017) are suggested as initial steps.

8.2.4 The integration of water shortage and flood risks modelling

Finally, the compound and simultaneous occurrence of water shortage and flood risks should be investigated. At this study, the water shortage was considered from the conceptual framework, with the analysis of how risk perception and coping capacity (RP and CC) of residents in risk are interrelated for the two extreme events, and with the contribution of stakeholders that analysed how solutions for FR can be planned regarding the semiarid climate, and WSR specificities. Additionality, the analysis of solutions provides reflections about the WS and FR.

As for the modelling software used, specific limitations were detailed in each chapter (5, 6 and 7). Next stages of the research should look for adaptation of the methodology prepared in chapter 5, expanding the method for mapping WSR vulnerability. The flood-water shortage vulnerability mappings can provide meaningful information for management, including their interrelationships and how the population can be affected while facing the two extreme events. Similarly, the datasets used in the GIS mappings (chapters 5, 6 and 7) can be adapted for other cities. Since the census 2022 was not made available yet, it is suggested to adapt the datasets used with the new census, when available.

APPENDICES

Appendices

A. Literature Review
B. Methodology
C. Article 02: Place-Based Citizen Science for Assessing Risk Perception and Coping Capacity of Households Affected by Multiple Hazards.
D. Article 03: An integrated socio-environmental framework for mapping hazard-specific vulnerability and exposure in urban areas.
E. Article 04: Land-Use and Legislation-Based Methodology for the Implementation of Sustainable Drainage Systems in the Semi-Arid Region of Brazil
F. Article 05: Understanding NEEDS for ACTING: A risk-based spatial-participatory framework for planning Nature-Based Solutions in Brazil.

Appendix A: Literature Review of the Brazilian Context

Table A1 – The detailed list of articles analysed in the Brazilian context. Each column refers to the categories for the quantitative analysis of articles. GR refers to Green Roofs, RG to Rain Gardens, PP to Permeable Pavements, and RWH to Rainwater Harvesting.

DATABASE SOURCE	AUTHORS	YEAR	JOURNAL	REGION	SCALE OF ANALYSIS	TYPES OF SUSTAINABLE SOLUTIONS	MODELLING APPROACH	PARTICIPATORY APPROACH	STAKEHOLDERS INVOLVED
SCOPUS	Alves et al.	2020	Sustainability Journal	Northeast	Catchment	GR, RG, PP	SWMM	No	No
SCOPUS	Baptista et al.	2017	Water Resources Management Journal	Southeast	Catchment	-	ArcGIS (ESRI)	No	No
SCOPUS	Bertilsson et al.	2019	Journal of Hydrology	Southeast	Neighbourhood	GR, PP, Floodable parks, Tanks	MODCEL	No	No
SCOPUS	Bianco et al.	2013	ICE - Civil Engineering Journal	North	Catchment	-	Modeleur and Hydrosim	No	No
SCOPUS	Brito and Koide	2020	Sustainability Journal	Midwest	Households	Swales	SWMM, PCSWMM	No	No
SCOPUS	Calixto et al.	2020	Urban Water Journal	Southeast	Catchment	PP, Tanks	HEC-HMS, HEC-GeoHMS, HEC-RAS	No	No
SCOPUS	De Macedo et al.	2019	Science of the Total Environment	Southeast	Prototype	Bioretention	Water balance equation	No	No
SCOPUS	De Macedo et al.	2019	Journal of Environmental Management	Southeast	Catchment	Bioretention	Water balance equation	No	No
SCOPUS	Fileni et al.	2019	Brazilian Journal of Water Resources	Midwest	Catchment	PP, Tanks	SWMM, PCSWMM	No	No
SCOPUS	Gonçalves et al.	2018	Sustainability Journal	South	Neighbourhood	RG, Infiltration trenches, Tanks	SWMM, PCSWMM	No	No
SCOPUS	Gonçalves and Nucci	2017	A Revista RAEGA - O Espaço Geográfico em Análise	South	Catchment	RG, Bioretention, Swales	GIS	No	No
SCOPUS	Lourenço et al.	2020	Journal of Cleaner Production	Southeast	Catchment	-	Urban Flow Cell Model - MODCEL	No	No
SCOPUS	Machado et al.	2019	Land use policy	Northeast	City-wide	-	GIS	No	No
SCOPUS	McClymont et al.	2020	Journal of Environmental Management	Southeast	Catchment	GR, PP, Bioretention, Swales, RWH	INFO SWMM	No	No

SCOPUS	Miguez and Verol	2017	SAGE - Environment and Planning B: Urban Analytics and City Science	Southeast	Catchment	GR, RG, PP, RWH	MODCEL	No	No
SCOPUS	Miguez et al.	2012	WIT Transactions on Ecology and the environment	Southeast	Neighbourhood	Tanks	MODCEL	No	No
SCOPUS	Miguez et al.	2013	WIT Transactions on Ecology and the environment	Southeast	Catchment	-	mathematical model	No	No
SCOPUS	Miguez et al.	2014	WIT Transactions on Ecology and the environment	Southeast	Neighbourhood	PP, Tanks, Swales	MODCEL	No	No
SCOPUS	Miguez et al.	2015	J. Urban Plann. Development	Southeast	Catchment	Tanks	MODCEL	No	No
SCOPUS	Miguez et al.	2015	Sustainability Journal	Southeast	Catchment and neighbourhood	Parks	MODCEL	No	No
SCOPUS	Moura et al.	2016	Journal of Flood Risk Management	Southeast	Neighbourhood	PP, Bioretention, Tanks	mathematical model	No	No
SCOPUS	Jacob et al.	2019	Water Science & Technology	Southeast	Neighbourhood	Swales	MODCEL	No	No
SCOPUS	Ronchi and Arcidiacono	2019	Sustainability Journal	Southeast	Neighbourhood	GR, PP	InVEST software	No	No
SCOPUS	Rosa et al.	2020	Water Science & Technology	Southeast	Catchment	GR, PP, Infiltration trenches, RWH	SWMM	No	No
SCOPUS	dos Santos et al.	2021	Sustainable Cities and Society	Southeast	Neighbourhood	Infiltration trenches, Swales	SWMM	No	No
SCOPUS	da Silva et al.	2018	Water	Southeast	Catchment	RG, PP, Infiltration trenches	PCSWMM	No	No
SCOPUS	Silva et al.	2010	Environ Sci Biotechnol	Southeast	Neighbourhood	Tanks, RWH	mathematical model	No	No
SCOPUS	Tavares et al.	2018	Journal of Urban and Environmental Engineering	Southeast	Catchment	-	HEC-HMS, HEC-RAS and SWMM	No	No
SCOPUS	Veról and Miguez	2020	Proceedings of the Institution of Civil Engineers - Municipal Engineer	Southeast	Catchment	GR, RG, PP, Infiltration trenches	MODCEL	No	No
SCOPUS	Veról et al.	2020	Sustainability Journal	Southeast	Catchment	Tanks, RWH	MODCEL	No	No
SCOPUS	Young and Papini	2020	Sustainable Cities and Society	Southeast	Catchment	-	Decision Support System for Flood Analysis (DSSFA)	No	No
SCOPUS	Zanandrea and Silveira	2019	Eng. Sanit. Ambient	South	Catchment	PP, Swales	SWMM	No	No

WEB OF SCIENCE	De Macedo et al.	2021	Critical Reviews in Environmental Science and Technology	Reviews	-	-	Review	No	No
WEB OF SCIENCE	Filho et al.	2018	Mitig Adapt Strategies Glob Change	Southeast	Catchment	-	Review	No	No
WEB OF SCIENCE	Mansur et al.	2018	Regional Environmental Change	North	City-wide	-	CENSUS	Semi-structured interviews, focus group discussions, observational and archival data, and photo documentation	Residents, civic leaders, local researchers, and municipal representatives
WEB OF SCIENCE	Miguez et al.	2018	Journal of Flood Risk Management	Southeast	Catchment	GR, PP, RWH	MODCEL	No	No
WEB OF SCIENCE	Teston et al.	2018	Water	Reviews	-	-	Review	No	No
CONNECTED PAPERS	Antuna-Rozado et al.	2019	IOP Conferences Series: Earth and Environmental Science	Southeast	Neighbourhood	RG, Swales	Participation	Grassroots	Citizens, public and private institutions
CONNECTED PAPERS	Ardaya et al.	2017	International Journal of Disaster Risk Reduction	Southeast	City-wide	-	Questionnaire, interviews	Interview, quantitative questionnaires	Citizens and authorities
CONNECTED PAPERS	Brasil et al.	2021	Water	Reviews	-	GR, Bioretention, Tanks	Review	No	No
CONNECTED PAPERS	Young et al.	2019	International Journal of Disaster Risk Reduction	Southeast	City-wide	-	Subjective and objective tools	Workshop and questionnaire	Public agencies, including staff from civil defence and municipal departments engaged in spatial planning
CONNECTED PAPERS	Silva et al.	2020	Journal of Environmental Management	Northeast	Households	Tanks	SWMM	No	No
SCOPUS	Watrin et al.	2020	ICE - Civil Engineering Journal	North	Prototype	GR	Experimental	No	No
SCOPUS	Tassi et al.	2016	Ambiente Construído Journal	South	Neighbourhood	-	Statistics	Questionnaire	Residents
SCOPUS	Londe et al.	2015	R. bras. Est. Pop	Northeast and South	Catchment	-	CENSUS	No	No

Appendix B: Methodology (PLANEJEEE Project)

Summary – In person survey for residents (2019):

Consent and willingness to participate

Personal questions:

- Name, address, gender, education, average income, age, employment status
- The number of people living in the household, if there are children in the property, house ownership, if they receive any incentives from the government,
- If they do any volunteer work, participation in neighbourhood meetings, how they inform themselves about FR.

About flood risk (FR) and water shortage risk (WSR):

- Perception of causes for FR and WSR
- Previous experiences with FR and WSR in the past
- Previous experiences with FR inside their properties
- Damage with FR in the past
- Evacuation because of flood exposure
- Probability of FR and WSR occurrence in the next ten years

About the management of FR and WSR:

- Their role in FR and WSR management
- Trust in public administration in relation to FR and WSR
- About FR: if they live in a FR area (CPRM), if they issued formal complaints in the past
- If they participated of trainings to mitigate FR and WSR
- About FR and WSR early warning systems

About mitigation solutions for FR and WSR:

- If they have any adaptive and are willing to do permanent solutions such as moving house
- If they receive any monetary incentives from the government
- How they would be more willing to do any investment in their household to mitigate risk
- Which solutions they would apply in their households
- The effectiveness of solutions for FR and WSR (including grey, management and green solutions).

Feedback and acknowledgments

Figure B1: Residents' estimation of the flood height during previous flood risk events, photos a) to d) refers to different neighbourhoods of the city.

Survey and workshop with policymakers and local specialists:

Summary – In person survey for policymakers and local specialists (2019):

Consent and willingness to participate

Personal questions:
- Name, email, background, work affiliation, years of experience, details of where they work

About flood risk (FR) and water shortage risk (WSR):
- Perception of causes for FR and WSR
- About the law format and the requirements to implement the innovative solutions for FR and WSR

About the management, legislation, and solutions for risk mitigation:
- The distribution of responsibilities on FR and WSR management
- The responsibility for adopting mitigation solutions
- Strategies for improving the adoption of mitigation solutions in the city
- The appropriate stage for integrating the mitigation solutions in the urban planning
- Key reasons for the low implementation of solutions in the city
- If mitigation strategies are within the legislation but subsequently are not implement, what tend to be the reason?
- Biggest difficulties to include multidisciplinary stakeholder in risk management
- Challenges for the implementation of FR and WSR solutions

About mitigation solutions for FR and WSR:
- Strategies for motivating residents to apply local solutions in their households
- If residents have the needed risk information for dealing with FR and WSR
- The effectiveness of solutions for FR and WSR (including grey, management and green solutions).

Feedback and acknowledgments

Summary – Online and in person survey with policymakers and local specialists (2021):

Consent and willingness to participate

Personal information
- Name, email, background, work affiliation, years of experience, details of where they work

Effectiveness and preferences of sustainable solutions for FRR
- *Green roofs, rain gardens, permeable pavements, rainwater harvesting, infiltration trenches (participations could suggest new solutions)*

Preferred multiple benefits to be acquired with solutions
- Full list provided in chapter 7

Feedback and acknowledgments

Summary – Workshop (2019):

1) Presentation and consent for participation
2) Survey application
3) General exposition of the PLANEJEEE Project
4) Introduction of participants
5) Division in the focus groups:
6) Provision of the underlining guidance: mappings and questions in general
   - *Do the citizens have any responsibility for the management of extreme events?*
   - *How do citizens can participate in the elaboration of legislations for the reduction of extreme events in the city?*
   - *What are the main challenges for the implementation of FR mitigation solutions in the city?*
   - *How can the citizens contribute with the implementation and maintenance of risk mitigation solutions in the city?*
7) Discussion and elaboration of a recommendations for each case (I to IV):
   - *Main challenges for FRR*
   - *Main suggestions for FRR*
8) Discussions with the main group
9) Next stages and future collaborations
10) Summary and closing

Figure B2: Flood vulnerable cases discussed in the workshop with stakeholders in 2019. Cases I to IV refers to different neighbourhoods of the city, shown in photos a) to d).

(a) Case I: Conceição.

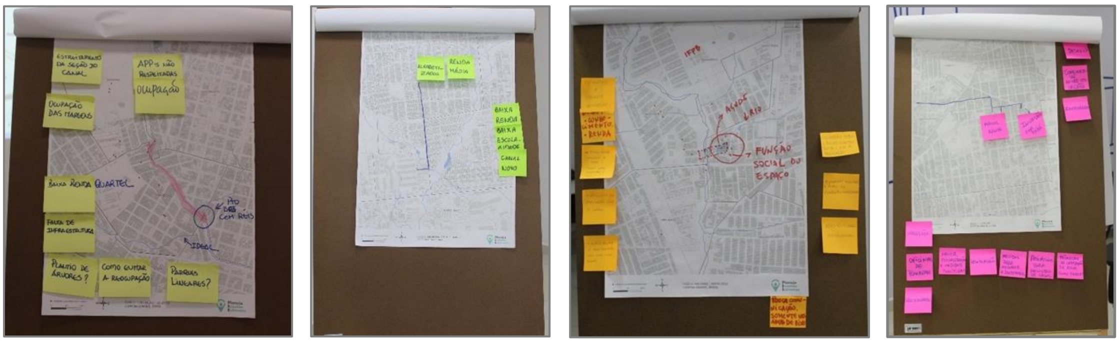
(b) Case II: Liberdade.

(c) Case III: Jardim Paulistano/Tambor.

(d) Case IV: Bodocongó/Santa Cruz.

Figure B3: PLANEJEEE Project (2019): participants of the workshop with stakeholders and PLANEJEEE team.

Figure B4: PLANEJEEE Project (2019): summary of stakeholders' discussions and findings in the division of vulnerable cases (cases I to IV).



Summary – Workshop with policymakers (2021):

1) Goals of the integrated framework (i.e., NEEDS and ACTION phases)
2) Consent for participation
3) Previous activities
    a. Participatory approach in 2019 (summary)
    b. Engagement with residents
    c. Discussion with policymakers and local specialists
4) Summary of results:
    a. Societal challenges of Campina Grande
    b. Analysis of legislations
    c. Social, structural, and institutional vulnerabilities
    d. The mappings produced (hazard, vulnerability, and exposure)
    e. The effectiveness of sustainable solutions in a representative area
5) Discussion about the implementation of sustainable solutions in the city according to the definition of the social context, especially the vulnerabilities (from this point forward, each participant was invited to participate)
    a. Pilot area
    b. Awareness program with residents
    c. Master Plan revision
    d. Integration of urban and water resources management
    e. Collaboration with specialists, policymakers, and residents
6) Discussion about manners to disseminate the research
7) Discussion about future collaborations
8) Summary and closing

Figure B5: PLANEJEEE Project in 2021. Photos refer to the workshop and informal meetings with stakeholders.

Appendix C:

Article 02: Place-Based Citizen Science for Assessing Risk Perception and Coping Capacity of Households Affected by Multiple Hazards.

Table C1 – Details of the questions to analyse risk perception and coping capacity.

RISK PERCEPTION
Cognitive
Awareness (A): How do you classify the severity of the floods and water shortage?
Worry (W): How likely is flooding and water shortage going to occur within the next ten years?
Behavioural
Preparedness (P): How likely do you receive warnings before the disasters?
Knowledge (K): Do you think you can handle disasters better with adaptation measures in your home?
COPING CAPACITY
Adaptation
Responsiveness (R): Which of the following measures would you use in your home to prevent flooding and water shortage?
Adaptive measures (A.M.): Would you make any investment in your home to reduce the risk of flooding and water shortage?
Permanent measures (P.M.) If you had a chance to move home because of flooding or water shortage, would you?

Table C2 – Influence of social factors in risk perception and coping capacity.

	Key indicator	Flooding		Water shortage	
		Social factor with significant influence	**p-value**	**Social factor with significant influence**	**p-value**
RP	Awareness	Direct experience	0.000	Direct experience	0.000
		Indirect experience	0.000	Income	0.041
		House ownership	0.028	Age	0.048
		Hazard proximity	0.037		
	Worry	Indirect experience	0.001	Direct experience	0.001
		Hazard proximity	0.042		
	Preparedness	-	*Non-significant*	-	*Non-significant*
	Knowledge	-	*Non-significant*	-	*Non-significant*
CC	Adapt. measures taken (responsiveness)	House ownership	0.003	-	*Non-significant*
		Age	0.009		
		Direct experience	0.000		
	Adapt. measures (future)	Management trust	0.010	-	*Non-significant*
	Perm. measures (future)	Education	0.022	Age	0.05

Influence (p<0.05): Wilcoxon Z and Mann Whitney U tests.

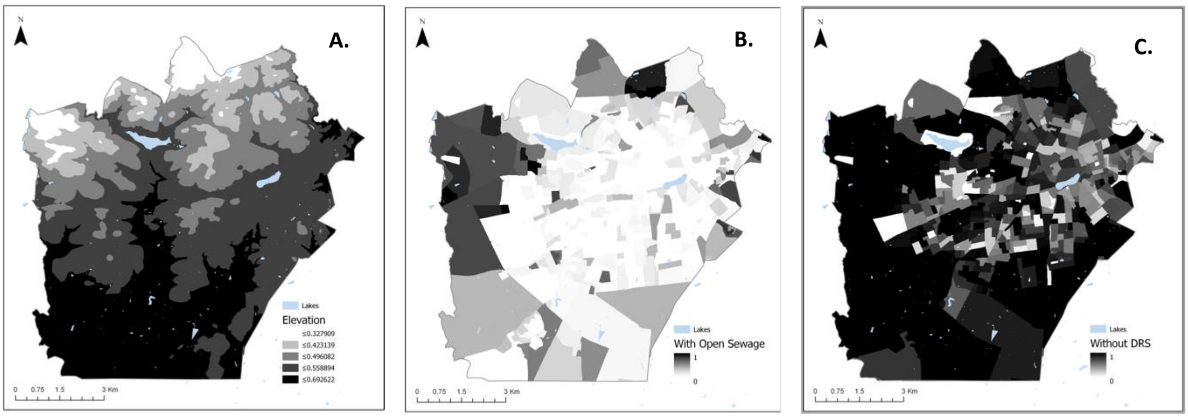
Appendix D:

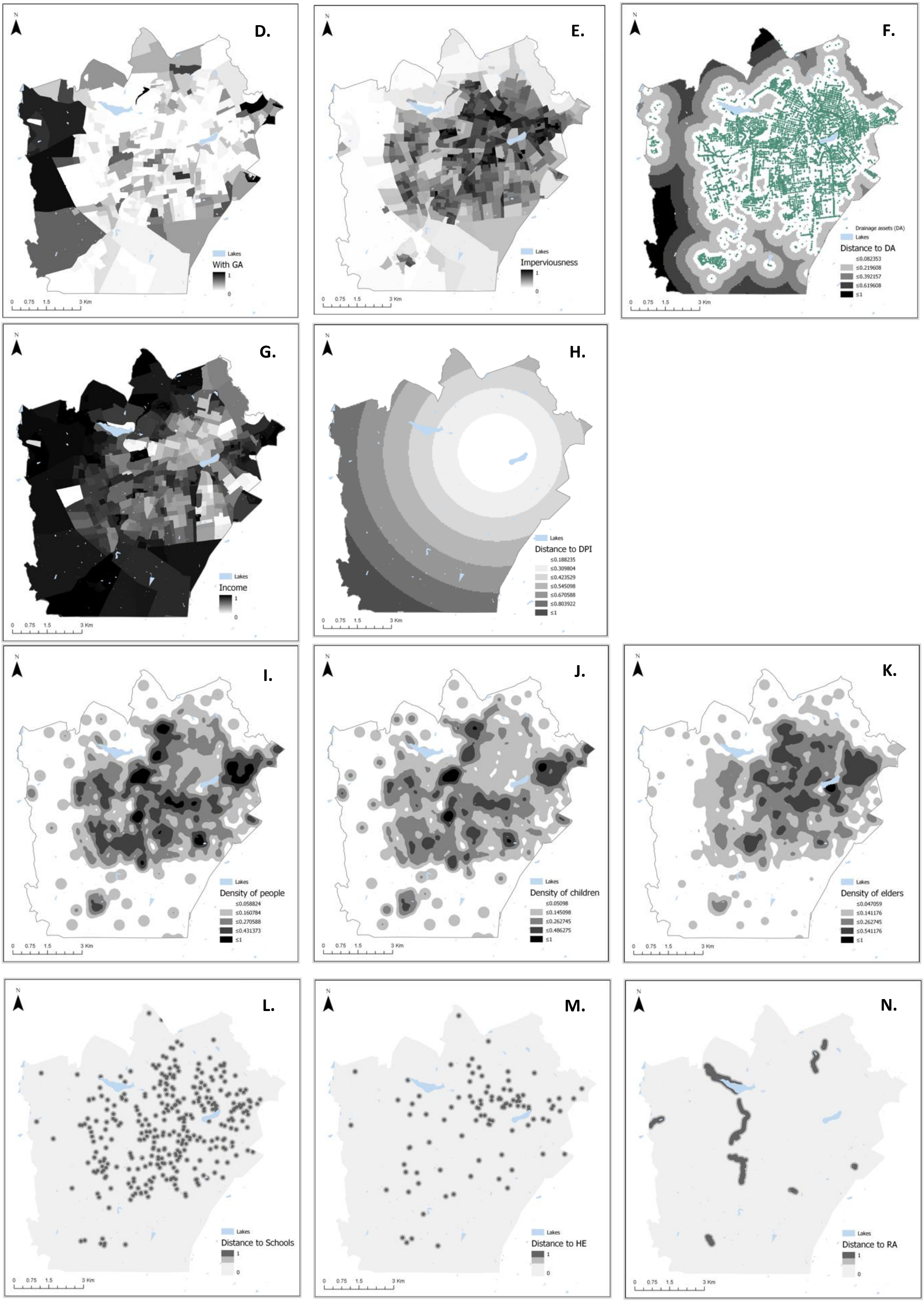
Article 03: An integrated socio-environmental framework for mapping hazard-specific vulnerability and exposure in urban areas.

Table D1 - Summary of challenges for flooding management discussed in the PLANEJEEE Project (To Plan Extreme Events).

Challenges	Quantitative - Surveys	Qualitative - Workshop
Location	Buildings in risk areas Problems with the design and maintenance of drainage network	Buildings in risk areas Illegal properties Buildings near to channels
Residents	Low income of residents Presence of children and elders	Low income of residents Lack of knowledge and awareness of the population Low flexibility of population The social link between residents and the place
Legislation	Increase of urbanisation There are laws, but they are neglected and not implemented	Lack of inspection by authorities Uncertainty of legislation application
Management	Lack of appropriate risk communication	Lack of appropriate risk communication Lack of public participation Lack of communication between stakeholders Lack of monetary incentives
Data		Lack of adequate data

Figure D1 - Standardised indicators of vulnerability and exposure mappings: a) Elevation, b) With Open Sewage, c) Without Drainage System, d) With Garbage Accumulated, e) Imperviousness, f) Distance to Drainage Assets, g) Income, h) Distance to Disaster Prevention Institutions, i) Density of people, j) Density of children, k) Density of elders, l) Distance to schools, m) Distance to health establishments and, n) Distance to risk areas.




D.
Lakes
With GA
1
0
0 0.75 1.5 3 Km
E.
Lakes
Imperviousness
1
0
F.
Drainage assets (DA)
Lakes
Distance to DA
≤0.082353
≤0.219608
≤0.392157
≤0.619608
≤1
G.
Lakes
Income
1
0
H.
Lakes
Distance to DPI
≤0.188235
≤0.309804
≤0.423529
≤0.545098
≤0.670588
≤0.803922
≤1
I.
Lakes
Density of people
≤0.058824
≤0.160784
≤0.270588
≤0.431373
≤1
J.
Lakes
Density of children
≤0.05098
≤0.145098
≤0.262745
≤0.486275
≤1
K.
Lakes
Density of elders
≤0.047059
≤0.141176
≤0.262745
≤0.541176
≤1
L.
Lakes
Distance to Schools
1
0
M.
Lakes
Distance to HE
1
0
N.
Lakes
Distance to RA
1
0

Appendix E:

Article 04: Land-Use and Legislation-Based Methodology for the Implementation of Sustainable Drainage Systems in the Semi-Arid Region of Brazil

Figure E1. a) Percentage of runoff volume reductions with PP application in scenario 1, b) Percentage of runoff volume reductions with PP application in scenario 2, c) Percentage of runoff volume reductions with RG application in scenario 1, d) Percentage of runoff volume reductions with RG application in scenario 2.

Appendix F:

Article 05: Understanding NEEDS for ACTING: An integrated framework for planning Nature-Based Solutions in Brazil

Table F1 – Scenarios for the calibration and validation of the flooding model in CADDIES. "SC" refers to scenarios.

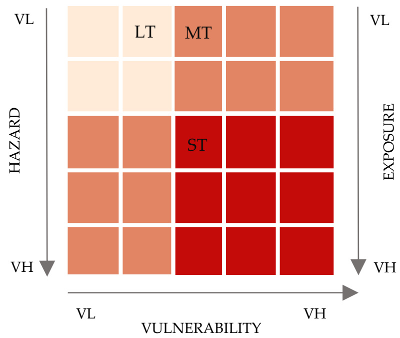
SC	Infiltration (mm/h)							Rain	Validation*
	Buildings	**Roads**	**Urban areas**	**Channels**	**Parks**	**Crossroads**	**Green areas**		**Percentage (%)**
1	12	10	12	10	15	12	15	2020	52.38
2	10	10	12	10	20	12	20	2020	38.10
3	0	10	12	10	20	12	20	2020	42.86
4	10	10	15	10	30	15	30	2020	23.81
5	0	10	15	10	30	15	30	2020	0.00
6	0	10	15	10	25	15	25	2020	28.57
7	12	10	12	10	15	12	15	2011	66.67
8	10	10	12	10	20	12	20	2011	61.90
9	0	10	12	10	20	12	20	2011	66.67
10	10	10	15	10	30	15	30	2011	61.90
11	0	10	15	10	30	15	30	2011	61.90
12	0	10	15	10	25	15	25	2011	61.90
13	20	20	20	20	30	20	30	2020	28.57
14	30	30	30	30	40	30	40	2020	0.00
15	20	10	20	10	50	20	50	2020	0.00
16	20	20	20	20	30	20	30	2011	61.90
17	30	30	30	30	40	30	40	2011	57.14
18	40	40	40	40	50	40	50	2011	57.14
19	0	10	12	10	15	12	15	2020	52.38
20	5	15	10	15	18	10	18	2020	52.38
21	10	15	10	17	22	10	22	2020	38.10
22	0	10	12	10	15	12	15	2011	**71.43***
23	5	15	10	15	18	10	18	2011	66.67
24	10	15	10	17	22	10	22	2011	66.67

**The validation process was finalised when more than 70% of the points were confirmed*

Table F2– The classification of DR maps (i.e., hazards, vulnerability, resident's exposure, and critical infrastructure exposure) in ArcGIS (Pro) environment. The classification used natural breaks, quantile, and manual categorisation. Maps were validated accordingly (Alves et al 2021b).

	Very Low (VL)	**Low (L)**	**Moderate (M)**	**High (H)**	**Very High (VH)**
Flooding (CFS)	$\leq$ 0.15m	$\leq$ 0.30m	$\leq$ 0.60m	$\leq$ 1.0m	+ 1.0m
Flooding (FFS)	$\leq$ 0.15m	$\leq$ 0.30m	$\leq$ 0.60m	$\leq$ 1.0m	+ 1.0m
Flood Vulnerability	$\leq$ 0.107	$\leq$ 0.159	$\leq$ 0.246	$\leq$ 0.387	$\leq$ 0.620
Flood Exposure (CI)	$\leq$ 0.043	$\leq$ 0.126	$\leq$ 0.225	$\leq$ 0.348	$\leq$ 0.786
Flood Exposure (Res)	$\leq$ 0.043	$\leq$ 0.121	$\leq$ 0.241	$\leq$ 0.333	$\leq$ 0.739

Figure F1 – The description of the queries for mapping "areas in risk of disaster" or "hotspots". Each hotspot is briefly described in the different boxes. Colours indicates the level of impacts: "dark red" refer to urgent hotspots, "orange" to warning hotspot and "light beige" to caution hotspots. LT stands for long-term, MT



Short-term (urgent hotspots):

- Deep flooding affecting community, and/or
- Bad structure capacity affecting whole properties and communities, and/or
- Danger to life and infrastructure

Medium-term (warning hotspots):

- Deep and shallow flooding affecting parts of communities, and/or
- Mixed drainage capacity disrupting properties and communities, and/or
- Possible danger to life and infrastructure

Long-term (caution hotspots):

- Shallow flooding affecting parts of communities, and/or
- Better drainage structure in properties and communities, and/or
- Less danger to life and infrastructure

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