Water Science & Technology

Water Science & Technology Vol 85 No 4, 987 doi: 10.2166/wst.2021.513

Understanding the NEEDS for ACTING: An integrated framework for applying nature-based solutions in Brazil

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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.

Key words: multiple benefits, nature-based solutions, participatory approach, resilience, spatial analysis, vulnerability

HIGHLIGHTS

- The proposal of nature-based solutions (NBS) requires in-depth knowledge of the area's needs.
- The integration of spatial and participatory tools provides insights into risk reduction.
- NBS can generate social, environmental, and economic benefits simultaneously, but at different scales and rates.
- The analysis of current needs, multiple benefits and spatial justice is suggested for applying NBS in communities facing risks.

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 (Nesshover *et al.* 2017; Sahani *et al.* 2019; Kumar *et al.* 2020). 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 wellbeing 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 at a *broader* scale and beyond water-related hazards (Qin *et al.* 2013; Martin-Mikle *et al.* 2015; Ahmed *et al.* 2017; 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), among others.

This context will generate specific challenges that will need to be managed effectively to implement NBS (Raymond *et al.* 2017a, 2017b). The first barrier for applying NBS is based on the understanding that context affects performance directly since they are significantly influenced by hazard intensities (Qin *et al.* 2013), placement (Passeport *et al.* 2013; Ahmed *et al.* 2017), climate (Alves *et al.* 2020d), land use (Martin-Mikle *et al.* 2015) and social inequalities (Heckert & Rosan

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2018). This suggests there is no 'one-size-fits-all' approach that can be applied everywhere (Colléony & Shwartz 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 the sustainable solutions on a local scale. For example, Kuller *et al.* (2019) built the GIS-MCDA Spatial Suitability ANalysis TOol (SSANTO) for the application of WSUD solutions as a relationship between the current context and the spatial opportunities (i.e., land use) offered in Melbourne, 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 analyses the context and built environment to indicate the priority sites for BGI in the city of Newcastle (UK) (Dawson *et al.* 2020). Other tools can be seen in Colléony & Shwartz (2019), Cortinovis & Geneletti (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 & Fenner 2019; Vercruysse *et al.* 2019) have pointed how part of the literature analyses mitigation strategies without the full consideration of risk. Similarly, Albert *et al.* (2020) and Shah *et al.* (2020) suggest that 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). Integrating social and environmental aspects appears to be particularly important for Disaster Risk Reduction (DRR). The distribution of NBS might influence the generation of cascading effects or even differently affect people and create more inequalities (Hendricks & Van Zandt 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; Pappalardo *et al.* 2017; Heckert & Rosan 2018; Wen *et al.* 2020). However, La Rosa & Pappalardo (2020) highlight that approaches linking 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 (Raymond *et al.* 2017b; Debele *et al.* 2019; Kumar *et al.* 2020), focusing more on 'environmental' aspects. Others suggest deficits in managing trade-offs and synergies for obtaining multiple benefits (Colléony & Shwartz 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 & Geneletti (2020), however, the insights of NBS uptake in policy and planning are limited, and stakeholder perspectives are lacking from current research. Findings 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 demonstrates the fragility of the country's traditional and structural drainage systems (Jacob *et al.* 2019).

In that sense, this paper addresses those barriers by developing 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 into the *needs' definition*, and 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 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 follows. Firstly, the general elements of the NEEDS for ACTION framework are presented. After that, the specific aspects of the application are given 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.

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* (Climent-Gil *et al.* 2018; Albert *et al.* 2020). The tool is divided into six phases that combine spatial and participatory approaches (Figure 1).

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, whole 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 evaluates the *needs* (P1 to P3) for proposing *actions* (P4 to P6).

2.2. Defining the context and societal challenges

Phases 1 to 3 (Figure 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 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.

2.3. Mapping areas at risk of disasters

Disasters result from hazard, vulnerability, and exposure interactions (UNISDR 2021), creating risks in different regions (Equation (1)). Phase 3 (P3) assesses 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

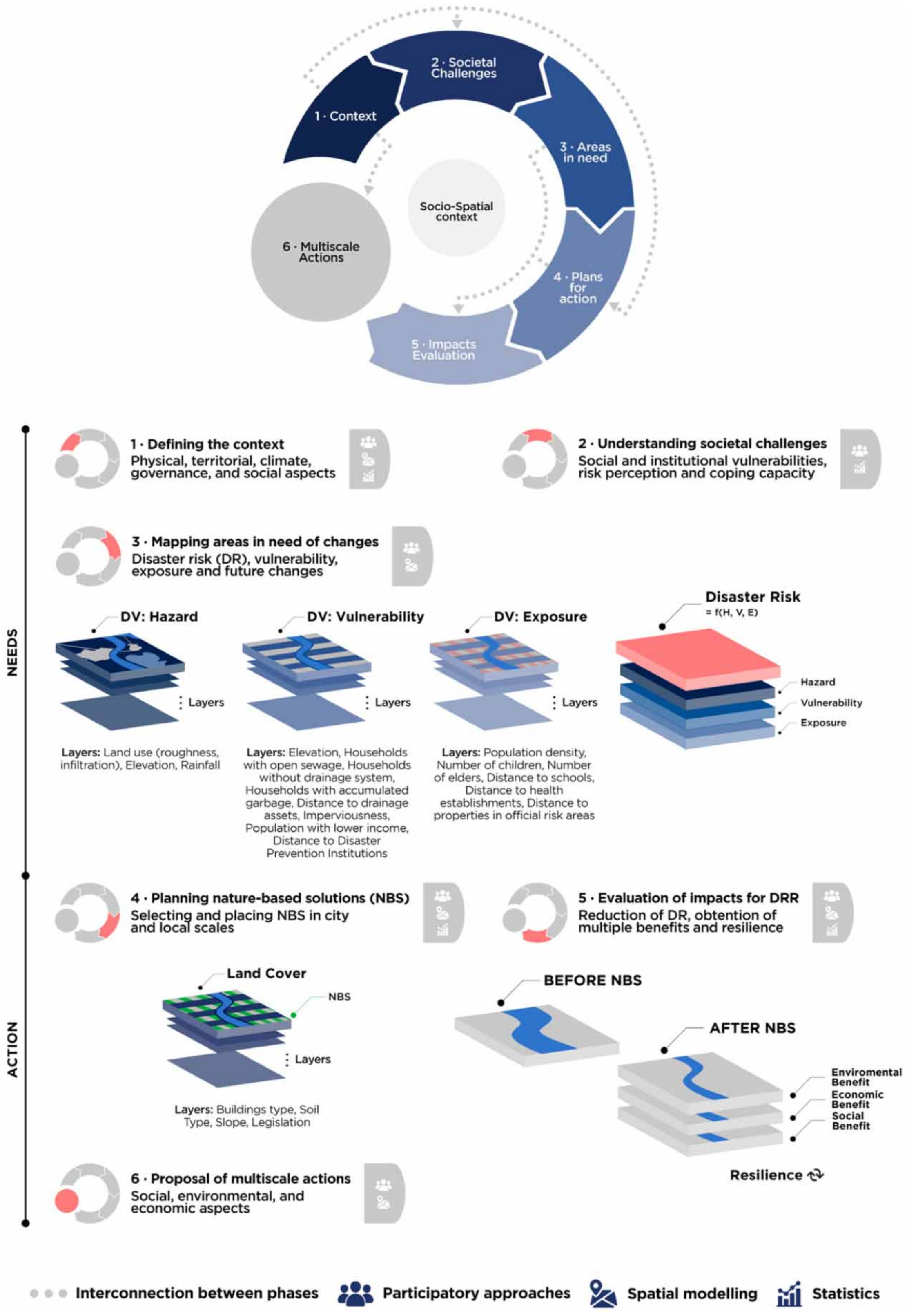


Figure 1 | The NEEDS for ACTION framework. Phases 1, 2, and 3 correspond to the understanding of the 'NEEDS' of the place, and phases 4, 5 and 6 refer to the planning of 'ACTIONs'. Each phase is analysed with a combination of spatial and participatory approaches. The 'layers' for analysing each phase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

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 1 are in the context of flooding.

Secondly, the DVs mappings are combined with the application of Equation (1) for mapping DR. Outputs of this phase are called 'hotspots', referred to as 'geographical areas with high vulnerability and exposure' (IPCC 2014) (Figure 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.

$$Disaster\ Risk\ (DR) = f(Hazard,\ Vulnerability,\ Exposure) \tag{1}$$

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 (2). Flood increase is a subtraction of the flooding after urbanisation ($FR_{\mathrm{Urb(future)}}$) with the flooding in the current situation ($FR_{\mathrm{Urb(now)}}$).

$$Flood\ increase = FR_{\mathrm{Urb(future)}} - FR_{\mathrm{Urb(now)}} \tag{2}$$

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' opinions (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 on 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 1). The evaluation is based on the concept of 'disaster resilience' (Cutter *et al.* 2008), covering 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 can 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 ($DR_{\mathrm{beforeNBS}}$) NBS implementation (Wang *et al.* 2019), whilst the number of recovered areas indicates the system is increasing its resilience after NBS use (Equation (3)).

$$Res = DR_{\mathrm{afterNBS}} - DR_{\mathrm{beforeNBS}} \tag{3}$$

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).

3. CASE STUDY: CAMPINA GRANDE, BRAZIL

Campina Grande is localised in the Northeast of Brazil, also called the Brazilian 'semiarid region' (Figure 2(a)). 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 the last available national census is from 2010, 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 its neighbourhoods (in number and boundaries limits), which can indicate more built-up surfaces, paved streets, and imperviousness (Figure 2(b)). In fact, beyond the neighbourhoods shown in Figure 2(b), two other neighbourhoods are being analysed by the city council for inclusion in the following months of 2021.

Due to the climate constraints of the semiarid region, Campina Grande faces the occurrence of constant events of drought (Del Grande *et al.* 2016; Cordão *et al.* 2020). 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 (Santos *et al.* 2017; Alves *et al.* 2018).

The city associates flooding and water shortage risk with existing social, physical, structural, and institutional vulnerabilities (Del Grande *et al.* 2016; 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.

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 1). The project had the objective to involve stakeholders in the definition of needs

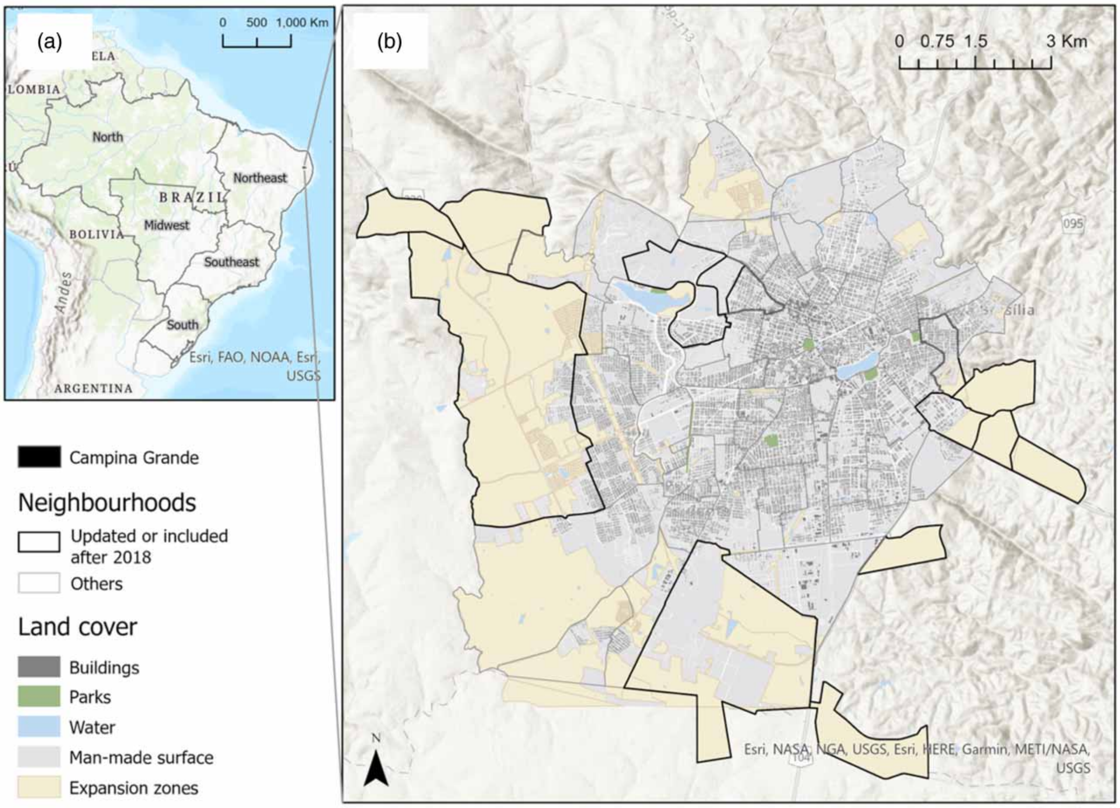


Figure 2 | The context of Campina Grande, Brazil. (a) Location in the Northeast region of Brazil, (b) city growth and land cover of the urban area.

and for planning actions for FRR, in a sense that it can increase the understanding of NBS and facilitate the application of solutions in real life (Lund 2015; Hardoy *et al.* 2019). 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, 2021)).
- In 2021, the project promoted several opportunities for defining an action plan to implement NBS on the 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).

3.2. GIS input for mapping of hazard, vulnerability, and exposure

From the FR definition, the mappings of hazards, vulnerability, and exposure are prerequisites for the definition of 'areas at risk of disaster' (i.e., phase 3, Figure 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 1.

3.2.1. 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 1 and Figure 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 2(b)). Land-use and DEM (Tsuyuguchi 2015) were inserted as 10×10 m 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).

Table 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	–	Chow (1959)
Streets	10	0.013	–	Arcement & Schneider (1989)
Man-made surface	12	0.025	–	McCuen (1989)
Expansion zone	12	0.040	–	Environment Agency (2013)
Green areas	15	0.100	–	Chow (1959)
Green roofs (GR)	12	0.060	–	Webber *et al.* (2019). Vamvakeridou-Lyroudia *et al.* (2020)
Permeable pavement (PP)	8 (+10)	0.015	–	Liu *et al.* (2018)
Rainwater harvesting (RWH)	–	–	20	Webber *et al.* (2019)
Green Areas (GA) with minimal vegetation	15	0.065	–	Liu *et al.* (2018), Wang *et al.* (2019)
Drainage System Improvement (DSI)	10 (+10)	0.020	–	Webber *et al.* (2019)

To ensure a greater consistency of the flood model, the calibration of the input data was made with 24 test 'scenarios' with 1 h 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., Supplementary Material, Table A1). 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 0.01 s 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 periods (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 & Verόl, 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.

3.2.2. 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, using 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.

3.2.3. 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 (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.

$$\mathit{Disaster\ Variable}\ (DV) = \sum_{j=1}^{n} w_j * f_j \tag{4}$$

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 is exemplified in Figure 1.

3.2.4. 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 was 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.* 2020b).
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 until at least 70% of the flood points were confirmed in the simulations. More details are discussed further in the results and Alves *et al.* (2020c).

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 1).

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 in 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.

3.3.1. Scenarios

The meetings with stakeholders in 2021 ($n = 33$) examined the appropriate scales for applying NBS. A summary of scenarios is seen in Table 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 cases 1 to 32, reflecting 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 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, permeable pavements are applied in the streets).

Alternative 1 refers to green roofs (GR) in buildings. GR are considered as extensive, with soil thickness from 30 to 150 mm (Webber *et al.* 2019). 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.* 2018). 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) (Liu *et al.* 2018). 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 recent years (Alves *et al.* 2020d). 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.

Table 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

The improvement of the drainage system (DSI) is also simulated even though it is not a green infrastructure. This was included in the PLANEJEEE Project since stakeholders highlighted many issues of the drainage system in the city (Alves *et al.* 2021). Since the city council has not provided the complete design of the drainage system, we represented the measures by increasing 10 mm/h of infiltration in the streets of the city (i.e., n final = 10 + 10) (Webber *et al.* 2019) 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 1) (Chow 1959; Arcement & Schneider 1989). For proposing rainwater capture tanks (RWH), local merchants of water tanks were surveyed, and we opted to use a 2000 L capacity. The contributing area is considered as buildings of 100 m^2. The rainfall capture of these measures is obtained by dividing the total storage volume by the size of the area situated (i.e., more details of this approach can be seen in Webber *et al.* (2019)) (Table 1).

NBS were also combined with GR and RWH in alternative 6, and with 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 2).

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 (Eggermont *et al.* 2015; Raymond *et al.* 2017a, 2017b; O'Donnell *et al.* 2018; Albert *et al.* 2020; Ruangpan *et al.* 2020). Participants could opt with an '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 (3). 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.

4. RESULTS

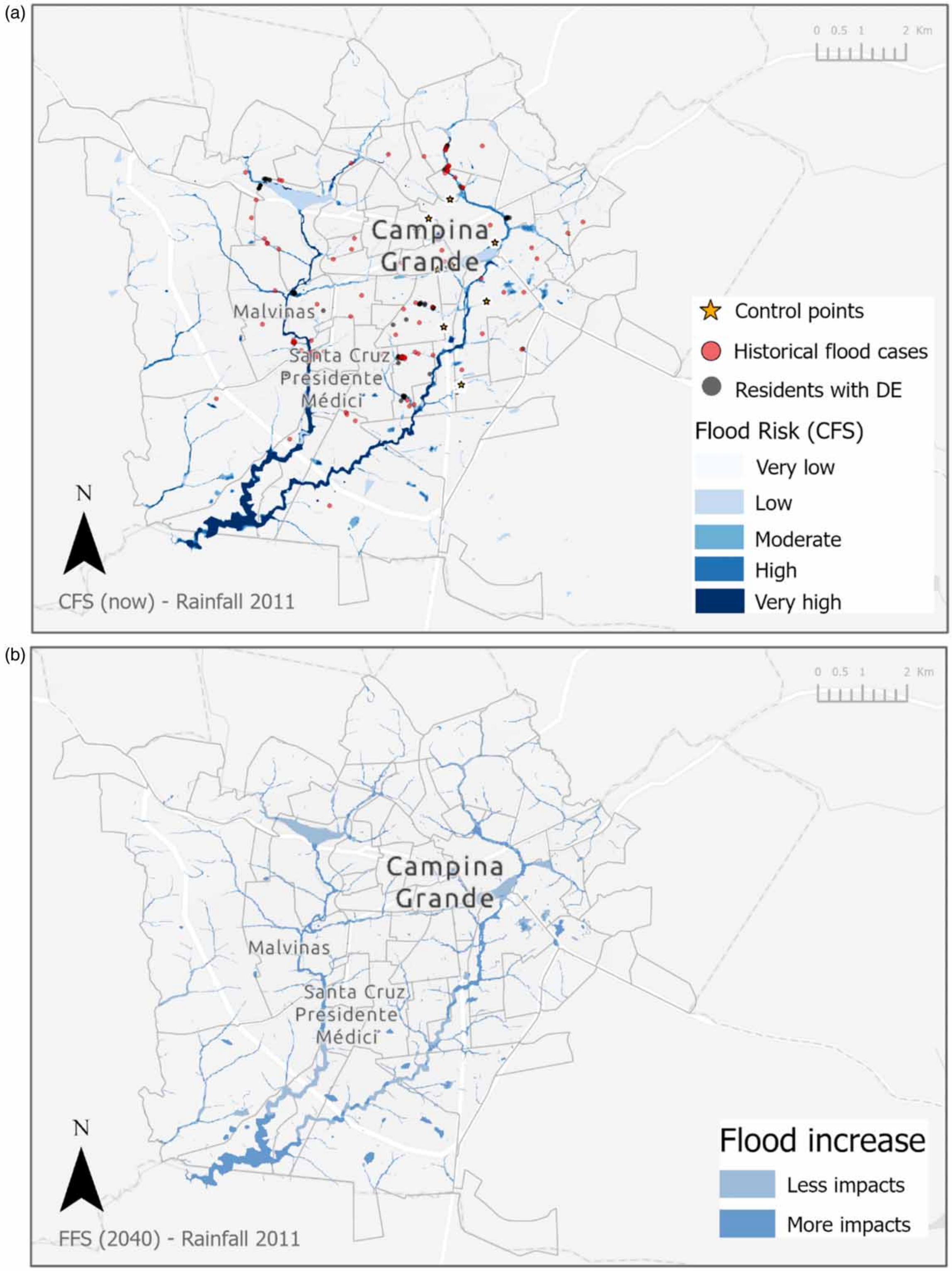
The results cover the NEEDS and ACTION phases (Figure 1) by answering: (1) *What* are the city's needs? (2) *What* are the benefits preferred by the stakeholders? (3) *Which* benefits can be acquired with NBS?

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 3(a) shows the final modelling of the current flooding situation (CFS) of Campina Grande with CADDIES model. 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 Supplementary Material, Table A1). Figure 3(a) 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. Of 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 3(a)). 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.* 2020b). 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 3(a)).

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 the other 15 severe control-flood



Esri, HERE, Garmin, METI/NASA, USGS

Figure 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 2011.

points of the city was compared separately with the 24 CADDIES scenarios (Figure 3(a)). This was made to confirm if these severe flood 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. Complete results of the verification of flood points are detailed in Supplementary Material, Table A1.

Despite the model uncertainties relating to the input data, especially the lack of detailed data of the drainage system, the results suggest the proposed 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.

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 3(b)). FR outputs from after and before urbanisation were analysed with Equation (2), which shows that in 2040 there will be an increment of flooding in approximately 52% of the pixels (Figure 3(b)). 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 1 with the '*Cell Statistics*' tool in ArcGIS (Pro) (ESRI). Figure 4 shows which places need more attention of management, named here as 'hotspots'. Mapping hotspots allow visualising aspects that makes 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.

Box 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 the Supplementary Material).*

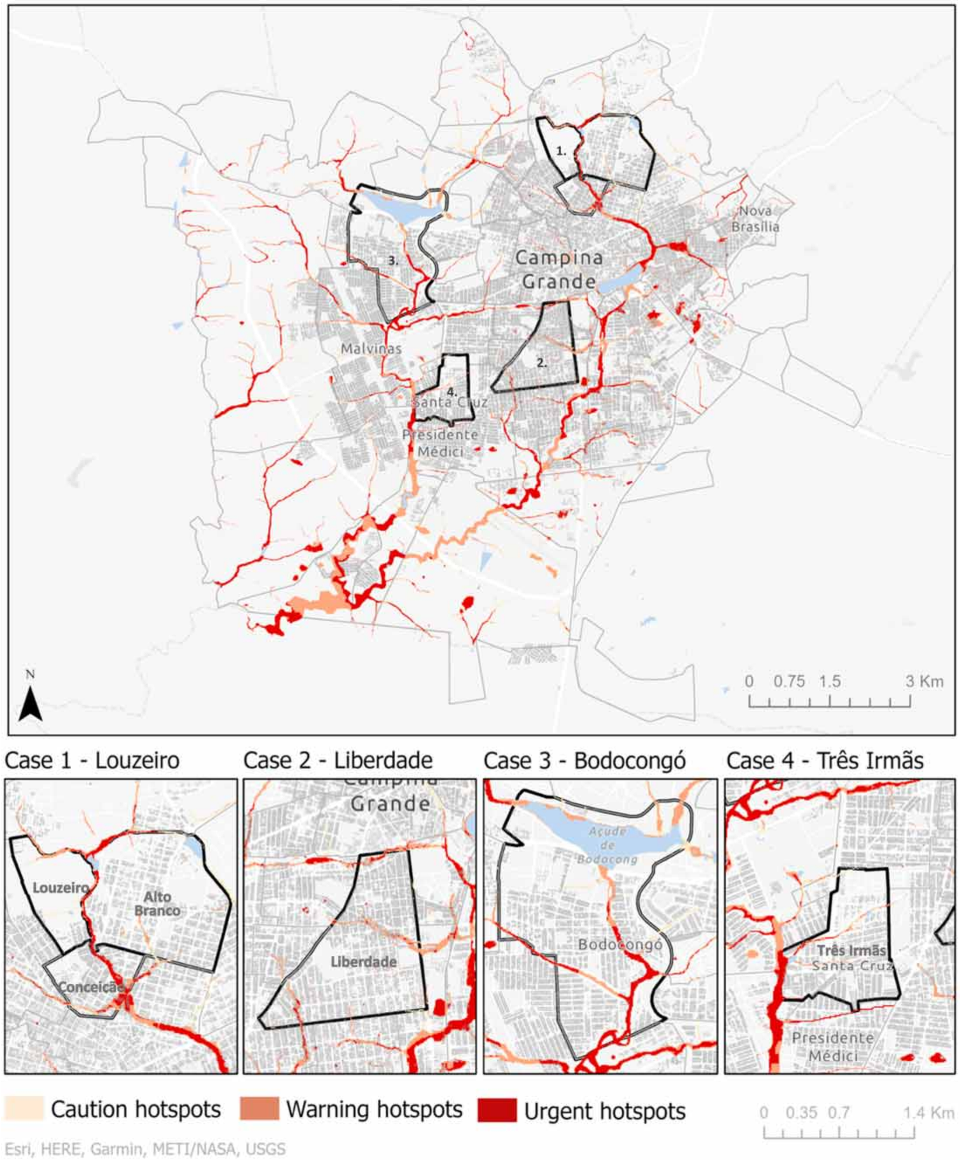


Figure 4 | Spatial analysis of interactions between hazard (flooding), vulnerability and exposure that generate DR. The hotspots represent areas that, according to level of impacts created with DR, need more attention in stormwater management. Four case studies are highlighted: (1) Louzeiro, (2) Liberdade,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

4.2. What benefits can be obtained with NBS?

4.2.1. 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 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 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 rationing zones (Del Grande *et al.* 2016; Cordão *et al.* 2020). Each zone has water available on different days, making the entire city exposed to the hazard

Table 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	*Wellbeing*	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

(Del Grande *et al.* 2016). The context is different from FR since only parts of the city are exposed to 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)).

The benefit 'access to nature' is also ranked as first 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 second to fourth ranking positions. The 'reduction of flooding zones' occupies the fifth 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 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 (O'Donnell *et al.* 2017; Bissonnette *et al.* 2018; 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, it 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.* 2017a, 2017b). 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.

4.2.2. 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 0.37 m, 0.64 m and 0.80 m, respectively. This result shows an increasing flood depth when comparing the least to the most intense rainfall events (Table 4). NBS alternatives were applied separately and then combined to evaluate the MDs reduction in each rainfall event, totalling 24 simulations. Table 4 shows that NBS are more effective for the 10-year rainfall event, which agrees with other studies that affirm 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 2). When combining GR and RWH (alternative 6), the MD reduction arises for 18.92%, which is a good option due to the city's simultaneous occurrence of water shortage hazards. 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 compared to the other alternatives of NBS in the same rainfall event. For example, in RT 25 and RT 100, GA have the best efficiency after alternative 7 (second 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 4, flood depth >1 m) was calculated by subtracting the pixels within the VH flood risk after and before the use of NBS (i.e., Equation (2)). Table 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

Table 4 | Summary of environmental, social, and economic benefits obtained with the implementation of NBS. 'SC' refers to scenarios and 'DRes' for 'disaster resilience'

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

33% of the VH-pixels in the RT 10-year, RT 25-year, and RT 100-year, respectively (Table 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) (ESRI) analysed the flood zone situation of residential, commercial, and institutional buildings of the urban area (Figure 4). Table 4 expresses the reduction of properties with each alternative and rainfall event. 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 to the residents located in the critical flood areas, being particularly important since the reduction of flood depth will not always 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 estimated 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 4). The metric demonstrates that when NBS are applied in combination (alternatives 6 and 7), the resilience increases in each return period investigated (Table 4). When applied alone, GA will provide more resilience, followed by GR, RWH, DSI, and PP – in this order (Table 4).

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 & Alexander 2019). The city's needs are characterised in Figures 3(a), 3(b), and 4.

Figure 3(a) shows that Campina Grande currently faces FR in different parts of the city, especially near channels. When analysing the FR in the future, Figure 3(b) shows how urbanisation will lead to more risk, in which approximately 50% of the flooded pixels will have a flood increase. Additionally, the mapping in Figure 4 represents how the interaction between hazard, vulnerability, and exposure generates the risk and affects the 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 an 'equitable' manner in the city (Heckert & Rosan 2018). FR represents a process inherently unfair since water occupies very different spaces in cities after flooding events (Johnson *et al.* 2007; La Rosa & Pappalardo 2020). 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 & Van Zandt 2021), and should have access to the same level of services in the urban environment (La Rosa & Pappalardo 2020). In this sense, the mappings produced in Figures 3 and 4 can evaluate how the intersection between flood (hazard), vulnerability, and exposure will impact the city on a local scale in the current and future situations.

For example, case 1 of Figure 4 refers to three neighbourhoods (*'Louzeiro', 'Alto Branco'* and *'Conceição')* that are in the upper part of Campina Grande (Figure 4). With the 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). Still, even though some residents may 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, the CPRM monitors only part of the flooded zones 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 lets us see how risk impacts must be evaluated to understand the area and its 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 that multiple benefits can be obtained using NBS; however, these are seen in different scales and rates (Table 4). NBS's effectiveness will vary according to the land-use area and rainfall return periods (Majidi *et al.* 2019), with higher 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 for urbanised areas (Miguez *et al.* 2015; Versini *et al.* 2016; Lourenço *et al.* 2020).

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'Donnell *et al.* (2018) and Morgan & Fenner (2019). This can be seen when analysing the different NBS alternatives, in which strategies will not always provide multiple benefits. Table 4 and Figure 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 & Rosan 2018; La Rosa & Pappalardo 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 & Pappalardo 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.* 2017a, 2017b), and the resilience (Ashley *et al.* 2020) which can be 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 in 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 a thorough analysis 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, 2020d, 2021).

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.

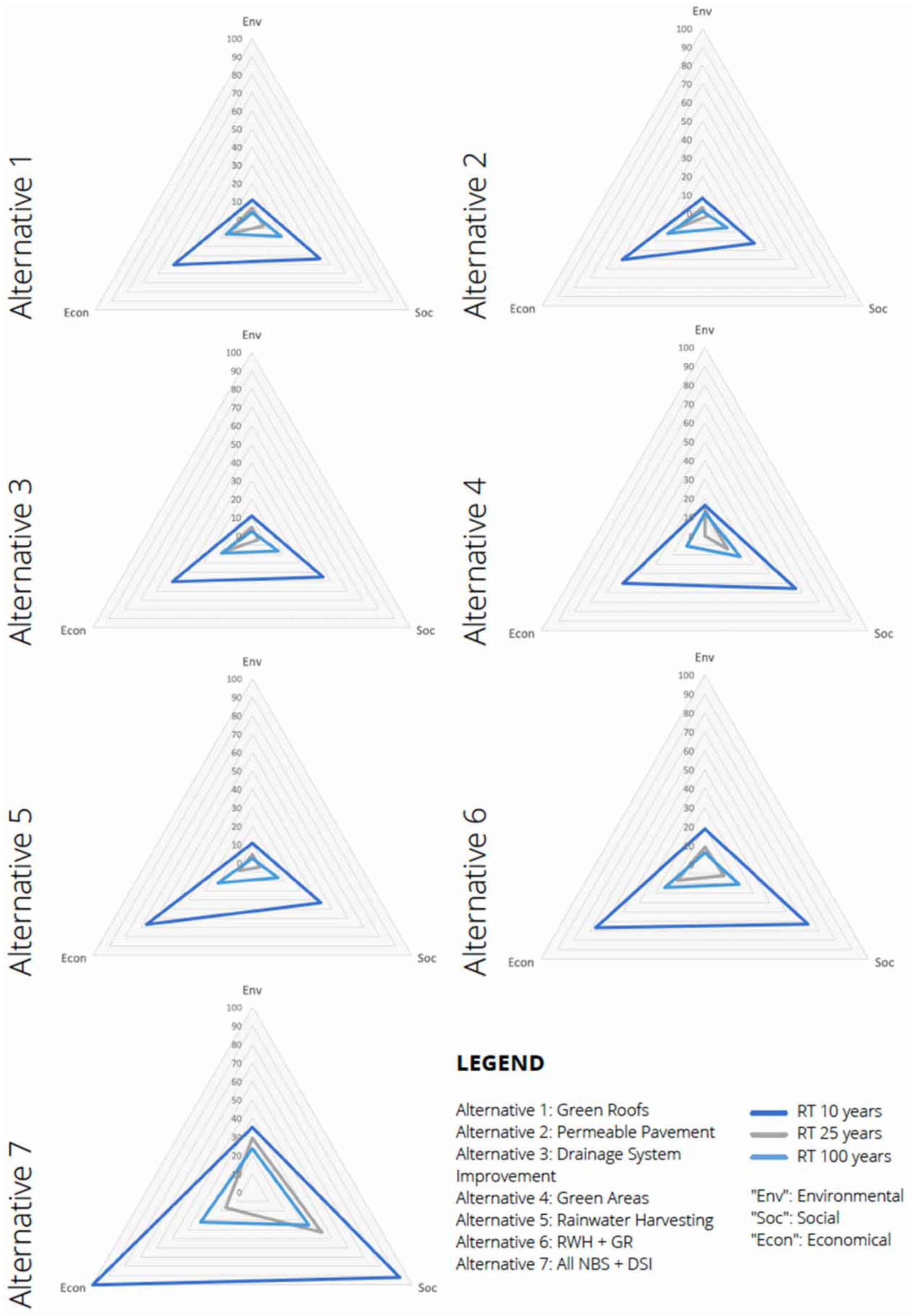


Figure 5 | The multiple actions diagram for DRR: Alternatives 1 to 7 are organised in quantitative approach highlighting the environmental, social, and economic benefits in each of the 10, 25 and 100 years return periods ('*Env*' refers to environmental, '*Soc*' to social and '*Econ*' to economic benefits).

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). Since PMCG has not provided such detailed data, it was not possible to insert the dataset in CADDIES. Still, 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, 2019; Webber *et al.* 2019) 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 overestimated 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 (Ecosystem-based 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 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 & Rosan 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 & Padawangi 2017).

Finally, next studies of the integrated framework can also include the analysis of the adverse cascade effects with NBS implementation, as it is considered a challenge of current proposals of solutions for DRR (Pescaroli & Alexander 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 & Fenner (2019)).

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 & Shwartz 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 answers 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 (Dagenais *et al.* 2016; Kuller *et al.* 2017; Bissonnette *et al.* 2018; Albert *et al.* 2020).

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, and societal challenges prevalent in developing countries (de Loyola Hummell *et al.* 2016; Khan *et al.* 2018; dos Santos *et al.* 2021). In this sense, the findings show the spatial distribution of flooding in 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 3(a) and 3(b)). 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' targets for concentrating efforts for risk mitigation (Figure 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 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 offers 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.

ACKNOWLEDGEMENTS

The authors are grateful for the support of the Federal University of Campina Grande, Hydraulics Laboratory II, and the collaboration of Campina Grande City Council and Civil Defence in sharing the data. We thank all the stakeholders for collaborating in the participatory approach.

FUNDING

Authors were supported by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (Capes) – Finance Code 001 (Grant No 88881.129673/2016-01). The project has also received some funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 778120 (Geores Project).

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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First received 20 September 2021; accepted in revised form 15 November 2021. Available online 29 November 2021