An integrated socio-environmental framework for mapping hazard-specific vulnerability and exposure in urban areas

Priscila Barros Ramalho Alves, Slobodan Djordjević & Akbar A. Javadi

Taylor & Francis
Taylor & Francis Group

RESEARCH ARTICLE

OPEN ACCESS   Check for updates

An integrated socio-environmental framework for mapping hazard-specific vulnerability and exposure in urban areas

Priscila Barros Ramalho Alves [ID], Slobodan Djordjević [ID] and Akbar A. Javadi [ID]

Centre for Water Systems, University of Exeter, Exeter, UK

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 hazard 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.

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. 2016).

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, Shepherd, and Gaither 2015).

There is a significant interest in the concept of vulnerability in the literature. For Cutter, Boruff, and Shirley (2003), the concept of place vulnerabilities integrates biophysical and social vulnerabilities (i.e. social inequalities). According to Pescaroli and Alexander (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 2012b). 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 and Ravindranath 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 and Ravindranath 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, Schinke, and Naumann 2014), many applications still consider vulnerability only as the impacts of a disaster (Yang et al. 2018; Weis et al. 2016; Kc, Shepherd, and Gaither 2015) which can confuse the policy-makers and reduce the applicability in real cases.

1.1. 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

CONTACT Priscila Barros Ramalho Alves ✉ pr327@exeter.ac.uk

different social groups, the vulnerability also varies over time and space, which provide barriers for the assessment in different areas (Pescaroli and Alexander 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 and Rinner 2015). The choice of indicators and the quality of available data requires a deep understanding of the complex system (Frigerio et al. 2016). 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 and Yazdandoost 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 and Chung 2017) with consensus agreement (de Brito, Evers, and Höllermann 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, Boruff, and Shirley 2003). We suggest that vulnerability and exposure indicators must represent hazard-specific attributes (Sharma and Ravindranath 2019), expressing the strengths and weaknesses on a temporal and spatial scale but with both objective and subjective methods for assessment. Specifically, our paper aims to answer two specific questions:

(i) *How can social and environmental tools be integrated towards vulnerability and exposure mapping assessments?*
(ii) *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.

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 1(a)), 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 10 'risk areas' across the city, which refers not only to flooding but also to landslides and other disasters (Figure 1(b)). However, flooding cases are seen spatially dispersed in different areas of the city (Figure 1(b)), not only in the 'risk areas', which suggests there is a need for developing more accurate information for effective management (Alves et al. 2018). The middle-sized city (IBGE 2018) lacks in having sufficient flooding preparedness strategies for the population (Alves et al. 2020; Santos, Rufino, and Filho 2017) and has a weak integration of urban planning and water resources management (de Araújo Grangeiro, Ribeiro, and de Miranda 2019).

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 (IPCC 2012b) (Figure 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 and Alexander 2019). 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 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 (2012a), *exposure* refers to the
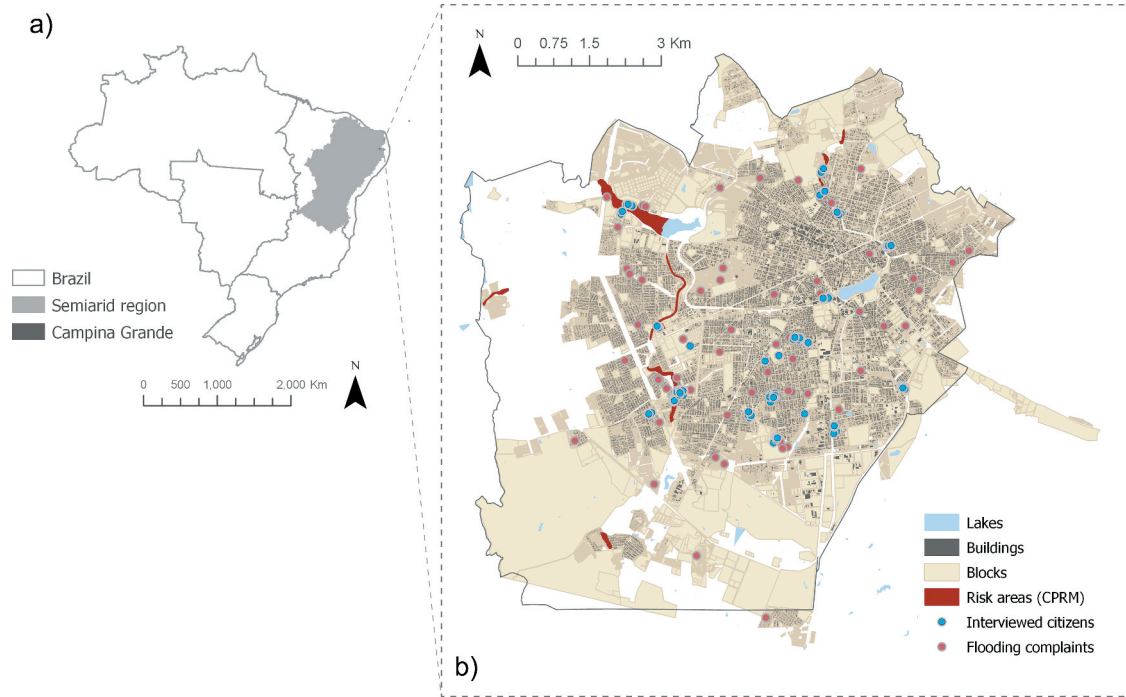
Figure 1. Location of Campina Grande – Brazil: (a) Brazilian Semiarid; (b) Spatialisation of official risk areas (CPRM), flooding complaints (Civil Defence) and interviewed residents (PLANEJEEE Project).
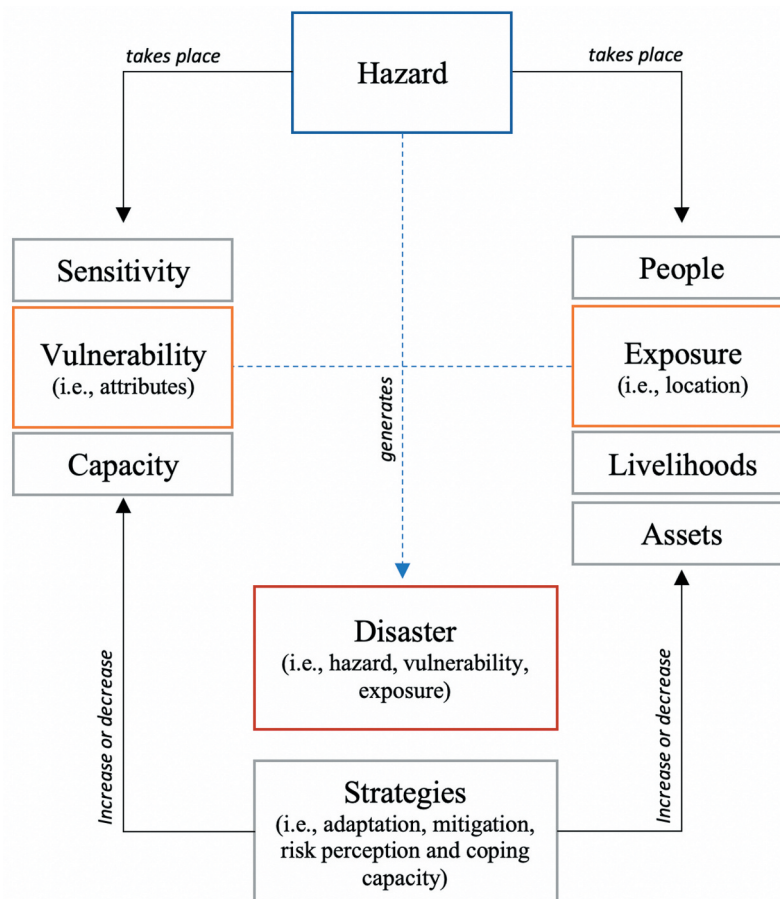

Figure 2. Conceptualisation of vulnerability and exposure as 'hazard-specific' components.

presence of a vulnerable system at a *location* that could be adversely affected and can be represented by people, livelihoods, and assets.

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 and Ravindranath 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. 2016). 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 2). Therefore, the concept of vulnerability is a starting situation of the affected population before any interventions are undertaken (Climent-Gil, Aledo, and Vallejos-Romero 2018), which means that mapping vulnerabilities is a prerequisite 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, Kuhlicke, and Meyer (2011)), we merged the definition of each disaster variable (Figure 2) in a socio-environmental framework detailed in Figure 3. The methodology reflects a combination of social and environmental phases (SS and ES), which are detailed below.

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 to 2011. These points (Figure 1(b)) 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
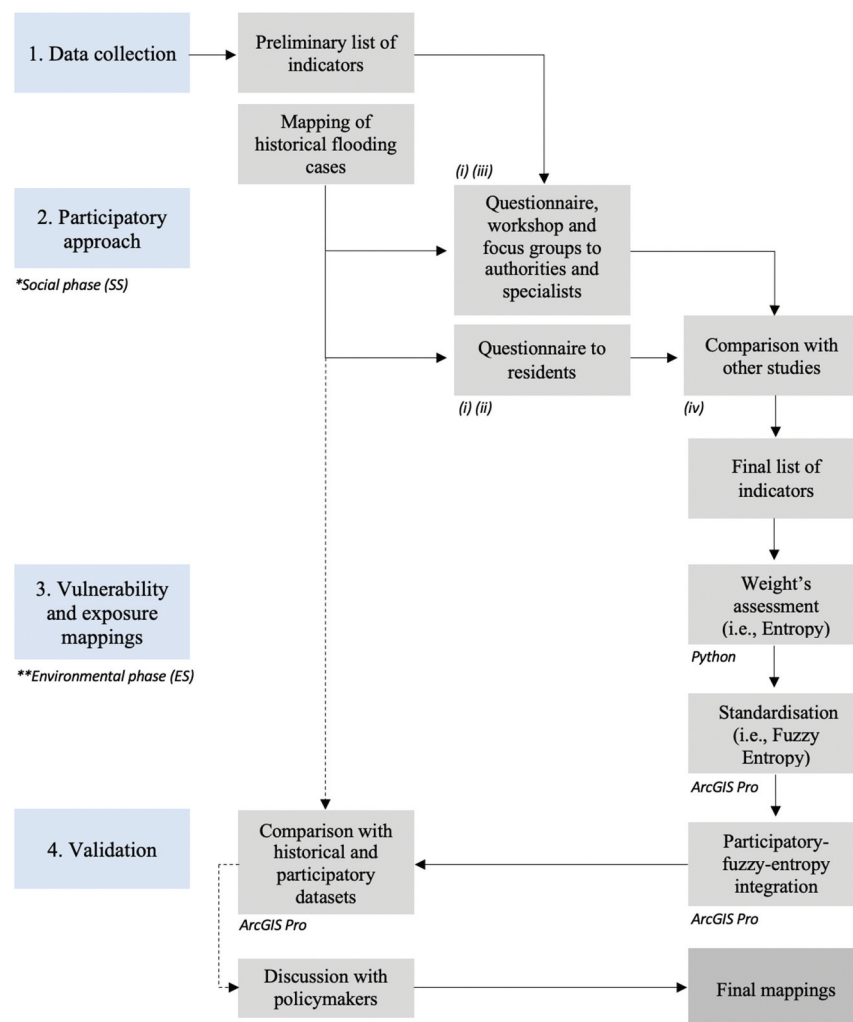

Figure 3. The integrated methodology for mapping vulnerability and exposure with a combination of social (SS) and environmental sciences (ES).

for preparing a preliminary list of vulnerability and exposure indicators.

3.2. The participatory approach

Subsequently, we developed a place-based citizen science project, called PLANEJEEE Project: To Plan Extreme Events ('*Planeje Eventos Extremos*' in Portuguese) from May to June of 2019 with specialists, policymakers, and citizens. The participatory approach was built upon the review of other citizen science studies (Ajibade and McBean 2014; Eitzel et al. 2017; Duan et al. 2018), 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 and Feldman 2019). Details of the PLANEJEEE Project are detailed below.

Citizens were selected based on 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 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 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, Gencer, and Winograd 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 1). The options encompassed four main categories of vulnerability suggested by Ghajari et al. (2017) and Pescaroli and Alexander (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 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 answers. 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

Table 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
Households 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 – Interventions 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 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'.

'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 and 5 Likert scales) and SD 0.72.

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 discussed the importance of other indicators like elevation and damages of important assets in case of flooding, which were included in the list of indicators. A summary of discussions is expressed in the Table X1 in the supplementary materials.

Lastly, the final choice of indicators took into consideration studies in similar fields (Table 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 damage if they are exposed to the hazard. Table 2 provides a brief explanation of each indicator.

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 and Yazdandoost 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 10 m × 10 m 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:

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \qquad (1)$$

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

$$E_j = -k * \sum_{i=1}^{m} r_{ij} * \ln r_{ij} \qquad (2)$$

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

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

$$d_j = 1 - E_j \qquad (3)$$

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

$$w_j = \frac{d_j}{\sum_{i=1}^{n} d_j} \qquad (4)$$

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 3.

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 and Feizizadeh 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 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 1(a–n) in the Supplementary Materials). 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:

$$Disaster\ Variable\ (DV) = \sum_{j=1}^{n} w_j * f_j \qquad (5)$$

where DV is the disaster variable (vulnerability and exposure) of flooding hazard in each pixel, w_j stands for the weight of each criterion and f_j for the fuzzy standardised criterion. The final maps are presented in Figure 4(a–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'.
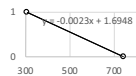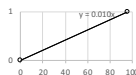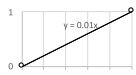
4. Results
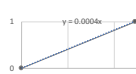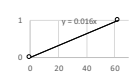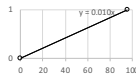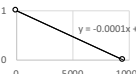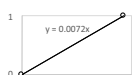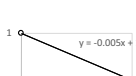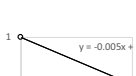
The flood vulnerability of Campina Grande is shown in Figure 4 (c). Overall, the final map reveals areas that are more susceptible to flood, according to a combination of physical, social, structural, environmental, and institutional vulnerabilities. The mapping expresses the different levels of flood 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 3). In summary, the 'very high' and 'high' vulnerabilities correspond to 15.80% and 25% of the city area, respectively. The

Table 2. Summary of final list of indicators to each disaster variable (sensitivity, capacity, and exposure).

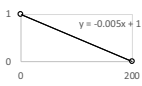| Disaster variables	Indicator	Criterion	Description	Literature citation
Sensitivity (weaknesses)	Physical (Phys. Vuln)	Elevation (m)	The higher elevation indicates the lesser risk of flooding	(Caldas et al. 2018; Ouma and Tateishi 2014)
Sensitivity (weaknesses)	Household characteristics (St. Vuln)	With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

'Phys. Vuln' stands for 'Physical Vulnerability', 'St. Vuln' stands for 'Structural Vulnerability', 'S. Vuln' to 'Social Vulnerability' and 'Inst. Vuln' for 'Institutional Vulnerability'.

Table 3. Description of the linear fuzzy functions and entropy weights to each criterion.

Criterion	Fuzzy linear functions	Weights	Sources
a) Elevation (m)	$y = -0.0023x + 1.6948$ (300, 500, 700)	−0.0013	Tsuyuguchi (2015)
b) With open sewage (%)	$y = 0.010x$ (0, 20, 40, 60, 80, 100)	+0.1513	IBGE (2010)
c) Without drainage system (%)	$y = 0.01x$ (0, 20, 40, 60, 80, 100)	+0.0146	IBGE (2010)
d) With accumulated garbage (%)	$y = 0.011x$ (0, 20, 40, 60, 80, 100)	+0.2402	IBGE (2010)
e) Distance to drainage assets (nodes) (m)	$y = 0.0004x$ (0, 1000, 2000)	+0.2487	Provided by the city council
f) Imperviousness (%)	$y = 0.016x$ (0, 20, 40, 60)	+0.2861	City Council
g) Lower income (%)	$y = 0.010x$ (0, 20, 40, 60, 80, 100)	+0.0165	IBGE (2010)
h) Distance to Disaster Prevention Institutions (m)	$y = -0.0001x + 1$ (0, 5000, 10000)	−0.0422	City Council
i) Population density (%)	$y = 0.0072x$ (0, 150)	+0.0200	IBGE (2010)
j) Number of children (%)	$y = 0.001x$ (0, 1000)	+0.2770	IBGE (2010)
k) Number of elders (%)	$y = 0.0015x$ (0, 200, 400, 600, 800)	+0.7031	IBGE (2010)
l) Distance to schools (m)	$y = -0.005x + 1$ (0, 200)	−0.2326	City Council
m) Distance to health establishments (m)	$y = -0.005x + 1$ (0, 200)	−0.3484	City Council

(*Continued*)

Table 3. (Continued).

Criterion	Fuzzy linear functions	Weights	Sources
n) Distance to properties in official flood risk areas (m)	$y = -0.005x + 1$	−0.4190	CPRM – Serviço Geológico do Brasil & Defesa Civil – Campina Grande (2013)

' + ' indicates an increasing function.
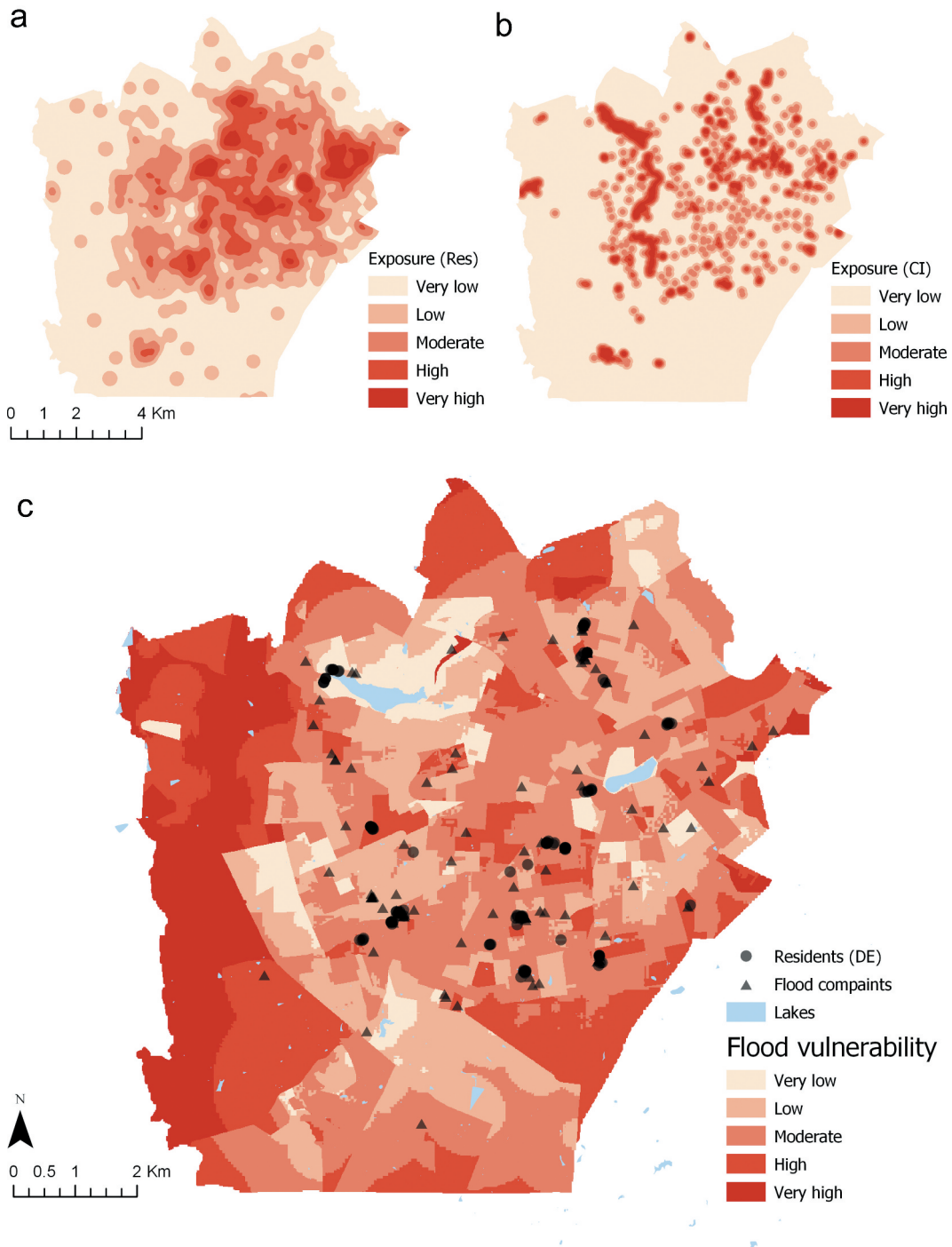' − ' indicates a decreasing function

Figure 4. Final mappings: (a) Exposure (Residents), (b) Exposure (critical infrastructure) and (c) Overall flood vulnerability.

'moderate' vulnerabilities are seen spread throughout the city (34.20% of the city area). The least vulnerable ('very low' and 'low') areas represent approximately 25% 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 to 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 4(c)).

The validation was performed by extracting the vulnerability mapping pixel values with the 'Sample tool' within ArcGIS Pro (ESRI). Since the flooding in the 224 points was 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 and Alexander 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 2 and 3) and final outputs (Figure 4(a–c)) were discussed and approved by authorities of Campina Grande in meetings held in January 2021.

5. 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 and Alexander 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. 2016). 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 and Alexander 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, Savenije, and Blöschl 2012) and the reduction of social and institutional vulnerabilities (Cunico and Lohmann 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 to contribute to the socio-environmental discussion of how to mitigate flooding with a vulnerability perspective.

5.1. 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 shows correlations from −1 to 1, indicating negative and positive correlations, respectively. In this phase, our intention was not to state causality
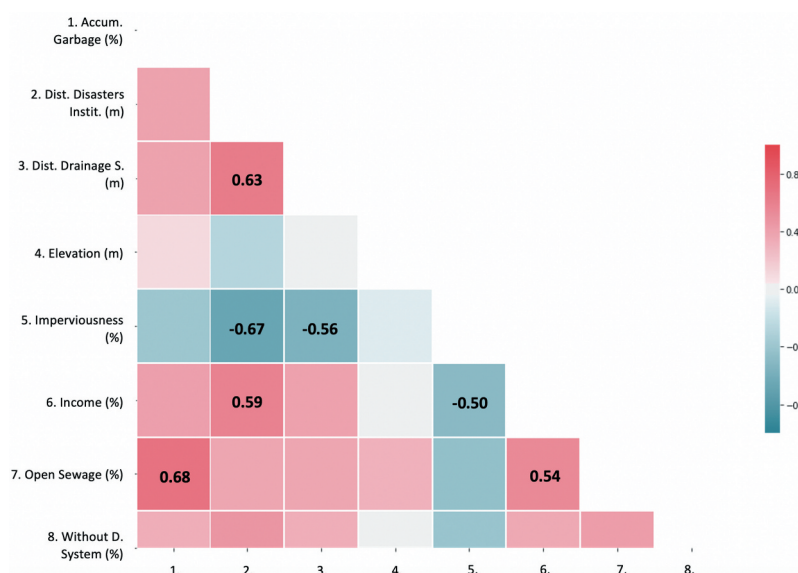

Figure 5. Pearson correlation between the indicators of flood vulnerability (sensitivity and capacity mappings).

between datasets but to evaluate how the indicators typically move together.

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 1). Overall, structural vulnerabilities are suggested as flood causations in Brazil, particularly related to the drainage capacity (Sarmento Buarque et al. 2020; Goncalves et al. 2018). 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 of 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. 2020) (i.e. see Alves et al. (2020) for a complete legislation analysis).

Stakeholders of the PLANEJEE 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 10 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 (de Araújo Grangeiro, Ribeiro, and de Miranda 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 (IPCC 2012b; Hazarika et al. 2018). The blue boxes on Figure 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 incomes live. This result corroborates with Cutter, Boruff, and Shirley (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, the 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 on the community to cope with flooding (de Brito, Evers, and Höllermann 2017). For Fuchs, Kuhlicke, and Meyer (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 4 (a,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.

5.2. 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 and Alexander 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, our 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 error possibilities since conception (Sharma and Ravindranath 2019) until applying the framework (Malczewski and Rinner 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, Kuhlicke, and

Meyer (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. Similar to vulnerability, the risk is complex and dynamic, which requires regular re-assessment (Peduzzi 2019). Using our framework, the reassessment 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. In addition, 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.

6. 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 2014, 2012b). 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, Gencer, and Winograd 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 variable 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.

Disclosure statement

The authors declare no conflict of interest.

ORCID

Priscila Barros Ramalho Alves http://orcid.org/0000-0003-3489-8552
Slobodan Djordjević http://orcid.org/0000-0003-1682-1383
Akbar A. Javadi http://orcid.org/0000-0001-8376-4652

References

Ajibade, I., and G. McBean. 2014. "Climate Extremes and Housing Rights: A Political Ecology of Impacts, Early Warning and Adaptation Constraints in Lagos Slum Communities." *Geoforum* 55: 76–86. doi:10.1016/j.geoforum.2014.05.005.

Alves, P. B. R., H. M. Filho, B. B. Tsuyuguchi, I. A. A. Rufino, and P. H. C. Feitosa. 2018. "Mapping of Flood Susceptibility in Campina Grande County – PB: A Spatial Multicriteria Approach." *Bulletin of Geodetic Sciences* 24 (1): 28–43. doi:10.1590/S1982-21702018000100003.

Alves, P. B. R., I. Alexandra Alves Rufino, P. Hermínio Cunha Feitosa, S. Djordjević, and A. Javadi. 2020. "Land-Use and Legislation-Based Methodology for the Implementation of Sustainable Drainage Systems in the Semi-Arid Region of Brazil." *Sustainability* 12 (2). doi:10.3390/su12020661.

ANA. 2018. *Conjuntura dos recursos hídricos no Brasil 2018: informe anual*. Brasília: Agência Nacional de Águas – ANA.

Assumpção, T. H., I. Popescu, A. Jonoski, and D. P. Solomatine. 2018. "Citizen Observations Contributing to Flood Modelling: Opportunities and Challenges." *Hydrology and Earth System Sciences* 22 (2): 1473–1489. doi:10.5194/hess-22-1473-2018.

Birgani, Y. T., and F. Yazdandoost. 2018. "An Integrated Framework to Evaluate Resilient-Sustainable Urban Drainage Management Plans Using a Combined-adaptive MCDM Technique." *Water Resources Management* 32 (8): 2817–2835. doi:10.1007/s11269-018-1960-2.

Birkmann, J. 2007. "Risk and Vulnerability Indicators at Different Scales: Applicability, Usefulness and Policy Implications." *Environmental Hazards* 7 (1): 20–31. doi:10.1016/j.envhaz.2007.04.002.

Boroushaki, S. 2017. "Entropy-Based Weights for MultiCriteria Spatial Decision-Making." *Yearbook of the Association of Pacific Coast Geographers* 79 (1): 168–187. doi:10.1353/pcg.2017.0009.

Bryan, K., S. Ward, S. Barr, and D. Butler. 2019. "Coping with Drought: Perceptions, Intentions and Decision-Stages of South West England Households." *Water Resources Management* 33 (3): 1185–1202. doi:10.1007/s11269-018-2175-2.

Caldas, A., T. Pissarra, R. Costa, F. Neto, M. Zanata, R. Parahyba, L. S. Fernandes, and F. Pacheco. 2018. "Flood Vulnerability, Environmental Land Use Conflicts, and Conservation of Soil and Water: A Study in the Batatais SP Municipality, Brazil." *Water* 10 (10). doi:10.3390/w10101357.

Cheung, W., and D. Feldman. 2019. "Can Citizen Science Promote Flood Risk Communication?" *Water* 11 (10). doi:10.3390/w11101961.

Cinner, J. E., W. N. Adger, E. H. Allison, M. L. Barnes, K. Brown, P. J. Cohen, S. Gelcich, et al. 2018. "Building Adaptive Capacity to Climate Change in Tropical Coastal Communities." *Nature Climate Change* 8 (2): 117–123. doi:10.1038/s41558-017-0065-x.

Ciullo, A., A. Viglione, A. Castellarin, M. Crisci, and G. Di Baldassarre. 2017. "Socio-hydrological Modelling of Flood-risk Dynamics: Comparing the Resilience of Green and Technological Systems." *Hydrological Sciences Journal* 62 (6): 880–891. doi:10.1080/02626667.2016.1273527.

Climent-Gil, E., A. Aledo, and A. Vallejos-Romero. 2018. "The Social Vulnerability Approach for Social Impact Assessment." *Environmental Impact Assessment Review* 73: 70–79. doi:10.1016/j.eiar.2018.07.005.

CPRM – Serviço Geológico do Brasil & Defesa Civil – Campina Grande, PB. 2013. *Ação Emergencial para Delimitação de Áreas em Alto e Muito Alto Risco a Enchentes e Movimentos de Massa*. Campina Grande, Paraíba. Accessed 1 July 2019. http://rigeo.cprm.gov.br/xmlui/handle/doc/19740

Cunico, C., and M. Lohmann. 2017. "Vulnerabilidade Socioambiental De Curitiba: Correlação Com Os Eventos De Alagamentos Registrados Entre 2005 E 2010 Pela Defesa Civil Municipal." *Geografia Ensino & Pesquisa* 21 (3): 165. doi:10.5902/2236499424724.

Cutter, S. 1996. "Vulnerability to Environmental Hazards." *Progress in Human Geography* 20 (4): 529–539. doi:10.1177/030913259602000407.

Cutter, S. L., B. J. Boruff, and W. L. Shirley. 2003. "Social Vulnerability to Environmental Hazards." *Social Science Quarterly* 84 (2): 242–261. doi:10.1111/1540-6237.8402002.

Cutter, S. L., L. Barnes, M. Berry, C. Burton, E. Evans, E. Tate, and J. Webb. 2008. "A Place-based Model for Understanding Community Resilience to Natural Disasters." *Global Environmental Change* 18 (4): 598–606. doi:10.1016/j.gloenvcha.2008.07.013.

de Araújo Grangeiro, E. L., M. M. R. Ribeiro, and L. I. B. de Miranda. 2019. "Análise da governança dos recursos hídricos na bacia hidrográfica do Rio Paraíba." *Revista Ibero-Americana de Ciências Ambientais* 10 (5): 314–330. doi:10.6008/cbpc2179-6858.2019.005.0028.

de Brito, M. M., M. Evers, and A. D. S. Almoradie. 2018. "Participatory Flood Vulnerability Assessment: A Multicriteria Approach." *Hydrology and Earth System Sciences* 22 (1): 373–390. doi:10.5194/hess-22-373-2018.

de Brito, M. M., M. Evers, and B. Höllermann. 2017. "Prioritisation of Flood Vulnerability, Coping Capacity and Exposure Indicators through the Delphi Technique: A Case Study in Taquari-Antas Basin, Brazil." *International Journal of Disaster Risk Reduction* 24: 119–128. doi:10.1016/j.ijdrr.2017.05.027.

Driessen, P., D. Hegger, Z. Kundzewicz, H. van Rijswick, A. Crabbé, C. Larrue, P. Matczak, et al. 2018. "Governance Strategies for Improving Flood Resilience in the Face of Climate Change." *Water* 10 (11): 1595. doi:10.3390/w10111595.

Duan, J., Y. Wang, C. Fan, B. Xia, and R. de Groot. 2018. "Perception of Urban Environmental Risks and the Effects of Urban Green Infrastructures (Ugis) on Human Well-being in Four Public Green Spaces of Guangzhou, China." *Environmental Management* 62 (3): 500–517. doi:10.1007/s00267-018-1068-8.

Eitzel, M. V., J. L. Cappadonna, C. Santos-Lang, R. E. Duerr, A. Virapongse, S. E. West, C. C. M. Kyba, et al. 2017. "Citizen Science Terminology Matters: Exploring Key Terms." *Citizen Science: Theory and Practice* 2 (1). doi:10.5334/cstp.96.

Frigerio, I., S. Ventura, D. Strigaro, M. Mattavelli, M. De Amicis, S. Mugnano, and M. Boffi. 2016. "A GIS-based Approach to Identify the Spatial Variability of Social Vulnerability to Seismic Hazard in Italy." *Applied Geography* 74: 12–22. doi:10.1016/j.apgeog.2016.06.014.

Fuchs, S., C. Kuhlicke, and V. Meyer. 2011. "Editorial for the Special Issue: Vulnerability to Natural Hazards—the Challenge of Integration." *Natural Hazards* 58 (2): 609–619. doi:10.1007/s11069-011-9825-5.

Ghajari, Y., A. Alesheikh, M. Modiri, R. Hosnavi, and M. Abbasi. 2017. "Spatial Modelling of Urban Physical Vulnerability to Explosion Hazards Using GIS and Fuzzy MCDA." *Sustainability* 9 (7). doi:10.3390/su9071274.

Gheshlaghi, H. A., and B. Feizizadeh. 2017. "An Integrated Approach of Analytical Network Process and Fuzzy Based Spatial Decision Making Systems Applied to Landslide Risk Mapping." *Journal of African Earth Sciences* 133: 15–24. doi:10.1016/j.jafrearsci.2017.05.007.

Golz, S., R. Schinke, and T. Naumann. 2014. "Assessing the Effects of Flood Resilience Technologies on Building Scale." *Urban Water Journal* 12 (1): 30–43. doi:10.1080/1573062x.2014.939090.

Gomez Martin, E., R. Giordano, A. Pagano, P. van der Keur, and M. Manez Costa. 2020. "Using a System Thinking Approach to Assess the Contribution of Nature Based Solutions to Sustainable Development Goals." *Science of the Total Environment* 738: 139693. doi:10.1016/j.scitotenv.2020.139693.

Goncalves, M. L. R., J. Zischg, S. Rau, M. Sitzmann, W. Rauch, and M. Kleidorfer. 2018. "Modeling the Effects of Introducing Low Impact Development in A Tropical City: A Case Study from Joinville, Brazil." *Sustainability* 10 (3): 728.

Groulx, M., M. C. Brisbois, C. J. Lemieux, A. Winegardner, and L. Fishback. 2017. "A Role for Nature-Based Citizen Science in Promoting Individual and Collective Climate Change Action? A Systematic Review of Learning Outcomes." *Science Communication* 39 (1): 45–76. doi:10.1177/1075547016688324.

Hammond, M., A. S. Chen, J. Batica, D. Butler, S. Djordjević, P. Gourbesville, N. Manojlović, O. Mark, and W. Veerbeek. 2018. "A New Flood Risk Assessment Framework for Evaluating the Effectiveness of Policies to Improve Urban Flood Resilience." *Urban Water Journal* 15 (5): 427–436. doi:10.1080/1573062x.2018.1508598.

Hardoy, J., E. Gencer, and M. Winograd. 2019. "Participatory Planning for Climate Resilient and Inclusive Urban Development in Dosquebradas, Santa Ana and Santa Tomé." *Environment and Urbanization* 31 (1): 33–52. doi:10.1177/0956247819825539.

Hazarika, N., D. Barman, A. K. Das, A. K. Sarma, and S. B. Borah. 2018. "Assessing and Mapping Flood Hazard, Vulnerability and Risk in the Upper Brahmaputra River Valley Using Stakeholders' Knowledge and Multicriteria Evaluation (MCE)." *Journal of Flood Risk Management* 11: S700–S16. doi:10.1111/jfr3.12237.

Hong, H., P. Tsangaratos, I. Ilia, J. Liu, A. X. Zhu, and W. Chen. 2018. "Application of Fuzzy Weight of Evidence and Data Mining Techniques in Construction of Flood Susceptibility Map of Poyang County, China." *Science of the Total Environment* 625: 575–588. doi:10.1016/j.scitotenv.2017.12.256.

IBGE. 2010. *Censo demográfico - 2010*. Brasília, Brazil: Instituto Brasileiro de Geografia eE statística. Accessed 15 January 2020. https://censo2010.ibge.gov.br

IBGE. 2018. *Estimativa de população para os municípios*. Brasília, Brazil: Instituto Brasileiro de Geografia e Estatística. Accessed 15 January 2020. https://cidades.ibge.gov.br

IPCC. 2007. *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 104. Geneva, Switzerland: IPCC.

IPCC. 2012a. *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*, 582. Cambridge, UK: Cambridge University Press.

IPCC. 2012b. "Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation." In *A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change*, edited by C. B. Field, V. Barros, T. F. Stocker, D. Qin, D. J. Dokken, K. L. Ebi, M. D. Mastrandrea, et al., 582. Cambridge, UK: Cambridge University Press.

IPCC. 2014. *Summary for policymakers. In: Climate Change: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 1–32. Cambridge, UK: Cambridge University Press.

Kanani-Sadat, Y., R. Arabsheibani, F. Karimipour, and M. Nasseri. 2019. "A New Approach to Flood Susceptibility Assessment in Data-scarce and Ungauged Regions Based on GIS-based Hybrid Multi Criteria Decision-making Method." *Journal of Hydrology* 572: 17–31. doi:10.1016/j.jhydrol.2019.02.034.

Kc, B., J. M. Shepherd, and C. J. Gaither. 2015. "Climate Change Vulnerability Assessment in Georgia." *Applied Geography* 62: 62–74. doi:10.1016/j.apgeog.2015.04.007.

Kelman, I. 2020. *Disaster by Choice: How Our Actions Turn Natural Hazards in Catostrophes*. Oxford: Oxford University Press.

Kia, M. B., S. Pirasteh, B. Pradhan, A. R. Mahmud, W. N. A. Sulaiman, and A. Moradi. 2011. "An Artificial Neural Network Model for Flood Simulation Using GIS: Johor River Basin, Malaysia." *Environmental Earth Sciences* 67 (1): 251–264. doi:10.1007/s12665-011-1504-z.

Kunapo, J., T. D. Fletcher, A. R. Ladson, L. Cunningham, and M. J. Burns. 2018. "A Spatially Explicit Framework for Climate Adaptation." *Urban Water Journal* 15 (2): 159–166. doi:10.1080/1573062x.2018.1424216.

Lund, J. R. 2015. "Integrating Social and Physical Sciences in Water Management." *Water Resources Research* 51 (8): 5905–5918. doi:10.1002/2015wr017125.

Malczewski, J., and C. Rinner. 2015. "Advances in Geographic Information Science." *Springer New York Heidelberg Dordrecht London* 1 (1): 335. doi:10.1007/978-3-540-74757-4.

Marchezini, V., R. Trajber, D. Olivato, V. A. Muñoz, F. de Oliveira Pereira, and A. E. O. Luz. 2017. "Participatory Early Warning Systems: Youth, Citizen Science, and Intergenerational Dialogues on Disaster Risk Reduction in Brazil." *International Journal of Disaster Risk Science* 8 (4): 390–401. doi:10.1007/s13753-017-0150-9.

Nguimalet, C.-R. 2018. "Comparison of Community-based Adaptation Strategies for Droughts and Floods in Kenya and the Central African Republic." *Water International* 43 (2): 183–204. doi:10.1080/02508060.2017.1393713.

Ouma, Y., and R. Tateishi. 2014. "Urban Flood Vulnerability and Risk Mapping Using Integrated Multi-Parametric AHP and GIS: Methodological Overview and Case Study Assessment." *Water* 6 (6): 1515–1545. doi:10.3390/w6061515.

Parker, L., C. Bourgoin, A. Martinez-Valle, and P. Laderach. 2019. "Vulnerability of the Agricultural Sector to Climate Change: The Development of a Pan-tropical Climate Risk Vulnerability Assessment to Inform Sub-national Decision Making." *PLoS One* 14 (3): e0213641. doi:10.1371/journal.pone.0213641.

Peduzzi, P. 2019. "The Disaster Risk, Global Change, and Sustainability Nexus." *Sustainability* 11 (4): 957. doi:10.3390/su11040957.

Perera, E. N. C., D. T. Jayawardana, P. Jayasinghe, and M. Ranagalage. 2019. "Landslide Vulnerability Assessment Based on Entropy Method: A Case Study from Kegalle District, Sri Lanka." *Modeling Earth Systems and Environment* 5 (4): 1635–1649. doi:10.1007/s40808-019-00615-w.

Pescaroli, G., and D. Alexander. 2019. "What are Cascading Disasters?" *UCL Open Environment*. doi:10.14324/111.444/ucloe.000003.

Robinson, K. F., A. K. Fuller, R. C. Stedman, W. F. Siemer, and D. J. Decker. 2019. "Integration of Social and Ecological Sciences for Natural Resource Decision Making: Challenges and Opportunities." *Environmental Management* 63 (5): 565–573. doi:10.1007/s00267-019-01141-2.

Roodposhti, M. S., J. Aryal, H. Shahabi, and T. Safarrad. 2016. "Fuzzy Shannon Entropy: A Hybrid GIS-Based Landslide Susceptibility Mapping Method." *Entropy* 18 (10). doi:10.3390/e18100343.

Santos, E., I. Silva, H. M. Filho, and I. A. A. Rufino. 2017. "Atlas Digital de Dados Censitários em Cidades no Semiárido." Paper presented at the *VIII GeoNordeste - Simpósio Regional de Geoprocessamento e Sensoriamento Remoto,* Salvador, Bahia, October 3–6.

Santos, K. A., I. A. A. Rufino, and M. N. M. B. Filho. 2017. "Impacts of the Disordered Land Occupancy: A Study about an Urban Consolidated Area in Campina Grande – PB." *Eng Sanit Ambient* 22 (5): 934–952. doi:10.1590/S1413-41522016146661.

Sarmento Buarque, A. C., N. Bhattacharya-Mis, M. C. Fava, F. A. A. de Souza, and E. M. Mendiondo. 2020. "Using Historical Source Data to Understand Urban Flood Risk: A Socio-hydrological Modelling Application at Gregório Creek, Brazil." *Hydrological Sciences Journal* 65 (7): 1075–1083. doi:10.1080/02626667.2020.1740705.

Sharma, J., and N. H. Ravindranath. 2019. "Applying IPCC 2014 Framework for Hazard-specific Vulnerability Assessment under Climate Change." *Environmental Research Communications* 1 (5): 051004. doi:10.1088/2515-7620/ab24ed.

Sivapalan, M., H. H. G. Savenije, and G. Blöschl. 2012. "Socio-hydrology: A New Science of People and Water." *Hydrological Processes* 26 (8): 1270–1276. doi:10.1002/hyp.8426.

Song, J. Y., and E.-S. Chung. 2017. "A Multi-Criteria Decision Analysis System for Prioritising Sites and Types of Low Impact Development Practices: Case of Korea." *Water* 9 (4). doi:10.3390/w9040291.

Tingsanchali, T., and Y. Keokhumcheng. 2019. "A Method for Evaluating Flood Hazard and Flood Risk of East Bangkok Plain, Thailand." *Proceedings of the Institution of Civil Engineers - Engineering Sustainability* 172 (7): 385–392. doi:10.1680/jensu.17.00031.

Tsuyuguchi, B. B. 2015. "Macrodrenagem e ocupação do solo no município de Campina Grande: Caracterização, simulação e análises sistêmicas [Macrodrainage and Occupation of Campina Grande: Characterization, Simulations and Analysis]." Masters diss., Federal University of Campina Grande.

UNDRR. 2019. *Global Assessment Report on Disaster Risk Reduction*. Geneva, Switzerland: United Nations Office for Disaster Risk Reduction (UNDRR).

Weis, S. W. M., V. N. Agostini, L. M. Roth, B. Gilmer, S. R. Schill, J. E. Knowles, and R. Blyther. 2016. "Assessing Vulnerability: An Integrated Approach for Mapping Adaptive Capacity, Sensitivity, and Exposure." *Climatic Change* 136 (3–4): 615–629. doi:10.1007/s10584-016-1642-0.

Yang, W., K. Xu, J. Lian, C. Ma, and L. Bin. 2018. "Integrated Flood Vulnerability Assessment Approach Based on TOPSIS and Shannon Entropy Methods." *Ecological Indicators* 89: 269–280. doi:10.1016/j.ecolind.2018.02.015.