A participatory spatial multi-criteria approach for flood vulnerability assessment

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Abstract

This paper presents the preliminary results of a participatory multi-criteria decision making (MCDM) approach for evaluating the vulnerability to floods while considering the interdependency among the criteria. The applicability of this method was demonstrated in the Taquari-Antas Basin, Brazil, where limited information on risk elements is available. A total of 101 researchers, policy makers, and practitioners were actively involved in the flood vulnerability index development. A participatory problem structuration, where the modellers work closely with the stakeholders to establish the structure of the index was used. In addition, participatory methods, such as Delphi technique, focus groups, and workshops were employed to select the input criteria, identify their relationships, and build utility curves to standardize the data. The preferences of each participant regarding vulnerability assessment were spatially modelled through the Analytical Network Process (ANP). After the two-round Delphi survey, 11 criteria were selected and grouped into three clusters, including coping capacity, social and physical vulnerability. The final product is a participatory, interdisciplinary flood vulnerability map. The approach proved useful for problem structuring in a collective, flexible and iterative way, improving the quality and effectiveness of the information exchange and the reflection process among actors.

Keywords: ANP, MCDM, participatory modelling, flood vulnerability.

1 Introduction

A proper understanding of flood vulnerability is crucial to promote resilient societies, leading to more efficient mitigation strategies. Nevertheless, integrating the dimensions of vulnerability in an overarching framework is complex due to conceptual and methodological constraints. Challenges always remain in (1) the selection of criteria to represent the vulnerability, (2) the determination of the importance of each criterion, (3) the data availability, and (4) the results validation (Müller, Reiter and Weiland, 2011). Typically, the rationale for decisions regarding criteria selection, weighting and aggregation is either unstated or justified based on simplicity or choices made in previous studies. Furthermore, the relationships between criteria are often neglected and they are assumed to be independent (Rufat *et al.*, 2015).

In addition to these methodological issues, the participation of multiple stakeholders in the index development is usually fragmented and limited to specific stages (de Brito and Evers, 2016). However, if practitioners are involved in creating an index that they find useful, it is more likely they will incorporate it into policy decisions (Oulahen *et al.*, 2015). Using collaborative methods that integrate the knowledge of stakeholders with different perspectives could foster such actions while assuring local context. This could be fulfilled through participatory multi-criteria decision making (MCDM) methods, in which stakeholders work together to guide the indicator development process.

Taking into account these challenges, this study aims to develop a participatory MCDM for evaluating flood vulnerability while considering the interdependency among the criteria. The Analytical Network Process (ANP) was used to actively involve researchers, policy makers and practitioners in the identification of the relationship between the vulnerability drivers and derivation of their weights.

This paper is structured as follows. Section 2 outlines the participatory approach developed to map the vulnerability to floods. In Section 3, the preliminary results are presented and discussed. Finally, Section 4 presents concluding remarks.

2 Material and methods

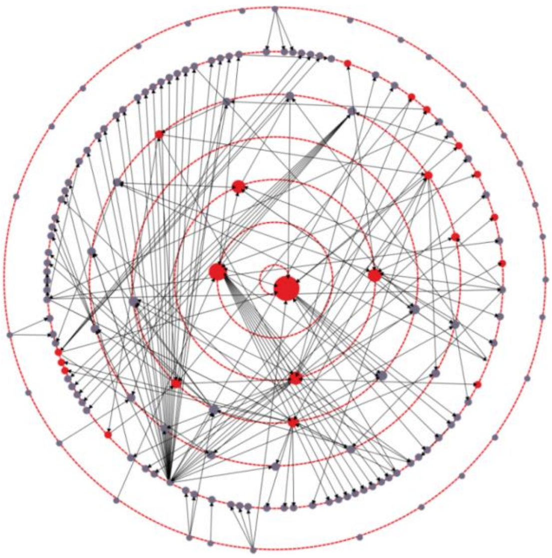
2.1 Study area

Given that vulnerability is site-specific (Cardona and van Aalst, 2012), the municipalities of Lajeado and Estrela, located in the Taquari-Antas river Basin, Brazil, were chosen to demonstrate the applicability of the proposed approach. Between 1980 and 2015, 66 floods have been reported in these municipalities, causing economic, social and environmental impacts. Due to this high susceptibility, they are considered by the Brazilian Government as a priority for disaster risk reduction (CEMADEN, 2017).

2.2 Selection of participants

A total of 117 experts from research institutes, government organizations, universities, private companies, and NGOs were selected through snowball sampling and invited to take part in the study. A sociogram with the relationship between these experts was created using *SocNetV* software (Figure 1). In this graph, the actors that were recommended by experts with many connections are located in the centre of the network. As they play a central role in terms of their reputation and prestige, they were invited to take part in workshops and focus groups in further steps of the study.

Figure 1: Social network diagram depicting the linkages between the selected experts. Each node represents an actor, and its size depends on their prestige. The arrow direction indicates who cited whom, while the circles collect all experts with the same degree of prestige. Red nodes denote the experts who took part in workshops and focus groups.



2.3 Selection of criteria through a Delphi survey

The Delphi technique (Chu and Hwang, 2008) was used to select the evaluation criteria in a systematic and transparent way. The 117 experts selected through snowball sampling (Figure 1) were invited to rate the importance of 26 criteria for vulnerability analysis on a 5-point scale. They could justify their score and suggest extra items. After the first questionnaire, a statistical feedback was sent to respondents, who were given the opportunity to modify prior estimates based on the answers of their anonymous colleagues. The aim was to allow them to consider the reasoning behind outlying opinions to decrease the response variability.

Consensus among participants was defined as an interquartile range of 1 or less (Alshehri, Rezgui and Li, 2015). The Wilcoxon signed-ranks test was performed to assess the stability of responses between rounds. Additionally, bootstrap analysis was carried out to verify the sensitivity of the ratings. This approach is a Monte Carlo-type data augmentation method, which replaces the original values and generates multiple samples as a proxy to the real sample (Akins, Tolson and Cole, 2005). In this study, 1,000 samples were generated from the first round results. If the group judgments fell within the 95% confidence interval of the resampled data, its performance is assumed to be reliable. The statistical analyses were performed using SPSS Statistics 22.

2.4 Criteria standardization

The selected evaluation criteria were transformed into 20 m raster files in ArcGIS 10.1. The source data used to create these maps were obtained through the Brazilian National Census or were mapped based on reports from municipal Civil Defences.

Since the criteria layers are represented by different measurement scales (e.g. ordinal, interval, nominal) they needed to be transformed into comparable units before being aggregated (Malczewski and Rinner, 2015). Hence, utility functions were applied to standardize the criteria into a continuous scale, from 0 (least vulnerable) to 1 (more vulnerable). The functions were chosen in such a way that pixels in the standardized map that are highly vulnerable obtained high values and less vulnerable pixels obtained low values. The definition of the control points and utility functions (e.g. linear, sigmoidal or J-shaped) was done in a focus group with 5 experts.

2.5 Assessment of criteria weights using ANP

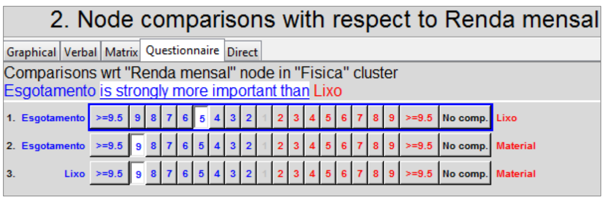
The relevance of each criterion for flood vulnerability assessment was determined through the ANP MCDM method (Saaty, 2004). The main innovation of ANP is its network structure with bilateral relationships, which enables inner and outer dependencies between criteria to be considered (Azizi *et al.*, 2014). This technique reduces complex decision problems into a sequence of pairwise comparisons, which can be easily understood by stakeholders.

The first step involves the construction of a conceptual model to determine relationships between clusters and nodes. For this purpose, a focus group with 9 experts was used. The participants were asked to determine the network relationships individually. Afterwards, the participants verbally put forward their ideas, and when everyone agreed with a decision the moderator recorded those on a whiteboard. When consensus was not met for a particular decision, the participants were asked to vote by show of hands.

The network structure was constructed using Super Decisions 2.6.0 Software, which automatically created a list of 40 pairwise comparisons needed to run the evaluation (Figure 2). The comparisons were carried out by asking "which of the two criteria is more important for vulnerability assessment?" and "which of the two criteria influences a third criterion more with respect to vulnerability assessment?".

A questionnaire with these comparisons was prepared, and the experts with more prestige within the network were invited to take part in 4 workshops to fill the survey. During these meetings, each participant was requested to fill the questionnaire with the 40 comparisons using a 9-point continuous scale. The final weights are obtained by using a supermatrix approach. A detailed description of mathematical foundations of ANP can be found in Saaty (2004) and Saaty and Vargas (2013).

Figure 2: Pairwise comparisons in Super Decisions software.



2.6 Criteria aggregation

Once the weights were established, a weighted linear combination (WLC) was employed to integrate the criteria layers into an overall vulnerability map. Due to its straightforwardness, WLC is one of the most common GIS aggregation methods (Boroushaki and Malczewski, 2008). It is based on the concept of a weighted average, where each standardized criterion is multiplied by its weight obtained through ANP. This procedure was executed for each expert using ArcGIS 10.1 raster calculator. In addition, a group scenario was created with the weights average.

All maps were presented in a web-GIS platform developed with MangoMap®. This allowed participants to have a comprehensive and synthetic view of their results through a customizable user-friendly graphical interface.

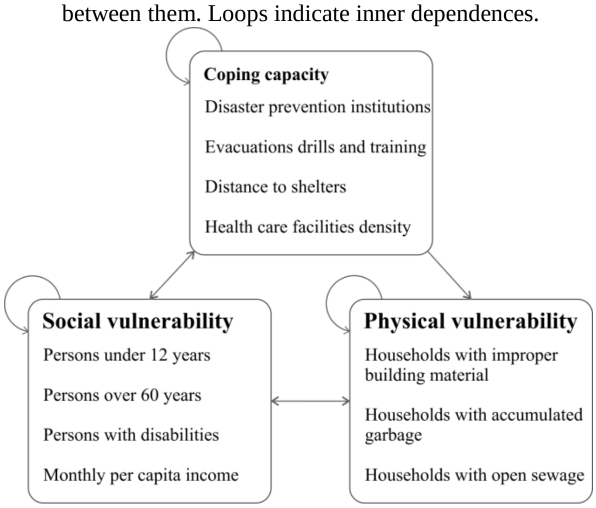
3 Preliminary results and discussion

Out of the 117 invited experts, 86.32% and 79.20% answered the first and second Delphi questionnaires, respectively. After the second round, response stability was achieved, indicating that no further rounds are required. Consensus was reached on 21 of the 26 criteria, lending legitimacy and credibility to the index. The sensitivity of the ratings was investigated by resampling the original data. Bootstrap analysis showed that the participant's opinions are representative of that of their colleagues. This, combined with the high response rate, makes the Delphi results particularly robust.

A total of 11 criteria obtained a mean superior to 3.5 and were included in the index. According to the ANP method, the problem needs to be structured in clusters constituted by various criteria (nodes) that influence the vulnerability. Thus, based on a focus group discussion with 9 experts, the 11 selected criteria were sorted into three clusters, including coping capacity, social and physical vulnerability. Figure 3 illustrates the conceptual model for flood vulnerability assessment, where the dependences among clusters and the direction of the influences are indicated. The influences reflect the dynamics of vulnerability drivers, where interactions exist between individual criteria, which can, positively or negatively, affect each other.

A total of 22 stakeholders attended the workshops designed to derive criteria weights using the ANP. Table 1 shows the group weights obtained by averaging the individual results. The coping capacity cluster was given the highest importance, which reflects the growing tendency to widen up the concept of vulnerability to incorporate the ability of communities to face disasters (Birkmann, 2006). This perspective shift acknowledges that citizens can act as important agents to reduce the adverse impacts of floods, thus diminishing their passive dependency from the relief offered by outsiders.

Figure 3: Conceptual model for flood vulnerability analysis in the study area. The direction of the arrows indicates the interdependence relationships between the criteria. A single direction arrow shows the dominance of one criterion by another. A double direction arrow shows the mutual influence between them. Loops indicate inner dependences.

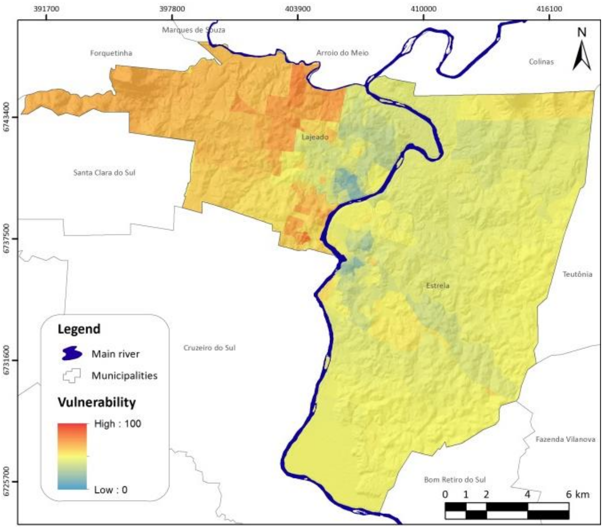


The criteria were standardized during a focus group, where 5 experts worked together to achieve a consensus regarding the utility curves and control points that should be used. The standardized maps were multiplied by the ANP weights to get the total vulnerability score for each pixel. The final vulnerability map shows that most of the study area has a medium vulnerability (Figure 4). The developed map can support local authorities to monitor highly vulnerable areas. It can also be useful to identify places for site-specific risk assessment, enabling to prioritize human, technological and financial resources.

Table 1: Aggregated group weights for each cluster and evaluation criteria obtained through the ANP technique

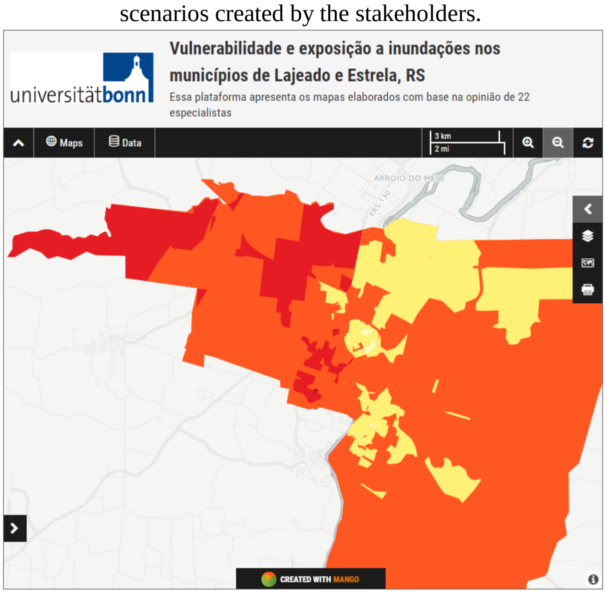
Cluster	Weight	Criteria	Weight
Social vulnerability	31.64	Persons under 12 years	4.37
		Persons over 60 years	3.96
		Persons with disabilities	8.84
		Monthly per capita income	13.49
Physical vulnerability	27.70	Households with improper building material	15.06
		Households with accumulated garbage	7.20
		Households with open sewage	6.41
Coping capacity	40.66	Disaster prevention institutions	9.36
		Evacuation drills and training	14.54
		Distance to shelters	7.26
		Health care facilities	9.51
TOTAL	**100.00**		**100.00**

Figure 4. Vulnerability to floods in the study area.



A Web GIS platform was developed to allow end users to view the model results in the form of thematic layers set in a geographical context and overlaid on background data (Figure 5). In this platform, the participants could select their scenarios and compare them with the other participant's results. Also, it was possible to visualize the hazard zones with different return periods, aiming to identify risk areas.

Figure 5: Web GIS platform with the 22 vulnerability scenarios created by the stakeholders.



An undergoing evaluation of the results revealed that the proposed participatory spatial MCDM approach was well appreciated by the stakeholders. The Delphi process allowed participants to change their views in a non-threatening, anonymous manner, which led to a decrease in the standard deviation of answers between rounds for 21 indicators. We could observe learning and negotiation processes for achieving consensus upon input criteria and their standardization. This demonstrates that a change in the understanding of vulnerability has taken place.

4 Conclusion

The developed participatory spatial MCDM approach relies on active stakeholders' engagement in all the main phases of the index development, including problem structuration, criteria selection, standardization, and weighting. This leads to: (1) an increased, shared understanding of the conceptual model for flood vulnerability assessment; (2) an ability to deal with uncertain variables by eliciting experts' opinions; and (3) an enhanced credibility and deployment of the final index as the needs and concerns of the stakeholders were taken into consideration.

To the best of our knowledge, this is the first time that the interdependence among criteria was considered to develop a flood vulnerability index. The ANP technique allowed capturing the complex relationships among vulnerability drivers in a transparent and participatory way. The proposed methodology can be easily implemented for different problems that involve multiple criteria with inner and outer dependences and contrasting views.

Future research will aim at conducting uncertainty and sensitivity analysis of the criteria weights as well as the validation of the developed maps. Furthermore, risk maps will be generated based on the vulnerability scenarios.

Acknowledgments

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