Chapter 28

Multi-Criteria Decision Analysis for Flood Risk Assessment

Daniel Jato-Espino
GITECO Research Group, Universidad de Cantabria, 39005 Santander, Spain

Mariana Madruga de Brito
Department of Geography, University of Bonn, 53115 Bonn, Germany

ABSTRACT
Floods are one of the most frequent and devastating natural disasters, causing important social and economic losses around the globe. To ensure their proper management, it is essential to have risk assessment methodologies to address the hazard and vulnerability aspects associated with the occurrence of these events integrally. Consequently, the aim of this chapter is to provide a generic framework to assess flood risk through the incorporation of Multi-Criteria Decision Analysis (MCDA) methods into Geographic Information Systems (GIS). The proposed approach considers a series of morphologic, hydrogeological, meteorological and socio-environmental factors characterised from open data available at a worldwide scale, which are weighted using participatory methods to engage stakeholders in the prioritisation of both flood hazard prone areas and vulnerability variables.
KEYWORDS: Multi-Criteria Decision Analysis, Flood Risk Assessment, Geographic Information Systems, Participatory Method, Stakeholders, Vulnerability

1. INTRODUCTION

Floods were the natural disaster leading to the highest number of fatalities during the 20th century, amounting to 6.8 million deaths (Doocy et al., 2013). The devastating effects of floods are especially remarkable in Asia, where almost half of these events took place (Jonkman, 2005). The occurrence and intensity of these phenomena is being favoured in recent years by the action of urban sprawl, resulting in an increase of flood damage over the last years (Elmer et al., 2012). In addition, climate change is another potential catalyser for the frequency of flooding in areas where mean precipitation and wet extremes are expected to rise (Guhathakurta et al., 2011).

In order to mitigate the negative impacts of floods, the Sendai framework for disaster risk reduction recommends that the design and implementation of risk management strategies should be based on a comprehensive understanding of risk in all its dimensions, including the hazard characteristics, the vulnerability, the coping capacity, and the exposure of persons and assets (UNISDR, 2015a). The assessment of risk, when carried out holistically, can provide the floodplain managers better tools to make informed decisions for flood mitigation at various levels. It can assist decision makers to elaborate land use planning policies and to identify areas where preventive and corrective measures are needed, and, if so, which option is most suitable. Additionally, it can help to raise the public awareness by providing an understandable visualization of the flooding risks.

The variables favouring flood hazard relate to conditioning aspects, such as the orography and permeability of the terrain, as well as to trigger factors, mainly represented by precipitation. Another relevant parameter boosting the probability of occurrence of floods is the proximity to water courses, whose rise can threaten the areas located in their vicinity. In the end, the integrated consideration of all of these elements makes urban areas particularly prone to floods, especially if they are close to the coast (Neumann et al., 2015).

The consequences stemming from the occurrence of floods are usually expressed as costs, which can be grouped into four categories depending on the assessment methods they require (Meyer et al., 2013): direct, business interruption, indirect and intangible. One way or another, all these categories refer to impacts that increase the vulnerability of people, goods, services and the environment, either in the form of physical damages or through interruptions, disruptions and depreciations.

The dual nature of floods, whereby they must be considered in terms of both hazard and vulnerability, provoked a conceptual evolution from a traditional approach only focused on protection to a more comprehensive framework focused on risk management (Schanze, 2006). Risk management must, in turn, be founded on risk assessment, which is the process that enables identifying hazards and how they affect the vulnerability of people and goods to their occurrence. In this context, risk assessment encompasses both the determination of hotspots in what concerns the susceptibility to floods (hazard) and the quantification of the human and material consequences stemming from these events (vulnerability). Therefore, the definition of risk proposed for this chapter considers it as the product between hazard and vulnerability. This is equivalent to express risk as the combination of probability and consequences or susceptibility and impact, which are two of the most widely used approaches in the literature (Bell and Glade, 2004).

Given the spatial condition of the variables involved in flood hazard and vulnerability, the development of risk assessment methodologies is usually supported by the use of Geographic Information Systems (GIS) (McMaster et al., 1997). GIS enables importing and geoprocessing the data required for mapping hazard and vulnerability variables. The aggregation of these individual layers to produce integrated risk maps can be assisted using Multi-Criteria Decision Analysis (MCDA) methods, since some of the factors to combine might be in conflict (Carver, 1991). One of the strengths of MCDA is that it provides a suitable platform to involve relevant stakeholders and gain insight into their priorities in terms of flood hazard and vulnerability (Pelling, 2007). Furthermore, it makes the criteria evaluation process more explicit and rational, by making subjective judgments visible in a transparent and fair way (San Cristóbal Mateo, 2012).

Under these premises, the aim of this chapter is to provide an integrated and generic approach to produce the lood risk maps through the combination of GIS and MCDA.

After establishing the current state of the art in terms of flood risk assessment through a literature review, the different steps forming the proposed framework are presented sequentially, highlighting their potential replicability due to the use of open access data and participatory methods.

2. LITERATURE REVIEW

In order to highlight the increasing relevance that flood risk assessment has gained over the years, this section provides an overview of the most relevant scientific outputs produced during the last two decades in this field of research. Table 1 summarises the main features of these investigations, which are presented in descending order according to their current number of citations in the Scopus database.

In addition to the number of citations achieved by each contribution so far, Table 1 includes the name, year and title of the scientific works addressed, as well as the country where the flood-related studies were conducted. The three remaining fields forming Table 1 focused on the most relevant aspects of the literature review from a conceptual point of view, since they indicated the way in which flood risk was approached, the MCDA methods used and whether the research item was participatory or not.

Regarding the geographic distribution of the studies addressed, almost half of them took place in Asia (48.39%), followed by Europe (35.48%), America (9.68%), Oceania (3.23%) and Africa (3.23%). The predominance of Asia in this sense is consistent with the data reported by the United Nations between 1995 and 2015 (UNISDR, 2015b), which highlighted the sensitivity of this continent to weather-related disasters due to the concentration of population in the surroundings of river basins and floodplains.

In addition to the strict components of risk, either as a whole or isolated (hazard and vulnerability), investigations concerning the evaluation of mitigation measures were also considered, since their inclusion can have attenuating effects on the occurrence and impact of floods. With this in view, the review yielded rather balanced results, whereby vulnerability emerged as the most addressed aspect (34.29%), but not very far from mitigation measures (25.71%), hazard (22.86%) and risk (17.14%). On the one hand, these results prove the relevance of the social dimension of floods, highlighting the importance of identifying critical areas in terms of exposure to these events. On the other hand, the fact that risk assessment was the approach taken less frequently suggests the need for developing the accessible and replicable frameworks for evaluating flood risk integrally.

The predominance of the Simple Additive Weighting Method (SAW) and the Analytic Hierarchy Process (AHP), which were present in 70% of the investigations reviewed, indicate a clear trend towards the application of simple and widely used Multi-Criteria Decision Analysis (MCDA) methods (Jato-Espino et al., 2014). SAW is the easiest technique to aggregate the different factors involved in the assessment of either hazard or vulnerability, especially in a context in which these variables must be processed with the support of Geographic Information Systems (GIS). Similarly to SAW, AHP is a straightforward, flexible, and easily understandable method (Cinelli et al., 2014). Thanks to these characteristics, it can be adapted to different problems without requiring previous knowledge from the analyst.

The application of the AHP method is usually linked to the use of participatory approaches, which are often based on establishing priorities in relation to flood risk according to the opinions provided by a group of stakeholders. The integration of participatory methods and the MCDA tools may facilitate the achievement of consensus, which is essential for finding solutions that reconcile conflicting interests and can be accepted by the majority (de Brito and Evers, 2016; Malczewski and Rinner, 2015; Simão et al., 2009). Despite this importance, more than half of the studies consulted (54.84%) disregarded this aspect, suggesting that there is still room for increasing the involvement of participants in the design of flood risk management strategies.

Table 1. Overview of the main existing research items related to flood risk assessment through Multi-Criteria Decision Analysis (MCDA)

Reference	**Country**	**Cites**	**Title**	**Approach**	**MCDA methods**	**Participatory**
(Meyer et al., 2009)	Germany	133	A multicriteria approach for flood risk mapping exemplified at the Mulde river, Germany	Vulnerability assessment; Mitigation measures	Disjunctive approach; MAUT	No
(Raaijmakers et al., 2008)	Spain	95	Flood risk perceptions and spatial multi-criteria analysis: An exploratory research for hazard mitigation	Vulnerability assessment	SAW	Yes
(Kienberger et al., 2009)	Austria	75	Spatial vulnerability units - Expert-based spatial modelling of socio-economic vulnerability in the Salzach catchment, Austria	Vulnerability assessment	Delphi; SAW	Yes
(Levy, 2005)	China	70	Multiple criteria decision making and decision support systems for flood risk management	Mitigation measures	ANP	No
(Wang et al., 2011)	China	69	A GIS-Based Spatial Multi-Criteria Approach for Flood Risk Assessment in the Dongting Lake Region, Hunan, Central China	Risk assessment	FAHP	No
(Kubal et al., 2009)	Germany	58	Integrated urban flood risk assessment - Adapting a multicriteria approach to a city	Vulnerability assessment	SAW	No
(Kenyon, 2007)	Scotland	51	Evaluating flood risk management options in Scotland: A participant-led multi-criteria approach	Mitigation measures	Rank sum; Rank order centroid; SAW	Yes
(Levy et al., 2007)	Japan	42	Multi-criteria decision support systems for flood hazard mitigation and emergency response in urban watersheds	Mitigation measures	ANP	Yes
(Lee et al., 2013)	South Korea	34	Integrated multi-criteria flood vulnerability approach using fuzzy TOPSIS and Delphi technique	Risk assessment	Delphi; FTOPSIS	No
(Kandilioti and Makropoulos, 2012)	Athens	30	Preliminary flood risk assessment: The case of Athens	Risk assessment	AHP; SAW; OWA	Yes
(Scolobig et al., 2008)	Italy	26	Integrating multiple perspectives in social multicriteria evaluation of flood-mitigation alternatives: The case of Malborghetto-Valbruna	Vulnerability assessment; Mitigation measures	NAIADE	Yes

Table 1 *(Continued)*

Authors (Year)	Country	Cites	Title	Approach	MCDA methods	Participatory
(Sharifi et al., 2002)	Bolivia	22	Application of GIS and multicriteria evaluation in locating sustainable boundary between the Tunari national park and Cochabamba city (Bolivia)	Vulnerability assessment; Mitigation measures	SAW	Yes
(Haque et al., 2012)	Bangladesh	19	Participatory integrated assessment of flood protection measures for climate adaptation in Dhaka	Mitigation measures	SAW	Yes
(Chen et al., 2015)	Australia	16	A spatial assessment framework for evaluating flood risk under extreme climates	Hazard assessment	AHP	No
(Solín, 2012)	Slovakia	14	Spatial variability in the flood vulnerability of urban areas in the headwater basins of Slovakia	Vulnerability assessment	MADM	No
(Sowmya et al., 2015)	India	13	Urban flood vulnerability zoning of Cochin City, southwest coast of India, using remote sensing and GIS	Risk assessment	SAW	No
(Malekian and Azarnivand, 2016)	Iran	12	Application of Integrated Shannon's Entropy and VIKOR Techniques in Prioritization of Flood Risk in the Shemshak Watershed, Iran	Hazard assessment	Entropy; VIKOR	Yes
(Yang et al., 2011)	China	12	Spatial multicriteria decision analysis of flood risks in aging-dam management in China: A framework and case study	Vulnerability assessment	SAW	Yes
(Xiao et al., 2017)	China	8	Integrated flood hazard assessment based on spatial ordered weighted averaging method considering spatial heterogeneity of risk preference	Hazard assessment	FAHP; OWA	No
(Ghanbarpour et al., 2013)	Iran	8	A comparative evaluation of flood mitigation alternatives using GIS-based river hydraulics modelling and multicriteria decision analysis	Mitigation measures	TOPSIS	No
(Fernandez et al., 2016)	Portugal	6	Social vulnerability assessment of flood risk using GIS-based multicriteria decision analysis. A case study of Vila Nova de Gaia	Vulnerability assessment	AHP; OWA; SAW	No

Table 1 *(Continued)*

Authors (Year)	Country	Cites	Title	Approach	MCDA methods	Participatory
(Seekao and Pharino, 2016)	Thailand	3	Assessment of the flood vulnerability of shrimp farms using a multicriteria evaluation and GIS: A case study in the Bangpakong Sub-Basin, Thailand	Hazard assessment	AHP; SAW	No
(Tang et al., 2018)	China	1	Incorporating probabilistic approach into local multi-criteria decision analysis for flood susceptibility assessment	Hazard assessment	AHP; SAW	No
(Hazarika et al., 2018)	India	1	Assessing and mapping flood hazard, vulnerability and risk in the Upper Brahmaputra River valley using stakeholders' knowledge and multicriteria evaluation (MCE)	Risk assessment	SAW	Yes
(Panhalkar and Jarag, 2017)	India	1	Flood risk assessment of Panchganga River (Kolhapur district, Maharashtra) using GIS-based multicriteria decision technique	Hazard assessment	AHP	No
(de Brito et al., 2018)	Brazil	1	Participatory flood vulnerability assessment: A multi-criteria approach	Vulnerability assessment	AHP; ANP	Yes
(Loos and Rogers, 2016)	U.S.	1	Understanding stakeholder preferences for flood adaptation alternatives with natural capital implications	Vulnerability assessment; Mitigation measures	MAUT	Yes
(Luu and von Meding, 2018)	Vietnam	0	A flood risk assessment of Quang Nam, Vietnam using spatial multicriteria decision analysis	Risk assessment	AHP	Yes
(Patrikaki et al., 2018)	Greece	0	Assessing flood hazard at river basin scale with an index-based approach: The case of Mouriki, Greece	Hazard assessment	AHP; SAW	No
(Zeleňáková et al., 2018)	Slovakia	0	Flood vulnerability assessment of Bodva cross-border river basin	Hazard assessment	AHP; SAW	No
(Mallouk et al., 2016)	Morocco	0	A multicriteria approach with GIS for assessing vulnerability to flood risk in urban area (case of Casablanca city, Morocco)	Vulnerability assessment	AHP	No

3. INTEGRATED FLOOD RISK ASSESSMENT

The main elements forming the framework conceived to assess flood risk is illustrated in Figure 1. On the one hand, the processing and combination of a series of morphologic and hydrogeological factors is proposed to determine the flood hazard. On the other hand, the vulnerability of people, goods and natural areas to floods is also examined, in order to evaluate their socioeconomic and environmental consequences. To get insight into the real dimension of floods, the use of participatory methods involving multiple stakeholders is suggested to both identify the hotspots in terms of flood hazard and prioritise the vulnerable elements requiring protection. Hence, the coupled and inclusive consideration of hazard and vulnerability enables determining flood risk integrally. For the sake of maximising the replicability of the proposed approach, the characterisation of all the variables involved in the calculation of flood risk is addressed through open data available at a worldwide scale. From a technical point of view, the only requirement for implementing this methodology is to use Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) methods to manage these data.

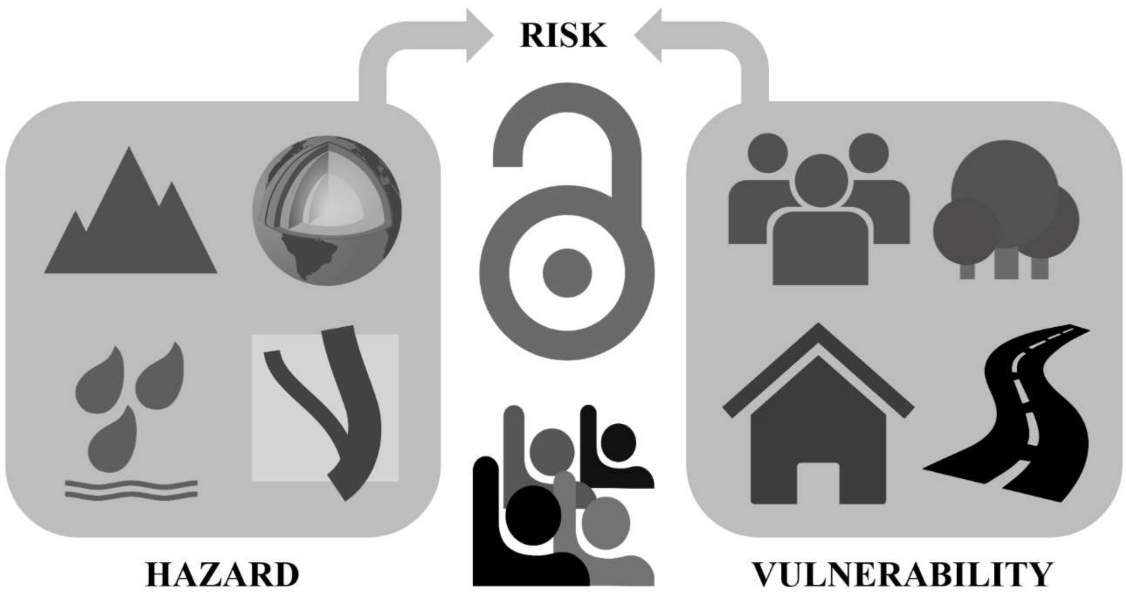

Figure 1. Outline of the generic framework proposed to assess flood risk

3.1. Definition of factors involved in flood risk using open data

The development of flood risk maps roughly consists of the processing and aggregation of a series of factors or criteria with the support of GIS and participatory MCDA methods. The characterisation of these factors requires the acquisition and further processing of a series of spatial data. To boost the replicability of the proposed framework, the factors suggested to assess flood risk in Table 2 meet two main requirements in terms of the data from which they stem: worldwide scale availability and open accessibility. Hence, the underlying aim of this approach is to enable its application all around the globe; however, the list of factors proposed in Table 2 can also be produced using different or complementary local or regional data with finer resolutions.

Table 2. List of datasets and factors suggested to assess flood risk

Category	Data	Source	Factor(s)	Units
Hazard	Digital Elevation Model (DEM)	(LP DAAC, 2014)	Elevation, slope, flow accumulation	m, º, No. of cells
	Lithology	(Hartmann and Moosdorf, 2012)	Soil permeability	Score
	Land cover	(Jun et al., 2014)	Curve number	Score
	Groundwater level	(Fan et al., 2013)	Water table depth	m
	Precipitation	(Hijmans et al., 2005)	Precipitation	mm
	Water bodies	(Geofabrik Download Server, 2018)	Proximity to water bodies	m
Vulnerability	Population density	(SEDAC, 2017)	Population density	km^2
	Protected areas	(IUCN, 2016)	Protected areas density	km^2
	Buildings	(Geofabrik Download Server, 2018)	Building density	km^2
	Infrastructures	(Geofabrik Download Server, 2018)	Infrastructure density	km^2

Consistent with the two main components involved in flood risk, the factors needed for its evaluation can also be divided into hazard and vulnerability. Hence, one of the cornerstones in the determination of flood hazard is the elevation of the terrain in the study area. This data can be obtained from the United States Geological Survey (USGS) Earth Explorer, which made available the Advanced Spaceborne Thermal Emission and

Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM), as a result of the collaboration between the U.S. National Aeronautics and Space Administration (NASA) and Japan's Ministry of Economy, Trade and Industry (METI) (LP DAAC, 2014). The ASTER GDEM is provided in raster format (GeoTIFF) with a pixel size of 30 m. The relationship between this factor and flooding is inversely proportional, since low elevation areas are prone to receive the large amounts of runoff.

Two other hazard-related criteria stem from the DEM. On the one hand, the slope of the terrain, which describes its steepness according to changes in elevation. Again, this variable is inversely related to the occurrence of floods, because the presence of flat slopes favours the concentration of water. On the other hand, flow accumulation represents the contributing area flowing to the same location with descendent slope. Hence, this factor is directly associated with flood hazard, such that the higher the value of flow accumulation, the more likely water to stagnate.

Soil permeability is a factor indicating the ability of subsurface layers to transmit water infiltrated from the ground. Hence, this variable has a negative effect on floods, in that high values of permeability facilitate water percolation and, therefore, reduce flood probability. The permeability of the underlying soil can be determined according to its characteristics and composition, which are available at the Global Lithological Map (GLiM) produced by the Institute for Biogeochemistry and Marine Chemistry of the University of Hamburg, with an average resolution of 1:3,750,000 (Hartmann and Moosdorf, 2012).

The next factor relates to the threshold runoff of the surface, i.e. the amount of excess rainfall accumulated over the ground after a storm event. The quantification of this variable can be approached using the Curve Number (CN) (Garen and Moore, 2005), which is an empirical parameter developed by the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (USDA, 2018). CN ranges from 30 to 100, such that the high values of CN indicate high runoff potential. Thus, this factor has a direct correspondence to flood hazard. CN stems from the combination of the land cover type and Hydrologic Soil Group (HSG) of the study area. The latter can be determined from a lithological map as described above, whilst the former is addressable from the data included in the GlobeLand30 initiative, an open-access map of Earth's land cover with a resolution of 30 m donated by China to the United Nations (Jun et al., 2014).

Groundwater is the water contained in the voids and fractures of the soil beneath the Earth's surface. This variable can contribute to flooding when groundwater rises above its common level and reaches the surface. Therefore, the shallower the groundwater level, the more likely the occurrence of floods. A study conducted by Fan et al. (2013) used measurements of water table depth from 1,603,781 sites, either provided by governments or published in the literature, to produce a regionalised 1 km grid dataset in NetCDF format that can be used to characterise this factor.

The next factor symbolises the precipitation patterns in the study area. Precipitation is a crucial variable in determining the amount of water that the terrain has to deal with, such that the high rainfall rates hinder the capacity of filtration of the ground and contribute to provoking floods. The data required to compute this factor can be obtained from the version 1.4 of WorldClim (Hijmans et al., 2005), which provides global climate maps with a cell size of 1 km. These data are available both under current (stationarity) and future (non-stationarity) conditions, enabling the projection of variations in flood hazard due to the impacts of climate change according to the different Global Circulation Models (GCM).

The last variable contributing to flood hazard concerns the proximity of the study area to water courses. Rainfall during a continued period can cause the overflow of water bodies and, by extension, the inundation of their surroundings. In this case, the probability of flooding increases as the distance to water courses is reduced, especially if their volume is high. This information is available via the OpenStreetMap project, which includes polygonal and vector layers indicating the location of water bodies (Geofabrik Download Server, 2018).

The first factor related to flood vulnerability is population density, which provides an indicator about hotspots in terms of concentration of people. Hence, this aspect accounts for the vulnerability of crowded areas, such that the higher population density, the greater the impacts caused by floods. The data needed for the creation of this factor is supplied by the Socioeconomic Data and Applications Center (SEDAC) via a global map containing the Gridded Population of the World (GWP) (SEDAC, 2017). This map provides the estimates of population density with a 1 km resolution for several years based on the national censures, population registers and United Nations counts.

The next aspect to consider for the assessment of vulnerability encompasses the environmental dimension of flood management, represented by the terrestrial and marine protected areas that might be subject to these phenomena. This factor can also be represented based on its density, such that the higher the presence of protected areas, the greater the impacts of floods on the environment. The World Database on Protected Areas (WDPA) (IUCN, 2016), jointly prepared by the United Nations Environment Programme (UNEP) and the International Union for Conservation of Nature (IUCN), includes the data required to model this factor.

Finally, the last two vulnerability-related variables focus on the main assets that might be damaged during the occurrence of floods: buildings and infrastructures. Affections to these elements may limit accessibility and cause the traffic disruptions, hindering the transit of people and vehicles across dense areas in terms of buildings and infrastructures and increasing their vulnerability to flooding events. Again, the data involved in the processing of these factors can be downloaded from OpenStreetMap (Geofabrik Download Server, 2018), which provides two layers symbolising the spatial arrangement of these facilities.

3.2. Participatory assessment of flood hazard and vulnerability

The previous reviews showed that the assessment of flood hazard and vulnerability using MCDA is seldom conducted in a systematic way (de Brito and Evers, 2016). The reasoning for the model assumptions, such as the selection of the input criteria, standardization of the data to a common scale, and definition of criteria weighs, is typically unstated and these decisions are restricted to researchers conducting the study (Beccari, 2016; Müller et al., 2011; Rufat et al., 2015; Tate, 2012). Even when stakeholders are involved, their participation is fragmented and constrained to information dissemination and consultation at specific stages (de Brito and Evers, 2016; Evers et al., 2018). Consequently, the vulnerability and hazard MCDA models are commonly perceived as black boxes by end-users, which limits the use and implementation of the model results.

To overcome these problems, participatory approaches for flood hazard and vulnerability assessment can be used to go beyond the limited perspective of a single expert by acknowledging the multiple standpoints and explicitly showing the rationale for model decisions. The key generic steps of the approach are illustrated in **Fehler! Verweisquelle konnte nicht gefunden werden.**, which shows that expert stakeholders should collaborate throughout the entire process. This allows the building trust among participants, facilitates information sharing and improves the model transparency, thus enhancing the results acceptance. A detailed description of the proposed methodology and its application in two case studies is provided by de Brito et al. (2017; 2018) and Katz et al. (2017).

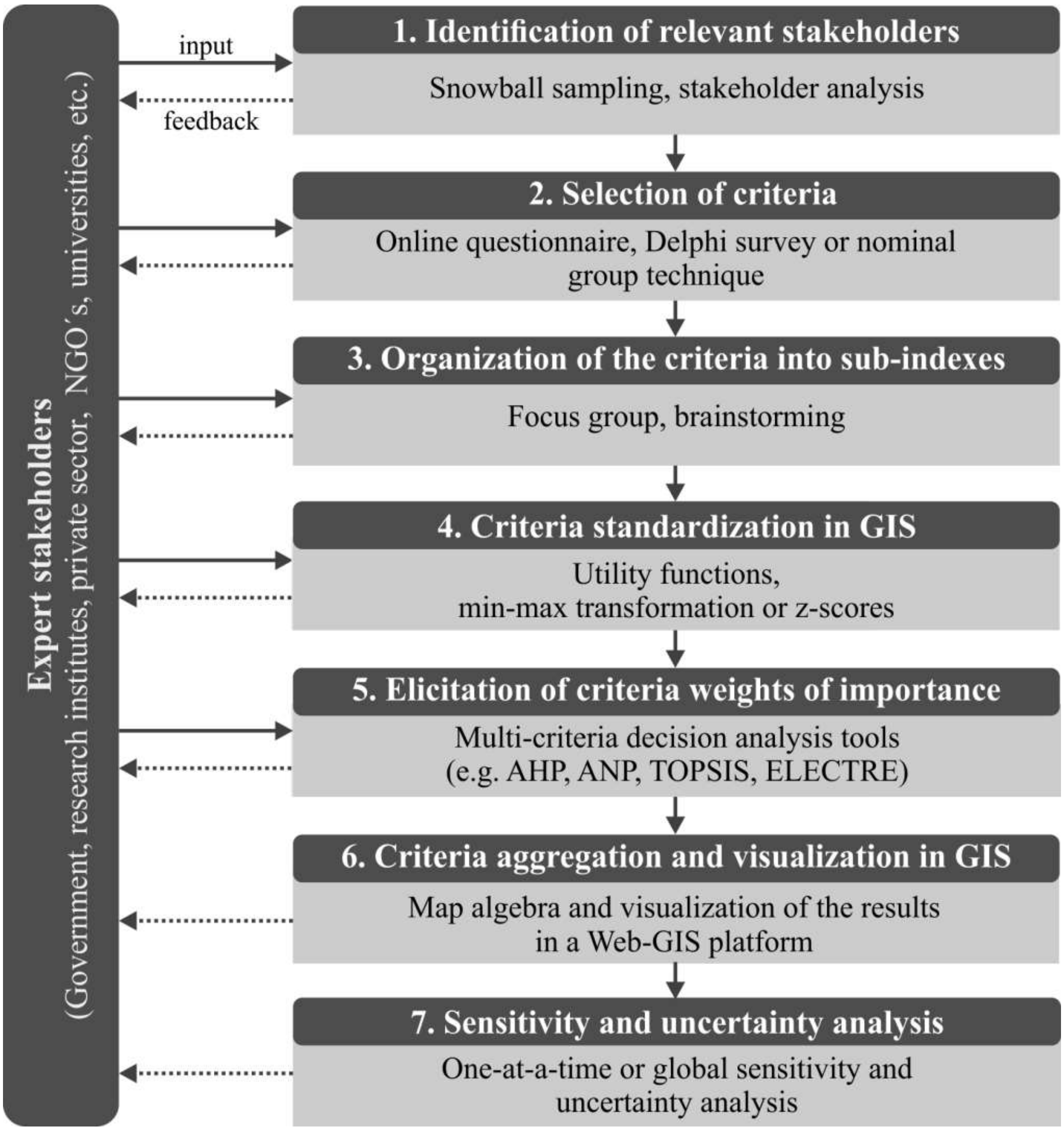

Figure 2. Methodological framework for flood vulnerability and risk assessment. Key steps and suggested methods are shown in boxes

The first step comprehends the identification of relevant expert stakeholders that have an in-depth knowledge of flood vulnerability and hazard assessment. For this purpose, the snowball sampling technique can be used (Wright and Stein, 2005). The basic idea is that initially sampled experts (i.e. starting seeds) indicate other specialists in the field, which in turn lead to the other prospective participants until the desired sample size is reached. Alternatively, iterative stakeholder analysis involving focus groups and brainstorming exercises can be conducted to ensure that all of the relevant actors have been included. The use of the previously mentioned tools can be complemented with social network analysis to investigate social structures and identify key experts that (1) have the unique positions in the network, hence, occupying non-redundant communication roles in the network; (2) come from the different stakeholder categories, thus allowing capturing contrasting opinions; and (3) are relatively well-connected to the others and tend to break across different segments of the network (Prell et al., 2008).

Step 2 involves the identification of a set of criteria or factors that are going to be incorporated into the model. The selection of the evaluation criteria is a crucial step in the development of any indicator, as the inclusion or exclusion of relevant criteria can have a dramatic impact on the model results. Hence, these should be preferentially independent, complete, concise, and operationally meaningful. The nominal group technique (NGT) can be applied to obtain the consensus among experts on the set of criteria (Harvey and Holmes, 2012). Alternatively, to avoid group effects (e.g. group-thinking or anticipatory consensus) obscuring individual preferences, anonymous questionnaires or the Delphi survey can be used.

The third step consists of organizing the selected criteria into sub-indexes (e.g. social, economic and environmental dimensions). The organization scheme, i.e., hierarchical or network, depends on the MCDA technique considered. For this purpose, the brainstorming sections can be conducted to have an unstructured discussion of the problem. In this setting, the participants propose solutions and the group actively debates what the best course of action is.

Step 4 comprises the standardization of the spatial data into a common scale. There is a number of methods for standardizing raw data to the comparable units, including value functions, min-max transformation, and z-score. Since vulnerability and hazard criteria usually do not have a linear behaviour, the use of value functions is recommended. The value function is a mathematical representation of human judgment (Malczewski and

Rinner, 2015). It relates possible decision outcomes (criterion or attribute values) to a scale which reflects the decision maker's preferences. The type and shape of the function can be defined individually, i.e., one value function per criterion defined by each participant, or consensus regarding the function type can be achieved based on focus group discussion. Nevertheless, due to the complexity of the task at hand, these meetings need to be restricted to a small number of participants.

In step 5, the importance of the criteria for the vulnerability analysis needs to be assessed. This is a critical phase, given that even small changes in weights may have a significant impact on the model results, leading to inaccurate outcomes (Feizizadeh and Blaschke, 2014). In the field of flood hazard and vulnerability assessment, the most used MCDA tools are: Analytic Hierarchy Process (AHP) (Saaty, 1980), Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) (Behzadian et al., 2012) and Simple Additive Weighting (SAW) (Abdullah and Adawiyah, 2014). The selection of the method to be used depends on the time and resources available and decision makers' objectives. Regardless of the MCDA method used, the weights can be elicited using either online or in-person questionnaires. Alternatively, since assigning weights requires a significant mental effort for most stakeholders, serious games (i.e. games including a non-entertaining purpose) in combination with MCDA could be used instead (Aubert et al., 2018). Voinov et al. (2016) argued that serious games are promising tools for participatory modelling due to (1) the stakeholders' engagement through intrinsic game motivational features, (2) the potential for interactive visualization and (3) the ability to create social learning.

Step 6 comprehends the aggregation of the criterion maps and decision maker's preferences (criterion weights) in a GIS environment using a combination rule. In general, the combination rules can be compensatory or non-compensatory, where the former takes into account the trade-offs between criteria, while the latter ignores the value of trade-offs. The compensatory methods allow trade-off of a low value on one criterion against a high value on another (Malczewski and Rinner, 2015). It is recommendable to display the aggregated results in a Web-GIS platform, where participants can compare their results with the maps from other actors.

The final step consists of a post-analysis study to check for the model inaccuracies. Uncertainty analysis (UA) investigates how uncertainty in model inputs translates into uncertainty in model outputs (Tate, 2012). Similarly, sensitivity analysis (SA) investigates how the results vary when the criteria are changed. This helps to identify crucial variables in the model and allows disagreements between individuals to be examined to see if they make a difference in the final results. At the end of the process, the outcomes of the MCDA analysis should be made available to all interested parties through the reports and other channels of communication.

Although the participatory MCDA phases are presented here as a logical sequence of steps, it should be emphasized that, in reality, the development of hazard and vulnerability indices process may be far from sequential and continuous. In practice, the whole process is iterative, possibly having internal conflicts that require an on-going review of the index structure to ensure that the results will be accepted by the majority of the participants.

3.3. Geoprocessing and aggregation of factors to assess flood risk

The determination of flood risk is based on the geoprocessing and aggregation of the factors listed in Table 2. This must be carried out with the support of GIS, which provides the tools needed for the management of the datasets used to produce the factors. Although the functionalities available in different GIS might vary from each other, there are several open source programs that include all the capabilities required to undertake the tasks for modelling flood hazard and vulnerability (Jato-Espino, 2016).

One common consideration for all the data involved in flood risk assessment is the clipping of the original vector or raster layers to the boundaries of the study area, in order to delimit further calculations to the workspace. The aggregation of different layers also requires their projection to the same reference system, as well as their resampling to the minimum cell size of the original data, in order to boost the accuracy of the results to achieve. Finally, those datasets originally available in vector format must be transformed into raster to enable their eventual combination with the remaining layers.

The DEM-related factors depend on calculations concerning the relative elevation of the cells of a raster map with respect to their adjacent pixels. This course of action enables determining the slope of the terrain, either in degrees or as a percentage, and a flow direction map according to the eight direction model proposed by Jenson and Domingue (1988), which assigns a value to each cell in the neighbourhood of the processing cell based on the changes in elevation. The further processing of the flow direction map through hydrology tools serves to aggregate the number of cells flowing to each cell in the workspace (Tarboton et al., 1991), yielding the flow accumulation map of the study area.

Soil permeability can be calculated from the description of the rocks in the study area, which enables classifying them in different levels according to their properties. To this end, first is the creation of a new field in the attribute table of the layer corresponding to the lithologic map, such that values of permeability or scores are allocated to each group depending on their characteristics. The number of groups into which divided the lithology of the workspace should be preferably four, in order to meet the HSG classification and, therefore, facilitate the processing of the CN of the terrain surface. The joint selection by attributes of the HSG and the land cover types in the study area leads to the production of the CN map sought (Jato-Espino et al., 2016b).

Water table depth is one of the most complex factors to manage, since it is provided in NetCDF format as a grid of points. Hence, the first step in the processing of this variable is the extraction and arrangement of the original raw data in tabular format, in order to use a GIS readable format. Once imported, the grid of points must be interpolated to generate a continuous surface of the values of water table depth. This can be carried out using both deterministic and geostatistical techniques, such that the goodness-of-fit of the resulting maps is measured by comparison between the interpolated and observed values (Jato-Espino et al., 2016a).

Unlike water table depth, precipitation and population density are already available as a continuous raster map in the data source suggested in Table 2, such that its processing only requires generic clipping and resampling tasks. Instead, the calculations of proximity and density associated with the remaining factors are based on the application of specific spatial tools with which to create the raster layers from the polygons and polylines defining water bodies, protected areas, buildings and infrastructures.

Once all of the factors have been processed and converted into raster layers, they must be normalised to enable their joint aggregation. Normalisation is the step whereby the ratings r_{ij} in each cell i of the workspace in relation to a factor j, measured in the units indicated in Table 2, are adjusted to a common scale by applying different transformations including value functions, min-max transformation or z-score, as described before.

The aggregation of the normalised ratings n_{ij} can be undertaken using the different MCDA techniques, but always taking into account the weights w_j of the factors. The use of one MCDA method or another, including distance-based, outranking, scoring or utility/value approaches, may involve different equations and calculations; however, they all are strongly dependent on the determination of the weights, which is carried out independently. These weights represent the relative importance of the factors in the computation of flood hazard and vulnerability. Consequently, the values of w_j must also be divided into hazard (w_{H_j}) and vulnerability (w_{V_j}), such that their coupled consideration leads to determining flood risk.

The weights of the vulnerability-related factors can be determined straightforwardly through participatory tools, either by direct allocation or using the MCDA methods, from the opinions collected from a panel of stakeholders, as described before. Instead, the information about flood hazard that can be obtained through public engagement may consist of an ordinal ranking of flood prone areas, based on the experience gathered from historical events in the study area. Hence, the goal with respect to flood hazard is to maximise the fit between the observed ranking of sensitive areas and the values determined via MCDA and GIS.

To this end, first is the definition of a series of weighting scenarios to provide both balanced and biased situations. Table 3 shows a potential list of weights to use, which apart from eight scenarios in which the importance of each factor clearly predominates over the others, contains three additional combinations where the factors are grouped by type (morphology, permeability and hydrology) and prioritised accordingly.

Table 3. Weighting scenarios proposed to fit the observed ranking of flood prone areas

Scenario	w_{H_1}	w_{H_2}	w_{H_3}	w_{H_4}	w_{H_5}	w_{H_6}	w_{H_7}	w_{H_8}
1	0.125	0.125	0.125	0.125	0.125	0.125	0.125	0.125
2	0.650	0.050	0.050	0.050	0.050	0.050	0.050	0.050
3	0.050	0.650	0.050	0.050	0.050	0.050	0.050	0.050
4	0.050	0.050	0.650	0.050	0.050	0.050	0.050	0.050
5	0.050	0.050	0.050	0.650	0.050	0.050	0.050	0.050
6	0.050	0.050	0.050	0.050	0.650	0.050	0.050	0.050
7	0.050	0.050	0.050	0.050	0.050	0.650	0.050	0.050
8	0.050	0.050	0.050	0.050	0.050	0.050	0.650	0.050
9	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.650
10	0.200	0.200	0.200	0.080	0.080	0.080	0.080	0.080
11	0.080	0.080	0.080	0.260	0.260	0.080	0.080	0.080
12	0.080	0.080	0.080	0.080	0.080	0.200	0.200	0.200

The next step in the calculation of flood hazard is the modelling of the association between the ranking of prone areas obtained through participatory methods and the summary statistics computed at such areas by aggregating the factors according to the weights in Table 3. The definition of the sensitive areas can be accomplished by establishing a buffer of 250 m around the streets where the floods are frequent (Jato-Espino et al., 2018; van Hove et al., 2015). Thus, the summary statistics refer to the mean, minimum, maximum and sum values enclosed by these buffer areas.

Since the observed data about flood prone areas is in ordinal format, its relationship to the summary statistics can be modelled using the Spearman's correlation coefficient (ρ), which measures the strength of the monotonic association between two variables. Hence, the goodness-of-fit of the hazard maps obtained for each scenario is represented by a value between -1 and 1, which indicates whether its correlation with the ranking of flood prone areas is perfectly negative or positive.

Then, the identification of the factors proving to be statistically significant for explaining flood hazard can be undertaken with the application Multiple Regression Analysis (MRA), which enables modelling the relationship between the list of values of ρ associated with the combinations of weights proposed in Table 3. In addition to linear terms, first order interactions should also be included to model potential combined effects, since some of the hazard factors suggested in Table 2 are related to each other. The results obtained from this analysis must be validated through the verification of the assumptions of normality, homoscedasticity, multicollinearity and independence of residuals (Osborne and Waters, 2003).

The final step to take for producing a validated flood hazard map might be addressed through two different approaches. The simplest option consists of determining the optimal weights for the factors based on their relative contribution to the MRA model, such that the optimal weight $\overline{w}_{H_j}$ of a factor j is computed as its contribution as a linear term plus half the sum of its contributions in the interaction terms in which it is included. Another approach might involve the application of optimisation methods to solve the problem formulated in Eq. (1), which seeks to maximise the Spearman's correlation coefficient, while complying the restrictions associated with the values of ρ and w_{H_j}. Due to the inclusion of interaction terms, the resolution of this optimisation problem requires the use of non-linear methods, such as the Generalized Reduced Gradient (GRG) (Abadie and Carpentier, 1969) or evolutionary algorithms (Elbeltagi et al., 2005).

$$\begin{aligned} &Maximise \quad \rho \\ &subject\ to: \quad -1 \leq \rho \leq 1 \\ &\qquad\qquad\quad 0 \leq w_{H_j} \leq 1, \qquad \forall\, f_j\ in\ the\ MRA\ model \end{aligned} \tag{1}$$

In consequence, the integrated flood risk assessment sought is provided by the multiplication of the validated hazard map, based on the calculation of these optimal weights, by that of vulnerability produced by aggregating the factors corresponding to this aspect (Table 2) according to their weights, which are obtained through participatory methods from the priorities of relevant stakeholders in the study area. The resulting flood risk map highlights by its foundations on open data globally available, which are processed with the support of the MCDA methods incorporated into GIS.

4. SUMMARY AND CONCLUSIONS

This chapter presents an integrated framework for flood risk assessment founded on the coupling of Multi-Criteria Decision Analysis (MCDA) with Geographic Information Systems (GIS). Both tools are supported with the inclusion of participatory methods to help the processing a list of hazard and vulnerability-related factors built from open data sources and involved in the probability of occurrence and potential impacts of flooding phenomena.

The use of open datasets contributes to boosting the replicability of the proposed approach, since the sources explicitly suggested are available at a worldwide scale and have enough resolution to produce the satisfactory results. However, the flexibility of this framework enables either the addition of new hazard and vulnerability factors or the replacement of some of them by others with higher precision, depending on the quality of the data available at regional or local scales.

The combination of MCDA with the participatory tools for flood hazard and vulnerability assessment can lead to an increased, shared understanding of the problem by avoiding the limited perspective of a single expert. The methodology described here can enhance the credibility and deployments of hazard and vulnerability indicators, as stakeholders' opinion, expert judgement and local knowledge are taken into consideration throughout the entire process. Furthermore, its transdisciplinary nature might support the social learning processes and develop the capacity through awareness raising.

In summary, the content included in this chapter is intended to provide a complete guide on how to assess flood risk integrally without requiring neither restricted data nor proprietary software. Instead, data are suggested to be either acquired from global open sources or generated through participatory methods and then processed using the MCDA techniques incorporated into free GIS, resulting in a generic resource that can help improving flood management all around of the globe in an easy, accessible and inclusive manner.

References

Abadie, J., Carpentier, J., 1969. Generalization of the Wolfe reduced gradient method to the case of nonlinear constraints, in Optimization, by R Fletcher, Ed., Academic Press, New York, pp. 37–47.

Abdullah, L., Adawiyah, C.W.R., 2014. Simple additive weighting methods of multi criteria decision making and applications: a decade review. Int. J. Inf. Process. Manag. 5, 39–49.

Aubert, A.H., Bauer, R., Lienert, J., 2018. A review of water-related serious games to specify use in environmental Multi-Criteria Decision Analysis. Environ. Model. Softw. 105, 64–78. https://doi.org/10.1016/j.envsoft.2018.03.023

Beccari, B., 2016. A comparative analysis of disaster risk, vulnerability and resilience composite indicators. PLoS Curr. Disasters 14. https://doi.org/10.1371/currents.dis.453df025e34b682e9737f95070f9b970

Behzadian, M., Otaghsara, S.K., Yazdani, M., Ignatius, J., 2012. A state-of the-art survey of TOPSIS applications. Expert Syst. Appl. 39, 13051–13069. https://doi.org/10.1016/j.eswa.2012.05.056

Bell, R., Glade, T., 2004. Quantitative risk analysis for landslides - Examples from Bíldudalur, NW-Iceland. Nat. Hazards Earth Syst. Sci. 4, 117–131.

Carver, S.J., 1991. Integrating multi-criteria evaluation with geographical information systems. Int. J. Geogr. Inf. Syst. 5, 321–339. https://doi.org/10.1080/02693799108927858

Chen, Y., Liu, R., Barrett, D., Gao, L., Zhou, M., Renzullo, L., Emelyanova, I., 2015. A spatial assessment framework for evaluating flood risk under extreme climates. Sci. Total Environ. 538, 512–523, https://doi.org/10.1016/j.scitotenv.2015.08.094

Cinelli, M., Coles, S.R., Kirwan, K., 2014. Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. Ecol. Indic. 46, 138–148. https://doi.org/10.1016/j.ecolind.2014.06.011

de Brito, M.M., Evers, M., 2016. Multi-criteria decision-making for flood risk management: a survey of the current state of the art. Nat. Hazards Earth Syst. Sci. 16, 1019–1033. https://doi.org/10.5194/nhess-16-1019-2016

de Brito, M.M., Evers, M., Almoradie, A.D.S., 2018. Participatory flood vulnerability assessment: a multi-criteria approach. Hydrol. Earth Syst. Sci. 22, 373–390. https://doi.org/10.5194/hess-22-373-2018

de Brito, M.M., Evers, M., Höllermann, B., 2017. Prioritization of flood vulnerability, coping capacity and exposure indicators through the Delphi technique: a case study in Taquari-Antas basin, Brazil. Int. J. Disaster Risk Reduct. 24, 119–128. https://doi.org/10.1016/j.ijdrr.2017.05.027

Doocy, S., Daniels, A., Murray, S., Kirsch, T.D., 2013. The Human Impact of Floods: a Historical Review of Events 1980-2009 and Systematic Literature Review. PLoS Curr. https://doi.org/10.1371/currents.dis.f4deb457904936b07c09daa98ee8171a

Elbeltagi, E., Hegazy, T., Grierson, D., 2005. Comparison among five evolutionary-based optimization algorithms. Adv. Eng. Informatics 19, 43–53. https://doi.org/10.1016/j.aei.2005.01.004

Elmer, F., Hoymann, J., Düthmann, D., Vorogushyn, S., Kreibich, H., 2012. Drivers of flood risk change in residential areas. Nat. Hazards Earth Syst. Sci. 12, 1641–1657. https://doi.org/10.5194/nhess-12-1641-2012

Evers, M., Almoradie, A., de Brito, M.M., 2018. Enhancing Flood Resilience Through Collaborative Modelling and Multi-criteria Decision Analysis (MCDA). Urban B. Ser. 221–236. https://doi.org/10.1007/978-3-319-68606-6_14

Fan, Y., Li, H., Miguez-Macho, G., 2013. Global Patterns of Groundwater Table Depth. Science (80-.). 339, 940–943. https://doi.org/10.1126/science.1229881

Feizizadeh, B., Blaschke, T., 2014. An uncertainty and sensitivity analysis approach for GIS-based multicriteria landslide susceptibility mapping. Int. J. Geogr. Inf. Sci. 28, 610–638. https://doi.org/10.1080/13658816.2013.869821

Fernandez, P., Mourato, S., Moreira, M., 2016. Social vulnerability assessment of flood risk using GIS-based multicriteria decision analysis. A case study of Vila Nova de Gaia. Geomatics, Nat. Hazards Risk 7, 1367–1389. https://doi.org/10.1080/19475705.2015.1052021

Garen, D.C., Moore, D.S., 2005. Curve number hydrology in water quality modeling: Uses, abuses, and future directions. J. Am. Water Resour. Assoc. 41, 377–388. https://doi.org/10.1111/j.1752-1688.2005.tb03742.x

Geofabrik Download Server, 2018. OpenStreetMap Data Extracts [WWW Document]. URL http://download.geofabrik.de/index.html (accessed 7.5.18).

Ghanbarpour, M.R., Salimi, S., Hipel, K.W., 2013. A comparative evaluation of flood mitigation alternatives using GIS-based river hydraulics modelling and multicriteria decision analysis. J. Flood Risk Manag. 6, 319–331.

https://doi.org/10.1111/jfr3.12017

Guhathakurta, P., Sreejith, O.P., Menon, P.A., 2011. Impact of climate change on extreme rainfall events and flood risk in India. J. Earth Syst. Sci. 120, 359–373. https://doi.org/10.1007/s12040-011-0082-5

Haque, A.N., Grafakos, S., Huijsman, M., 2012. Participatory integrated assessment of flood protection measures for climate adaptation in Dhaka. Environ. Urban. 24, 197–213. https://doi.org/10.1177/0956247811433538

Hartmann, J., Moosdorf, N., 2012. The new global lithological map database GLiM: A representation of rock properties at the Earth surface. Geochemistry, Geophys. Geosystems 13. https://doi.org/10.1029/2012GC004370

Harvey, N., Holmes, C.A., 2012. Nominal group technique: an effective method for obtaining group consensus. Int. J. Nurs. Pract. 18, 188–194. https://doi.org/10.1111/j.1440-172X.2012.02017.x

Hazarika, N., Barman, D., Das, A.K., Sarma, A.K., Borah, S.B., 2018. Assessing and mapping flood hazard, vulnerability and risk in the Upper Brahmaputra River valley using stakeholders' knowledge and multicriteria evaluation (MCE). J. Flood Risk Manag. 11, S700–S716. https://doi.org/10.1111/jfr3.12237

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25, 1965–1978. https://doi.org/10.1002/joc.1276

IUCN, 2016. World Database on Protected Areas [WWW Document]. URL https://www.iucn.org/theme/protected-areas/our-work/world-database-protected-areas (accessed 7.5.18).

Jato-Espino, D., 2016. Hydrological modelling of urban catchments under Climate Change for the design of a spatial decision support system to mitigate flooding using pervious pavements meeting the principles of sustainability. Universidad de Cantabria, Spain.

Jato-Espino, D., Castillo-Lopez, E., Rodriguez-Hernandez, J., Ballester-Muñoz, F., 2018. Air quality modelling in Catalonia from a combination of solar radiation, surface reflectance and elevation. Sci. Total Environ. 624, 189–200. https://doi.org/10.1016/j.scitotenv.2017.12.139

Jato-Espino, D., Castillo-Lopez, E., Rodriguez-Hernandez, J., Canteras-Jordana, J.C., 2014. A review of application of multi-criteria decision making methods in construction. Autom. Constr. 45, 151–162. https://doi.org/10.1016/j.autcon.2014.05.013

Jato-Espino, D., Sillanpää, N., Charlesworth, S.M., Andrés-Doménech, I., 2016a. Coupling GIS with Stormwater Modelling for the Location Prioritization and Hydrological Simulation of Permeable Pavements in Urban Catchments. Water (Switzerland) 8. https://doi.org/10.3390/w8100451

Jato-Espino, D., Sillanpää, N., Charlesworth, S.M., Rodriguez-Hernandez, J., 2016b. A simulation-optimization methodology to model urban catchments under non-stationary extreme rainfall events. Environ. Model. Softw. https://doi.org/10.1016/j.envsoft.2017.05.008

Jenson, S.K., Domingue, J.O., 1988. Extracting topographic structure from digital elevation data for geographic information system analysis. Photogramm. Eng. Remote Sensing 54, 1593–1600.

Jonkman, S.N., 2005. Global Perspectives on Loss of Human Life Caused by Floods. Nat. Hazards 34, 151–175. https://doi.org/10.1007/s11069-004-8891-3

Jun, C., Ban, Y., Li, S., 2014. Open access to Earth land-cover map. Nature 514, 434–434. https://doi.org/10.1038/514434c

Kandilioti, G., Makropoulos, C., 2012. Preliminary flood risk assessment: The case of

Athens. Nat. Hazards 61, 441–468. https://doi.org/10.1007/s11069-011-9930-5

Katz, E.C., Niedzwiedz, J., Steyer, L., 2017. Visualisierung sozialer vulnerabilität Kölns: eine ArcGIS-gestützte untersuchung. Zeitschrift für studentische wasserbezogene Forsch. I, 15–22.

Kenyon, W., 2007. Evaluating flood risk management options in Scotland: A participant-led multi-criteria approach. Ecol. Econ. 64, 70–81. https://doi.org/10.1016/j.ecolecon.2007.06.011

Kienberger, S., Lang, S., Zeil, P., 2009. Spatial vulnerability units – expert-based spatial modelling of socio-economic vulnerability in the Salzach catchment, Austria. Nat. Hazards Earth Syst. Sci. 9, 767–778. https://doi.org/10.5194/nhess-9-767-2009

Kubal, C., Haase, D., Meyer, V., Scheuer, S., 2009. Integrated urban flood risk assessment - Adapting a multicriteria approach to a city. Nat. Hazards Earth Syst. Sci. 9, 1881–1895. https://doi.org/10.5194/nhess-9-1881-2009

Lee, G., Jun, K.S., Chung, E.S., 2013. Integrated multi-criteria flood vulnerability approach using fuzzy TOPSIS and Delphi technique. Nat. Hazards Earth Syst. Sci. 13, 1293–1312. https://doi.org/10.5194/nhess-13-1293-2013

Levy, J.K., 2005. Multiple criteria decision making and decision support systems for flood risk management. Stoch. Environ. Res. Risk Assess. 19, 438–447. https://doi.org/10.1007/s00477-005-0009-2

Levy, J.K., Hartmann, J., Li, K.W., An, Y., Asgary, A., 2007. Multi-Criteria Decision Support Systems for Flood Hazard Mitigation and Emergency Response in Urban Watersheds. J. Am. Water Resour. Assoc. 43, 346–358. https://doi.org/10.1111/j.1752-1688.2007.00027.x

Loos, J.R., Rogers, S.H., 2016. Understanding stakeholder preferences for flood adaptation alternatives with natural capital implications. Ecol. Soc. 21, art32.

https://doi.org/10.5751/ES-08680-210332

LP DAAC, 2014. ASTGTM: ASTER Global Digital Elevation Model V002 [WWW Document]. URL https://lpdaac.usgs.gov/node/1079 (accessed 7.4.18).

Luu, C., von Meding, J., 2018. A Flood Risk Assessment of Quang Nam, Vietnam Using Spatial Multicriteria Decision Analysis. Water 10, 461. https://doi.org/10.3390/w10040461

Malczewski, J., Rinner, C., 2015. Multicriteria Decision Analysis in Geographic Information Science, 1st ed. Springer-Verlag Berlin Heidelberg, Heidelberg (Germany). https://doi.org/10.1007/978-3-540-74757-4

Malekian, A., Azarnivand, A., 2016. Application of Integrated Shannon's Entropy and VIKOR Techniques in Prioritization of Flood Risk in the Shemshak Watershed, Iran. Water Resour. Manag. 30, 409–425. https://doi.org/10.1007/s11269-015-1169-6

Mallouk, A., Lechgar, H., Malaainine, M.E., Rhinane, H., 2016. A Multicriteria Approach with GIS for Assessing Vulnerability to Flood Risk in Urban Area (Case of Casablanca City, Morocco). Springer Verlag, pp. 257–266. https://doi.org/10.1007/978-3-319-30301-7_27

McMaster, R.B., Leitner, H., Sheppard, E., 1997. GIS-based Environmental Equity and Risk Assessment: Methodological Problems and Prospects. Cartogr. Geogr. Inf. Sci. 24, 172–189. https://doi.org/10.1559/152304097782476933

Meyer, V., Becker, N., Markantonis, V., Schwarze, R., van den Bergh, J.C.J.M., Bouwer, L.M., Bubeck, P., Ciavola, P., Genovese, E., Green, C., Hallegatte, S., Kreibich, H., Lequeux, Q., Logar, I., Papyrakis, E., Pfurtscheller, C., Poussin, J., Przyluski, V., Thieken, A.H., Viavattene, C., 2013. Review article: Assessing the costs of natural hazards – state of the art and knowledge gaps. Nat. Hazards Earth Syst. Sci. 13, 1351–1373. https://doi.org/10.5194/nhess-13-1351-2013

Meyer, V., Scheuer, S., Haase, D., 2009. A multicriteria approach for flood risk mapping exemplified at the Mulde river, Germany. Nat. Hazards 48, 17–39. https://doi.org/10.1007/s11069-008-9244-4

Müller, A., Reiter, J., Weiland, U., 2011. Assessment of urban vulnerability towards floods using an indicator-based approach-a case study for Santiago de Chile. Nat. Hazards Earth Syst. Sci. 11, 2107–2123. https://doi.org/10.5194/nhess-11-2107-2011

Neumann, B., Vafeidis, A.T., Zimmermann, J., Nicholls, R.J., 2015. Future coastal population growth and exposure to sea-level rise and coastal flooding - A global assessment. PLoS One 10, e0118571. https://doi.org/10.1371/journal.pone.0118571

Osborne, J.W., Waters, E., 2003. Four assumptions of multiple regression that researchers should always test. Pract. Assessment, Res. and Eval. Vol. 8, Page 2.

Panhalkar, S.S., Jarag, A.P., 2017. Flood Risk Assessment of Panchganga River (Kolhapur District, Maharashtra) Using GIS-Based Multicriteria Decision Technique. Curr. Sci. 112, 785. https://doi.org/10.18520/cs/v112/i04/785-793

Patrikaki, O., Kazakis, N., Kougias, I., Patsialis, T., Theodossiou, N., Voudouris, K., 2018. Assessing Flood Hazard at River Basin Scale with an Index-Based Approach: The Case of Mouriki, Greece. Geosciences 8, 50. https://doi.org/10.3390/geosciences8020050

Pelling, M., 2007. Learning from others: The scope and challenges for participatory disaster risk assessment. Disasters 31, 373–385. https://doi.org/10.1111/j.1467-7717.2007.01014.x

Prell, C., Hubacek, K., Quinn, C., Reed, M., 2008. “Who”s in the network?’ When stakeholders influence data analysis. Syst. Pract. Action Res. 21, 443–458. https://doi.org/10.1007/s11213-008-9105-9

Raaijmakers, R., Krywkow, J., van der Veen, A., 2008. Flood risk perceptions and spatial multi-criteria analysis: an exploratory research for hazard mitigation. Nat. Hazards 46, 307–322. https://doi.org/10.1007/s11069-007-9189-z

Rufat, S., Tate, E., Burton, C.G., Maroof, A.S., 2015. Social vulnerability to floods: review of case studies and implications for measurement. Int. J. Disaster Risk Reduct. 14, 470–486. https://doi.org/10.1016/j.ijdrr.2015.09.013

Saaty, T.L., 1980. The analytic hierarchy process. McGraw-Hill, New York, USA.

San Cristóbal Mateo, J.R., 2012. Multi Criteria Analysis in the Renewable Energy Industry, Green Energy and Technology. Springer London, London. https://doi.org/10.1007/978-1-4471-2346-0

Schanze, J., 2006. Flood risk management - A basic framework, in: Schanze, J., Zeman, E., Marsalek, J. (Eds.), Flood Risk Management: Hazards, Vulnerability and Mitigation Measures. Springer, Dordrecht, Netherlands, pp. 1–20.

Scolobig, A., Broto, V.C., Zabala, A., 2008. Integrating Multiple Perspectives in Social Multicriteria Evaluation of Flood-Mitigation Alternatives: The Case of Malborghetto-Valbruna. Environ. Plan. C Gov. Policy 26, 1143–1161. https://doi.org/10.1068/c0765s

SEDAC, 2017. Gridded Population of the World (GPW), v4 [WWW Document]. URL http://sedac.ciesin.columbia.edu/data/collection/gpw-v4/sets/browse (accessed 7.5.18).

Seekao, C., Pharino, C., 2016. Assessment of the flood vulnerability of shrimp farms using a multicriteria evaluation and GIS: a case study in the Bangpakong Sub-Basin, Thailand. Environ. Earth Sci. 75, 308. https://doi.org/10.1007/s12665-015-5154-4

Sharifi, M.A., van den Toorn, W., Rico, A., Emmanuel, M., 2002. Application of GIS and multicriteria evaluation in locating sustainable boundary between the tunari National Park and Cochabamba City (Bolivia). J. Multi-Criteria Decis. Anal. 11, 151–164. https://doi.org/10.1002/mcda.323

Simão, A., Densham, P.J., (Muki) Haklay, M., 2009. Web-based GIS for collaborative planning and public participation: An application to the strategic planning of wind farm sites. J. Environ. Manage. 90, 2027–2040. https://doi.org/10.1016/j.jenvman.2007.08.032

Solín, Ľ., 2012. Spatial variability in the flood vulnerability of urban areas in the headwater basins of Slovakia. J. Flood Risk Manag. 5, 303–320. https://doi.org/10.1111/j.1753-318X.2012.01153.x

Sowmya, K., John, C.M., Shrivasthava, N.K., 2015. Urban flood vulnerability zoning of Cochin City, southwest coast of India, using remote sensing and GIS. Nat. Hazards 75, 1271–1286. https://doi.org/10.1007/s11069-014-1372-4

Tang, Z., Yi, S., Wang, C., Xiao, Y., 2018. Incorporating probabilistic approach into local multi-criteria decision analysis for flood susceptibility assessment. Stoch. Environ. Res. Risk Assess. 32, 701–714. https://doi.org/10.1007/s00477-017-1431-y

Tarboton, D.G., Bras, R.L., Rodriguez-Iturbe, I., 1991. On the extraction of channel networks from digital elevation data. Hydrol. Process. 5, 81–100. https://doi.org/10.1002/hyp.3360050107

Tate, E., 2012. Social vulnerability indices: A comparative assessment using uncertainty and sensitivity analysis. Nat. Hazards 63, 325–347. https://doi.org/10.1007/s11069-012-0152-2

UNISDR, 2015a. Sendai framework for disaster risk reduction 2015 -2013. Geneva, Switzerland..

UNISDR, 2015b. The human cost of weather-related disasters 1995-2015. Brussels (Belgium) and Geneva (Switzerland).

USDA, 2018. Natural Resources Conservation Service [WWW Document]. URL https://www.nrcs.usda.gov/wps/portal/nrcs/site/national/home/ (accessed 7.5.18).

van Hove, L.W.A., Jacobs, C.M.J., Heusinkveld, B.G., Elbers, J.A., Van Driel, B.L., Holtslag, A.A.M., 2015. Temporal and spatial variability of urban heat island and thermal comfort within the Rotterdam agglomeration. Build. Environ. 83, 91–103. https://doi.org/10.1016/j.buildenv.2014.08.029

Voinov, A., Kolagani, N., McCall, M.K., Glynn, P.D., Kragt, M.E., Ostermann, F.O., Pierce, S.A., Ramu, P., 2016. Modelling with stakeholders - Next generation. Environ. Model. Softw. 77, 196–220. https://doi.org/10.1016/j.envsoft.2015.11.016

Wang, Y., Li, Z., Tang, Z., Zeng, G., 2011. A GIS-Based Spatial Multi-Criteria Approach for Flood Risk Assessment in the Dongting Lake Region, Hunan, Central China. Water Resour. Manag. 25, 3465–3484. https://doi.org/10.1007/s11269-011-9866-2

Wright, R., Stein, M., 2005. Snowball Sampling, in: Encyclopedia of Social Measurement. Elsevier, pp. 495–500. https://doi.org/10.1016/B0-12-369398-5/00087-6

Xiao, Y., Yi, S., Tang, Z., 2017. Integrated flood hazard assessment based on spatial ordered weighted averaging method considering spatial heterogeneity of risk preference. Sci. Total Environ. 599–600, 1034–1046. https://doi.org/10.1016/j.scitotenv.2017.04.218

Yang, M., Qian, X., Zhang, Y., Sheng, J., Shen, D., Ge, Y., 2011. Spatial multicriteria decision analysis of flood risks in aging-dam management in China: A framework and case study. Int. J. Environ. Res. Public Health 8, 1368–1387. https://doi.org/10.3390/ijerph8051368

Zeleňáková, M., Dobos, E., Kováčová, L., Vágo, J., Abu-Hashim, M., Fijko, R., Purcz, P., 2018. Flood vulnerability assessment of Bodva cross-border river basin. Acta Montan. Slovaca 23, 53–61.