Flood Vulnerability Analysis in Urban Context: A Socioeconomic Sub-Indicators Overview

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Review

Flood Vulnerability Analysis in Urban Context: A Socioeconomic Sub-Indicators Overview

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Abstract: Despite indicators-based assessment models for flood vulnerability being a well-established methodology, a specific set of indicators that are universally or widely accepted has not been recognized yet. This work aims to review previous studies in the field of vulnerability analysis in order to overcome this knowledge gap identifying the most accepted sub-indicators of exposure, sensitivity and adaptive capacity. Moreover, this review aims to clarify the use of the terms of vulnerability and risk in vulnerability assessment. Throughout a three-phase process, a matrix containing all the sub-indicators encountered during the review process was constructed. Then, based on an adaptation of the Pareto diagram, a set of the most relevant sub-indicators was identified. According to the citation count of each sub-indicator, indeed, 33 sub-indicators were chosen to represent the most universally or widely accepted sub-indicators.

Keywords: flood; vulnerability; indicators; urban; IPCC

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1. Introduction

The prevention of disastrous flood events is supported by models and quantitative flood risk assessments that provide the evidence for risk-based decision making [1]. Nevertheless, the understanding of present and future flood risk is still a challenge [2], since both contextual characteristics and climate changes influence flood risk with uncertain and unclear impacts [3,4]. Contextual characteristics include both the geographical dimension (hazard formation and its interaction with the territory) and the socio-economic aspects of the society (social, economic and political conditions, cultural and institutional norms, societal networks, governance and historical processes) [5]. Consequently, a modern approach relies more on flood risk management—involving not only purely technical measures—rather than only on flood protection [6–8]. Thereby, the information on the vulnerability of a territory to flood events support risk-informed decision-making approaches.

The IPCC Fifth Assessment Report [3] defines the vulnerability as "the propensity or predisposition to be adversely affected [by hazards]. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt". Moreover, it stresses that "vulnerability and exposure are dynamic, varying across temporal and spatial scales, and depend on economic, social, geographic, demographic, cultural, institutional, governance, and environmental factors". Thus, a territory may be more or less prone to natural hazards risk based on social conditions [9]. For example, [10] proposes the definition of social vulnerability in terms of individual and social groups capacity to respond to any external stress threatening their well-being, with a special attention to socioeconomic and institutional constraints. This framework proposes a proactive approach and the importance of reducing the vulnerability before a hazardous event occurs [11]. However, the geographic effect on the overall vulnerability of the place includes also the positioning and the condition of the place, as well as the proximity to hazard sources. In the end, the interaction of the social and biophysical vulnerability elements mutually produces the overall vulnerability of the place [12]. Factors such as high education level, good condition dwellings and the existence of flood warning systems reduce the vulnerability of a territory, whereas factors such as poverty, social inequalities and institutional adaptation [13] can limit the capacity to cope effectively.

Vulnerability quantification is frequently based on indicator-based assessment models [14] due to their capacity to give a precise vision of overall flood vulnerability in each area [15]. The determination of the vulnerability of a territory, hence, is based on the definition of sub-indicators of exposure, sensitivity and adaptive capacity.

Indicator-based assessment models for flood vulnerability, though, do not have a specific set of indicators that are universally or widely accepted [16]. Moreover, [5] highlights the situational variability of social vulnerability drivers. Not all drivers, indeed, have a priori a reliable influence on social vulnerability in all contexts, even for the most widely agreed upon characteristics such as age and class. The great flexibility of the methodology, however, affects the comparability of the results. This indicates a need to identify the sub-indicators of exposure, sensitivity and adaptive capacity on which greater agreement exists. However, indicator-based vulnerability assessments are complicated by i) standardization procedures, weighting and aggregation methods [15] and ii) cross-disciplinarity of the issue. In fact, vulnerability studies are carried out from researchers in different fields. Sometimes, indeed, researchers wrongly address this quantification as a risk analysis. The risk, rather, is defined as "the interaction of social and environmental processes, from the combination of physical hazards and the vulnerabilities of exposed elements" [17]. Therefore, the terms risk and vulnerability should not be used interchangeably as sometimes occurs [18].

In the past, previous studies have reviewed works concerning vulnerability assessments with different purposes. For example, [15] reviews the more accepted assessing methods (curve method, disaster loss data method, computer modeling methods and indicator-based methods) concluding that the indicator-based approach provides a wider, rapid and trustworthy evaluation of flood vulnerability in a specific geographical region compared to other approaches. Drawbacks of this approach entail the quantification of social sub-indicators and good data requirement. In fact, another study [19], tracing the evolutionary pathway of urban vulnerability assessments, remarks that the so-called water flooding infrastructure-related stimuli studies—mainly related to the impact stage—still prevail on comprehensive vulnerability assessments finalized to the adaptation. However, rather than being a supremacy, the outnumbered highlights a stagnation in its evolution, suggesting the need to shift the focus towards the integration of multi-objective and dynamic research requirement.

A review published in 2015 identifies and classifies the leading drivers of social vulnerability to floods (in its broadest sense) contributing to the development of indicator-based assessment modelling. In particular, the sub-indicators are sorted by their frequency of appearance, impact on vulnerability, flood type and development context [5]. Nonetheless the review focuses only on social vulnerability drivers rather than on the overall vulnerability drivers. Therefore, although it is specifically exhaustive concerning social vulnerability, this review lacks completeness regarding the overall concept of vulnerability. Similarly, [18] outlines an inventory of popularly used indicators for flood vulnerability assessments. The review groups the sub-indicators in thematic classes (social/residential vulnerability, economic, dynamic vulnerability, physical/structural/landscape vulnerability, geomorphological/geophysical, risk perception and building vulnerability) but does not clarify the indicator of belonging of each thematic class.

This works aims to review previous works in the field of vulnerability analysis in order to (i) overcome this knowledge gap identifying the most accepted sub-indicators of exposure, sensitivity and adaptive capacity; (ii) clarify the use of the terms' vulnerability and risk in vulnerability assessment.

The remainder of the paper is organized as follows.

Section 2 clarifies the definition of vulnerability and risk used in this paper. Section 3 provides information on the methods adopted to conduct the literature review, to screen and select the papers as well as to identify the thresholds for sub-indicators retention. Section 4 provides and describes the results concerning the most widely used sub-indicators, along with the discussion of the results. Conclusions are provided in Section 5.

2. The Definition of Vulnerability and Risk

The vulnerability is generally set out as [20–23]:

$$V = (E \times S)/AC, \tag{1}$$

where S is the physical predisposition of human beings, infrastructure and environment to be affected by a dangerous phenomenon due to lack of resistance and predisposition to suffer harm as a consequence of intrinsic and context conditions; E refers to the inventory of elements in an area in which hazardous events may occur. Exposure is a necessary, but not sufficient, determinant of risk; AC is the ability of an individual, family, community, or other social group to adjust to changes in the environment guaranteeing survival and sustainability.

The risk is usually set out as [24–26]:

$$R = H \times E \times V, \tag{2}$$

where H refers to the possible, future occurrence of natural or human-induced physical events that may have adverse effects on vulnerable and exposed elements; E refers to the inventory of elements in an area in which hazardous events may occur; V refers to the propensity of exposed elements such as human beings, their livelihoods and assets to suffer adverse effects when impacted by hazard events.

3. Methods

3.1. Terms of Search and Literatura Database Used

The proposed review was completed in a three steps process: a general review of the outcomes of the searches, a brief review of a narrow set of papers and the content analysis in order to establish the most used sub-indicators. Considering the topic of interest, the authors selected some keywords that are intentionally general although fitting for the purpose:

TITLE: ["vulnerability OR risk"]
TITLE, ABSTRACT AND KEYWORDS: ["indicator OR index", "flood", "urban", NOT "coast"]

Since the existence of alternative words, some terms were searched using the instruction OR. In particular, the terms "vulnerability OR risk" were searched in the title field, while the terms "indicator OR index" were searched in the title-abstract-keywords fields along with the terms "flood" and "urban". Considering that many studies involve coastal flooding vulnerability and risk, the authors decided to exclude the term "coast" and its alternative forms. Other options of search used were (1) finalized publications (2) in the type form of article or book chapter (3) contained in sources such as journals and books. Reviews were purposely left out from the research in order to retain only original use of sub-indicators in the vulnerability assessment applications.

The search was performed in three different literature databases: Scopus, Science Direct and Web of Science.

3.2. Paper Selection Processes

The selection process was then realized eliminating irrelevant results, most of which focused on different natural or non-natural hazards related to flood events, e.g., contamination processes, health consequences, as well as applications to rural contexts that were not of interest for this review.

Since the focus of this review is the socio-economic conditions, another significant selection criterion was the presence of socio-economic sub-indicators demonstrating that social vulnerability factors are taken into consideration.

However, since the vulnerability concept is investigated in a variety of disciplines, the selected papers belong to different subject areas as well (Figure 1). Consequently, it would be a challenge to perform a cross-check review of the references contained in the eligible papers. A common characteristic of the papers is the publication date after 2009. In 2009, the publication of [27,28], indeed, marked a division. Even if the attention to the disaster risk management emerged in the 1990s when the United Nations General Assembly recognized the need for reducing the impact of natural disasters [29] generating a worthwhile debate on disaster risk components. These were discussed and investigated based on the pioneering studies on the social component of vulnerability of Blaikie et al. [9] and Cutter et al. [12,30], furtherly reviewed by [16]. However, the holistic approaches of [27,28] contributed greatly to the creation of indicator-based assessment models literature. All the territories and societies are vulnerable to floods, with impacts that differ from cases and situations, additionally to the occurrence of the hazard. This consideration of systemic impacts is then embraced in water resources decision making.

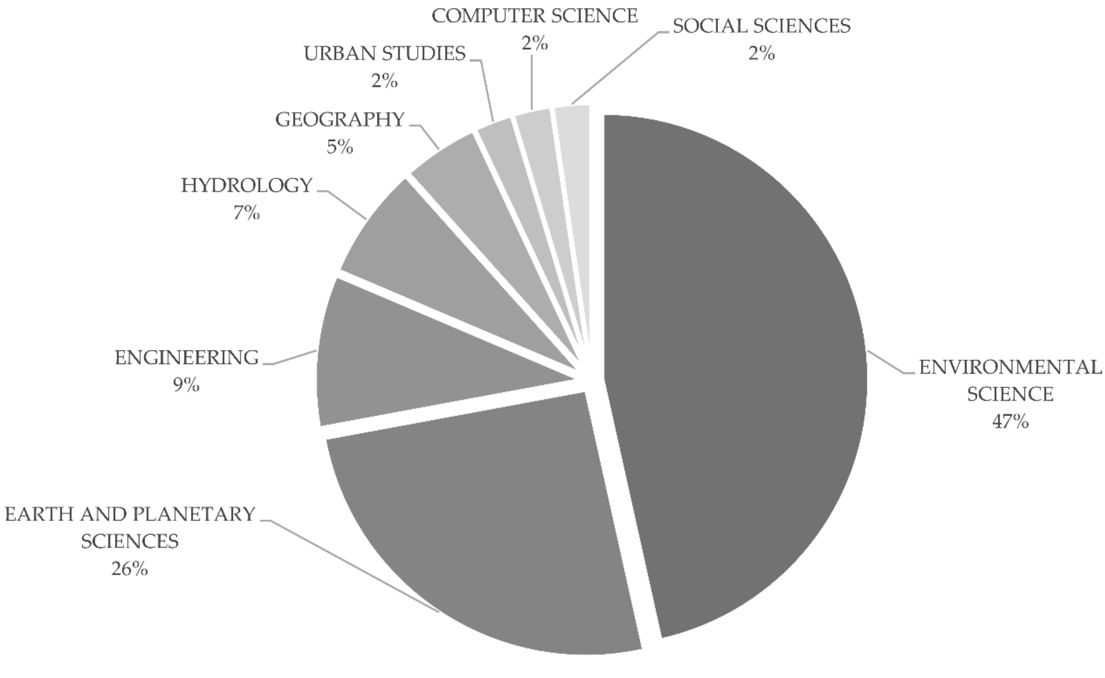

Figure 1. Subject areas of selected papers.

3.3. Threshold Identification for Sub-Indicators Retention

At the end of the selection process, the sub-indicators were screened using an adaptation of the Pareto diagram. The Pareto diagram, indeed, is used when it is necessary to evaluate the importance of the elements, i.e., priorities, decisions [31]. In this case, it helps in identifying the threshold above which we decide to keep a sub-indicator using a specific threshold for the indicators of exposure, sensitivity and adaptive capacity. Based on the matrix results, the sub-indicators were divided in citation count classes then separated in two different groups, one containing the 80% of the cumulative relative frequency of the classes that contain the least cited sub-indicators and the other containing the remaining 20% that contains the most cited sub-indicators. The higher frequency value contained in the cut-off class is used as the sub-indicators' acceptance threshold. In this way, we select the sub-indicators that appear more frequently in the papers reviewed.

4. Results and Discussion

4.1. Study Selection

The search in Web of Science obtained 176 results, in Scopus 196 results, in Science Direct 50 results. The review was then conducted in a three steps process (Figure 2). Another publication was added to the collection through the service Mendeley Suggest that provides recommendations for papers to read according to the most recent query performed. After all duplicates were removed, the collection resulted in a selection of 227 papers. This selection contained also irrelevant results that were not of interest for this review. The results not relevant for this review were applications to different natural disasters (landslide, earthquake, storm surge, hurricane or tsunamis) or other type of disasters (water contamination, heavy metal contamination) or focused on rural contexts (for a total amount of 45 papers). Then, after the selection based on the presence of socio-economic sub-indicators, which constituted the main reason based on which the papers were discarded, this process of general review ended with the selection of a narrow set of 60 papers.

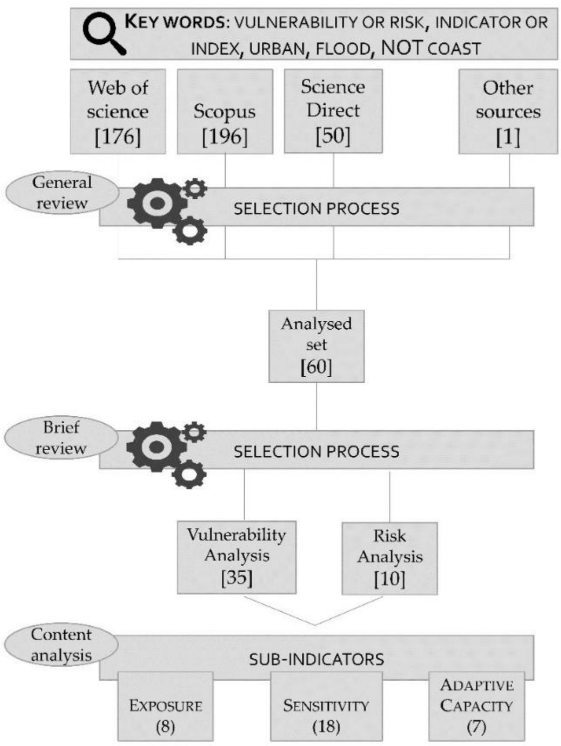

Figure 2. The review process.

This set of 60 papers contained both flood vulnerability analysis and risk analysis in an urban context. In fact, even if this review focuses on vulnerability analysis, the misuse of the term risk also determines the investigation of the so-called risk analysis that are vulnerability analysis. At the end of the second selection process, the collection was composed of 35 papers focusing on vulnerability analysis and 25 papers focusing on risk analysis.

4.2. Brief Review: Risk Analysis Studies Selection Process

In the set of 25 papers focusing on risk analysis, different combinations of indicators are found although the usual definition of risk should be H × E × V as suggested by [23,24]. In fact, only 10 out of 25 apply the definition as above suggested. The remaining studies apply the vulnerability definition (10 results) either an extension of the risk definition that includes sensitivity sub-indicators (five results) (references without formatting in Table 1). The difference between the definitions of vulnerability and risk stands in the estimation of the adaptive capacity of a system.

Therefore, only the papers containing sub-indicators of adaptive capacity (10 results) were retained for the subsequent content analysis, as they are completely comparable to vulnerability analysis (references in bold italics in Table 1).

Table 1. Sub-indicators used in the papers performing risk analysis. The papers retained are highlighted in bold italics.

		HAZARD	EXPOSURE	VULNERABILITY	SENSITIVITY	ADAPTIVE CAPACITY
2017	Armenakis et al. [32]	x	x	x		
2019	Cai et al. [33]	x	x	x		
2019	***Chen* et al.** [34]	x	x		x	x
2020	***Chen* et al.** [35]	x	x		x	x
2015	Domeneghetti et al. [36]	x	x	x		
2014	Edjossan-Sossou et al. [37]					
2018	***Elboshy* et al.** [38]	x	x		x	x
2020	***Ellena* et al.** [39]	x	x	x	x	x
2020	Geng et al. [40]	x	x	x		
2020	Hossain and Meng [41]	x	x		x	
2011	Kaźmierczak and Cavan [42]	x	x	x	x	
2020	***Koc and Işik*** [43]		x		x	x
2009	Kubal et al. [44]	x	x	x		
2013	***Li* et al.** [45]	x	x	x	x	x
2020	Lin et al. [46]	x		x		
2020	***Lv* et al.** [47]		x	x	x	x
2010	Maantay et al. [48]		x	x	x	
2014	Muller [49]	x	x	x	x	
2018	***Rana and Routray*** [50]	x	x		x	x
2015	Ronco et al. [51]	x	x	x		
2019	***Shi* et al.** [52]	x	x	x	x	x
2017	***Sun* et al.** [53]	x	x		x	x
2020	Wang et al. [54]	x	x	x		
2014	Yoon et al. [55]	x		x		
2019	Yu et al. [56]	x	x	x		

4.3. Content Analysis

A matrix was constructed gradually integrating the sub-indicators encountered during the reading of the papers. Therefore, as the review progressed, additional sub-indicators were included.

The final matrix, reported in Table A1 in the Appendix, contains 165 sub-indicators: 40 sub-indicators of exposure, 97 sub-indicators of sensitivity and 28 sub-indicators of adaptive capacity/resilience.

To establish the sub-indicators' acceptance threshold, an adaptation of the Pareto diagram is used. Based on the matrix results, the sub-indicators were divided in citation count classes (each class represent the number of citations received for each sub-indicator). In the diagram in Figure 3, these classes are arranged, depending on their absolute frequency, with a decreasing order. The vertical dashed bar identifies the cut-off class that divides the 80% of the cumulative relative frequency of the classes that contain the least cited sub-indicators from the remaining 20% that contains the most cited sub-indicators. The higher frequency value contained in the cut-off class is used as sub-indicators' acceptance threshold. In this way, we selected the sub-indicators that appeared more frequently in the papers reviewed. In fact, even if the absolute frequency of the remaining classes is higher, these are not relevant citation count classes, as they are referring to the least cited sub-indicators. Thus, we will use the thresholds of six citation counts for exposure, sensitivity and adaptive capacity. Accordingly, the total number of sub-indicators retained as the most widely used is 33: 8 exposure sub-indicators, 18 sensitivity sub-indicators, seven adaptive capacity sub-indicators (Table 2).

Table 2. Matrix containing the most widely used sub-indicators. Sub-indicators contained in the dashed boxes are usually assessed by qualitative research techniques. Exposure sensitivity and adaptive capacity acceptance threshold = 6. CC stands for citation count.

EXPOSURE		SENSITIVITY		ADAPTIVE CAPACITY	
Sub-Indicators	**CC**	**Sub-Indicators**	**CC**	**Sub-Indicators**	**CC**
Population density	29	% People with disabilities	14	Preparedness/awareness	13
Inhabitants aged 65 or older	26	Unemployment rate	14	Drainage network/pipelines density	12
Inhabitants aged 0-4/5	22	Building condition (quality/type of the materials)	14	Past experience	11
Inhabitants aged 5-13	14	Education level	12	Warning system	9
Household size	10	% Female	11	Risk insurance	8
Urbanized area, built-up area	8	Households with 1 story above ground level and/or 1 story below ground level	11	Road density	7
Topography (elevation)	8	Age of construction	10	Evacuation routes	6
Green spaces/Urban green coverage	7	Households with 2 or more stories above ground level	9		
		Number of dwellings located at flood prone area	8		
		Per capita income	7		
		Dependency rate	6		
		Illiterate people	6		
		Population with low education level (<years)	6		
		Foreigners	6		
		Dependency on public infrastructure	6		
		Type of utilization (of the building)	6		
		Percentage of home rented/owned	6		
		Industries and other economic activities	6		

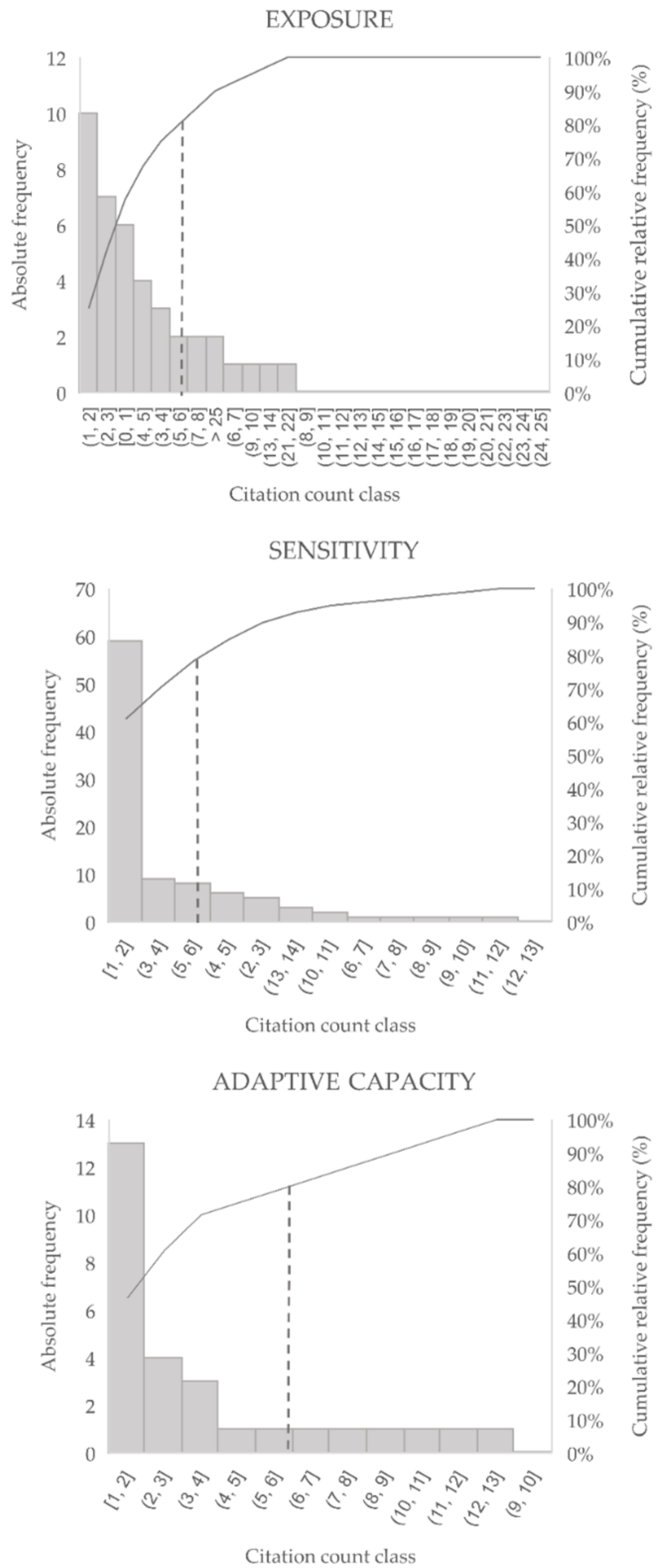

Figure 3. Pareto diagrams for the selection the of sub-indicators' acceptance threshold. On the x-axis: citation count class (from the left, the least cited sub-indicators' classes to the right, the more cited sub-indicators' classes). On the y-axis: **left**) absolute frequency; **right**) cumulative relative frequency (%). The vertical dashed bar demarcates the 80–20% boundary.

4.4. Discussion on the Sub-Indicators Selected

The most used exposure's sub-indicators are related to population characteristics, above all population density along with population specification like inhabitants age groups (0–4/5, 5–15, >65 years) and household size. Population density and its dynamical variation in time and space along with age stratification measures the different exposition of the territory in terms of people that may be affected when inundation occurs [57]. Other sub-indicators concern the contextual environment, in particular, the urbanized area/built-up area, topography and the presence of green spaces or urban green coverage. Those characteristics influences the severity of a flood event, since they all modify the surface run-off and the soil permeability/imperviousness [58]. These sub-indicators belong to the category of geomorphological and physical sub-indicators that are taken into consideration in this analysis, as they influence socioeconomic aspects.

Sensitivity is more subjected to variability in terms of sub-indicators retained. However, most of them can be attributed to an "entrapment situation". In fact, relevant sub-indicators belong to social characteristics that reduce the ability to cope with flood events, such as having a low education level or different form of disabilities as well as being foreigners or dependent on others. For example, minorities and foreigners are considered more sensitive targets, because they may have different languages and cultural barriers impeding the penetration of warnings and risk awareness. Moreover, since they occupy lower classes in society, they are prone to live in hazardous areas [59] and may experience difficulties in receiving disaster recovery funds. Being a female is equally considered a sensitivity sub-indicator; however, this application should be limited to context where women have a subordinated role compared to men in terms of education and economic dependence, i.e., less developed countries. The housing type, age of construction, stories above or below ground level, renters or owners also play a role in the sensitivity indicator, since the house may be more or less prone to be damaged and, consequently, exposing the occupiers to injuries or fatalities [49]. It is demonstrated that home owners are more likely to take measures to reinforce the building as prevention measure, and, at the same time, they are more connected to the neighborhood tissue due to a more stable residence [30,60,61]. Being unemployed or having an irregular occupation, indeed, increase the sensitivity as those people have lower saving capacity for house protection [60] and, at the same time, spend most of their time at home[30]. In the case of urban areas, the sub-indicator identifying industries and other important economic activities give a measure of the economic damages if inundation occurs [57].

The sub-indicators retained for the adaptive capacity concern past experience and preparedness to flood events in terms of individual abilities to contrast adverse situations along with institutional ability to communicate good practices, but also infrastructural preparedness. Therefore, the adaptive capacity includes road density and existence of evacuation routes sub-indicators, as proxies for the ability to escape [62], and drainage network density that measures the capacity to collect rainstorm water, preventing flooding [38]. Sub-indicators assessing personal and communities' preparedness and coordination such as preparedness and awareness, past experience and, to a certain extent, also the performance of warning system are usually investigated through the support of techniques that require people and/or experts' involvement, i.e., focus groups, structured interviews and questionnaires [38,50,63].

These results contribute to answer to the issue of which sub-indicators should be used to assess the vulnerability of a territory to flood events. However, the lack of agreement on core sub-indicators pairs with the difficulty of placing the sub-indicators detected in the correct indicator of exposure or sensitivity. In fact, there is neither agreement among the researchers on the collocation of the sub-indicators in one or another category. For example, the age class of the inhabitants has no certain collocation. Several studies [24,64–68] place the age groups in the sensitivity category, while others [69,70] place them in the physical exposure and finally, only one [71] places the youngest and the oldest age classes in the sensitivity indicator and the people between 15 and 64 years in the resilience class.

This is because the age group classes are a specification of the demographic density and, therefore, a sub-indicator of exposure. However, it can also be considered a characteristic of the sensitivity to floods since both children and old people are care-dependent. Moreover, [71] distinguishes these categories from the adult category, since they can help evacuate people during a flash flood event, and, thus, it can be considered a sub-indicator of adaptive capacity.

Similarly, in the exposure indicator, very different forms of the same sub-indicators are used. For example, the group of rainfall contains the following variety of forms: annual maximum precipitation, average annual rainfall, flood seasonal rainfall, monthly average precipitation, monthly total precipitation, continuous rainfall day, maximum rainfall in 24 h and heavy rainfall. However, these different forms could be counted as the same sub-indicator, since they are different rainfall specifications, and the choice of a specific form is just context-related. Therefore, even if they appear in their exact form only 1–3 times, their cumulative count suggests that the rainfall sub-indicator should be taken into consideration as an important sub-indicator when performing vulnerability analysis. Likewise, in the group of geography and topography, the sub-indicators of urbanized area, rural area, degraded area, vegetation cover, green spaces, forested area and land use could be grouped together in the land use and land cover class (LULC) and researchers can choose to use the form according to context characteristics and data availability instead of necessarily using the sub-indicators of urbanized/built-up area and green spaces/urban green coverage resulted from the Pareto diagram.

Therefore, we here identify a set of 33 most used sub-indicators; however, following the reasons abovementioned, the set should be expanded including indicators of rainfall and LULC as well.

5. Conclusions

This review aimed at identifying the most accepted sub-indicators of exposure, sensitivity and adaptive capacity, filling a gap in vulnerability assessment literature. To date, in fact, researchers have not agreed on the sub-indicators that should be used for assessing the vulnerability of a territory to flood events. Therefore, a systematic review was performed in order to construct a matrix containing all the sub-indicators encountered during the review of the papers. Throughout the Pareto diagram the most used sub-indicators in flood vulnerability analysis were identified. The Pareto diagram, however, is not able to capture similarities among sub-indicators. Therefore, other considerations on sub-indicators were evaluated suggesting the additional use of sub-indicators of rainfall and LULC.

The review contributed also to shed light on the definition of vulnerability and risk that are often use interchangeably. Throughout the revision process, papers conducting a vulnerability analysis instead of a risk assessment—evaluated based on the use of the indicators and the presence of adaptive capacity/resilience sub-indicators—were integrated in the set of papers analyzed.

The set of 33 sub-indicators should be seen a starting point to construct an indicators-based assessment model for flood vulnerability with the due limits above discussed.

More work will be needed, however, to determine the sensitivity of the results both to the variables selected and to the index construction. In fact, results could be affected by aggregation techniques and weight attribution and by minor changes in sub-indicators used as well. Sensitivity analysis on an aggregation and weights issue is investigated by several studies with different outcomes. Works on weighting and aggregation sensitivity were carried by [72–76] for flood-specific index and by [77,78] for broader natural-disasters. Further sensitivity analysis are sometimes applied limited to social vulnerability sub-indicators, as in [79–82], or with an hazard-oriented view, as in [83–85]. Sensitivity analysis on minor changes in sub-indicators used for the index construction are performed by [86–88] focusing on the comparison of the performance of the Social Vulnerability Index (SoVI) [30]—mostly applied in the U.S.A.—with other flood vulnerability indices or with sub-indicators subset of the SoVI itself. The paper of [88] finds that the employed subset of sub-indicators provided similar results to that derived using the full set of SoVI. However, [87] provides different results when compared to another widely used index (Center for Disease Control Social Vulnerability Index or CDC SVI). The SoVI is more equipped to find age related vulnerability, while the CDC SVI is better at finding socioeconomic related vulnerability. The results of [86] argue that, besides the internal validity of the SoVI, the index fails to explain empirical disaster outcomes. The explanatory sensitivity analyses conducted for the SoVI demonstrates the need for further investigation to obtain indices characterized by internal validity and empirical efficiency. Therefore, a fruitful area of research could start from a set of universally recognized indicators, as here proposed, to weigh and validate them in different contexts in order to achieve satisficing comparable results, rather than a maximizing result for which there is still a long way off.

This review contributes to shorten the sub-indicators selection process, as this work examined the most recent and relevant studies in the field, even if the variety of disciplines to which it refers may constitute a limit. At the same time the multidisciplinarity considered by this work opens up the boundary of the research on socioeconomic vulnerability giving the opportunity to apply the sub-indicators selected in analysis of different fields. Moreover, the choice of the sub-indicators is based on an innovative use of the Pareto diagram for citation counting that facilitates the sub-indicators selection process. The results of this work can be used in future applications as is, or else, researchers could apply the proposed methodology to other natural hazards.

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Appendix A

Table A1. The matrix of the sub-indicators of exposure, sensitivity and adaptive capacity presented along with the reference of the papers that mention each sub-indicator, respectively.

EXPOSURE		
GROUP	**SUB-INDICATORS**	**REFERENCES**
Topography/geography	Imperviousness/vertical permeability	[67,89,90]
	Urbanized area, built-up area	[27,35,47,91–94]
	Rural area	[91,92]
	Degraded area	[27,92]
	Topography (elevation)	[35,52,53,60,67,92,94,95]
	Vegetation cover	[65,67,90]
	Green spaces/urban green coverage	[14,35,59,76,90,96,97]
	Slope	[27,52,59,66]
	Forested area	[27,57,91]
	Land use	[14,27,53,65,95]
River/flood	Distance from the river	[52]
	River network	[52,53]
	Flooded area/submerged area/inundation area	[50,67,96–98]
	Water depth/inundation depth	[27,50,66]
	Flood duration	[27,50,66,98]
	Runoff	[57,96]
	Sedimentation load	[27]
	River discharge	[27,57,66]

	Return period	[14,27,59,63,66]
Rainfall	Comprehensive rainfall value	[39]
	Flood seasonal rainfall	[45,52,94]
	Continuous rainfall day	[35,53]
	Monthly average precipitation/monthly total precipitation	[35,53]
	Maximum rainfall in 24 h	[35,53,94]
	Annual maximum precipitation	[95]
	Average annual rainfall	[52,57,59,72,96]
	Heavy rainfall	[27,35]
Other physical factors	Evaporation	[27,57]
Population	Total Population	[64,71]
	Population in flooded area	[27,35,45,66]
	Unpopulated area	[27]
	Population density	[27,28,38,39,43,47,52,55,57,60,61–63,65,67,69,71,90–93,95,97,99–101]
	Rural population	[27,28]
Household composition	Inhabitants aged 0–4/5	[61,64,65,67,68,71,90,91,95,98]
	Inhabitants aged 5–13	[14,38,39,60,61,63,68,69,71,72,90,91,93,95,99,100,102,103]
	Inhabitants aged 15–64	[14,28,63,71,72,90,91]
	Inhabitants aged 65 or older	[14,28,38,39,60,61,63–69,71,72,89–91,93,95,98–100,102–104]
	Household where people aged 65 or older live	[61,63,71,100,105]
	Household size	[50,58,63,66,90,91,97–100]
	SENSITIVITY	
GROUP	**SUB-INDICATORS**	**REFERENCES**
Social point of interest	Kindergartens	[61,64,69,71,106]
	Elementary schools	[61,64,69,71,106]
	Secondary schools	[64,69,71,106]
	Retirement homes	[71,106]
	Health centers, hospitals	[27,57,64,69,71]
	Church	[64]
Facilities	Electrical transformers in flood prone area	[39,89,106]
	Bridges and overpasses located in flood prone area	[39]
	Length of street at flood prone area	[106]
	Parks and gardens at flood prone area	[106]
	Roads	[39]
	Water network	[69,89]
Residential/commercial building	Productivity land	[65]
	% Buildings with no residential function	[89,91]
	Number of dwellings located at flood prone area	[58,64,66,89,91,92,99,106]
	Main houses	[89,91,106]
	Damages to building (use, type)	[39,43]
	Secondary houses	[89,105]
Social characteristics	Dependency rate	[50,71,97,98,100,104]
	Population projections/growth	[27,57,71,90]
	Population changes over time (past)	[62]
	Illiterate people	[61,69,71,98–100]

	Population with low education level (<9 years)	[28,59,61,64,91,104]
	Population with high education level (> university degree)	[61,91]
	Education level	[27,38,43,50,58,60,66,67,97–100]
	Child mortality	[27,57]
	Foreigners	[59,61,63,69,71,100]
	Minorities	[93,102,103]
	Institutionalized groups (e.g., correctional institutions, nursing homes)	[50]
	% People with disabilities	[27,38,50,57,60,65,69,71,89,95,97,98,100,104]
	% Population living under poverty level	[27,60,65,100]
Household economic characteristics	Unemployment rate	[14,27,28,50,57,60,63,67,76,90,93,98,100,106]
	People without permanent income	[76,97]
	Long-term unemployed people	[71]
	Household where unemployed people live	[71]
	Benefit claimants	[70–98]
	Low-income households	[62,68,104]
	Dependency on public infrastructure	[14,58,68,90,93,97]
	HH responsible that earn at least twice the min salary	[64]
	Income gap between urban and rural residents	[105]
Building characteristics	Permanent households	[71]
	Vacant households	[71]
	Type of utilization	[38,43,50,52,95,100]
	Percentage of homes rented/owned	[50,60,61,90,91,97]
	One- or two-family homes	[28]
	Age of construction	[43,50,52,59,61,71,91,97,99,103]
	Underground built-up area/entries	[71,95]
	Building condition (quality/type of the materials)	[14,38,39,43,50,60,66,71,76,90,92,96,97,100]
	Households with 1 story above ground level and/or 1 story below ground level	[14,43,50,71,76,90,91,95,97,103,106]
	Households with 2 or more stories above ground level	[14,71,90,91,97,99,100,103,106]
	Economic value	[65]
	Living space (HH space per capita)	[28,71,76,99]
Travel time	Distance to train station	[62]
	Distance to the nearest hospital	[71,92]
	Travel time to the nearest hospital	[58,71]
	Distance to the nearest health center	[71]
	Travel time to the nearest health center	[50,71,97,98]
Society characteristics	Number of workers in agricultural sector	[106]
	Number of workers in industry, construction and service sector	[61,62,71,89]
	Self employed	[62]
	Income classes subdivision	[14,68,90,98,102]
	% Female	[38,50,61,62,65,67,91,97,98,100,104]
	Social level	[89]
	Crime rate	[100]

	Relationship between the neighbors	[58,90,97,98]
	Industries or other economic activities	[57,59,66,96,98,105]
Economic indexes	Municipal debt per inhabitants	[71,106]
	Municipal available budget per inhabitant	[71,106]
	Tax base of the property tax	[59,106]
	Per capita income	[50,61,71,93,97,100,106]
	GDP per capita/GDP per HH/GDP per neighborhood	[27,35,52,53]
	Ratio between taxable income and taxpayers in each municipality	[39]
	Fixed investment per inhabitants	[71,106]
	Ratio of investment over the total GDP/revenue–expenditure ratio	[47,57]
	Replacement cost for dwellings located at flood prone area	[106]
Transportation	Vehicle available	[39,69,89,97,106]
	Mean age of the vehicle fleet	[106]
	Traffic volume	[95]
	Mean duration of commute	[99]
Development	Per capita/city's fixed asset investment	[47,94]
	Per capita water resources	[45]
	Urbanization rate	[39,45,52]
	Human Development Index	[27,57]
	Inequality	[27,100]
	Life expectancy index	[27,100]
	Urban growth	[27,57]
	Infrastructure development level	[105]
	Natural reservation	[27]
	Urban water area %	[35,94]
Other	Primary industrial output value	[94]
	Per capita secondary and tertiary industrial output value	[94]
	Arable lands	[45,52]
	Protected objects of historical interest	[27,39,66,71]
	Unplanned settlements	[38,60]
	Unplanned waste deposits	[67,68]
	Damages from previous flood/direct economic loss from previous flood	[45,50,90,98]
	Tourist accommodation capacity	[71,106]
	ADAPTIVE CAPACITY	
GROUP	**SUB-INDICATORS**	**REFERENCES**
Economic indexes	Investment for damage reparation	[89]
	Public disaster response capacity	[35,45]
	Economic recovery/disaster relief investment/post disaster reconstruction capability	[27,35,94]
	Municipal flood control investments	[45]
	Risk insurance	[27,50,53,57,66,67,89,90]
	Warning system	[27,57,60,64,66,70,89,97,100]
Warning system	Past experience	[27,50,57,58,64,66,69,90,98,105]
	Preparedness/awareness	[27,38,39,43,50,57,60,64,66,89,90,97,100]
	Communication devices	[50]

	Communication penetration rate	[27,100]
	Temporary displacement to another place	[58]
Emergency response	Government assistance	[58]
	Road density	[43,45,52,89,92,98,99]
	Evacuation routes	[27,57,60,66,69,97]
	Number of people working in the emergency services	[27,57,66,69,95]
	Reserve and distribution capacity of flood control materials	[45]
	Emergency rescue capacity of public administration	[45]
	Hospital beds	[47,71,100]
	Medical staff	[47,69,71,105]
	Reception centers	[69]
	Investment in coping capacity	[27,64]
Preventive measures	Land use regulation	[60,89]
	Flood control standards/plans	[39,43,94]
	Hydraulic infrastructures	[39]
Protective infrastructures	Dikes/levees	[27,57,66,100]
	Drainage network/pipelines density	[35,43,45,47,52,53,57,68,70,92,94,96]
	Dams storage capacity/reservoir capacity	[27,52,57]
	Protection of rivers at flood prone area	[14,66,100,106]

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