Risk Mapping in Managing Flood Vulnerability in Disaster Management

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Abstract

Flood risk is a product of hazard and vulnerability, and is important in managing floods, making decisions, and developing policies. While different approaches can be used to construct these maps, Geographic Information System (GIS)-based maps are increasingly being adopted, which requires researchers to utilize different layers of information. Poorly constructed indices can present misleading messages; therefore, this chapter analyzes existing vulnerability indicators across geographic region and flood type. Moreover, all the indicators are examined for their selection criteria where a priority is given to each, to understand which

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A. Singh (ed.), *International Handbook of Disaster Research*,
https://doi.org/10.1007/978-981-16-8800-3_177-1

indicator is more important than another. These weights were then inputted into a sankey diagram to easily interpret which vulnerability dimension, indicator, and flood type is of highest priority. While these diagrams will assist researchers with their indicator selection process they will still encounter challenges with data scarcity and outdated data. Therefore, we propose the use of non-traditional data sources like social media to further enhance the flood vulnerability maps, a crucial requirement for crisis responders who need to prioritize their response operations.

Keywords

Flood · Vulnerability · Indicators · GIS · Social media

Introduction

Climate change is increasing the intensity and frequency of floods around the globe, resulting in huge damages. While flooding causes great disruption to livelihoods and the society, it largely leaves a negative impact on the economy in short- to medium-term context. In order to mitigate the impacts caused by various disasters, the United Nations' Sendai Framework for Disaster Risk Reduction 2015–2030 outlines a strategy based on four guiding principles: understanding disaster risk, strengthening disaster risk governance to manage disaster risk, investing in disaster risk reduction for resilience, and enhancing disaster preparedness for effective response (Asian Disaster Reduction Center, 2015). The first principle emphasizes the need to understand and assess flood disaster risk at various scales (i.e., national and local levels), where the specific sub-goal is to reduce hazard exposure and vulnerability to disasters. There is an emphasis on both hazard and vulnerability together because measuring hazard alone does not provide valuable information to disaster response teams. For example, if a community is located in a flood-prone area and is not vulnerable to a natural disaster, then response efforts should not be prioritized for this specific region. Instead, the limited rescue and response resources can be redirected to highly vulnerable regions which is only possible when disaster risk is taken into account.

Disaster risk is defined as the potential losses, which could occur to a particular community or a society over some specified future time period, where different types of potential losses include lives, health status, livelihoods, assets, and services (United Nations, 2009). Nowadays there is a consensus that risk (R) depends on the interactions between hazard (H) and vulnerability (V), which is generally calculated using the following equation (WBGU–Wissenschaftlicher Beirat der Bundesregierung Globale, 1998; ISDR Terminology, 2004):

$$R = H \times V \tag{1}$$

where R is a representation of the potential for adverse impacts; H is the likelihood of experiencing a certain intensity of a natural or human-induced hazardous event (i.e., flood, earthquake, or cyclone, etc.) at a specific location; V is a reference to how the exposed elements at risk are vulnerable and susceptible to the adverse impacts of the hazard event.

Interestingly, recent literature has shifted away from vulnerability and began focusing more on resilience as vulnerability deals with the preparedness phase of a disaster, whereas resilience deals with the post-event response and recovery from disasters (Cutter et al., 2014, 2008; Sajjad & Chan, 2019). While there is an open debate about whether resilience or vulnerability should be used, this book chapter focuses on vulnerability as it is widely accepted by international organizations like the United Nations. Equation 1 is widely used for the calculation of disaster risk, but there is still no consensus on how the three factors of vulnerability (V): exposure (E), susceptibility (S), and coping capacity (C) are aggregated and calculated. Most of the debate relies on whether an additive aggregation method (Balica, 2007) (refer to Eq. 2) or a multiplicative aggregation method (Balica et al., 2009; Villordon & Gourbesville, 2014) (refer to Eq. 3) should be used when constructing the vulnerability composites as both methodologies can produce varying outcomes. However, it is noted that as these composites are relative measures of vulnerable aspects of a specific community or society, the outcome and overall essence of the vulnerability is preserved no matter which method is employed for aggregation.

$$V = E + S - C \tag{2}$$

$$V = \frac{E \times S}{C} \tag{3}$$

where V is the function of exposure, susceptibility, and coping capacity; E is the presence of elements such as people, infrastructure, systems, and other elements are subject to potential losses; S is when the exposed elements are susceptible to damage with the occurrence of a disaster event; C is the ability to react to and recover from the effects of a hazard in a timely and manner.

This book chapter focuses on flood-related disasters. This is because, according to a report by the United Office for Disaster Risk Reduction (UNDRR) (UN Office for Disaster Risk Reduction, 2020), floods are the most common type of disaster to occur over a 20-year period of 2000 and 2019, and have affected the 1.65 billion people. Specifically, floods accounted for 44% of all the total 7348 disaster events recorded between 2000 and 2019. Moreover, flood events are anticipated to become more frequent and intense due to the combined effect of population growth and climate change (Gu et al., 2011; Miller & Hutchins, 2017; Saurav et al., 2021). Thus, it is imperative to understand how vulnerability to flooding hazards can be assessed and mapped accurately to assist effective mitigation of potential damages and adaptation to future events.

Examining vulnerability is an integral part of flood risk management (analysis, profiling, and communication) where there lie several approaches within the existing literature for the assessment of flood vulnerability. These approaches include stage damage functions (Papathoma-Köhle et al., 2017; Tarbotton et al., 2015), damage matrices (Papathoma-Köhle et al., 2017), computer modeling methods (Balica et al., 2013), and vulnerability indices (Barroca et al., 2006; Müller et al., 2011). The first three methods rely on physical vulnerability indicators and neglect other important dimensions like social, economic, and environmental vulnerability, thus making these methods unrepresentative. While indicator-based assessment models are the only method to provide a holistic overview of flood vulnerability (Nasiri et al., 2016) by considering the multi-dimensional factors, it is important to note that these models do not have a specific set of indicators that are universally accepted. This is primarily due to site-specific environmental, socioeconomic, institutional, political, and organizational settings in different areas. Another reason behind this discord is the availability of relevant data on the scale of assessment (i.e., local, sub-national, and national) which is one of the biggest challenges researcher encounter when dealing with data scarce regions. In this context, poorly constructed indices can misrepresent the situation, which could potentially be misleading in terms of decision-making and resource allocation. Therefore, it is necessary to have a clear understanding of all indicators to allow decision and policymakers to set precise targets to reduce vulnerability.

Existing review papers have attempted to assess the different types of indicators involved in constructing vulnerability maps from indicator-based methods. For example, Bigi et al. (2021) analyzed all the socioeconomic indicators and sub-indicators for urban areas only. Moreover, it considered citation count as a criteria to determine the relevancy of indicators. While their study only focused on reviewing one vulnerability dimension for one geographic region, this will only be beneficial to researchers interested in mapping vulnerability in urban regions for socioeconomic vulnerability. Similarly, other review papers either focused on one vulnerability dimension (i.e., Fatemi et al. (2017)) or one geographic region (i.e., Giampieri (2021)). While Moreira et al. (2021a) attempted to focus on all vulnerability dimensions over a set of geographic regions limited to urban, rural, or both regions, it still missed coastal and riverine geologies; and mainly focused on reviewing the different stages involved in the construction of flood vulnerability indices, instead of the indicator selection process. Therefore this chapter first aims to conduct an extensive analysis of indicators belonging to all the vulnerability dimensions across four geographic regions: urban, rural, coastal, and riverine and varying flood type. Moreover, this chapter aims to identify the selection criteria of indicators as indicators derived by experts, household surveys, interviews, and practitioners, which would have higher priority than indicators derived by researchers themselves. This method of distinction is more valuable than citation count and will help researchers easily identify a list of indicators relevant to their study.

This systematic analysis of indices will examine published studies from four different perspectives: (1) vulnerability dimension, (2) type of geographic region, (3) type of flood, and (4) selection criteria. While this evaluation will assist planners, practitioners, and future researchers with their indicator selection process, it will not resolve the challenges of finding relevant data for the indicators in different regions where there is no centralized database for geospatial indicators or when the data sources are outdated. To overcome these two challenges, we introduce the integration of traditional and non-traditional data sources, which can serve two purposes: (1) replace existing geospatial indicators that are outdated, and/or (2) enhance existing indicators by combining both sources. This will bring about several advantages where firstly the vulnerability maps will be even more accurate as near real-time data from non-traditional data sources is being used to represent the changing vulnerability over time, rather than treating it statically with traditional indicators. Secondly, utilizing the public knowledge through non-traditional data sources is more appealing as it would give a natural distribution of indicators during a disaster where real-time weights can be applied. This is not the case with traditional indicators selected through expert elicitation, which is one of the potential reasons of human bias where individuals are inclined in providing more importance to indicators in line with their specific domain of work.

The remainder of the chapter is organized as follows. Section "Methodology" details the methodology used to select, screen, and review a specific number of papers for analysis. Section "Analysis" presents an overview of the indicators analysis for each geographic region. Section "Non-Traditional Data Sources" introduces a new data source that can be integrated to further enhance flood vulnerability evaluation and profiling through detailed mapping, and section "Conclusion" finally concludes the paper.

Methodology

Databases and Search Terms Used

To begin with, a bibliographic search was performed by focusing on studies that produced flood vulnerability mapping through indicator-based methods. For the purpose of this chapter, three different globally known literature databases including Scopus, ScienceDirect, and Web of Science were accessed in February 2022. The authors selected a few tailored keywords that would retrieve highly relevant papers, where the title was considered to narrow down the search space substantially. The following search criteria were used in the Scopus database: TITLE(flood*) AND TITLE(vulnerability) AND TITLE(indicator* OR index* OR indices). This is slightly different from the search performed in Web of Science: Title contains flood* AND Title contains vulnerability AND Title contains indicator* OR index* OR indices, while in the ScienceDirect the following was used in the TITLE: (flood OR flooding) AND vulnerability AND (indicator OR indicators OR index OR indexes OR indices). The search criteria are the same across the three databases, which combined three sub-criteria by the AND operator. Some keywords were included with asterisk (*) so that both the singular and plural forms of those keywords are considered in the search. However, it is noted that only Scopus and Web of Science databases supported such operation. Moreover, some keywords are separated by an OR operator to include the various derivations of the term "indicator" used within flood vulnerability literature. This systematic search resulted in 90 papers from Scopus, 134 from Web of Science, and 18 from ScienceDirect.

Paper Selection Process

An open search was conducted across all three bibliographic databases with no date limit which elicited 243 papers in total. A set of filtering options was used to ensure that the papers belonged to the (1) final publication stage and was an (2) article or book chapter. Only articles and book chapters written in (3) English language and (4) contained in journals and books were included for the evaluation presented in this chapter. This initial filtering stage reduced the number from 243 papers to 175, where duplicate removal was then applied to retrieve a unique set of 92 papers published between 2006 and 2022. These 92 papers were then manually screened based on the title, abstract, and keyword, to remove irrelevant papers that were not useful for the purpose of this review. A set of inclusion criteria was used during the manual screening stage where papers focused only on (1) flooding, (2) community-based flood vulnerability, and (3) vulnerability indicators were selected to be included. Similarly, a set of exclusion criteria was set to remove papers that focused on (1) multiple hazards, (2) climate change or sea level rise, and (3) other vulnerability topics such as building or agriculture vulnerability. This manual, screening step reduced the number of papers from 92 to 32, where the full text of the 30 open access papers was then reviewed in detail. Figure 1 provides an overview of the search and selection process where the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Tricco et al., 2018) flow diagram was used.

Analysis

The 30 papers were first examined for three main characteristics including region type, flood type, and selection criteria, where each characteristic is detailed below.

Region Type In this study, we categorize the papers into four broad regions based on the area of interest they focused their analysis on. These regions include urban, rural, coastal, and riverine. Urban regions are characterized with a high population density with features of a built environment. This is completely opposite to rural regions which are comprised of lower population settlement and large amounts of undeveloped land. Coastal zones consist of areas between land and sea and come in different features like cliffs, beaches, and mudflats. With respect to river floodplains, this consists of large flat land occurring on either side of rivers.

Flood Type A distinction can be made between the four most common types of floods: urban floods, flash floods, coastal floods, and river floods. Urban floods tend to result from the accumulation of extreme local rainfall, which causes blocked drainage systems. Flash floods can result from intense rainfall, dam failures, or the sudden release of water from ice jams which often occur over a small geographic area and causes huge damage. Coastal floods occur when storms coincide with high tides or from high tidal waves created by tsunamis, hurricanes, or tropical storms. River floods are a result of increased water flow from rainfall that causes overtopping of the banks, thus spilling water onto the surrounding land.

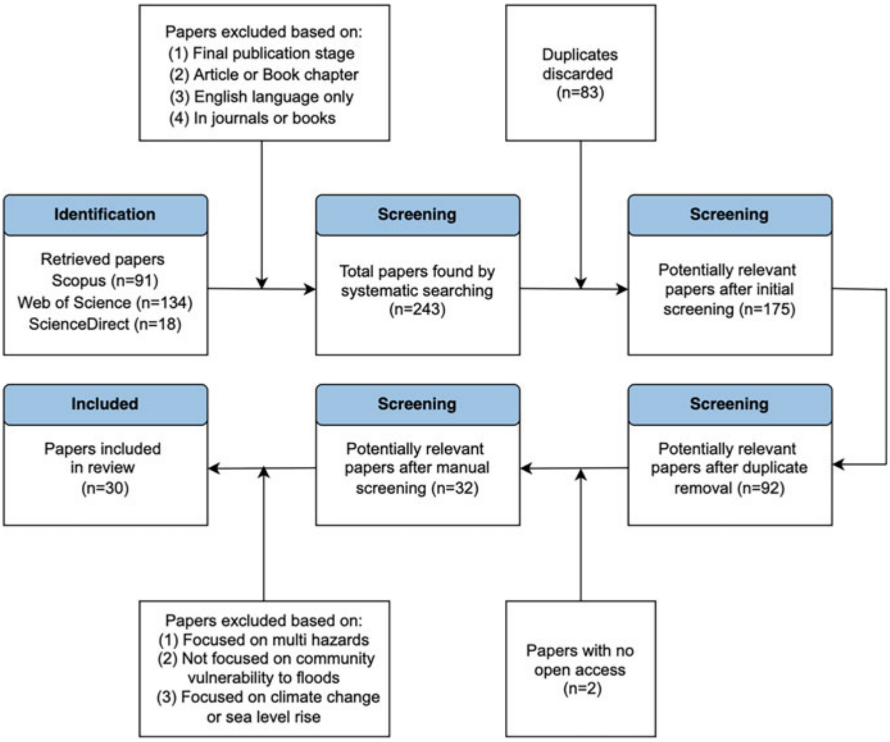

Fig. 1 Flow diagram of the search and selection process based on PRISMA

Selection Criteria Indicators can be selected from a variety of sources where some studies have conducted interviews and surveys with local households to understand which indicators are relevant and how they contribute to increase or decrease the vulnerability. Other researchers rely on conducting Delphi surveys to understand the opinions of experts and practitioners in the field of flood management. Other than interviews, questionnaires, and surveys, which are all primary data, some researchers have relied on secondary data by consulting the published literature to identify the commonly used indicators relevant for their area of study.

Table 1 shows the final 30 papers organized by region type where each paper was then examined for flood type and source of indicators selection. It is evident that a large proportion of these papers belong to the urban region, while the remaining rural, riverine, and coastal regions have almost similar number of fewer papers. These statistics show that researchers are increasingly focusing on examining flood vulnerability across different urban regions. The potential reason for this focus could be the higher exposure of urban areas to flooding along with the likelihood of largest impact and damage due to higher population and capital investments in cities. The next step involved analyzing all the indicators by region type with different vulnerability dimensions in mind. A detailed list of all the indicators can be found in the Appendix.

Table 1 Overview of 30 papers categorized by selection criteria and flood type

	Number	Selection criteria	Flood type	Reference
Urban	1	Literature	Flood	Baeck et al. (2014)
	2	Experts	River, coastal, and urban flood	Oulahen et al. (2015)
	3	Literature	Flash flood	Aroca-Jiménez et al. (2017)
	4	Statistical analysis	Flood and flash flood	de Andrade and Szlafsztein (2018)
	5	Literature, experts, household survey	Flood	Rodrıguez-Gaviria et al. (2019)
	6	Literature	Flood	Liew et al. (2019)
	7	Expert	Flash flood and monsoon flood	Nasiri et al. (2019)
	8	Literature	Flood	Salazar-Briones et al. (2020)
	9	Literature and stakeholder engagement	Flood	Mason et al. (2021)
	10	Expert	River flood	Rashetnia and Jahanbani (2021)
	11	Literature	Flood	Cian et al. (2021)
	12	Literature	Flood	Karmaoui and Balica (2021)
	13	Household survey	Perennial floods	Harahap (2021)
	14	Experts and household survey	River flood	Membele et al. (2022)
	15	Literature	Flood	(Chang and Chen (2016)
	16	Researcher	River	Zachos et al. (2016)
	17	Statistical analysis	Flash floods	Aroca-Jiménez et al. (2020)
Rural	1	Household survey, focus groups	Flood	Antwi et al. (2015)
	2	Literature	River flood	Yang et al. (2018)
	3	Questionnaire survey, literature review	River flood	Hidayah et al. (2021)
	4	Literature	River flood	Moreira et al. (2021b)
Riverine	1	Questionnaires	Flood	Vári et al. (2013)
	2	Literature	Recurrent floods	Jha and Gundimeda (2019)
	3	Statistical analysis	Flash floods	Aroca-Jiménez et al. (2020))
Coastal	1	Literature	Flash floods	Andres et al. (2015)
	2	Researcher	Flood	Martınez-Graña et al. (2016)
	3	Researcher	Coastal flood	Tao (2021)

(continued)

Table 1 (continued)

	Number	Selection criteria	Flood type	Reference
	4	Household survey and stakeholder survey	Riverine, coastal, and urban	Bernadel et al. (2016)
	5	Literature	Coastal flooding	Giannakidou et al. (2019)
	6	Literature	Flood	Giampieri (2021)

Table 2 The priority list developed for weighting the different selection criterion's

Selection criteria	Priority	Description
Household survey or interview	6	This involves surveying the affected locals in flood-prone areas
Stakeholder or organizational engagement	5	This involves collecting data from organizations and stakeholders
Expert questionnaire or focus groups	4	This involves collecting data from experts in the disaster domain
Statistical analysis	3	This involves using statistical techniques to get relevant indicators
Literature	2	This involves conducting a literature review of the indicators used
Researcher	1	Researchers use their GIS knowledge to include relevant indicators

While this comprehensive list of indicators is a good starting point for researchers in the field of flood vulnerability assessment and mapping, they will still struggle to understand which indicators should be prioritized. To tackle this problem, we devised a priority list as seen in Table 2 where we assigned the highest priority score (6) to indicators that are derived by surveying or interviewing individuals in flood-prone regions. This first-hand information is highly valuable and is the most representative of the vulnerability situation of a community at the highest possible resolution. The second highest priority (5) includes indicators collected from interviewing or surveying key stakeholders or governmental/non-governmental organizations in the disaster response and recovery phase. The next priority (4) relates to gathering insights from experts who have been in the domain of disaster risk reduction, whether that is being part of research institutes or educational institutes. After this, the priority score (3) is given to indicators that are proven to be statistically significant for the past researchers area of interest, where common techniques include the Analysis of Variance (ANOVA) and the Principal Component Analysis (PCA) conducted by different researchers. The second last priority score (2) relates to indicators that were collected by consulting past flood vulnerability literature, which is already published after the formal peer-review procedures. Finally, the lowest priority (1) is given to indicators derived by researchers themselves and can introduce bias if the researcher is not very knowledgeable or experienced in this field.

Urban Region

All the indicators from the 17 papers were analyzed and consolidated, to create a final list of 60 indicators, which belonged to either social, economic, or physical vulnerability dimensions. In particular, 30 indicators belonged to social vulnerability, 11 to economic vulnerability, and the remaining 18 to physical vulnerability. For effective communication and to visualize these indicators appropriately, the Sankey diagram is used to present the flow of indicators in relation to both vulnerability dimension and flood type, as presented in Fig. 2. The thickness of the lines represents the weight given to each indicator based on the selection criteria involved. In cases where an indicator has multiple selection criteria, an average of the priority weights is taken. These weights are reflected in the diagram which is separated by a colon.

Figure 2 shows the social vulnerability indicators for urban regions, where all 30 indicators have similar weights between 2 and 4 indicating that all of them are commonly used. Within urban regions there exists different types of floods, and the greatest emphasis can be seen on flash floods, river floods, and flooding in general.

Figure 3 displays the economic and physical vulnerability indicators, where the overall weight of the physical dimension is greater than economic but less than social vulnerability. With regard to the economic dimension, the majority of the indicators are applicable to coastal flooding, river flooding, and urban flooding, whereas for physical vulnerability, most of the indicators are used in river flooding scenarios.

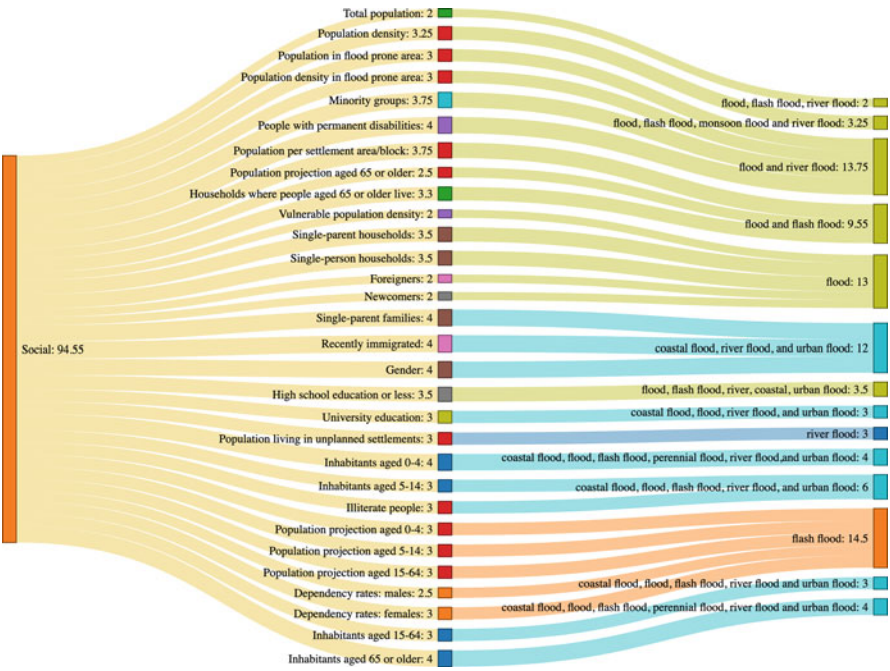

Fig. 2 Overview of social vulnerability indicators for urban regions

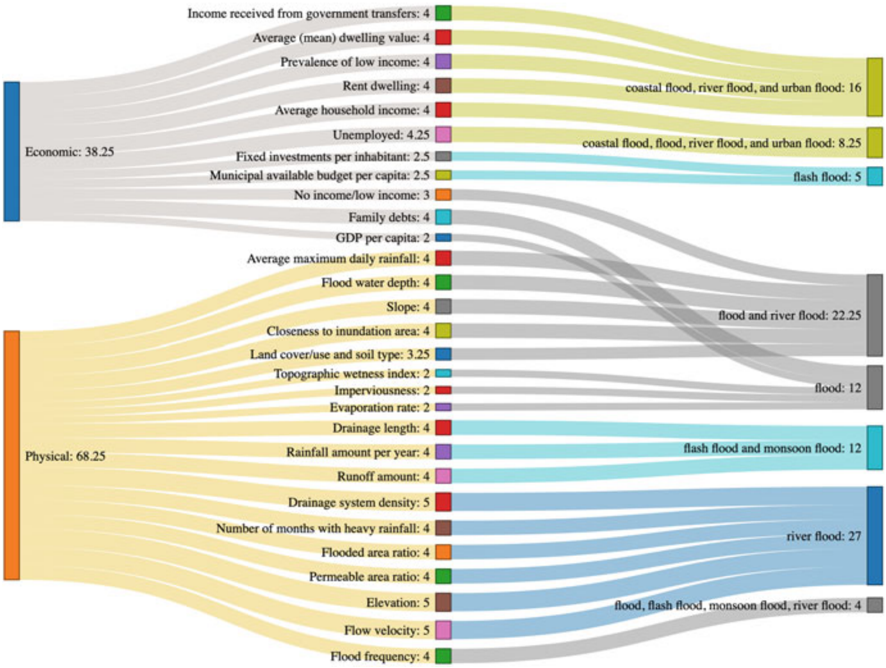

Fig. 3 Overview of economic and physical vulnerability indicators for urban regions

Rural Region

For rural regions, indicators are spread across four dimensions with physical vulnerability being the highest priority followed by ecological, environmental, and political vulnerability as seen in Fig. 4. All 35 indicators either belonged to general flooding and river flooding where flood-related indicators have a combined overall weight higher than river flooding indicators. Only the environmental vulnerability indicators are used in river flooding scenarios while the physical, ecological, and political indicators are spread across general flooding and river flooding.

Coastal Region

Figure 5 visualizes all 71 indicators, which are distributed across physical, institutional, social, and economic dimensions. Interestingly, 47% of the indicators for flood vulnerability assessment over coastal regions belong to the physical dimension only. Within the physical dimension, three indicators have higher priority than the rest, which include frequency of flooding, height of flooding, and number of cyclones/typhoons. These three indicators are applicable to coastal flooding, river flooding, and urban flooding. Next, the institutional dimension has six indicators with the same weights, which can be used in general flooding scenarios. Coming to the social dimension which is the second most important dimension after physical vulnerability,

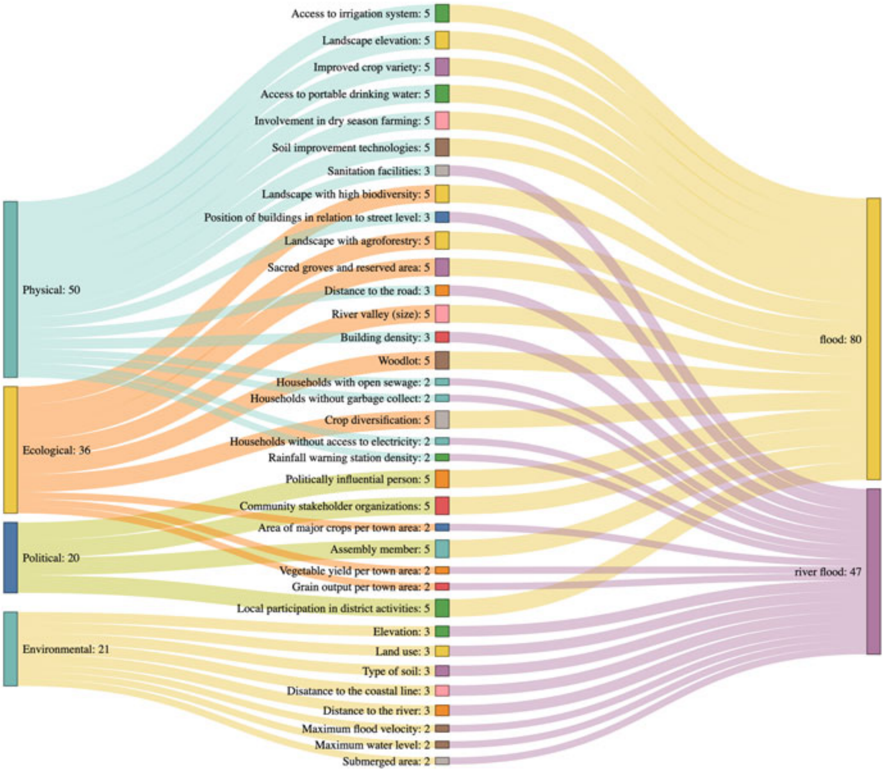

Fig. 4 Overview of physical, ecological, political, and environmental vulnerability indicators for rural regions

we see that five indicators in particular have greater priority over the others including housing conditions, houses with no access to improved sanitation, houses with no access to an improved water source, presence of rats in the vicinity, and presence of waterlogged areas in the vicinity. While data for these five indicators can be gathered only through first-hand information from locals, researchers who cannot collect this information will not be able to include these indicators in these studies. Thus, there is a need for introducing non-traditional indicators, which can be incorporated into the vulnerability assessment and profiling, as a proxy of these traditional indicators collected through primary data sources. Lastly, within the economic dimension, there are two indicators applicable to coastal, river, and urban flooding which should be given importance, and this includes family income and property insurance.

Riverine Region

In total there are 49 indicators applicable to rural regions which either belong to the social or economic dimension. Similar to the other regions, the social vulnerability indicators have almost similar weights as all of them are commonly used by

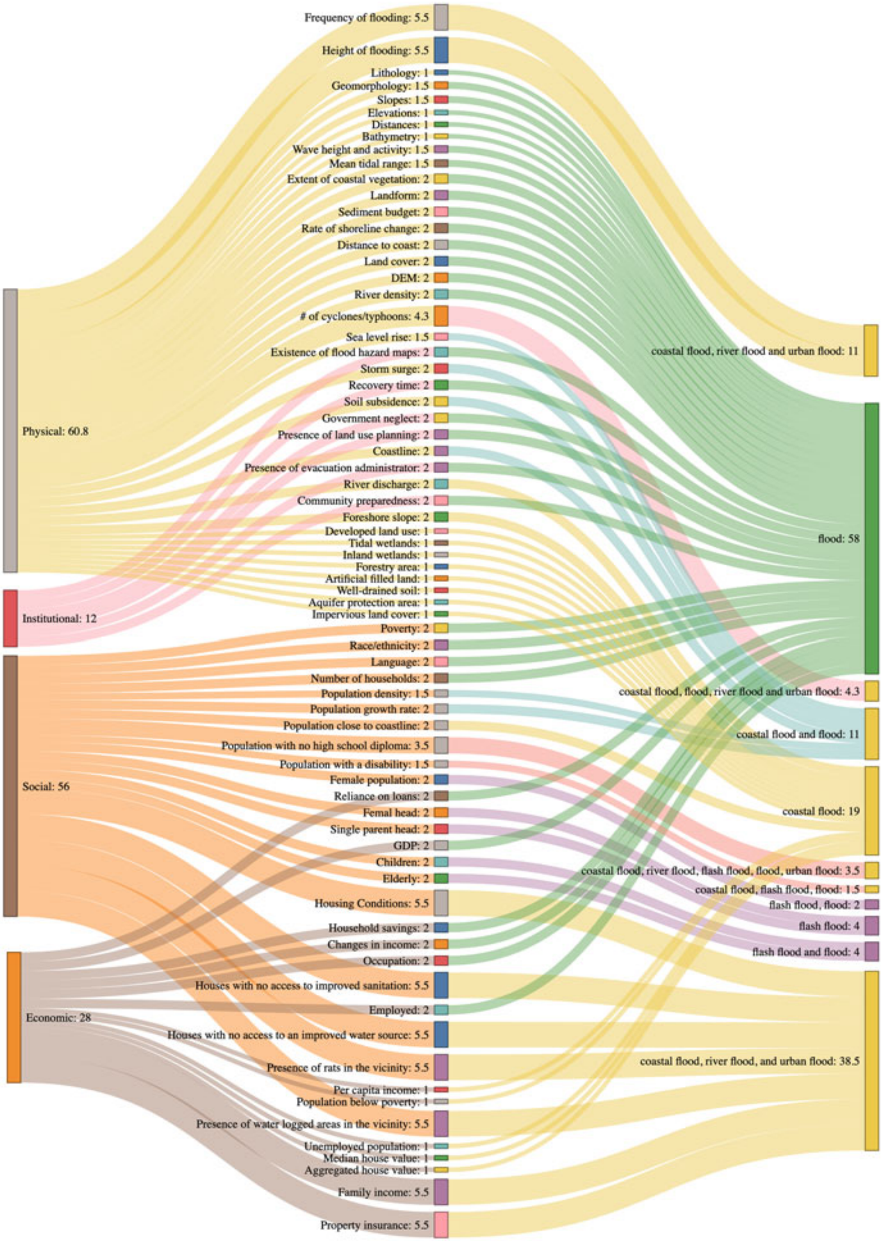

Fig. 5 Overview of social, economic, physical, and institutional vulnerability indicators for coastal regions

researchers, where most of these indicators are used in studies examining flash floods in riverine regions. Coming to the economic dimension, there is one indicator that stands out amongst the rest which is fixed investments per inhabitant which has a

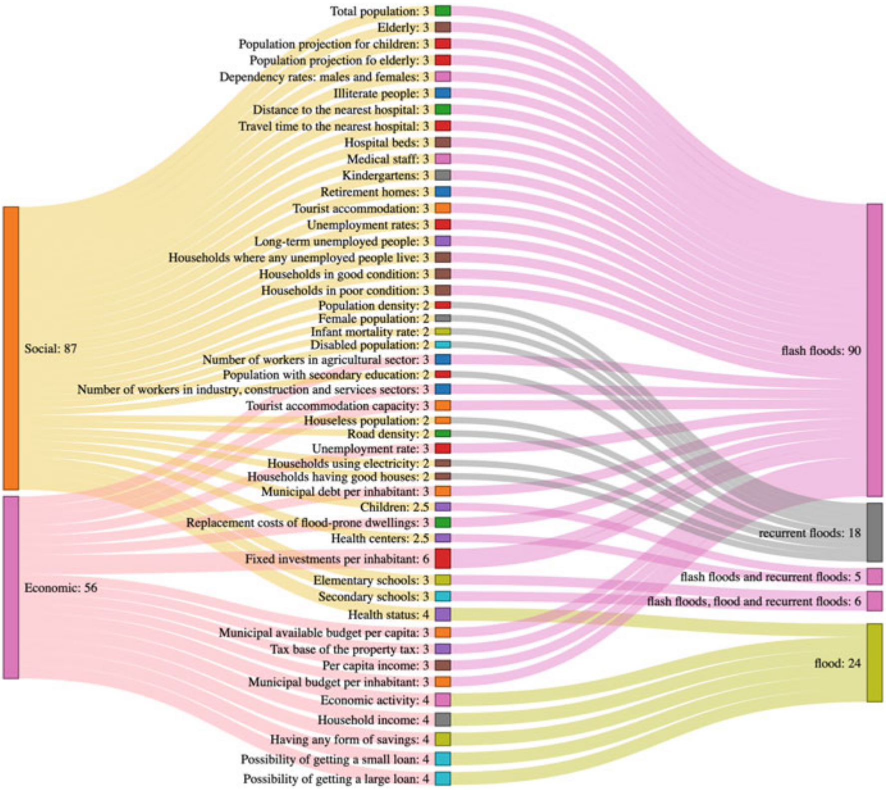

Fig. 6 Overview of physical and social vulnerability indicators for river regions

weightage of 6. Almost 75% of the indicators are applicable to flash floods while the remaining can be applied to general flooding scenarios (Fig. 6).

Non-Traditional Data Sources

Volunteered geographic information (VGI) refers to the creation of user-generated information, which has been disseminated voluntarily by individuals (Goodchild, 2007). During an onset of a disaster, social media, in particular, acts as a VGI platform to deliver real-time geospatial information about the disaster with the help of geolocation features. Provisioning of such kind of information can progressively help inform response teams about the location of affected people who need assistance so that rescue and relief operations can be directed in an efficient and informed manner. Similarly, decision makers will be able to make smart as well as more informed decisions around deploying resources for recovery operations as they would have a better situational awareness of the disaster, which would not be possible otherwise. This ability of VGI platform-based information has an upper hand as compared with traditional data sources, which are static in nature and are mostly outdated due to carrying out the surveys well before or after the disaster event. Hence, leveraging the power of VGI platform-based data to formulate non-traditional vulnerability indicators has a wide scope, particularly for near-real-time situation awareness and assessment of vulnerability assessment in data-scare regions (i.e., developing countries).

While social media platforms like Twitter harness the local knowledge and provide the advantage of filling in the information gap during a disaster event, there comes the drawback of the quality and reliability of this information. Nevertheless, this type of information is continuously being explored in the domain of flood management, where several studies have explored the potential use of Tweet text and images in producing flood extent maps and damage assessment maps, identifying local hotspots, and examining the spatial variation in social media activity during a disaster (Bono et al., 2022; Cervone et al., 2016; Amir Masoud Forati and Rina Ghose, 2022; Kersten & Klan, 2020; Yuan & Liu, 2018). However, there still lies a gap in this domain, where no studies to the best of our knowledge have utilized social media information for the enhancement of indicator-based flood vulnerability maps, which could provide opportunities to direct efforts for the mitigation of vulnerable aspects during an emergency situation. This is because the data sets utilized in the construction of indicator-based flood vulnerability maps are always static where some indicators rely on outdated information sources, such as national census data. Moreover, finding indicator-related data sources can become challenging in data scarce regions like small island states and developing countries where no centralized data management infrastructure is available. To overcome these limitations, user-generated information from social media can be introduced into the flood vulnerability index to provide an enhanced overview of the flood situation in near real-time to benefit response teams.

Social Media Indicators

Social media indicators for flood vulnerability mapping can be used in two different ways: (1) replace existing geospatial indicators or (2) enhance existing geospatial indicators by introducing proxy social media indicators. The first scenario is applicable when traditional indicators are hard to find in data scarce regions or when there is no access to experts or local knowledge in order to get data for these traditional indicators. The second scenario is applicable when traditional indicators exist but are outdated making it unrepresentative and thus there is a need to use up-to-date non-traditional data sources. Therefore, the first step is to understand what type of social media indicators can be used to proxy for the traditional indicators.

For this, a recent study that explored the fusion of remote sensing and social media for flood mapping provided insights into three different types of contextual information evident from social media text and images (Sadiq et al., 2022). This includes Needs and Requests, Impact Assessment, and Situational Awareness reports as seen in Table 3. For example, if a researcher is focusing on a coastal region and is interested in using social vulnerability indicators like "Houses with no access to improved sanitation" as seen in Fig. 5 and they cannot find data for this indicator, they can refer to the Situational Awareness section and see the proxy indicator for "Population without access to sanitation hygiene" which is "NO. of sanitation and hygiene reports." These

Table 3 Overview of traditional indicators and its proxy non-traditional indicators

	Traditional indicator	Non-traditional indicator
Needs and requests	Population under poverty	No. of monetary aid requests
	Persons with disabilities	No. of disability item requests
	Lost family members	No. of rescue requests
	Population without access to food and water supply	No. of food and water requests
	Human health	No. of medical assistance requests
	Shelters	No. of shelter requests
Impact assessment	Household without sewage disposal system	No. of water system and sewage damage reports
	Household without electricity	No. of electricity damage reports
	House damage value	No. of infrastructure damage reports
	Crop lost value	No. of agriculture, crops, livestock damaged
	Damages to public utilities	No. of utilities damage reports
	Unplanned waste deposits	No. of pollution and contamination reports
Situational awareness	Population affected	No. of affected individuals
	Population in flood area	No. of affected areas
	Household member with illness	No. of health and disease-related reports
	Crime rate	No. of safety and security-related reports
	Population without access to sanitation and hygiene	No. of sanitation and hygiene reports
	Warning system	No. of weather information and updates
	Warning system communication penetration rate	No. of cautionary/advice reports
	Awareness	No. of donations and volunteering reports
	Dependency on public infrastructure	No. of logistics and transportation reports
	Flood insurance	No. of insurance reports

reports can come from either social media text or images which are geolocated with relevant classifier information, where the following approach can be used:

Traditional and Non-Traditional Indicators

1. Collect social media text and images available in the area of interest that has been affected by a flood event. For example, with the Twitter platform the Artificial Intelligence for Disaster Response (AIDR) system (Imran et al., 2014) can be

used to automatically trigger the collection of tweets based on a geographic region and/or a set of flood-related keywords.
2. Geo-tag as many social media posts as possible. For example, the methodology proposed in (Qazi et al., 2020) can be used to assign city, county, state, and country information to tweets based on various metadata fields like geo-coordinates, user location, place, user profile description, and tweet text.
3. Filter out irrelevant social media texts by passing the social media posts through text classification models. For example, CrisisDPS (Alam et al., 2019) can be used to classify tweet texts based on disaster type, informativeness, and humanitarian information. Social media texts classified as "flood," "informative," and any relevant humanitarian category can then be considered.
4. Filter out irrelevant social media images with the help of image classification models. For example, the disaster type prediction model proposed by Weber et al. (2020) can be used to extract images classified as "heavy rainfall" and "flooded."

Once relevant geolocated social media text and images are collected, the next step involves deciding how to aggregate the information presented in these point data instances. Such aggregation could be made using the imaginary boundaries (i.e., grids with specific resolution – 30, 50, or 100 m) or over the localized administrative boundaries of the region of interest. While both have their own advantages and shortcomings, the utilization of administrative boundaries has an upper hand as it can effectively inform the stakeholder and professionals working in the field of flood management. The use of administrative region makes it easy to communicate the outcome as people and familiar with these names as compared with grids that are assigned assumed codes for reference. There exists three different aggregation techniques within literature which include using an additive or multiplicative approach (Sajjad, 2021; Sajjad & Chan, 2019), mode approach (Sajjad et al., 2020), or rates approach. Below we describe how each method can be used to create flood vulnerability maps using social media indicators:

1. **Sum:** In order to show the intensity of each dimension (i.e., needs and requests, Impact assessment, and situational awareness), the aggregation of relevant tweets using a simple sum could be used (i.e., the additive approach).
2. **Multiplicative:** In order to show the intensity of each dimension (i.e., needs and requests, Impact assessment, and situational awareness), the aggregation of relevant tweets using a multiplicative method could be used.
3. **Mode:** In order to evaluate all aspects, the proportion of each dimension within the total tweets can be used to aggregate for a specific administrative boundary.
4. **Rate:** In order to show the dominant dimensions as well as to evaluate the rates of different dimensions, the population weighted aggregation method can be used.

It is noted that as the resultant vulnerability maps represent a relative measure, utilization of any aggregation method will suffice. Once the aggregation method is selected and applied to the social media points, the output layer can then be used as part of the final flood vulnerability map construction. Additionally, such maps can further be used to identify the patterns and trends, if any, in flood vulnerability by the application of several spatial information models. However, this would require proper understanding, skills, and additional resources.

Conclusion

This study analyzed 30 indicator-based flood vulnerability assessment papers to holistically understand the different indicators used across four region types: urban, rural, riverine, and coastal regions. All the indicators were categorized among common vulnerability dimensions and to understand which indicator within a dimension should be given importance, a priority list was devised in order to apply weights to each indicator depending on which selection criteria was used in deriving the indicator. For example, indicators collected through household surveys and interviews were given the highest priority as it is highly representative of the locals in flood-prone areas unlike indicators gathered by researchers who do not have knowledge of the reality, thus making researcher-derived indicators the lowest priority. These weights were then applied to all the indicators and were inputted into the sankey diagrams where the thickness of the line represented the weight. These diagrams revealed several insights such as which vulnerability dimension is more important than others, which indicator within a dimension has higher priority over others, and finally which type of flood is most commonly used for flood vulnerability assessment. While these findings would assist researcher with their indicator selection process, they are bound to encounter challenges with finding data for some of these traditional indicators, especially for data scarce regions or when the data is outdated. Thus, we propose that non-traditional data sources like social media should be used as proxy indicators to either replace or enhance traditional indicators, where we provide a step-by-step approach to achieving these flood vulnerability maps through the aggregation of social media point data.

Acknowledgments This chapter was made possible by BFC grant #BFC03-0630-190011 from the Qatar National Research Fund (a member of Qatar Foundation). The findings herein reflect the work, and are solely the responsibility, of the authors. The authors would like to gratefully acknowledge the financial support of the project Re-Energize Governance of Disaster Risk Reduction and Resilience for Sustainable Development (Re-Energize DR3) provided by the Belmont Forum's first disaster-focused funding call DR3 CRA Joint Research, which was supported by the Ministry of Science and Technology (MOST) of Chinese Taipei in partnership with funders from Brazil (FAPESP), Japan (JST), Qatar (QNRF), the UK (UKRI), and the US (NSF).

Appendix

Refer to Tables 4, 5, 6, and 7 for a detailed list of all the indicators.

Table 4 Overview of vulnerability indicators for urban regions where the following key is used for the selection criteria: R for Researcher, L for Literature, HS for Household Survey, SE for Stakeholder Engagement, SA for Statistical Analysis, E for Experts

	Selection criteria	Flood type	References
Social vulnerability			
Total population	R, SA, L	Flood, flash flood, river flood	de Andrade and Szlafsztein (2018), Aroca-Jiménez et al. (2017, 2020), Zachos et al. (2016)
Population density	L, R, E, HS	Flood, river flood, flash flood, monsoon flood	Baeck et al. (2014), Chang and Chen (2016), Karmaoui & Balica, 2021, Membele et al. (2022), Nasiri et al. (2019), Rashetnia and Jahanbani (2021), Salazar-Briones et al. (2020), Zachos et al. (2016)
Population density in flood-prone area	L, E	Flood, river flood	Liew et al. (2019), Rashetnia and Jahanbani (2021)
Population in flood-prone area	L, E	Flood, river flood	(Karmaoui and Balica (2021), Liew et al. (2019), Rashetnia and Jahanbani (2021)
Population per settlement area	L, HS, E, SA	Flood, flash flood	Aroca-Jiménez et al. (2017, 2020), Rodrıguez-Gaviria et al. (2019)
Vulnerable population density	L	Flood	Baeck et al. (2014)
Single-parent families	E	River, coastal, urban flood	Oulahen et al. (2015)
Recently immigrated	E	River, coastal, urban flood	Oulahen et al. (2015)
High school education or less	E, SA, L, SE	Flood, flash flood, river, coastal, urban flood	de Andrade and Szlafsztein (2018), Cian et al. (2021), Mason et al. (2021), Oulahen et al. (2015), Rashetnia and Jahanbani (2021)
University education	E, L	Flood, river, coastal, urban flood	Oulahen et al. (2015), Salazar-Briones et al. (2020)
Minority groups	L, R	Flood, river flood	Chang and Chen (2016), Zachos et al. (2016)
Population living in unplanned settlements	L, E	River flood	Mansur et al. (2016)

(continued)

Table 4 (continued)

	Selection criteria	Flood type	References
Inhabitants aged 0–4	E, SA, L, HS, SE	Flood, perennial flood, flash flood, river, coastal, urban flood, perennial flood, flash flood, river, coastal, urban flood	de Andrade and Szlafsztein (2018), Aroca-Jiménez et al. (2017, 2020), Cian et al. (2021), Harahap (2021), Liew et al. (2019), Mansur et al. (2016), Mason et al. (2021), Membele et al. (2022), Oulahen et al. (2015), Rashetnia and Jahanbani (2021), Salazar-Briones et al. (2020)
Inhabitants aged 5–14	E, SA, L, HS	Flood, flash flood, river, coastal, urban flood	de Andrade and Szlafsztein (2018), Aroca-Jiménez et al. (2017, 2020), Liew et al. (2019), Mansur et al. (2016), Membele et al. (2022), Oulahen et al. (2015)
Population projection aged 0–4	SA	Flash flood	Aroca-Jiménez et al. (2017, 2020)
Population projection aged 5–14	SA	Flash flood	Aroca-Jiménez et al. (2017, 2020)
Inhabitants aged 15–64	E, SA, L	Flood, flash flood, river, coastal, urban flood	de Andrade and Szlafsztein (2018), Aroca-Jiménez et al. (2017, 2020), Liew et al. (2019), Mansur et al. (2016), Oulahen et al. (2015)
Population projection aged 15–64	SA	Flash flood	Aroca-Jiménez et al. (2017, 2020)
Inhabitants aged 65 or older	E, SA, L, HS, SE	Flood, perennial flood, flash flood, river, coastal, urban flood	de Andrade and Szlafsztein (2018), Aroca-Jiménez et al. (2017, 2020), Cian et al. (2021), Harahap (2021), Mansur et al. (2016), Mason et al. (2021), Membele et al. (2022), Oulahen et al. (2015), Rashetnia and Jahanbani (2021), Salazar-Briones et al. (2020)
Population projection aged 65 or older	L, SA	Flood, flash flood	Aroca-Jiménez et al. (2017, 2020), Liew et al. (2019)
Dependency rates: males	L, SA	Flash flood	Aroca-Jiménez et al. (2017, 2020)
Dependency rates: females	SA	Flash flood	Aroca-Jiménez et al. (2020)

(continued)

Table 4 (continued)

	Selection criteria	Flood type	References
Households where people aged 65 or older live	SA, L, SE	Flood, flash flood	Aroca-Jiménez et al. (2017, 2020), Mason et al. (2021)
Illiterate people	E, L, SA	Flood, river, coastal, urban flood, flash flood	Aroca-Jiménez et al. (2017, 2020), Liew et al. (2019), Oulahen et al. (2015)
People with permanent disabilities	L, HS, E	Flood, river food	Liew et al. (2019), Membele et al. (2022), Rashetnia and Jahanbani (2021), Rodrıguez-Gaviria et al. (2019)
Gender	E	River, coastal, urban flood	Oulahen et al. (2015)
Single-parent households	L, SE	Flood	Mason et al. (2021)
Single-person households	L, SE	Flood	Mason et al. (2021)
Single-person households	L, SE	Flood	Mason et al. (2021)
Foreigners	L	Flood	Cian et al. (2021)
Newcomers	L	Flood	Cian et al. (2021)
Economic vulnerability			
No income/low income	L, E	Flood, river flood	Mansur et al. (2016), Salazar-Briones et al. (2020)
Income received from government transfers	E	River, coastal, urban flood	Oulahen et al. (2015)
Average household income	E, L, HS	Flood, river, coastal, urban flood	Chang and Chen (2016), Liew et al. (2019), Membele et al. (2022), Oulahen et al. (2015), Rodrıguez-Gaviria et al. (2019)
Average (mean) dwelling value	E	River, coastal, urban flood	Oulahen et al. (2015)
Prevalence of low income	E	River, coastal, urban flood	Oulahen et al. (2015)
Rent dwelling	E	River, coastal, urban flood	Oulahen et al. (2015)
Unemployed	E, L, HS, SE	Flood, river, coastal, urban flood	Mason et al. (2021), Membele et al. (2022), Oulahen et al. (2015), Salazar-Briones et al. (2020)
Fixed investments per inhabitant	L, SA	Flash flood	Aroca-Jiménez et al. (2017)

(continued)

Table 4 (continued)

	Selection criteria	Flood type	References
Municipal available budget per capita	L, SA L, SA	Flash flood	Aroca-Jiménez et al. (2017)
Family debts	L, E, HS	Flood	Rodrıguez-Gaviria et al. (2019)
GDP per capita	L	Flood	Liew et al. (2019)
Physical vulnerability			
Average maximum daily rainfall	L, E, HS	Flood, river flood	Karmaoui and Balica (2021), Liew et al. (2019), Membele et al. (2022), Rashetnia and Jahanbani (2021)
Flood water depth	L, E, HS	Flood, river flood	Liew et al. (2019), Membele et al. (2022)
Drainage length	E	Flash flood, monsoon flood	Nasiri et al. (2019)
Drainage system density	E, HS	River flood	Membele et al. (2022), Rashetnia and Jahanbani (2021)
Rainfall amount per year	E	Flash flood, monsoon flood	Nasiri et al. (2019)
Runoff amount	E	Flash flood, monsoon flood	Nasiri et al. (2019)
Number of months with heavy rainfall	E	River flood	Rashetnia and Jahanbani (2021)
Flood frequency	L, E, HS	Flood, flash flood, monsoon flood, river flood	Liew et al. (2019), Membele et al. (2022), Nasiri et al. (2019)
Slope	L, E, HS	Flood, river flood	Membele et al. (2022), Rashetnia and Jahanbani (2021), Salazar-Briones et al. (2020)
Closeness to inundation area	L, E, HS	Flood, river flood	Karmaoui and Balica (2021), Membele et al. (2022), Salazar-Briones et al. (2020)
Topographic wetness index	L	Flood	Karmaoui and Balica (2021), Salazar-Briones et al. (2020)
Land cover/use and soil type	R, L, E, HS	Flood, river flood	Membele et al. (2022), Salazar-Briones et al. (2020), Zachos et al. (2016)
Flooded area ratio	E	River flood	Rashetnia and Jahanbani (2021)
Permeable area ratio	E	River flood	Rashetnia and Jahanbani (2021)
Imperviousness	L	Flood	Cian et al. (2021)
Evaporation rate	L	Flood	Karmaoui and Balica (2021)
Elevation	E, HS	River flood	Membele et al. (2022)
Flow velocity	E, HS	River flood	Membele et al. (2022)

Table 5 Overview of vulnerability for rural regions where the following key is used for the selection criteria: HS for Household Survey, FG for Focus Group, QS for Questionnaire Survey, and L for Literature

	Selection criteria	Flood type	References
Physical vulnerability			
Access to irrigation system	HS, FG	Flood	Antwi et al. (2015)
Landscape elevation	HS, FG	Flood	Antwi et al. (2015)
Improved crop variety	HS, FG	Flood	Antwi et al. (2015)
Access to portable drinking water	HS, FG	Flood	Antwi et al. (2015)
Involvement in dry season farming	HS, FG	Flood	Antwi et al. (2015)
Soil improvement technologies	HS, FG	Flood	Antwi et al. (2015)
Sanitation facilities	QS, L	River flood	Hidayah et al. (2021)
Position of buildings in relation to street level	QS, L	River flood	Hidayah et al. (2021)
Distance to the road	QS, L	River flood	Hidayah et al. (2021)
Building density	QS, L	River flood	Hidayah et al. (2021)
Households with open sewage	L	River flood	Moreira et al. (2021b)
Households without garbage collect	L	River flood	Moreira et al. (2021b)
Households without access to electricity	L	River flood	Moreira et al. (2021b)
Rainfall warning station density (number of rainfall warning stations /number of flooded villages)	L	River flood	Yang et al. (2018)
Ecological vulnerability indicators			
Landscape with high biodiversity	HS, FG	Flood	Antwi et al. (2015)
Landscape with agroforestry	HS, FG	Flood	Antwi et al. (2015)
Sacred groves and reserved area	HS, FG	Flood	Antwi et al. (2015)
River valley (size)	HS, FG	Flood	Antwi et al. (2015)
Woodlot	HS, FG	Flood	Antwi et al. (2015)
Crop diversification	HS, FG	Flood	Antwi et al. (2015)
Area of major crops/town area	L	River flood	Yang et al. (2018)
Vegetable yield/town area (t-km-2)	L	River flood	Yang et al. (2018)
Grain output/town area (t-km-2)	L	River flood	Yang et al. (2018)
Environmental vulnerability			
Elevation	QS, L	River flood	Hidayah et al. (2021)
Land use	QS, L	River flood	Hidayah et al. (2021)
Type of soil	QS, L	River flood	Hidayah et al. (2021)

(continued)

Table 5 (continued)

	Selection criteria	Flood type	References
Distance to the coastal line	QS, L	River flood	Hidayah et al. (2021)
Distance to the river	QS, L	River flood	Hidayah et al. (2021)
Maximum flood velocity (m/s)	L	River flood	Yang et al. (2018)
Maximum water level (m)	L	River flood	Yang et al. (2018)
Submerged area (km_)	L	River flood	Yang et al. (2018)
Political vulnerability			
Politically influential person	HS, FG	Flood	Antwi et al. (2015)
Community stakeholder organizations	HS, FG	Flood	Antwi et al. (2015)
Assembly member	HS, FG	Flood	Antwi et al. (2015)
Local participation in district activities	HS, FG	Flood	Antwi et al. (2015)
Social vulnerability			
Total population	HS, FG, L	Flood, river flood	Antwi et al. (2015), Moreira et al. (2021b)
Population density	HS, FG, L	Flood, river flood	Antwi et al. (2015), Moreira et al. (2021b), Yang et al. (2018)
Households with more than five people	HS, FG	Flood	Antwi et al. (2015)
Knowledge on climate	HS, FG	Flood	Antwi et al. (2015)
Migration rate/rural-urban migration	HS, FG	Flood	Antwi et al. (2015)
Access to social services	HS, FG	Flood	Antwi et al. (2015)
Gender	QS, L	River flood	Hidayah et al. (2021)
Level of education	QS, L	River flood	Hidayah et al. (2021)
Age	QS, L	River flood	Hidayah et al. (2021)
Household size	QS, L	River flood	Hidayah et al. (2021)
Experience of flooding	QS, L	River flood	Hidayah et al. (2021)
Number of women	L	River flood	Moreira et al. (2021b)
Dependency rate	L	River flood	Moreira et al. (2021b)
Vulnerable groups (women, children, physically challenge invalids)	L	River flood	Moreira et al. (2021b)
Number of women head of homes	L	River flood	Moreira et al. (2021b)
Inhabitants aged 0–4 years	L	River flood	Moreira et al. (2021b)

(continued)

Table 5 (continued)

	Selection criteria	Flood type	References
Inhabitants aged more than 65 years	L	River flood	Moreira et al. (2021b)
Illiterate people	L	River flood	Moreira et al. (2021b)
Per capita income	L	River flood	Moreira et al. (2021b)
Unemployed people	L	River flood	Moreira et al. (2021b)
Sex ratio	L	River flood	Yang et al. (2018)
Labor force/town population	L	River flood	Yang et al. (2018)
Rural population/town population	L	River flood	Yang et al. (2018)
People living in rented houses	L	River flood	Moreira et al. (2021b)
Economic vulnerability			
Livelihood diversification (o_-farm income source)	HS, FG	Flood	Antwi et al. (2015)
Family welfare	QS, L	River flood	Hidayah et al. (2021)
Household's per capita monthly income equal 1/8 of the minimum wage	L	River flood	Moreira et al. (2021b)
House head without income	L	River flood	Moreira et al. (2021b)
House head's income less than 1 minimum wage	L	River flood	Moreira et al. (2021b)
House head's income less than 2 minimum wages	L	River flood	Moreira et al. (2021b)
Net income of farmers	L	River flood	Yang et al. (2018)
Township financial income	L	River flood	Yang et al. (2018)
Gross domestic product (GDP) on unit area	L	River flood	Yang et al. (2018)
Rural fixed asset investment/town population	L	River flood	Yang et al. (2018)

Table 6 Overview of vulnerability indicators for riverine regions where the following key is used for the selection criteria: SA for Statistical Analysis, L for Literature, and Q for Questionnaire

	Selection criteria	Flood type	References
Social vulnerability indicators			
Total population	SA	Flash floods	Aroca-Jiménez et al. (2020)
Population density	L	Recurrent floods	Jha and Gundimeda (2019)
Inhabitants aged 0–4/0–6	L, SA	Recurrent floods, flash floods	Aroca-Jiménez et al. (2020), Jha and Gundimeda (2019)
Inhabitants aged 5–14	SA	Flash floods	Aroca-Jiménez et al. (2020)
Inhabitants aged 15–64	SA	Flash floods	Aroca-Jiménez et al. (2020)
Inhabitants aged 65 or older	SA	Flash floods	Aroca-Jiménez et al. (2020)
Population projection aged 0–4/0–5	SA	Flash floods	Aroca-Jiménez et al. (2020)
Population projection aged 5–14	SA	Flash floods	Aroca-Jiménez et al. (2020)
Population projection aged 15–64	SA	Flash floods	Aroca-Jiménez et al. (2020)
Population projection aged 65 or older	SA	Flash floods	Aroca-Jiménez et al. (2020)
Dependency rates: males	SA	Flash floods	Aroca-Jiménez et al. (2020)
Dependency rates: females	SA	Flash floods	Aroca-Jiménez et al. (2020)
Female population	L	Recurrent floods	Jha and Gundimeda (2019)
Infant mortality rate	L	Recurrent floods	Jha and Gundimeda (2019)
Disabled population	L	Recurrent floods	Jha and Gundimeda (2019)
Illiterate people	SA	Flash floods	Aroca-Jiménez et al. (2020)
Population with secondary education	L	Recurrent floods	Jha and Gundimeda (2019)
Houseless population	L	Recurrent floods	Jha and Gundimeda (2019)
Distance to the nearest hospital	SA	Flash floods	Aroca-Jiménez et al. (2020)
Travel time to the nearest hospital	SA	Flash floods	Aroca-Jiménez et al. (2020)

(continued)

Table 6 (continued)

	Selection criteria	Flood type	References
Distance to the nearest health center	SA	Flash floods	Aroca-Jiménez et al. (2020)
Travel time to the nearest health center	SA	Flash floods	Aroca-Jiménez et al. (2020)
Health centers, e.g., per 10,000 population	L, SA	Recurrent floods, flash floods	Aroca-Jiménez et al. (2020), Jha and Gundimeda (2019)
Health status	Q	Flood	Vári et al. (2013)
Hospital beds	SA	Flash floods	Aroca-Jiménez et al. (2020)
Medical staff	SA	Flash floods	Aroca-Jiménez et al. (2020)
Kindergartens	SA	Flash floods	Aroca-Jiménez et al. (2020)
Elementary schools	Q, L, SA	Flood, recurrent floods, flash floods	Aroca-Jiménez et al. (2020), Jha and Gundimeda (2019), Vári et al. (2013)
Secondary schools	Q, L, SA	Flood, recurrent floods, flash floods	Aroca-Jiménez et al. (2020), Jha and Gundimeda (2019), Vári et al. (2013)
Retirement homes	SA	Flash floods	Aroca-Jiménez et al. (2020)
Tourist accommodation	SA	Flash floods	Aroca-Jiménez et al. (2020)
Road density	L	Recurrent floods	Jha and Gundimeda (2019)
Unemployment rates	SA	Flash floods	Aroca-Jiménez et al. (2020)
Long-term unemployed people	SA	Flash floods	Aroca-Jiménez et al. (2020)
Households where any unemployed people live	SA	Flash floods	Aroca-Jiménez et al. (2020)
Households in good condition	SA	Flash floods	Aroca-Jiménez et al. (2020)
Households in poor condition	SA	Flash floods	Aroca-Jiménez et al. (2020)
Households residing in house with a dilapidated condition	L	Recurrent floods	Jha and Gundimeda (2019)
Households having access to away location of drinking water	L	Recurrent floods	Jha and Gundimeda (2019)

(continued)

Table 6 (continued)

	Selection criteria	Flood type	References
Households not having latrine facility within the premises	L	Recurrent floods	Jha and Gundimeda (2019)
Households using electricity	L	Recurrent floods	Jha and Gundimeda (2019)
Households having good houses	L	Recurrent floods	Jha and Gundimeda (2019)
Economic vulnerability			
Economic activity	Q	Flood	Vári et al. (2013)
Household income	Q	Flood	Vári et al. (2013)
Having any form of savings	Q	Flood	Vári et al. (2013)
Possibility of getting a small loan	Q	Flood	Vári et al. (2013)
Possibility of getting a large loan	Q	Flood	Vári et al. (2013)
Number of workers in agricultural sector	SA	Flash floods	Aroca-Jiménez et al. (2020)
Number of workers in industry, construction, and services sectors	SA	Flash floods	Aroca-Jiménez et al. (2020)
Tourist accommodation capacity	SA	Flash floods	Aroca-Jiménez et al. (2020)
Unemployment rate	SA	Flash floods	Aroca-Jiménez et al. (2020)
Municipal debt per inhabitant	SA	Flash floods	Aroca-Jiménez et al. (2020)
Replacement costs of dwellings located at flood-prone areas	SA	Flash floods	Aroca-Jiménez et al. (2020)
Fixed investments per inhabitant	SA	Flash floods	Aroca-Jiménez et al. (2020)
Municipal available budget per capita	SA	Flash floods	Aroca-Jiménez et al. (2020)
Tax base of the property tax	SA	Flash floods	Aroca-Jiménez et al. (2020)
Per capita income	SA	Flash floods	Aroca-Jiménez et al. (2020)
Fixed investments per inhabitant	SA	Flash floods	Aroca-Jiménez et al. (2020)
Municipal budget per inhabitant	SA	Flash floods	Aroca-Jiménez et al. (2020)

Table 7 Overview of vulnerability indicators for coastal regions where the following key is used for the selection criteria: R for Researcher, L for Literature, HS for Household Survey, OS for Organization Survey

	Selection criteria	Flood type	Flood type
Physical vulnerability			
# of cyclones/typhoons etc.	L, HS, OS	Flood, coastal, riverine, urban flood	Giampieri (2021), Giannakidou et al. (2019), Bernadel et al. (2016)
Frequency of flooding	HS, OS	Riverine, coastal, urban flood	Bernadel et al. (2016)
Slopes	R, L	Flood	Giampieri (2021), Martınez-Graña et al. (2016)
Elevations	R	Flood	Martınez-Graña et al. (2016)
Distances	R	Flood	Martınez-Graña et al. (2016)
Bathymetry	R	Flood	Martınez-Graña et al. (2016)
Wave height and activity	R, L	Flood	Giampieri (2021), Martınez-Graña et al. (2016)
Sea level rise	R, L	Flood, coastal flood	Giampieri (2021), Giannakidou et al. (2019), Martınez-Graña et al. (2016)
Mean tidal range	R, L	Flood	Giampieri (2021), Martınez-Graña et al. (2016)
Geomorphology	R, L	Flood	Giampieri (2021), Martınez-Graña et al. (2016)
Height of flooding	HS, OS	Riverine, coastal, urban flood	Bernadel et al. (2016)
Lithology	R	Flood	Martınez-Graña et al. (2016)
Storm surge	L	Flood, coastal flood	Giampieri (2021), Giannakidou et al. (2019)
River discharge coastal	L	Flood	Giannakidou et al. (2019)
Foreshore slope	L	Coastal flood	Giannakidou et al. (2019)
Soil subsidence	L	Flood, coastal flood	Giampieri (2021), Giannakidou et al. (2019)
Coastline	L	Flood, coastal flood	Giampieri (2021), Giannakidou et al. (2019)
Developed land use (%)	R	Coastal flood	Tao (2021)
Tidal wetlands (%)	R	Coastal flood	Tao (2021)
Inland wetlands (%)	R	Coastal flood	Tao (2021)
Forestry area (%)	R	Coastal flood	Tao (2021)
Artificial filled land (%)	R	Coastal flood	Tao (2021)
Well-drained soil (%)	R	Coastal flood	Tao (2021)
Aquifer protection area (%)	R	Coastal flood	Tao (2021)
Impervious land cover (%)	R	Coastal flood	Tao (2021)

(continued)

Table 7 (continued)

	Selection criteria	Flood type	Flood type
Extent of coastal vegetation	L	Flood	Giampieri (2021)
Landform	L	Flood	Giampieri (2021)
Sediment budget	L	Flood	Giampieri (2021)
Rate of shoreline change	L	Flood	Giampieri (2021)
Distance to coast	L	Flood	Giampieri (2021)
Land cover	L	Flood	Giampieri (2021)
DEM	L	Flood	Giampieri (2021)
River density	L	Flood	Giampieri (2021)
Social vulnerability			
Population density	L, R	Flood, coastal flood	Giampieri (2021), Tao (2021)
Population close to coastline	L	Coastal flood	Giannakidou et al. (2019)
Population growth rate	L	Flood, coastal flood	Giampieri (2021), Giannakidou et al. (2019)
Population with no high school diploma	L, R, HS, OS	Flash flood, flood, coastal, riverine, urban flood	Giampieri (2021), Andres et al. (2015), Bernadel et al. (2016), Tao (2021)
Population with a disability	L, R	Flash flood, flood, coastal flood	Giampieri (2021), Andres et al. (2015), Tao (2021)
Female population	L	Flash flood, flood	Giampieri (2021), Andres et al. (2015)
Female head	L	Flash flood	Andres et al. (2015)
Single parent head	L	Flash flood	Andres et al. (2015)
Children	L	Flash flood, flood	Giampieri (2021), Andres et al. (2015)
Elderly	L	Flash flood, flood	Giampieri (2021), Andres et al. (2015)
Poverty	L	Flood	Giampieri (2021)
Race/ethnicity	L	Flood	Giampieri (2021)
Language	L	Flood	Giampieri (2021)
Number of households	L	Flood	Giampieri (2021)
Housing conditions	HS, OS	Riverine, coastal, urban flood	Bernadel et al. (2016)
Houses with NO access to improved sanitation	HS, OS	Riverine, coastal, urban flood	Bernadel et al. (2016)
Houses with NO access to an improved water source	HS, OS	Riverine, coastal, urban flood	Bernadel et al. (2016)
Presence of rats in the vicinity	HS, OS	Riverine, coastal, urban flood	Bernadel et al. (2016)
Presence of water-logged areas in the vicinity	HS, OS	Riverine, coastal, urban flood	Bernadel et al. (2016)

(continued)

Table 7 (continued)

	Selection criteria	Flood type	Flood type
Economic vulnerability			
Per capita income ($)	R	Coastal flood	Tao (2021)
Population below poverty (%)	R	Coastal flood	Tao (2021)
Unemployed population (%)	R	Coastal flood	Tao (2021)
Median house value ($)	R	Coastal flood	Tao (2021)
Aggregated house value ($)	R	Coastal flood	Tao (2021)
Family income	HS, OS	Riverine, coastal, urban flood	Bernadel et al. (2016)
Property insurance	HS, OS	Riverine, coastal, urban flood	Bernadel et al. (2016)
Reliance on loans	L	Flood	Giampieri (2021)
GDP	L	Flood	Giampieri (2021)
Household savings	L	Flood	Giampieri (2021)
Changes in income	L	Flood	Giampieri (2021)
Occupation	L	Flood	Giampieri (2021)
Employed	L	Flood	Giampieri (2021)
Institutional			
Existence of flood hazard maps	L	Flood	Giampieri (2021)
Recovery time	L	Flood	Giampieri (2021)
Government neglect	L	Flood	Giampieri (2021)
Presence of coastal management plan/land use planning	L	Flood	Giampieri (2021)
Presence of dedicated administrator for evacuation/preparedness	L	Flood	Giampieri (2021)
Community preparedness	L	Flood	Giampieri (2021)

References

Alam, F., Ofli, F., & Imran, M.. (2019). CrisisDPS: Crisis data processing services. In *ISCRAM*.

Amir Masoud Forati and Rina Ghose. (2022). Examining community vulnerabilities through multi-scale geospatial analysis of social media activity during Hurricane Irma. *International Journal of Disaster Risk Reduction, 68*, 102701.

Andres, J., Ignacio, F., et al. (2015). Assessing the effectiveness of a social vulnerability index in predicting heterogeneity in the impacts of natural hazards: Case study of the Tropical Storm Washi flood in The Philippines. In *Vienna Yearbook of Population Research*, pp. 91–129.

Antwi, E. K., et al. (2015). Community vulnerability assessment index for flood prone savannah agro-ecological zone: A case study of Wa West District, Ghana. *Weather and Climate Extremes, 10*, 56–69.

Aroca-Jiménez, E., et al. (2017). Construction of an integrated social vulnerability index in urban areas prone to flash flooding. *Natural Hazards and Earth System Sciences, 17*(9), 1541–1557.

Aroca-Jiménez, E., Bodoque, J. M., & Garcıa, J. A. (2020). How to construct and validate an Integrated Socio-Economic Vulnerability Index: Implementation at regional scale in urban areas prone to flash flooding. *Science of the Total Environment, 746*, 140905.

Asian Disaster Reduction Center. (2015). *Sendai framework for disaster risk reduction 2015–2030*. ADRC.

Baeck, S. H., et al. (2014). A study of evaluating and forecasting watersheds using the flood vulnerability assessment index in Korea. *Geomatics, Natural Hazards and Risk, 5*(3), 208–231.

Balica, S. F. (2007). *Development and application of flood vulnerability indices for various spatial scales*. UNESCO-IHE Institute for Water Education.

Balica, S. F., Douben, N., & Wright, N. G. (2009). Flood vulnerability indices at varying spatial scales. *Water Science and Technology, 60*(10), 2571–2580.

Balica, S. F., et al. (2013). Parametric and physically based modelling techniques for flood risk and vulnerability assessment: A comparison. *Environmental Modelling & Software, 41*, 84–92.

Barroca, B., et al. (2006). Indicators for identification of urban flooding vulnerability. *Natural Hazards and Earth System Sciences, 6*(4), 553–561.

Bernadel, M. B., Villordon, L., & Gourbesville, P. (2016). Community based flood vulnerability index for urban flooding: Understanding social vulnerabilities and risks. In *Advances in hydroinformatics* (pp. 75–96). Springer.

Bigi, V., et al. (2021). Flood vulnerability analysis in urban context: A socioeconomic sub-indicators overview. *Climate, 9*(1), 12.

Bono, C. et al. (2022). TriggerCit: Early flood alerting using Twitter and Geolocation – A comparison with alternative sources. In *arXiv preprint arXiv:2202.12014*.

Cervone, G., et al. (2016). Using Twitter for tasking remote-sensing data collection and damage assessment: 2013 Boulder flood case study. *International Journal of Remote Sensing, 37*(1), 100–124.

Chang, H.-S., & Chen, T.-L. (2016). Spatial heterogeneity of local flood vulnerability indicators within flood-prone areas in Taiwan. *Environmental Earth Sciences, 75*(23), 1–14.

Cian, F., Giupponi, C., & Marconcini, M. (2021). Integration of earth observation and census data for mapping a multi-temporal flood vulnerability index: A case study on Northeast Italy. *Natural Hazards, 106*(3), 2163–2184.

Cutter, S. L., et al. (2008). A place-based model for understanding community resilience to natural disasters. *Global Environmental Change, 18*(4), 598–606.

Cutter, S. L., Ash, K. D., & Emrich, C. T. (2014). The geographies of community disaster resilience. *Global Environmental Change, 29*, 65–77.

de Andrade, M. M. N., & Szlafsztein, C. F. (2018). Vulnerability assessment including tangible and intangible components in the index composition: An Amazon case study of flooding and flash flooding. *Science of the Total Environment, 630*, 903–912.

Fatemi, F., et al. (2017). Social vulnerability indicators in disasters: Findings from a systematic review. *International Journal of Disaster Risk Reduction, 22*, 219–227.

Giampieri, M. A. (2021). A review of flood vulnerability indices for coastal cities. In *Understanding disaster risk* (pp. 37–57). Elsevier.

Giannakidou, C., Diakoulaki, D., & Memos, C. D. (2019). Implementing a flood vulnerability index in urban coastal areas with industrial activity. *Natural Hazards, 97*(1), 99–120.

Goodchild, M. F. (2007). Citizens as sensors: The world of volunteered geography. *GeoJournal, 69*(4), 211–221.

Gu, C., et al. (2011). Climate change and urbanization in the Yangtze River Delta. *Habitat International, 35*(4), 544–552.

Harahap, B. A. (2021). Relevant indicators of social vulnerability during response phase context of flooding in Tebing Tinggi City, North Sumatra Indonesia. *IOP Conference Series: Earth and Environmental Science, 921*(1), 012015. IOP Publishing.

Hidayah, E., Wiyono, R. U. A., & Wicaksono, A. D. (2021). Development of the flood vulnerability index using a multi-element approach. *Journal of Water and Land Development*, 255–264.

Imran, M. et al. (2014). AIDR: Artificial intelligence for disaster response. In *Proceedings of the 23rd international conference on world wide web*, pp. 159–162.

ISDR Terminology. (2004). Basic terms of disaster risk reduction. In *Living with risk: A global review of disaster reduction initiatives*. United Nations.

Jha, R. K., & Gundimeda, H. (2019). An integrated assessment of vulnerability to floods using composite index – A district level analysis for Bihar, India. *International Journal of Disaster Risk Reduction, 35*, 101074.

Karmaoui, A., & Balica, S. (2021). A new flood vulnerability index adapted for the pre-Saharan region. *International Journal of River Basin Management, 19*(1), 93–107.

Kersten, J., & Klan, F. (2020). What happens where during disasters? A workflow for the multifaceted characterization of crisis events based on Twitter data. *Journal of Contingencies and Crisis Management, 28*(3), 262–280.

Liew, D. Y. C., Che Ros, F., & Harun, A. N. (2019). Developing composite indicators for flood vulnerability assessment: Effect of weight and aggregation techniques. *International Journal of Advanced Trends in Computer Science and Engineering, 8*, 383–392.

Mansur, A. V., et al. (2016). An assessment of urban vulnerability in the Amazon Delta and Estuary: A multi-criterion index of flood exposure, socioeconomic conditions and infrastructure. *Sustainability Science, 11*(4), 625–643.

Martınez-Graña, A. M., et al. (2016). Coastal-flood risk management in central Algarve: Vulnerability and flood risk indices (South Portugal). *Ecological Indicators, 71*, 302–316.

Mason, K., et al. (2021). Social vulnerability indicators for flooding in aotearoa New Zealand. *International Journal of Environmental Research and Public Health, 18*(8), 3952.

Membele, G. M., Naidu, M., & Mutanga, O. (2022). Using local and indigenous knowledge in selecting indicators for mapping flood vulnerability in informal settlement contexts. *International Journal of Disaster Risk Reduction, 71*, 102836.

Miller, J. D., & Hutchins, M. (2017). The impacts of urbanisation and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom. *Journal of Hydrology: Regional Studies, 12*, 345–362.

Moreira, L. L., de Brito, M. M., & Kobiyama, M. (2021a). A systematic review and future prospects of flood vulnerability indices. *Natural Hazards and Earth System Sciences, 21*(5), 1513–1530.

Moreira, L. L., de Brito, M. M., & Kobiyama, M. (2021b). Effects of different normalization, aggregation, and classification methods on the construction of flood vulnerability indexes. *Water, 13*(1), 98.

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. *Natural Hazards and Earth System Sciences, 11*(8), 2107–2123.

Nasiri, H., Yusof, M. J. M., & Ali, T. A. M. (2016). An overview to flood vulnerability assessment methods. *Sustainable Water Resources Management, 2*(3), 331–336.

Nasiri, H., et al. (2019). District flood vulnerability index: Urban decision-making tool. *International journal of Environmental Science and Technology, 16*(5), 2249–2258.

Oulahen, G., et al. (2015). Unequal vulnerability to flood hazards: "ground truthing" a social vulnerability index of five municipalities in Metro Vancouver, Canada. *Annals of the Association of American Geographers, 105*(3), 473–495.

Papathoma-Köhle, M., et al. (2017). Matrices, curves and indicators: A review of approaches to assess physical vulnerability to debris flows. *Earth-Science Reviews, 171*, 272–288.

Qazi, U., Imran, M., & Ofli, F. (2020). Geocov19: A dataset of hundreds of millions of multilingual covid-19 tweets with location information. *SIGSPATIAL Special, 12*(1), 6–15.

Rashetnia, S., & Jahanbani, H. (2021). Flood vulnerability assessment using a fuzzy rule-based index in Melbourne, Australia. *Sustainable Water Resources Management, 7*(2), 1–13.

Rodrıguez-Gaviria, E. M., et al. (2019). Computational bottom-up vulnerability indicator for low-income flood-prone urban areas. *Sustainability, 11*(16), 4341.

Sadiq, R., et al. (2022). Integrating remote sensing and social sensing for flood mapping. *Remote Sensing Applications: Society and Environment, 25*, 100697.

Sajjad, M. (2021). Disaster resilience in Pakistan: A comprehensive multidimensional spatial profiling. *Applied Geography, 126*, 102367.

Sajjad, M., & Chan, J. C. L. (2019). Risk assessment for the sustainability of coastal communities: A preliminary study. *Science of the Total Environment, 671*, 339–350.

Sajjad, M., Chan, J. C. L., & Lin, N. (2020). Incorporating natural habitats in to coastal risk assessment frameworks. *Environmental Science & Policy, 106*, 99–110.

Salazar-Briones, C., et al. (2020). An integrated urban flood vulnerability index for sustainable planning in arid zones of developing countries. *Water, 12*(2), 608.

Saurav, K. C., et al. (2021). Predicting flood events in Kathmandu Metropolitan City under climate change and urbanisation. *Journal of Environmental Management, 281*, 111894.

Tao, W. (2021). Quantifying coastal flood vulnerability for climate adaptation policy using principal component analysis. *Ecological Indicators, 129*, 108006.

Tarbotton, C., et al. (2015). The use of empirical vulnerability functions to assess the response of buildings to tsunami impact: Comparative review and summary of best practice. *Earth-Science Reviews, 142*, 120–134.

Tricco, A. C., et al. (2018). PRISMA extension for scoping reviews (PRISMAScR): Checklist and explanation. *Annals of Internal Medicine, 169*(7), 467–473.

UN Office for Disaster Risk Reduction. (2020). *The human cost of disasters – An overview of the last 20 years 2000–2019*.

United Nations. (2009). *UNISDR terminology on disaster risk reduction*. United Nations Office for Disaster Risk Reduction, Report.

Vári, A., Ferencz, Z., & Hochrainer-Stigler, S. (2013). Social indicators of vulnerability to floods: An empirical case study in two Upper Tisza flood basins. In *Integrated catastrophe risk modeling* (pp. 181–198). Springer.

Villordon, M. B. B. L., & Gourbesville, P. (2014). Vulnerability index for urban flooding: Understanding social vulnerabilities and risks.

WBGU–Wissenschaftlicher Beirat der Bundesregierung Globale. (1998). Umweltveränderungen (1999): Welt imWandel–Strategien zur Bewältigung globaler Umweltrisiken. In *Jahresgutachten des WBGU*.

Weber, E., et al. (2020). Detecting natural disasters, damage, and incidents in the wild. In *European conference on computer vision* (pp. 331–350). Springer.

Yang, W., et al. (2018). Integrated flood vulnerability assessment approach based on TOPSIS and Shannon entropy methods. *Ecological Indicators, 89*, 269–280.

Yuan, F., & Liu, R. (2018). Feasibility study of using crowdsourcing to identify critical affected areas for rapid damage assessment: Hurricane Matthew case study. *International Journal of Disaster Risk Reduction, 28*, 758–767.

Zachos, L. G., et al. (2016). Flood vulnerability indices and emergency management planning in the Yazoo Basin, Mississippi. *International Journal of Disaster Risk Reduction, 18*, 89–99.