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Bangladesh's vulnerability to cyclonic coastal flooding

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Abstract. In the Ganges–Brahmaputra–Meghna delta, covering most of Bangladesh, more than 165 million people live in low-lying coasts facing major extreme climatic events, such as cyclones. This article reviews the current scientific literature publications (2007–2020) in order to define vulnerability in the context of coastal Bangladesh facing cyclonic flooding. Based on this review, a new metric, called the socio-spatial vulnerability index (SSVI), is defined as function of both the probability of the cyclonic flood hazard and the sensitivity of delta inhabitants. The main result shows that the districts of Shariatpur, Chandpur and Barisal situated in the tidal floodplain of the Ganges–Brahmaputra–Meghna delta are in the fourth quartile, i.e., highest category, the most vulnerable areas. These districts are very densely populated (from 870 up to 1400 inhabitants per square kilometer) and exposed to inundation hazards with a large number of vulnerability factors. Finally, the delta's mouth was identified as a very vulnerable area to cyclonic flooding as well.

1 Introduction

Tropical cyclones are among the most devastating extreme natural events. When a cyclone approaches a coast, it can induce an increase of sea level, called storm surge. This storm surge can cause severe flooding of vast coastal low-lying areas and leads to profound societal and economic impacts. This is especially the case for the regions surrounded by the semi-enclosed sea of the Bay of Bengal. Although the frequency of the cyclone is weaker than in the Atlantic and Pacific oceans, most of them make landfall (Balaguru et al., 2014). This, combined with low-lying and high-populated areas, causes catastrophic impacts (Hoque et al., 2019). In April 1991, for example, 15 million people were affected in Bangladesh by the flooding that followed the landfall of Cyclone Gorky, causing about 140 000 fatalities and USD 1.8 billion worth of damage (source: International Emergency Events Database EM-DAT, https://www.emdat.be/, last access: 19 March 2019). These cyclone-induced storm surges are more frequent during the pre-monsoon (May) and post-monsoon (October–November) season, when the flow of the Ganges–Brahmaputra river system is relatively low and the rainfall is moderate (Uddin et al., 2019b), thereby reducing the likelihood of experiencing compound events, i.e., combined with other flood types such as pluvial and fluvial (Haque et al., 2018). The contribution of the heavy rainfall from landfalling cyclones to the floods, additional to the storm surge, still remains unexplored for this region. Therefore, hereafter, the study focused only on the cyclone-induced storm surge flood hazard. The development of accurate and understandable cyclone flooding knowledge and tools is therefore crucial to define effective strategies for adaptation to these extreme events. Today, the cyclone flood risk assessments has become an essential worldwide tool to assist in setting appropriate protection measures. However, the multiplication of the cyclone flood risk assessments raises important questions about how their findings are comparable, generalizable and easily transferable to the decision makers and communities.

In this study, we wonder, first and foremost, about the risk terminology. Although this terminology lacks uniformity between the social and the natural sciences, as well as within each (Roberts et al., 2009), both approaches recognize that risk combines hazard, vulnerability and exposure (and sometimes coping capacities and resilience). While natural sciences emphasize hazard above all and consider vulnerability mainly from the element at risk in physical and technical viewpoints, social sciences rather focus on structural factors that reduce the human system capacity to cope with a range of hazards (Baum et al., 2009; Roberts et al., 2009). Vulnerability has many facets influencing each other and may also be measured by susceptibility to loss, on physical (natural and man-made environments), social, economic, institutional and systemic levels. Therefore, more than the exposure or the hazard, vulnerability is a key factor for the relevance of all cyclone flood risk assessments.

In order to address the vulnerability to cyclone flooding, current approaches (among others Ghosh et al., 2019; Hoque et al., 2019; Quader et al., 2017; Sahoo and Bhaskaran, 2018) tend to focus on flood hazard and other social-vulnerability patterns but are rarely integrated into an interdisciplinary framework considering interaction between both (Rabby et al., 2019). Previous studies define the vulnerability of places, also called physical vulnerability, following if the risk of flooding can be enhanced or reduced by changes in the natural and built environment (Cutter, 2003; England and Knox, 2016). Cyclone flooding, topography, dikes, embankments, roads, houses and land use can therefore influence physical vulnerability. Moreover, although these places might have the same probability of being flooded by a cyclone, the sensitivity of people and their capacity to cope with a flood will be different (O'Hare and White, 2018). Therefore, in this work we considered a cyclone flood event in this integrated and interdisciplinary framework, as the intersection between physical vulnerability and individual/group sensitivity, resulting into the concept of socio-spatial vulnerability to a cyclone flood (Forrest et al., 2020).

Thus, more than developing a new vulnerability concept, the novelty of our study lies in the methodological adaptation of existing approaches, like the social-vulnerability index (Flanagan et al., 2011), to the cyclone-flooding-specific context. In this way, we define a new metric, called the socio-spatial vulnerability index (SSVI), as function of both the probability of the cyclone flood hazard and the sensitivity of inhabitants. This metric is used to identify the areas where the largest number of the most vulnerable people are exposed to frequent cyclone flooding.

This study explores the potential for the cyclone flood SSVI to highlight socio-spatial inequalities between the coastal districts in the case of Bangladesh, considered one of the most vulnerable countries in the world regarding extreme climatic events. In this region, 165 million people live on the low-lying land of the Ganges–Brahmaputra–Meghna (GBM) delta and face, among other things, catastrophic storm surge floods caused by cyclones (Ali, 1999; Becker et al., 2020; Nicholls et al., 2018; Uddin et al., 2019a). As mentioned above, several studies have already been carried out to assess the cyclone flood vulnerability of Bangladesh's coastal areas. However, as mentioned by Hoque et al. (2019), only two studies have proposed the production of a multi-parameter index such as a tool to characterize the physical vulnerability in the central and western part of the GBM delta (Islam et al., 2015, 2016). Another work made by Mahmood et al. (2020) proposes a cyclone flood vulnerability assessment located on the mouth area of the GBM delta, which is based on the coastal-vulnerability index developed by Hoque et al. (2019). Only physical parameters such as topography, shoreline change and coastal slope (among others) were taken into account. Therefore, here also the social dimension of cyclone flood vulnerability was not assessed.

The paper is organized as follows: Sect. 2 gives an overview of current paradigms used to conceptualize vulnerability; Sect. 3 presents the region study; Sect. 4 provides insights from a literature review into how vulnerability to cyclone flooding in Bangladesh is questioned and according to which indicators; and Sect. 5 proposes the socio-spatial vulnerability index for standardizing vulnerability to cyclone flooding in Bangladesh. Finally, two sections are devoted to the discussion and conclusion.

2 Overview of the vulnerability concept and its indicators

In the following, we provide a necessary overview of different vulnerability paradigms in order to understand how they were defined in these past decades and how such a conceptualization can be achieved. Following the authors, vulnerability is seen either as static or dynamic, including exposure or not. Chambers (1989) initiated a formal definition as "exposure to contingencies and stresses and the difficulty which some communities experience while coping with such contingencies and stresses". Hence, he identified two binaries of vulnerability: an external (the exposure to external shocks) and an internal vulnerability (the incapacity to cope). Lastly, he suggested that it is determined by the management and accessibility of assets. Here, exposure is included, but vulnerability is mainly considered a state (Roberts et al., 2009).

The pressure and release model proposed by Blaikie et al. (1994) considers that vulnerability is socially produced (Menoni et al., 2012). It is defined as "the characteristics of a person or group in terms of their capacity to anticipate, cope with, resist, and recover from the impact of a natural hazard". It focuses on both the social and temporal dimensions of a disaster (Kuhlicke et al., 2011) and proposes that vulnerability can be reduced through people's access to resources (Menoni et al., 2012).

Further developed by Wisner et al. (2004), the model includes a sense of progression into the vulnerability, which gradually evolves according to root causes (the unequal distribution of power and assets), dynamic pressures (societal characteristics, such as population density and growth) and unsafe conditions (evolving situation as its expression when the hazard occurs). This model conceptualizes vulnerability as a process, but it underestimates the exposure in the risk equation (Roberts et al., 2009). Vulnerability as a dynamic process was additionally developed by Birkmann (2006) in the Bogardi–Birkmann–Cardona (BBC) model which incorporates coping capacity into the vulnerability item of the risk equation. It also distinguishes between its social, economic and environmental components (Romieu et al., 2010). However, his model does not integrate physical vulnerability as impacting the social aspects. In most of these models, it is emphasized how it is a dynamic concept that does not only include socio-demographic characteristics.

Vulnerability is also the result of human interactions and networks and could change across time. De Marchi and Scolobig (2012) claim that the vulnerability of social systems is derived from characteristics of not only individuals and groups but also institutions. For those reasons, later authors offered to characterize its various components according to its associated people and threatened assets. In addition, those authors adopt a systemic perspective in which they distinguish between the individual and the institutional components of social vulnerability in order to explore their interactions. Individual vulnerability stresses the perceptions and attitudes impeding people from preparing and coping sufficiently in case of disaster. However, institutional vulnerability implies that agencies and services could paradoxically weaken the overall capacity of a specific system to deal effectively with disasters (De Marchi and Scolobig, 2012). For example, the authors demonstrate how the presence of structural devices (barriers, dams and embankments) can lessen the perception of risk and mislead to a "symbol of complete safety". This institutional vulnerability leads to a situation where the bigger the defense system is, the greater the increase of the impression of invulnerability is. This effect is well known in the literature as the "safety paradox" (Burby, 2006; Ferdous et al., 2020): increasing levels of flood protection can generate a sense of complacency among the protected people, which can reduce preparedness, thereby increasing vulnerability.

Furthermore, to assess vulnerability level, classical indicators are often social inequality indicators, such as age, gender, household composition, employment, income, educational level, ethnicity and race (Blaikie et al., 1994; IPCC AR5, 2014). Other socioeconomic indicators are added by the United Nations and the World Bank, such as the gross domestic product (GDP) per inhabitant, the Human Poverty Index (HPI), the inflation rate and population characteristics (density, growth, life expectancy at birth and illiteracy rate). These classical indicators of vulnerability may lack explanatory power, and so this type of parameter using quantitative data should be discussed and put into perspective with qualitative indicators (Kuhlicke et al., 2011). Indicators relying only on census data lack a full understanding because they do not take into account people's perceptions and culture of risk, norms, traditions, beliefs and behaviors. Another social dimension like "the ability of individuals and communities to cope seems to depend also on some intangible aspects, which can be described by terms such as energy, vigor, vitality, strength, courage, nerve, fortitude, and their antonyms" (De Marchi and Scolobig, 2012). Those aspects shape people's vulnerability, together with personal, contextual and material conditions.

As mentioned above, according to disciplinary approaches, the physical and social dimensions must be studied together and fit within a territory. This spatial dimension then appears unavoidable to assess vulnerability (Mazumdar and Paul, 2018). It enables, from a local to a national level, the definition of specific adaptation or mitigation strategies for each region, through the identification of hotspots, and the use of the map as a means of communication to meet the decision makers' needs. As mentioned by Mazumdar and Paul (2018), vulnerability is specific according to population, factors and locations. This is why we have chosen to assess the vulnerability to cyclone flooding through the socio-spatial vulnerability index (SSVI), a tool that enables both quantifying and mapping its levels. Socio-spatial vulnerability takes into account social conditions and measures the resistance or resilience of populations to a hazard; at the same time, it integrates the potential exposures of these same populations in particular territories (Cutter et al., 2003; England and Knox, 2016; Forrest et al., 2020; O'Hare and White, 2018). Thus, we consider the vulnerability in a structural perspective (Hufschmidt, 2011) and where "exposure", i.e., the spatial intersection of flood hazard and population density, is included as one of its components.

3 Region study

Bangladesh is situated between India, Myanmar and the Bay of Bengal. This country is one of the most vulnerable countries in the world regarding extreme climatic events. The entirety of coastal Bangladesh is under 10 m elevation (Becker et al., 2019) and is highly populated with a mean of 1240 people per square kilometer in 2018 (World Bank, 2018), which increases its exposure to coastal floods. Though people of the deltas have learned how to live with periodic coastal submersion, they face numerous constraints like ground instability because of fluvial alluvium and subsidence, the insalubrity of swamps, and ground salinity, which compelled the population to adapt its cultural activities like planting new rice varieties (Ali, 1999) or shifting from rice cultivation to shrimp farming.

Conventional methods for reducing the effect of cyclonic flooding in this region are embankments, polderization, coastal afforestation and shelter construction (Rahman and Rahman, 2015). Since the 1960s, Bangladesh has had a widespread system of embankments and polders (land surrounded by embankments), which initially improve agriculture and water-level management (Brown et al., 2018). However, as these earthen embankments systems were built for tidal flooding – without considering storm surges – they were not able to protect against extreme cases of cyclonic flooding. Besides, due to a lack of maintenance, most of coastal embankments nowadays are partially or completely eroded (Younus and Sharna, 2014). In 1972, the Cyclone Preparedness Program (CPP) was created by the Bangladeshi government to prepare weather forecasts and disaster warnings (Paul, 2009), whereby cyclone shelters were erected as multistory buildings – for example, in the form of a "school cum cyclone shelter" – to promote education as well as serve as shelter during storm surges. Flood hazards challenge the high and growing population density, where the majority of urban Bangladeshis live in the main cities (Dhaka, Khulna and Chittagong; Fig. 1a), which all contend with flood hazards. Floods threaten people's lives and assets but can also damage livelihoods, agriculture and impact almost all socioeconomic activities. Storm surge flooding in Bangladesh resulted in the greatest global death toll over the last century, such as from Cyclone Gorky in 1991, causing about 140 000 fatalities (Nicholls et al., 2018). In the previous decade, the floods triggered by Cyclone Sdir in 2007 and Cyclone Aila in 2009 caused thousands of fatalities (Ahmed et al., 2016; Paul, 2009) and displaced many others. In order to reduce people affected by cyclonic coastal flooding, a number of risk assessment studies (among others Mallick et al., 2017; Quader et al., 2017; Hoque et al., 2019) have been conducted in this region to determine which actions should be prioritized for policymakers to implement.

Recent progress in hydrodynamic modeling for the GBM delta showed that to accurately reproduce patterns of cyclonic coastal flooding, several parameters are essential such as accurate bathymetry and topography, inclusions of dikes, well-tuned bottom roughness, and forcing the model with an accurate representation of the cyclonic wind and pressure fields (Khan et al., 2021; Krien et al., 2017). Using this robust hydrodynamical-modeling schema, Khan et al. (2019) provided probabilistic cyclonic-flood-hazard maps over the coastal GBM delta from a dataset of statistically and physically consistent synthetic cyclone events (Emanuel et al., 2006). We presented in Fig. 1a the cyclonic flooding level with a 50-year return period estimated from Khan et al. (2019). This means that at a particular location in the GBM delta, the reported flooding height, due to cyclonic flooding, is expected to be observed on average once in 50 years. This type of metric aims to anticipate the cyclone flood occurrence and its consequences in order to alert the inhabitants and put in place effective strategies of evacuation. In dark blue in Fig. 1a, one observes the places which are exposed to flooding with the most extreme heights, up to 8 m from the mean sea level at the junction between the Ganges and the Meghna rivers. All the coastal islands areas are exposed to a 1-in-50-year flood, though the biggest ones, such as Hatiya, Sandwip and Kutubdia islands, are not totally exposed to the cyclonic inundation on their total area. For these large coastal islands, the presence of dikes makes a very large gradient in the inundation hazard. Along almost all the coastline, blue colors are darker – except in the south of Lakshmipur District – meaning that the embankments and their polders behind are strongly exposed to the inundation. This directly threatens the houses settled by the dikes as authors underlined (Alam and Collins, 2010).

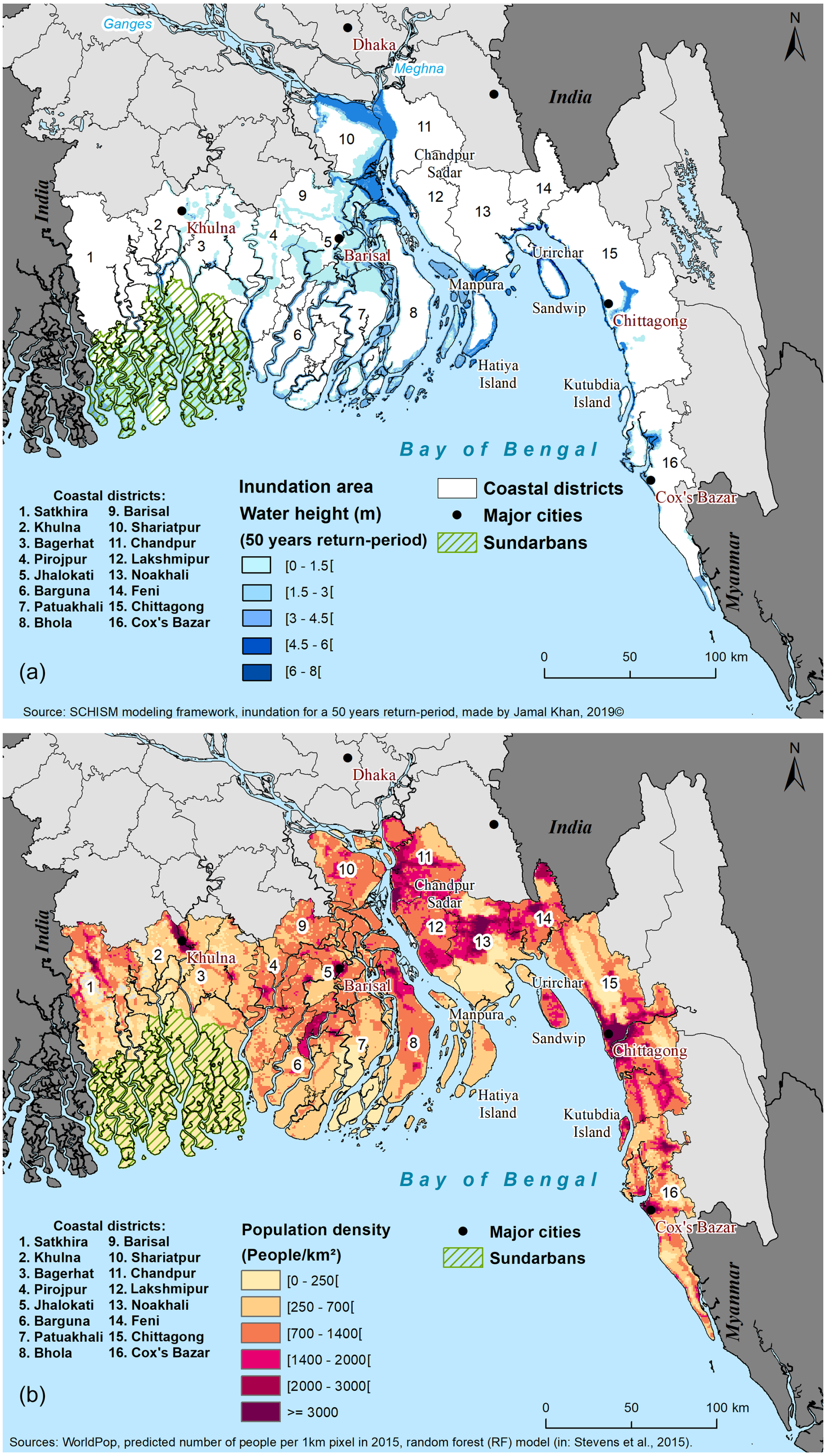
In addition to lots of places exposed to flooding with the most extreme heights, the population is aggregated around the main cities of the south: Khulna, Barisal, Chittagong and Cox's Bazar, as well as on big islands such as Sandwip and Kutubdia islands (Fig. 1b). While the area on the southwestern coast, behind the Sundarbans forest, is not very populated compared with other parts of the delta, the districts of the central and eastern coasts are much denser, such as in the Chandpur Sadar Upazila (sub-district) at the mouth of the GBM delta. In Khulna, the water height is lower but still significant when crossed with the high population density. In Satkhira and Khulna, the western coastal districts, population density is lower, but as the people of this area is highly dependent on natural resources, the flooding of the Sundarbans increases the vulnerability of the people in the area.

4 Assessing vulnerability to cyclonic coastal flooding in Bangladesh from a literature review

4.1 Methodology

To define and assess the vulnerability to cyclonic coastal flooding in Bangladesh, a literature review was conducted. This review was limited to peer-reviewed articles published between 2007 and December 2020. The analysis period started in 2007, taking this year as a turning point in terms of developments of vulnerability frameworks. Indeed, in 2007, the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) defined the significance of vulnerability social factors over the international research community. This review excludes non-peer-reviewed articles, in the aim to obtain a state-of-the-art review of the current knowledge extracted from scientific literature only to verify the use of high-scientific-quality standards in the selected articles (Räsänen et al., 2016). In those articles, a scientific methodology is employed to empirically test research hypotheses and to be sure that data gathering, treatment and results analysis are logical, verifiable and reproducible.

Finally, only English-language literature was included in order to keep references that can be widely read, to en-



Source: SCHISM modeling framework, inundation for a 50 years return-period, made by Jamal Khan, 2019©

Sources: WorldPop, predicted number of people per 1km pixel in 2015, random forest (RF) model (in: Stevens et al., 2015).

Figure 1. Study area. **(a)** Cyclonic inundation level with a 50-year return period estimated from a large number of hydrodynamic simulations (Khan et al., 2019). This means that at a particular location, the reported flooding height, due to cyclonic surges, is expected to be observed once in 50 years. **(b)** Population density in coastal districts of Bangladesh. SCHISM: Semi-implicit Cross-scale Hydroscience Integrated System Model.

able reproduction and to deepen this review. The search engines used for the literature review process are Istex, ScienceDirect, Scopus and Web of Science, four traditional academic citation databases. In addition, we completed the analysis with the literature extracted from the Google Scholar database. Despite it having been shown that the majority of literature identified using Web of Science was also found using Google Scholar (Haddaway et al., 2015), it has been also demonstrated that a large fraction (9 %–30 %) of highly cited documents in the social sciences and humanities could be invisible to the Web of Science and Scopus (Martín-Martín et al., 2018).

The initial search used inclusion criteria to be sure that the first selected range of articles focused on studies about vulnerability to cyclonic floods in Bangladesh. The following search sequence used in the electronic databases includes the hazard, the area of study and keywords related to vulnerability: ("coastal flood" OR "sea-level rise" OR "Storm surge" OR "Cyclonic storm" OR "Disaster risk reduction") AND ("Bangladesh" OR "Brahmaputra delta") AND ("vulnerability" OR "human exposure" OR "coping"). Those terms have been sought in the titles, abstracts and keywords of the articles (see Appendix A1 for more details on the strategy used). A second selection of the first range of articles screened documents one by one to check if they explored vulnerability to cyclones and if they specifically did focus on areas placed in coastal Bangladesh and not vulnerability to river floods for instance. From this research, 49 publications were kept for this review (see Appendix A2–A4).

4.2 Summary of the literature analysis

The first result shows the universities behind the analyzed articles: 85 % of the studies were conducted by Western or Asian scholars. Only seven articles were directed by Bangladeshi nationals, and the rest were made from a cooperation with a Bangladeshi. Amongst the authors' disciplines, the applied sciences are overrepresented with 26 articles (especially in the field of disaster risk management), followed by the humanities and social sciences and, finally, the natural sciences.

The methodologies used in half of the studies are mixed methods, using both quantitative (e.g., surveys) and qualitative data (focus group discussion and key informant interviews, for example). An inductive approach (bottom-up) was used in three-quarters of the articles, explaining that most of the studies were done at a small scale – villages and unions (a gathering of two or three municipalities) – to study some aspects of population vulnerability. While still more than half of the studies used surveys (structured questionnaires), five articles used the participatory rural appraisal (PRA) method to allow the participant to fully contribute even if they were illiterate (Ahmed et al., 2010; Ahsan, 2017; Shameem et al., 2014).

Most of the authors touch upon vulnerability in their articles, but surprisingly, not all give a definition of it, often taking the concept for granted. Among the studies defining the theory upon which they grounded their research, three articles define what they consider being vulnerability. First, for Mallick et al. (2009), "vulnerability to disasters refers to the inability of a society and its people to withstand adverse impacts from multiple stresses to which they are exposed. It has two sides: an external side of risks, shocks, and stress to which an individual or household is subject; and an internal side which is defenselessness, meaning a lack of means to cope". Second, Quader et al. (2017) mention "three main characteristic groups of social vulnerabilities (dimensions), namely the socio-demographic and economic characteristics of the population, their access to basic facilities and the proportion of physically or ethnically marginalized people". Then, Ishtiaque et al. (2019) define vulnerability "as the degree or extent to which a system is likely to be exposed and sensitive to a hazard, and the capacity of that system to adapt to the effects of climate impacts". Although those definitions do not have a lot in common, they are complementary. Therefore, those results show how little consensus exists on this concept in this region.

Finally, this literature review enables us to outline below the vulnerability factors' main characteristics discussed in the articles (physical and systemic infrastructures and social and economic aspects). Some authors agree that in the coastal zone globally, but especially in Bangladesh, it is imperative to consider both physical and socioeconomic factors in defining vulnerability (Miah et al., 2020; Mullick et al., 2019; Uddin et al., 2019a).

4.3 Identifying vulnerability indicators

4.3.1 Physical and systemic infrastructures

Infrastructures: road, cyclone shelter, embankment and communication facilities

According to the authors, the lack of proper road communication networks and transport infrastructure is an important factor of people's vulnerability to cyclone disasters. In the coastal area, roads are not uniformly distributed (Rabby et al., 2019), and most of them are narrow and unpaved and made of dirt tracks, since they often mark boundaries for crop fields (Alam and Collins, 2010), and embankments are also used as roads. During the rainy season, they are destroyed, and the mud makes any physical mobility difficult (Saroar and Routray, 2010). The lack of road infrastructure is particularly important when authorities should disseminate early warnings before a cyclone (Paul, 2009), but they are mainly inaccessible to motorized vehicles. When hazards are imminent, roads in good shape are needed for the population to travel to reach protective shelters (Kulatunga et al., 2014). Finally, after the cyclone, developed road communication networks enable effective evacuation and rescue during post-disaster relief operations (Hossain, 2015). Hence, it is concluded by authors that remote areas rarely get emergency assistance (Mallick et al., 2017).

The situation of the shelters is studied by many authors, showing how the long distances are to reach them and the lack of infrastructure facilities, and their deterioration is an issue to the nearby households when they have to decide to find shelter or not. Proximity, poor hygienic condition (Kulatunga et al., 2014), a lack of means of communication, and the delivery of sanitation and drinking water (Saha, 2015) are some examples for additional reluctant aspects for many of the families. People are also reluctant to take refuge in shelters not only because they are suspicious of cyclone alerts but also because they are afraid of having all their belongings stolen. There is also a forgetfulness about the impacts of past events (Ishtiaque et al., 2019). If each shelter can accommodate approximately 1000 people (Mallick and Vogt, 2011), they are often insufficient to host the dense population living in the area, not uniformly distributed on the territory, or are also too far from the houses in need (Alam et al., 2020; Hossain, 2015). The distance to a shelter may considerably increase the vulnerability of the people if they decide to walk to one (Alam and Collins, 2010).

The embankments are often very poorly maintained, including the sluice gates (Younus and Sharna, 2014). Embankment failure can also induce problems with drainage congestion and water logging (Mullick et al., 2019). Those coastal embankments are also breached on purpose to be penetrated by pipes that fill the basins of shrimp farms (Hossain, 2015).

It is worth noting that in the small island polders there is no electricity, and, in remote areas, it is harder to find hospitals or clinics as well as available doctors because they are located mainly in big towns and cities (Garai, 2017; Islam et al., 2014b). Those aspects definitely decrease people's coping capacities.

Houses: material and emplacement

Housing materials and emplacement are the main criteria of the household's vulnerability. Four main kinds of dwelling houses may be described in coastal Bangladesh. The *pucca* houses are the most solid and permanent houses. Made of brick and concrete, they are very rare and held by wealthy households. The *semi-pucca* buildings are made of semi-permanent material in the sense that they have a floor of mud, brick or cement, but their walls are bamboo mats or timber, and the roof is made of corrugated-iron (CI) sheets. The *kutcha* houses have floors made of mud; the walls are bamboo, sticks or straw; and the roof is made of paddy (rice) or wheat straw (Islam and Walkerden, 2015). Finally, the *jhupri* houses are mainly huts or made of CI sheets. *Semi-pucca* houses are not cyclone resilient, but *kutcha* and *jhupri* houses are organic-made structures totally vulnerable to this hazard (Miah et al., 2020; Parvin and Shaw, 2013). In the majority of the rural studies analyzed in the literature review, most of the houses are kutcha houses (Ahsan and Warner, 2014; Akter and Mallick, 2013; Younus and Sharna, 2014). Housing material fragility is accentuated by their settlement place: the more isolated and scattered the villages are, the more vulnerable they are.

Moreover, there is a dreadful situation when houses are settled along the embankments: they face huge casualties and damages with strong winds and waves or in the case of the breach of any dikes (Hossain, 2015). This also happens for people living out of the dikes: when their living places remain flooded in the days and weeks following a cyclonic inundation, people take shelter on embankments, building tent-like huts (Garai, 2017; Mallick et al., 2011). The main reason for explaining people's choice to install on embankments is because they are the major public spaces owned by the government along the coast which have become the last area above sea level not privately owned where displaced people may construct settlements (Alam and Collins, 2010).

Water: salinity, sanitation and drinking water

Saline intrusion due to cyclonic inundations is a serious problem highlighted by the coastal population, both for food and sanitation. Because of the lack of embankment reconstruction after cyclones such as Aila in 2009, saline water intrusion was still a problem 1 year later (Mallick et al., 2011). Salinity is especially dreadful for arable land, where farmers have to wait many years before restarting rice cultivation (Ahsan and Warner, 2014; Ishtiaque et al., 2019; Mallick et al., 2017; Rabby et al., 2019).

Many authors highlight that after cyclonic inundations, sanitation facilities are particularly challenged. The first main problem is the drinking water supply, which is disrupted and becomes scarce (Alam et al., 2017; Younus and Sharna, 2014). Polluted by waste or animal carcasses (Hossain, 2015), as well as human feces due to the lack of sanitation (Parvin and Shaw, 2013), the water is often contaminated by waterborne diseases like diarrhea or even cholera and typhoid (Ahsan and Warner, 2014).

Drinking water is also contaminated by saltwater intrusion, which is a serious problem for most the families that use pond springs (Das et al., 2020; Ishtiaque et al., 2019; Shameem et al., 2014). Besides failures in the access to sanitation and clean water, households are significantly disrupted, facing even long times with no electricity after a cyclone (Akter and Mallick, 2013), which can be an issue for communication purposes and economic recovery. It is worth noting that in the small island polders there is no electricity at all.

4.3.2 Social and cultural factors

A significant indicator influencing people's vulnerability is education. It was shown that less educated people were less able to understand the disaster forecast and to foresee the need for appropriate materials and food to store in the case of an evacuation (Paul and Routray, 2011). The analysis of the literature review establishes that five main social groups are particularly vulnerable during cyclonic inundations: women, children, the elderly, disabled people and religious minorities (Das et al., 2020; Mullick et al., 2019; Rabby et al., 2019). Firstly, in customary social order in Bangladeshi rural areas, men are usually the heads of the household, being the ones who decide how to prepare the family for a cyclone, where to take shelter and if to eventually evacuate from the house (Ahmed et al., 2010). Traditionally, women take care of family resources and have to wait for their husbands' consent to go to a protective shelter (Alam and Collins, 2010; Kulatunga et al., 2014). During the cyclone and post-disaster phase, large families (more than 10 members) are considered more vulnerable, in the sense that the elderly, children and people with disabilities are considered to be dependent people for the evacuation as well as in the recovery phase (Hossain, 2015; Quader et al., 2017). Generally, women have less access to income and assets because social norms limit their advocacy in the public sphere, although they can get access to microcredits offered by NGOs (non-governmental organizations) to support their recovery. Nonetheless, authors pointed out that financial relief is often distributed to particular religious, political and social groups, neglecting women, the poor and religious minorities, a situation that mainly gives advantage to the highest social class (Mallick et al., 2017). This social class, in the rural zone, corresponds to wealthy persons who regularly become elected representatives in the local government (Mallick et al., 2011). However, some NGOs emphasize that policies aimed at improving infrastructure to reduce vulnerability must be accompanied by a policy of sensitizing populations to the disaster in order to reduce illiteracy, poverty and increase livelihoods (Ishtiaque et al., 2019).

Beyond these social indicators, other cultural and/or political variables are mentioned in the literature. For example, despite the Cyclone Preparedness Program, many critics were found in the literature about the early-warning system's effectiveness because of either its dissemination or its understanding. The first problem in the preparedness phase is the population's access to the alert; since a large part does not have access to a radio, communication dissemination remains poor (Ahsan and Warner, 2014; Mallick et al., 2011; Paul and Routray, 2011; Saha, 2015). Moreover, several researchers noticed the surprise of the population at the arrival of the cyclone disasters because they failed to understand the warning systems (Mallick et al., 2017; Younus and Sharna, 2014). Other authors also report people are indifferent to the weather forecast because they use their own traditional forecast methods through indigenous signs (Hossain, 2015; Rakib et al., 2019). Therefore, signs in the environment (wind directions, clouds, sea birds and insect behaviors) are used instead to perceive impending hazards (Garai, 2017). When the early-warning information has been effectively transmitted to the people and they are aware of the imminent hazard, many scientists underline the population's resignation that a cyclone is God's will. They regard disasters as "common events" (Kulatunga et al., 2014), since they happen frequently. In the case of total flooding and destruction, people may end up having to move to another place. Nonetheless, authors observed that if people can temporarily move out of their village, they do not consider permanent relocation as an alternative (Ahmed et al., 2016). Some authors argued that the polders "create a false sense of security" (Sultana, 2010) and therefore increases people's vulnerability (Ishtiaque et al., 2017). This feeling of security can also diminish the efficiency of a cyclone warning system. In addition, authors note that memory loss from previous extreme events can be observed (Ishtiaque et al., 2019).

4.3.3 Economic factors

Some labor categories, tied to coastal economic development, are more vulnerable to cyclones, namely rice farmers, fishers and shrimp farmers. Cyclones particularly affect cultivated lands and fishing facilities, often leading to extreme poverty for the people who cannot practice their trade anymore (Mallick et al., 2017). Shrimp farmers are especially concerned with this problem, where a quarter of them suffered more damages than agricultural farmers after Cyclone Aila in 2019 (Ishtiaque et al., 2017). The expansion of shrimp farms in Bangladesh, especially on the western and eastern coasts, has raised a certain number of issues both for the people and for the environment. This culture has been developed mainly in the last 3 decades because of its great potential for exportation, bringing back value from foreign currency, until it became one of the most important sectors in the country especially concentrated in the coastal zones of Khulna, Satkhira, Bagerhat and Cox's Bazar (Ahamed et al., 2012).

Finally, to conclude this diagnosis, let us stress that according to Uddin et al. (2019a), the variables of population density, poverty and geomorphology (a coastal, flat and low-lying country facing sea-level rise) will be the most aggravating factors of future vulnerability. This literature review allows for the identification of the main characteristics to assess the vulnerability. While from a theoretical point of view, it can be defined on the basis of all these physical, socio-cultural and economic indicators, its spatial component is still not addressed, and the interrelation between a population and its territory of life is not analyzed or taken into account here. Yet, the spatial distribution of its different components (physical, socio-cultural and economic) enables defining its level for a territory. This is why the index approach was chosen because it allows for synthesizing all this information into a single variable and mapping it.

5 Socio-spatial vulnerability index

To identify places that are highly vulnerable to cyclonic flooding hazard, we focus on 16 coastal districts, the district being the spatial unit of reference (Fig. 1a). As widely discussed by the Program Development Office for Integrated Coastal Zone Management Plan (PDO-ICZMP, Uddin and Kaudstaal, 2003), the definition of a coastal zone is not simple and depends on selected criteria. According to the PDO-ICZMP classification, we have considered 12 "exposed" districts, i.e., ones adjacent to the sea and/or located in the lower estuaries (i.e., Khulna, Satkhira, Barguna, Cox's Bazar, Bagerhat, Patuakhali, Pirojpur, Chittagong, Noakhali, Bhola, Lakshmipur and Feni). The interior coastal districts (Jessore, Narail and Gopalganj) are less exposed to cyclone inundations than the other districts facing the sea. Moreover, following the literature review (Fig. 1a; see Appendix B) and given the trajectories of major cyclones such as Bhola, Gorky or Sidr, we considered that the districts in the mouth area, i.e., Barisal, Shariatpur and Chandpur, are also highly exposed to cyclonic flooding. Finally, the district of Jhalokati, cited in the literature review and bounded by Barisal, Pirojpur and Barguna, is added to maintain a territorial coherence.

There are two popular approaches to constructing a vulnerability index: the variable reduction and the variable addition. The first one is an inductive approach, with a large set of variables being used, assuming that they have a potentially larger or smaller influence (i.e., weight) on the index calculation. Principal component analysis, although fairly complex, is often used to estimate these weights to be assigned to each indicator (Cutter et al., 2003; Das et al., 2020; Quader et al., 2017; Uddin et al., 2019a). Although a large number of variables may be useful for descriptive purposes, including non-influential variables in the index, aggregation may decrease both the explanatory power and easiness of its use and understanding. On the contrary, the variable addition is a deductive approach. Deductive models can contain a few dozen variables or fewer, which are normalized and aggregated to the index, which could be separated into groups sharing the same underlying vulnerability dimension. This approach is the most common structure applied to vulnerability indices. A deductive approach, based on a data-driven mindset from expert knowledge (e.g., literature review) and parsimony, helps to identify and trace underlying themes running through the data, different than an inductive approach where the statistical models obfuscate underlying data. The literature review is a rich source to understand the main causes, translated as indicators of vulnerability, as well as their relative importance and interactions. Therefore, we chose to apply this simple method, based on the vulnerability factors deduced from our literature review, to determine the SSVI.

5.1 Methodology

From the literature review (Sect. 4) three components based on local experts' knowledge are highlighted: physical and infrastructural, socio-cultural, and economic components. As explained above, exposure is included in the vulnerability, and so a fourth component is added: cyclone protection and exposure.

The calculation of the SSVI is based on the methodology developed by Flanagan et al. (2011). In order to construct it, each of the variables selected was ranked from the highest to lowest vulnerability degree. A percentile rank was then calculated, by using the formula Percentile Rank = $(\text{Rank} - 1)/(N - 1)$, where N is the total number of data points, for each district over each of these factors. In addition, a percentile rank is calculated for each of the four components or domains (adapted from Flanagan et al., 2011), defined as (1) socioeconomic status, (2) household composition and disability, (3) housing and infrastructures, and (4) cyclone protection and exposure, based on a sum of the percentile ranks of the factors comprising that domain (see Appendix C for the full methodology). Finally, an overall percentile rank for each district is calculated as the sum of the domain percentile rankings and defined as the SSVI. The interpretation of the SSVI is as follows: for example, a district being in the 85th percentile (ranking of 0.85) means that 85 % of these districts are either below or equal to that particular district regarding the SSVI.

5.2 Data and sources

From the literature review, 17 variables were identified to assess the level of vulnerability of each coastal district (Fig. 2). The representativeness of each variable, defining the four components, is characterized according to the frequency they were cited in the literature review. The frequencies are in the range of 12 % (minorities) to 47 % (education), and the median is ~ 27 % (children), i.e., about 13 studies of the 49 considered (for more details, see Appendix B).

All the data considered here are freely available, accessible online and given at the district scale. These data come from different national sources such as the Bangladesh Bureau of Statistics (2011 and 2014 surveys) and from international sources such as the World Bank. Full details of the data used are in Appendix D.

To describe the socioeconomic status, two variables are used: poverty rate, which corresponds to the poor comprising both the lower and upper poverty line as a percentage of the total, and education rate, which corresponds to the percentage of children who have more than 10 years of school (Alam et al., 2017; Islam et al., 2014a; Ishtiaque et al., 2019).

The household composition and disability domain is characterized by five variables (Alam et al., 2020; Ishtiaque et al., 2019; Rabby et al., 2019): age 14 or younger (%), age 60 or older (%) (ages 14 and 60 are chosen as limits accord-

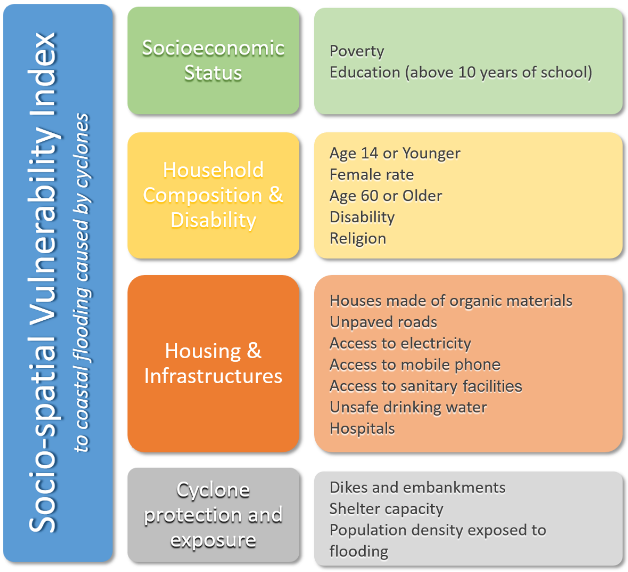


Figure 2. Socio-spatial vulnerability index scheme (adapted from Flanagan et al., 2011).

ing to Akter and Mallick, 2013, and correspond to the addition of categories between ages 0–14 years and categories above 60 years, respectively, expressed as a percentage), female rate (%); disability (the percentage of disabled people per district) and religion (the percentage of Muslims and percentage of religious minorities including Buddhists, Hindus, Christians and others) (Akter and Mallick, 2013; Das et al., 2020; Garai, 2017; Ishtiaque et al., 2019; Rabby et al., 2019; Roy and Blaschke, 2015).

The third domain, called housing and infrastructures, includes the percentage of houses made of organic materials (*kutcha* and *jhupri* are structures totally vulnerable to coastal flooding; Parvin and Shaw, 2013); unpaved roads (the percentage of the length of roads that is not paved); access to electricity, a mobile phone and sanitary facilities (toilet with water and sealed; representing the percentage of the population which has access to these infrastructures); unsafe drinking water (the percentage of population which does not have access to safe drinking water; unsafe drinking water corresponds to all spring water that does not come from the tap or from tube wells); and the number of hospitals per district (Ahsan and Warner, 2014; Das et al., 2020; Ishtiaque et al., 2019; Islam et al., 2014a).

The last domain of cyclone protection and exposure is described by three variables: dikes and embankments (Alam et al., 2010; Hossain, 2015; Rabby et al., 2019), which correspond to the length of dikes and embankments in each district; shelter capacity, which is computed by the difference between the shelter capacity (number of people) and the number of people present within a 1 km radius of the shelter; and exposure, which corresponds to the percentage of people per district concerned by the cyclonic inundation with a 50-year return period (Fig. 1). As we have seen above (Sect. 3), this cyclonic inundation probability, resulting from hydrodynamical modeling, integrates components such as topography, bathymetry, slope, dikes, embankments, soil roughness and vegetation, which allows for indirectly integrating the physical vulnerability into the SSVI. Although authors proposed population density as a variable to characterize the vulnerability (Ahsan and Warner, 2014; Ishtiaque et al., 2019; Kulatunga et al., 2014; Miah et al., 2020), none used the population density actually affected by cyclonic floods.

5.3 Socio-spatial vulnerability index to cyclonic flooding mapping

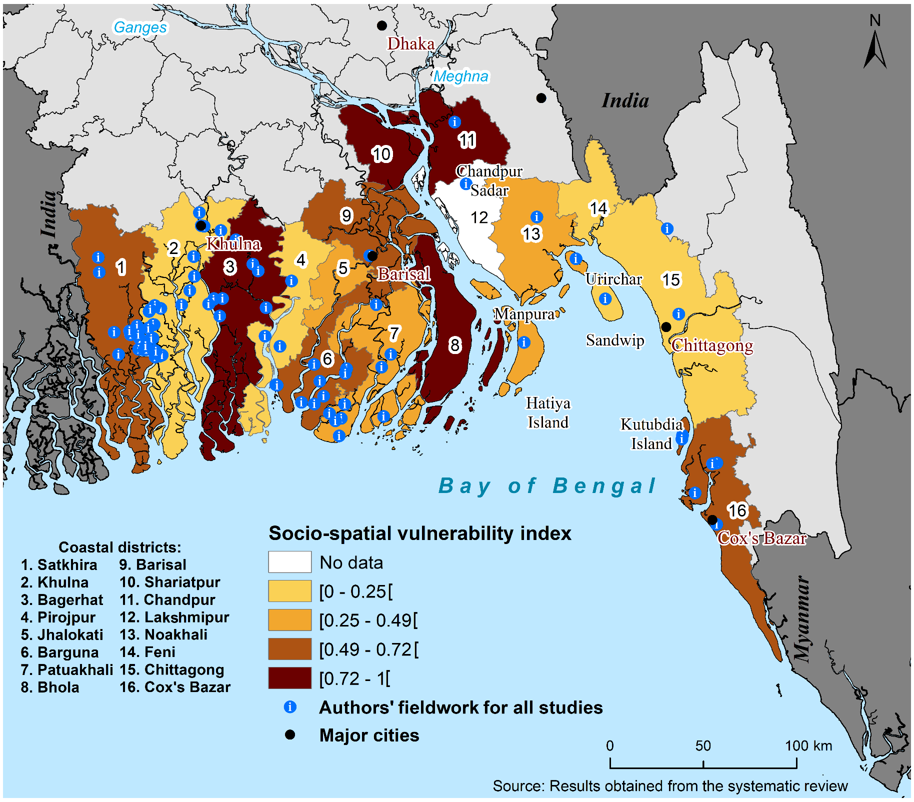
Figure 3 presents the SSVI. We deduced that the inhabitants of the districts at the mouth of the GBM rivers, i.e., Chandpur, Shariatpur and Barisal, and Bagerhat on the western coast, where the SSVI is in the highest category, are more vulnerable to cyclonic flooding relative to other districts. It appears clearly that these districts are very densely populated and poor, have a low percentage of high-school completion, and are extremely exposed to the inundation hazard with insufficient cyclone protections. However, this analysis does not mean that the population of other districts is not vulnerable but only less vulnerable.

For the districts that appear to be the least vulnerable according to the index (Fig. 3), the cyclone protection and exposure domain is the one that appears to be the most critical for these districts, for example, Feni, Khulna, Pirojpur and Patuakhali (Fig. 4). Then, it would appear that the household composition and disability domain is the most vulnerable domain for the district where the vulnerability level is moderate (Barguna and Satkhira). Concerning the last two most vulnerable districts (Chandpur and Shariatpur), the three domains of socioeconomic, household composition and disability, and cyclone protection and exposure have very high values, exceeding 0.8.

6 Discussion

6.1 Main findings and contributions

Although considerable effort has been made in Bangladesh, as shown in the literature review (Sect. 4), to understand patterns of social, economic and environmental variables that render inhabitants more or less vulnerable to cyclonic flood, much less effort has been spent to consider the socio-spatial vulnerability. This study provides, from an interdisciplinary approach, a methodology and an integrated index, called the socio-spatial vulnerability index (SSVI), for assessing the ways in which socio-spatial vulnerability to cyclonic flooding is distributed across the coastal territory. This new metric is a function of the probability of the cyclone flood hazard and the sensitivity of inhabitants.



Source: Results obtained from the systematic review

Figure 3. Socio-spatial vulnerability index to cyclonic flooding and location of case studies upon which the articles included in the literature review are based.

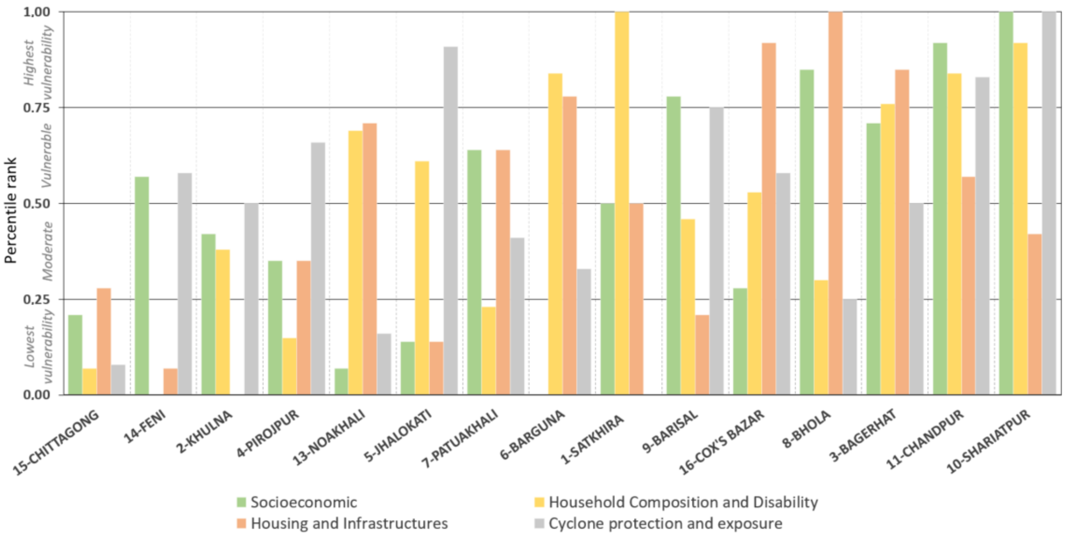


Figure 4. Contribution of each domain to the socio-spatial vulnerability level.

Compared to recent studies on vulnerability assessment, our approach differs in several aspects. First, our study is intended to be general in scope, considering the entire population and territories affected by the cyclonic flooding, in contrast to studies that target either a category of the population (Alam et al., 2020; Swapan et al., 2020) or a particular site, at the village scale, for example in Rakib et al. (2019). These highly localized studies have the advantage of being more detailed and enriched with qualitative observations on the perception and representation of natural hazards, although they are not generalizable to the scale of coastal districts. These studies are useful at the local level for strategic decision making and the orientation of risk management but remain too specific for the implementation of such strategies at the national level like the deployment of Bangladesh Delta Plan 2100 (Ministry of Planning, 2018).

Our study offers an analysis of the vulnerability to the hazard of cyclonic flooding. It does not voluntarily take into account information on the adaptive capacities of populations and territories as proposed by Uddin et al. (2019a). Adaptive capacity and resilience are fields of study in their own right that must, in our opinion, be distinguished from vulnerability. Indeed, the latter authors integrate, among other things, the presence of local and private banks and the possibility for small farmers to make loans, enabling them to restart their activity after a natural disaster. This information defines the capacity of these populations to cope rather than their vulnerability, as distinguished by Quader et al. (2017).

On the other hand, we argue it is essential to integrate the exposure of populations and territories to a hazard into the definition of vulnerability. A population, whatever its socioeconomic and demographic characteristics, is not vulnerable if it is not exposed. Contrary to Rabby et al. (2019) and Das et al. (2020), who assess vulnerability solely on the basis of social factors and infrastructural factors (among others quality of housing and access to drinking water, electricity and sanitation), the SSVI that we provide integrates the exposure to the hazard. The population densities actually affected by the floods and the possibility to find shelter or to be protected by defense structures are essential and indispensable pieces of information to the evaluation of socio-spatial vulnerability. In many studies, only the whole density of the population is used to represent exposure (i.e., Ishtiaque et al., 2019; Das et al., 2020), without distinguishing the population actually affected by cyclonic flooding.

One of our goals in this study is to produce transferable information for decision makers. This is why we chose an approach that combines all the dimensions of vulnerability. We believe the territorial approach is essential in the decision-making process. The first step is to identify which regions are the most vulnerable to a hazard before identifying which dimensions of vulnerability need to be improved. Our results could help with the deployment of the flood risk management strategies (FR) of Bangladesh Delta Plan 2100 for the districts identified as failing on this dimension of vulnerability. Sub-strategies FR 1.1, 1.2 and 1.3[1], for example, correspond to the cyclone protection and exposure dimension of the SSVI, for which the districts of Shariatpur and Jhalokati appear to be the most vulnerable (see Fig. 4).

The approaches proposed by Uddin et al. (2019a), for instance, present a mapping of vulnerability by dimensions: demographic vulnerability, economic vulnerability, agricultural vulnerability and so on. Deprived of a synthetic map, it is not clear if the decision maker can decide where and how to intervene on the territory. Other studies are specific to a single dimension of vulnerability, as physical vulnerability (Islam et al., 2015., 2016; Hoque et al., 2019) or social vulnerability (Rabby et al., 2019; Das et al., 2020). Nevertheless, the SSVI empowers one to integrate all the dimensions of vulnerability and provides usable information for decision makers.

Comparing vulnerability studies of coastal districts exposed to cyclonic flooding risk remains very difficult because the definition of the vulnerability concept varies greatly from one study to another. The study of Quader et al. (2017) is certainly a recent one reporting on the most relevant definition and assessment of vulnerability for our study. The results corroborate that the districts in the mouth of the Meghna (central coast) up to the districts of Chandpur and Shariatpur, as well as Bagerhat and Cox's Bazar, are highly vulnerable. The only notable difference is situated in Satkhira District, which is vulnerable according to our study, while it is not very vulnerable according to Quader et al. (2017). In detail, the different dimensions of vulnerability are not described in the same way by the two studies. For example, accessibility to electricity is used to define demographic and basic-facilities vulnerability in the Quader et al. (2017) study, while it is used to define the vulnerability of infrastructure and housing in our SSVI. Likewise, disability is either used to define household vulnerability (SSVI) or considered a separate dimension of vulnerability (Quader et al., 2017). Moreover, we used a robust probabilistic cyclonic-flood-hazard map based on a dataset of 3600 statistically and physically consistent synthetic cyclone events (Emanuel et al., 2006; Khan et al., 2019), whereas Quader et al. (2017) used a low level of confidence cyclone hazard density for an interpolated map based on historical cyclone tracks (~ 160 events in 1877–2015). Although the level of detail provided by this union-wide study is significant, the closeness of the results is meaningful. However, social vulnerability is defined from 141 variables and a consistent workflow with several statistical methods. On the contrary, in our study we dedicated a strong consideration to the theoretical links between indicators and underlying vulnerability to cyclonic flooding by conducting a strict literature review. Therefore, the SSVI is computed from only 17 variables, and a simple computation of the index makes its construction easier to understand and to replicate by decision makers.

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[1] This refers to the following: protect the development and improvement of embankments, barriers and water control structures (including ring dikes) for economic priority zones and major urban centers; construct adaptive and flood storm-surge-resilient buildings; and adopt spatial planning and flood hazard zoning based on the intensity of a flood.

6.2 Representativeness and quality of the data at the district scale

A first limitation concerns the availability of the dataset to construct the SSVI. The dataset used for this study was produced at different dates: from 2010 for the poverty level to 2018 for paved/unpaved roads. However, the main information defining social vulnerability comes from the BBS (Bangladesh Bureau of Statistics) census of 2014, which gives some homogeneity to the description of the sociodemographic characteristics of the population.

Besides, a few variables used to calculate the SSVI have some underlying assumptions that might differ from reality and may give a false representation of the situation in the field. For example, we assumed that dikes and embankments protect people and agricultural production, but everything depends on their condition, maintenance and breach presence (Younus and Sharna, 2014; Mullick et al., 2019; Hossain, 2015). In recent studies, dike breaching is found to be the reason behind flooding (e.g., Hossain, 2015; Adnan et al., 2019; Khan et al., 2021). For example, Hossain (2015) mentioned that dikes and embankments may be in very poor condition and may not perform their protective function. Similar results are suggested by Khan et al. (2021) from analysis of Cyclone Amphan that made landfall in May 2020. Additionally, based on the results presented in Adnan et al. (2019), one might argue that the dikes were not adequate to protect against a certain event (either because of their design or by the gradual degradation of the dikes). As noted in this article for Sidr, if the dike had not had breached, the inundation would have been 18 % of the coastal area, whereas the dike breach increased the number to 35 %. Unfortunately, current dike condition information is not available nor accessible in public data, and according to our understanding, it is not monitored either. The assumption in our hydrodynamical modeling is that the dikes are in a well-serviced condition; e.g., dike breaching (which is a different geotechnical process and far from the scope of this paper) was not modeled. Furthermore, after a cyclone, populations can and do settle on dikes, sometimes the only free public spaces left to the people, making them very exposed (Alam and Collins, 2010). Undoubtedly this issue about the balance between the negative and the positive contribution of dikes and embankments should be taken into account in future studies on vulnerability to cyclonic flooding in this region.

The shelter capacity is another example of a variable that does not appear to always be representative of the situation in the field. It can be assumed the presence of cyclone shelters reduces people's exposure and therefore their vulnerability. However, the presence of cyclone shelters in close proximity to homes, within a radius of 1 to 1.5 km, does not mean that they are useful and used. As mentioned by Mallick et al. (2017), shelters are not optimally placed on territories in order to be easily accessible and accommodate as many people as possible but are rather situated near upper-class dwellings. These buildings are not always maintained and do not meet the requirements of the local society: men and women are mixed; there are no women-only sanitary facilities; and people may feel insecure (Kulatunga et al., 2014; Saha, 2015). Accessibility to cyclone shelters is also determined by the state of the roads to get there. Therefore, we chose to represent the road condition by the variable "paved or unpaved road". However, we can consider this information to be valid for estimating vulnerability only before the passage of a cyclone (in the pre-disaster phase) because the roads can be very damaged afterwards, as mentioned by Saroar and Routray (2010), as well as during the rainy season (even more impacting during the post-disaster phase).

The sub-district-level case study presents advantages in data mining, the use of participatory methods and capturing the fine complexity of vulnerability, but these studies are very specifically local and therefore are difficult to compare with other regions. Moreover, the integration into a vulnerability index of different local qualitative and quantitative data, which have their own logic of underlying scales and patterns, implies a loss of information and relevance (Fekete et al., 2010).

Here, using the "district" scale is related to the multifold aims of our research. One of the objectives was a spatial identification of hotspots of vulnerability to cyclonic flooding, intending both to identify the spatial variability linked to cyclonic flooding facing the district and the districts where the combined effects of multiple social, economic and environmental stressors are most prevalent regarding cyclonic flooding. Therefore, the districts have been chosen as units of analysis for several reasons: (1) districts are relatively homogeneous in size in comparison with sub-districts, municipalities or unions; (2) cyclonic hazard management is organized and supervised on the district level (e.g., the alert and cyclone warning dissemination system and maintaining cyclone shelters and assisting in evacuation procedures; Kulatunga et al., 2014); (3) a sufficient number of variables is freely available online from the Bangladesh Bureau of Statistics; (4) the district unit can be more easily transposable and replicated in other delta regions (e.g., applied in the 13 provinces of the Vietnamese Mekong Delta or in the 6 districts of the Ayeyarwady Delta); and (5) as a administrative unit, the districts are easily understood by decision makers, planners and end users.

Moreover, using this territorial delimitation enables us to zoom out from the research fieldwork conducted from 2007, in order to show which zones have been under the scope of science and which others have been very exposed and vulnerable but almost forgotten in studies. While most of the analyzed studies worked on local places, they did not give a whole picture to the reader about the work made in coastal Bangladesh. The distribution of the studies on the map (Fig. 3) shows that two main districts on the western coast were over-studied (Satkhira and Khulna) compared to the need for studying the most vulnerable districts now, situated in the mouth of the delta.

6.3 Limits of the research

A significant limitation to this work is the approach intrinsically used in this literature review: the exclusion criteria left out the analysis of grey literature to focus solely on peer-reviewed articles. By doing so, we excluded reports from local NGOs in Bangladesh that could bring to light new elements only known at the local scale after a long period of time. Nonetheless, we obtained a clear view of what is done throughout scientific articles in terms of coastal vulnerability. Additionally, we obtained 42 out of 49 analyzed articles which involved either Western or Asian scholars likely to assign concepts to Bangladesh that would normally work only into their own foreign country. Thus, the outcome of socio-spatial vulnerability is defined mainly from a Western perspective because the majority of the articles included Western researchers.

Moreover, it should be noted the results of the top-down approach used in this paper were based on aggregated data from studies that employed different methodologies. Consequently, a bias could occur, since by aggregating the data, we lost some accurate information and perhaps considered a concept defined with the same word but conceptualized differently between different studies. Another issue raised with the top-down approach is the absence of local-community participation in this assessment. This feature is necessary to give a complete validity to such an evaluation, by taking into account people's opinions and perceptions about their own vulnerability (Rakib et al., 2019; Sattar and Cheung, 2019). It is also through their participation that possible solutions and strategies of adaptation to disasters may be formulated (Pouliotte et al., 2009).

However, in this study, the objective of the SSVI mapping exercise is to open a dialogue around vulnerability to cyclonic flooding in Bangladesh and to help stakeholders and researchers to identify the most vulnerable places that are understudied. Therefore, as the SSVI objective is not to participate in adaptation practice or decision making, the validation question, while important, is not central (De Sherbinin et al., 2019). Moreover, as the SSVI is multidimensional and not directly observable and because there are few published explicit procedures that outline how to validate it, a persistent challenging validation question is posed (Tate, 2012; Rufat et al., 2019). Moreover, the human and economic cost from the cyclone impact reports, if available, are unusable to the SSVI validation because they address mainly the exposure component and undervalue the vulnerability. Nevertheless, some vulnerability index validation research tracks seem to emerge from them: (1) external validation from independent proxy data such as death tolls, physical wounds, diseases, economic loss and a household survey and (2) internal validation from a sensitivity analysis. A future SSVI regarding cyclonic flooding in Bangladesh research should be a validation-scheme-based investigation, for example, of qualitative work describing social stratification in pre- and post-disaster settings (Fekete, 2019) using targeted surveys and participatory approaches which would be conducted in different districts.

Additionally, we pointed out that vulnerability of people dependent on natural resources of the Sundarbans was underestimated. Moreover, in this prawn-farming region, it is amplified by the illegal or forced occupation of land that often leads to violence. Vulnerability is also stressed by intensive, potentially hazardous and poorly paid working conditions, especially for women (Ito, 2002; Paul and Vogl, 2011). Nonetheless, specific populations such as the ones living in slums or Rohingya refugees are underrepresented in our study (Alam et al., 2020; Swapan et al., 2020). In the same way, it should be noted that there are a lot of new proxies in social, environmental and economic datasets (social networks, mobile phones and satellites) that would allow for the estimation of the SSVI over finer geographical resolution to better represent the cyclone flooding vulnerability.

7 Conclusion

In this article, we defined vulnerability to cyclonic flooding in coastal Bangladesh based on publications in the scientific literature (2007–2020). This enables both the scientific testing of the research procedure to assess socio-spatial vulnerability and the stating of the coastal places in Bangladesh which are understudied or which are neglected, in order to direct research where a need is identified for the coastal population. Therefore, the mouth of the Ganges appears to be a relatively little studied area, although it is very exposed to cyclonic flooding and vulnerable due to the density of the population (Chandpur and, to a lesser extent, Shariatpur).

Thus, we argue a better understanding of socio-spatial vulnerability can help sensitive classical cyclone flooding vulnerability analysis that tends to consider those groups or communities to be equiprobably exposed to the hazard in a given spatiality. Consequently, we define the socio-spatial vulnerability index (SSVI) as a function of both the probability of the cyclonic flood hazard and the sensitivity of delta inhabitants. Through this index, we quantify and map levels of this vulnerability. The SSVI is also a new methodology to highlight socio-spatial inequalities between the coastal districts of Bangladesh by considering social, physical and infrastructural aspects of vulnerability. The concept is within a systemic and interdisciplinary framework, considering these vulnerability aspects from the social and natural sciences and their interactions in between. With this index and through its different components, we can better reveal why some groups or communities, at the district level in the case of our study, are more vulnerable to cyclonic flooding and could also be slower to recover than others.

Finally, we identify the most vulnerable places that are understudied, leading us to differently consider the coastal area for the state, NGOs and IOs (international organizations) in their prioritization of preparedness and recovery programs. Climate change could increase the intensity and frequency of tropical cyclones in the Bay of Bengal. It is therefore necessary to access appropriate cyclonic flood hazard from efficient hydrological-modeling tools, in order to predict future socio-spatial vulnerability patterns.

Appendix A

A1 References of the articles used for the review analysis

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Ahmed, B., Kelman, I., Fehr, H., and Saha, M.: Community resilience to cyclone disasters in coastal Bangladesh, Sustainability, 8, 805, https://doi.org/10.3390/su8080805, 2016.

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Table A1. Search strategy used to identify studies for inclusion (adapted from Alderman et al., 2012).

Keywords in the title or abstract	Keywords relating to flood disasters (hazard)		Keywords relating to social vulnerability (outcome)	Keywords relating to the area of study
Words used for the research	Coastal flood/-ing Sea-level rise Storm surge Cyclonic/tropical storm Disaster risk reduction	AND	(Social) *vulnerability* (index/assessment) Human exposure Coping (capacities)	Brahmaputra delta Bangladesh
Search engines used	Google Scholar, Istex, Scopus, ScienceDirect			
Limits	Date of publication: 2007–2019; abstract available; English language; peer-reviewed articles			

Table A2. Selected articles for the review.

Search engines	Total selected articles	Significant articles	Insignificant or redundant
Google Scholar	66	28	38
Istex	39	10	29
Scopus	24	6	18
ScienceDirect	21	5	16
Total	149	49	101
Total selected for analysis		49	

A2 Guiding-question details

1. *Who*. Although inclusion criteria established the research only upon peer-reviewed literature, it is specified if they are academic or non-university researchers by mentioning their home institution. The disciplinary backgrounds give the academic outlook of the authors involved in the research and is defined according to the author's affiliated working department or faculty.

2. *Where*. The spatial scales address the locations where the vulnerability assessments were made across Bangladesh. Firstly, they report if the assessment takes place in a rural, urban or mixed environment. Secondly, they specify the scales: divisions, namely a region or *zila*, which are districts; *upazilas* (*thana*), namely subdistricts; unions, which are a gathering of two to three municipalities; or finally, the household scale, if the analysis takes place there.

3. *When*. The temporal scales of assessment refer to the hazard. The authors either consider a short-term period by focusing on a specific event like a cyclone or a longer period, which could encompass a wider phenomenon, such as sea-level rise.

4. *How*. The theoretical approach used by the author should reveal the definition given to the vulnerability. For example, some authors refer to the 2007 or 2014 IPCC definitions. Methods to assess vulnerability refer to the study design used by the authors. We distinguish quantitative (indicator-based, spatialized data and impact modeling), qualitative (interviews, participatory approaches and open surveys) and mixed methods (including both index and qualitative case studies).

5. *What*. The scheme of the vulnerability categories encompassed a broad definition of vulnerability, potentially including a reference to what the authors could mean by social, human or personal vulnerability. We distinguish then between aspects and definitions of physical and systemic vulnerabilities.

Appendix B

Appendix C: Methodology of the socio-spatial vulnerability index (SSVI) to cyclonic flooding

The socio-spatial vulnerability index (SSVI) database comprises 17 variables, 4 themes and 16 districts. The calculation of the SSVI is based on the methodology developed in Flanagan et al. (2011) and presented below:

- *Tier 1*. For each of the 17 variables (poverty, education (above 10 years of school), age 14 or younger, female rate, age 60 or older, disability, religion, houses made of organic materials, unpaved roads, access to electricity, access to mobile phone, access to sanitary facilities, unsafe drinking water, hospitals, dikes and embankments, shelter capacity, and population density exposed to flooding), rank the values from lowest to highest vulnerability degree and calculate percentile rank (PR) for each district as Percentile Rank = $(\text{Rank} - 1)/(N - 1)$, where N is the number of districts. The district with the

Table B1. Citation frequency in the literature review of the selected variables (B.a) and coastal districts (B.b).

B.a	Total	% ($n = 49$ studies)	B.b	Total	% ($n = 49$ studies)
Education	23	47 %	Khulna	18	37 %
Shelters	22	45 %	Satkhira	17	35 %
Female	20	41 %	Barguna	13	27 %
Houses materials	19	39 %	Cox's Bazar	12	24 %
Dikes – embankments	19	39 %	Bagerhat	11	22 %
Poverty	17	35 %	Patuakhali	11	22 %
Drinking water	16	33 %	Pirojpur	7	14 %
Road	14	29 %	Chittagong	7	14 %
Children	13	27 %	Barisal	7	14 %
Population density	12	24 %	Noakhali	6	12 %
Sanitary-facility access	10	20 %	Jhalokati	5	10 %
Disability	9	18 %	Bhola	5	10 %
Electricity access	8	16 %	Lakshmipur	5	10 %
Mobile-phone access	8	16 %	Feni	5	10 %
Elderly	7	14 %	Shariatpur	2	4 %
Hospital	7	14 %			
Minorities	6	12 %			

highest vulnerability degree for a specific variable will have a PR score of 1, and the lowest vulnerability degree will have a PR score of 0.

- *Tier 2*. For each of the four thematic domains (socioeconomic, household composition and disability, housing and infrastructures, and cyclone protections and exposure), sum the PR score of variables by domain, rank the values from lowest to highest vulnerability degree and calculate a PR score for each district.
- *Tier 3*. For an overall SSVI value, sum the PR score of the four thematic domains, rank the values from lowest to highest vulnerability degree and calculate the PR for each district.

  An exemplary interpretation is as follows: if a district is in the 80th percentile (ranking of 0.80) for the SSVI, then 80 % of the districts are either below or equal to that particular district with regards to the SSVI.

Appendix D

Table D1. Map layer sources and description used for cartography. GIS: geographic information system. Humdata: Humanitarian Data. OCHA: United Nations Office for the Coordination of Humanitarian Affairs.

Map layer description	Details	Sources
Bay of Bengal map	Delimitation: Bay of Bengal	Marine Gazetteer Placedetails. Indian Ocean/IHO Sea Area, https://marineregions.org/ (last access: 2 March 2022)
Bangladesh map	Administrative units: borders (admin_0), divisions, districts, *upazilas* (admin_4)	DIVA-GIS data
Ganges–Brahmaputra–Meghna rivers	Major rivers in Bangladesh	Humdata, OCHA
Sundarbans map	Delimitation: Sundarbans	Zhang et al. (2015)
Hospital location	Health sites in Bangladesh	Humdata, https://healthsites.io/ (last access: 2 March 2022)
Population density	Predicted number of people per square kilometer, represented by pixel; estimated using the random forest (RF) model as described in Stevens et al. (2015)	The most recent data were found on WorldPop (2020); the data could differ from the reality, but this source currently remains the most recent data available to map density
Coastal flooding map	For a 50-year return period	Model by Jamal Khan (Khan et al., 2019)
Embankment location	Coastal embankments in Bangladesh	Bangladesh Water Development Board
Cyclone shelter location	Points of shelter in coastal Bangladesh	https://geodash.gov.bd/ (last access: 2 March 2022)
Level of poverty	Percentage of people living under the poverty line Total of poor comprising both the lower and upper poverty line	*Zila*-level PovMap estimates (2010) from the World Bank, World Food Programme and BBS
Paved or unpaved roads	Paved or unpaved roads	District-wise length of road by road classification in 2018 under RHD (in km), *Statistical Year Book Bangladesh 2018*, 38th edition (p. 258)
Cyclones shelters	Shapefile inventories of 3777 shelters to protect the coastal population from the cyclones and their capacity	Available on https://geodash.gov.bd/layers/geonode:cyclone_shelters_mrva (last access: 2 March 2022)
Religious minorities	Indicator aggregates of religions such as Buddhist, Hindu, Christian and others; the official statistics inventory migration from urban areas to urban and rural areas on the one hand and from rural areas to rural and urban places on the other hand	Aggregated from BBS online census 2014
Unsafe water	Water not coming from the tap or from tube wells, thus coming from simple wells, canal rivers and ponds	Aggregated from BBS online census 2014
Education level	More than 10 years of school	BBS online census 2014
Age group (by years)	Addition of categories between 0–14 years Addition of categories above 60 years	
Disabled	Total disabled people per district	
Sex	Gender (male or female)	
Type of structure (housing material)	Housing materials: *jhupri*, *kutcha*, *semi-pucca*, *pucca* and other housing structures Weak housing	
Sanitary facility	Access to sanitary facilities	
Mobile phone	Access to mobile phone	

Data availability. The data used to construct the socio-spatial vulnerability index and the values obtained for this index are available at https://doi.org/10.5281/zenodo.5997080 (Long, 2022). The data sources used are listed in Table D1 in Appendix D.

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