TOPICAL REVIEW

Social vulnerability in a multi-hazard context: a systematic review

Oronde Drakes*1,2 and Eric Tate1*

1 University of Iowa, Geographical & Sustainability Sciences, 316 Jessup Hall, Iowa City, IA, 52242, United States of America
2 US Geological Survey

* Author to whom any correspondence should be addressed.

E-mail: odrakes@usgs.gov

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Abstract

The interacting effects of multiple hazards pose a substantial challenge to poverty reduction and national development. Yet, social vulnerability to multiple hazards is a relatively understudied, though growing concern. The impacts of climate hazards in particular, leave increasingly large populations becoming more exposed and susceptible to the devastating effects of repeat, chronic and sequential natural hazards. Multi-hazard research has focused on the physical aspects of natural hazards, giving less attention to the social facets of human-hazard interaction. Further, there is no single conceptualization of ‘multi-hazard’. This systematic review utilizes correlations and hierarchical clustering to determine how social vulnerability is assessed in the context of the three most common classifications of ‘multi-hazard’: aggregate, cascading and compound. Results reveal these classifications of ‘multi-hazard’ each focus on different aspects of social vulnerability. Studies in the aggregate classification of multi-hazard were more likely to represent social vulnerability as an outcome of hazard events, while those in the cascading and compound classifications more often addressed social vulnerability as a preexisting condition. Further, knowledge of social vulnerability to multi-hazards comes mainly from the aggregate classification and the mitigation phase of the disaster cycle. The difference in perspectives of social vulnerability covered, and limited context in which multi-hazard studies of social vulnerability have been applied, mean a full understanding of social vulnerability remains elusive. We argue that research should focus on the cascading and compound classifications of multi-hazards, which are more suited to interrogating how human-(multi)hazard interactions shape social vulnerability.

1. Introduction

The last two decades have witnessed a marked rise in global disaster occurrence and impacts (UNDRR, CRED 2020). Seminal events such as the 2010 Russian heat wave, Hurricane Katrina in 2005, and Hurricane Maria in 2017, produced record breaking impacts from deaths, material losses, and lost productivity. Such individual events laid bare social disparities and forced reevaluations of recovery and mitigation programs. Efforts toward disaster risk reduction (DRR) are further complicated by disasters stemming from multiple hazards (multi-hazards), as they require not only understanding hazard-society interactions, but how those interactions progress across hazards. Climate multi-hazards, such as drought and extreme heat followed by wildfires, are a particular challenge, as they are expected to grow in intensity and frequency as human-induced warming continues (IPCC 2012b, AghaKouchak et al 2020). What was a one in 50 year extreme heat event in the 1850–1900 period is now almost five times more likely to occur and almost nine times more likely to occur under a 1.5 °C or 14 times more likely in 2 °C global temperature increases (IPCC 2021). Recent research has investigated the physical aspects of multi-hazards (Gill and Malamud 2014, Tilloy et al 2019), but far less attention has been directed to the social facets of these events.

Social vulnerability in the context of multi-hazards provides a holistic means of understanding how populations interact with the different natural hazards they face. Social vulnerability refers to the increased likelihood of some populations to suffer negative hazard effects and a reduced capacity to deal with these effects (McCarthy et al 2001, Wisner et al 2004, Wolf et al 2013). This population susceptibility and resistance are influenced by
factors such as demographics, land tenure, living conditions, socioeconomic status, health, risk perception and exposure (Clark et al 1998, Cutter et al 2000, Rufat et al 2013), collectively called determinants of social vulnerability. Just as places are differentially affected by unique combinations of hazards, people have different capacities to withstand and recover due to these determinants of social vulnerability. Variations in these determinants help to explain why similarly exposed populations often suffer different impacts from hazard events. Additionally, these capacities may vary for different hazards faced. It is therefore important to identify processes contributing to unequal conditions and disproportionate burdens impacting social vulnerability across the full scope of natural hazards faced (UN 2002, Buck and Summers 2020).

Multi-hazard social vulnerability is a valuable, yet underutilized aid for DRR policy and programming. The multi-hazard view of social vulnerability provides insight for actions to reduce social vulnerability, improve mitigation, enhance resilience, and promote disaster risk management. Such multi-hazard thinking is central to ‘building back better’ internationally in the Sendai Framework (IPCC 2012a, UNISDR 2015), nationally via the US Disaster Mitigation Act of 2000 (H.R.707 - 106th Congress), and in many local jurisdictions. However, particularly at higher spatial scales, many multi-hazard assessments focus on generalized conditions of vulnerability rather than providing more explicit information about how populations interact with the specific hazards faced. In other cases, multiple single hazard assessments are brought together without accounting for interactions between hazards. In both cases the full power of multi-hazard assessments remains underutilized.

Despite decades of research on hazard assessment and general acceptance of multi-hazard assessment, there is no single concept of ‘multi-hazards’. Multi-hazards can occur sequentially (Gill and Malamud 2014), trigger other events (Gill and Malamud 2016, 2017, Girgin et al 2019), or occur concurrently in the same location (Liu et al 2016, AghaKouchak et al 2020). These classifications of multi-hazard types, each reflect different interactions among hazards, or between hazards and human systems.

A clear understanding of social vulnerability in multi-hazard settings remains elusive. Existing research tends to focus on interactions among natural hazards, rather than how social vulnerability evolves across, or affects outcomes of, multiple hazard events. Further, the divergent ways classes of ‘multi-hazards’ view hazard interactions have meaningful but unexplored implications for understanding social vulnerability. As observed by Gill and Malamud (2017), the lack of detailed review and characterizations of multi-hazard interactions constrains understanding of these implications. Important considerations for a systematic approach to measuring all elements of social vulnerability to multi-hazards remain poorly described. To address this gap, we identify and profile multi-hazard approaches for measuring social vulnerability via the following research question: what is the relationship between the classification of multi-hazard and determinants of social vulnerability?

The reminder of the article is organized as follows. Section 2 provides background on multi-hazard social vulnerability and different classifications of ‘multi-hazard’. Section 3 outlines the methods used for our analysis. Section 4 describes the major distinctions in how multi-hazard classifications measure social vulnerability. In section 5 we discuss the implications of these differences for understanding social vulnerability in the multi-hazard context and provide conclusions in section 6.

2. Literature review

2.1. Multi-hazard social vulnerability

Social vulnerability to multi-hazards differs from social vulnerability to single hazards. A population’s reaction to different hazards varies due to social factors as well as physical conditions faced. For example, limited experience with low frequency hazards may limit risk perception. This lower awareness of risk can create situations where actions taken to mitigate a more frequent hazard unintentionally increase exposure and susceptibility to the lower frequency event. Such was the case of the 2010 Haiti earthquake where heavy masonry structures designed to withstand hurricane winds were unreinforced and ill-equipped to survive an earthquake (Hou and Shi 2011). Attempts to identify causes of disparities in hazard encounters and their outcomes have significant potential to underestimate exposure, vulnerability, resilience, and risk, when only one hazard is examined. This is because processes causing hazards and societal responses often interact, ultimately producing the diversified consequences of disaster losses (Dawson 2015, Qie and Rong 2017, Zscheischler et al 2018, Balch et al 2020). The chief advantage of multi-hazard studies of social vulnerability is understanding ‘overlapping factors that drive the accumulation of risk’. The multi-hazard view can interrogate the full range of hazards with which populations interact (Adelekan et al 2015). In this way, the resulting mechanisms of interdependency (functional, physical, geographic, economic, institutional, policy, and social) which amplify or attenuate risk and subsequent outcomes are brought into focus. Yet ‘multi-hazards’ has seen limited use in social vulnerability research.

2.2. The multi-hazard concept in social vulnerability research

‘Multi-hazards’ is a core, but often overlooked element of hazard theory. In ‘The Hazardousness of
a Place’, Hewitt and Burton (1971) interrogated the effects of all hazards faced at a location. They lamented the single hazard focus of studies and called for a ‘more systematic cross-hazard approach’. This orientation has changed little in the last 50 years. Several conceptual models now address social aspects of human-hazard interactions and accommodate multi-hazard connections. For example, the Hazards of Place model (Cutter 1996) dynamically combines vulnerability from biophysical systems and social conditions to identify the specific vulnerability of a particular place. In this model natural hazards and human systems are equal parts of the vulnerability picture. Conversely, the Pressure and Release and Access models (Wisner et al 2004) see vulnerability as a property of human systems arising from unequal access to resources, opportunities and supporting institutions. In this model natural hazards act as external stressors which reveal this underlying condition of human systems. The Turner Framework (Turner et al 2003) takes a social-ecological system perspective where human and natural systems are constantly interacting as part of a single, tightly coupled system. See Burton et al (2018) for more detailed comparison of vulnerability models.

While these conceptual models describe interactions across hazards, multi-hazard studies typically address social vulnerability to each hazard separately, rather than jointly examining interactive elements of the multiple hazards and social conditions. A small number of studies have sought to identify common patterns of vulnerability in closely related hazards and in specific contexts, such as Romero-Lankao et al (2012) working on urban vulnerability to heat waves and extreme heat hazards. However there remains a need for a synthesis of the ways social vulnerability has been studied in the multi-hazard context.

2.3. Classifying multi-hazards
There are three major classifications of multi-hazards in social vulnerability research: aggregate, cascading, and compound hazards. These classes are based on how causal factors combine to produce multi-hazard events and their collective effects (figure 1).

The aggregate classification describes the accumulation of impacts from multiple independent events (figure 1(A)). Such hazard events may be unrelated, occurring sequentially at the same location (e.g. multiple hurricane landfalls in the same season) or simultaneously in different locations with concurrent impacts (e.g. simultaneous drought in different grain producing areas). Computationally, aggregate is the simplest multi-hazard approach to vulnerability assessment. It typically entails evaluating several hazards individually before summing their effects and, is often applied in hazard mitigation plans under the (Disaster Mitigation Act of PL 106-390)). The aggregate classification is most useful when assessing multiple occurrences of the same hazard type over a single place. However, it is commonly employed in assessments covering a variety of hazard types.

The cascading classification refers to events where one hazard triggers other hazards (figure 1(B.1)). For example, Hurricane Harvey produced inland flooding, which then disrupted power, triggering chemical spills. In their review of natural hazard interactions, Gill and Malamud (2014) define instances where two or more hazards intersect to trigger secondary hazards (figure 1(B.2)). Natural-technological (Natech)
hazards are a special instance of cascading multi-hazards where natural hazards trigger technological hazard/disaster events (Krausmann et al 2017, Girgin et al 2019). With the increasing complexity and interconnectedness of modern socioeconomic structures, hazard cascades may expand far beyond the original locations of the triggering events (Cutter 2021).

The compound classification (figure 1(C)) describes the interaction of hazards, which may include single extreme events, multiple coincident (concurrent hazards) and sequential events. These events are correlated in space and/or time but result from distinct causal pathways (IPCC 2012a). Nevertheless, their interaction produces effects which would not have arisen otherwise. Leonard et al (2014) and Zscheischler et al (2018) focus on the combined impact from multiple variables or events as the defining characteristic of compound events e.g. St Vincent responding to the COVID-19 pandemic then having to evacuate and shelter the population from 1/3 of the island due to the La Soufrière volcano eruption. Since these hazard interactions may be distant in space and time, operate on multiple spatial and temporal scales, and affect communities differently, compound multi-hazards is conceptually and computationally the most difficult approach to employ.

2.4. Minding the gap
It is unclear how the use of a particular classification of ‘multi-hazards’ impacts subsequent understanding of social vulnerability compared to using a different classification of ‘multihazard’. Multi-hazard classifications may have implications for the framing of social vulnerability, methods used, interpretation of results, and ultimately, success in reducing exposure and vulnerability (Zscheischler and Seneviratne 2017, Tilloy et al 2019, Balch et al 2020). We aim to identify how the understanding of social vulnerability is affected by the use of different multi-hazard classifications.

3. Data and methods
3.1. Data collection
We used keyword searches of the Web of Science Core Collection and Scopus databases to select relevant articles on multi-hazard assessments of social vulnerability. Conducted on 1 September 2020 the keyword search covered articles published from 2000 to 2020. We applied the following search terms to titles, abstracts, and keywords of papers: (‘social vulnerability’) and (‘multiple hazard’ or ‘multi-hazard’ or ‘multihazard’). We removed content from the physical sciences which was unrelated to social vulnerability. We selected 1114 research articles (873 from Web of Science and 241 from Scopus) based on the keyword search (figure 2).

We reviewed abstracts of each selected article for relevance to the research objectives; retaining those measuring social vulnerability of individuals, households, or communities, and where this measurement was conducted across multiple natural hazards. This 2nd round of selection excluded articles measuring only physical effects, exposure of the built environment, natech hazards, resilience, and social vulnerability to single hazards. To focus on how social vulnerability is measured, we excluded articles describing, but not actually measuring social vulnerability. The two-stage selection process resulted in 158 empirical articles selected for review. We could not obtain ten of the selected articles and 57 not address multi-hazard approaches to social vulnerability. Following the full reading, 91 articles were retained for analysis.

Our data is limited to academic papers published in the English language. The grey literature may add insights into how social vulnerability is conceptualized and assessed in multi-hazard contexts. However, we were unable to access the grey literature in a systematic manner. Reliance on English language publications results in a sample covering a subset of the academic literature on multi-hazard social vulnerability, and a bias towards places where English is widely spoken.

3.2. Analysis
Our systematic review is based on a matrix of theoretical determinants of social vulnerability and disaster context. Such matrices aid data classification and provide a platform for analysis (Mieselhorn 2005, Rufat et al 2015). The evaluated variables (table 1) facilitated comparative assessment and identified trends in assessing social vulnerability to multi-hazards. We identified and coded into the matrix theoretical determinants of social vulnerability from themes commonly found in the literature—see Clark et al (1998), Cutter et al (2000), Tate et al (2010), Flanagan et al (2011), Hinkel (2011), Rufat et al (2015), Naithani et al (2019). These determinants included coping capacity, demographic characteristics, land tenure, living conditions, socioeconomic status, risk perception, health, and exposure. The assessed determinants and their specific indicators are further described in appendix.

We applied a vote-counting methodology (see Romero-Lankao et al 2012) to synthesize the results of the 91 studies. This methodology identified the leading approaches to measuring multi-hazard social vulnerability, and which determinants of social vulnerability are reflected in multi-hazard assessments. In cases where complex events such as hurricanes were mentioned, we recorded the perils measured. For example, if the hazard was listed as hurricane, this was entered into the matrix. However, if the study investigated individual hurricane perils (storm surge, wind damage, pluvial flooding), these were entered into the matrix instead of ‘hurricane’.
Figure 2. Data collection overview.

Table 1. Meta-analysis variables.

| Concept                        | Specific framing                                      |
|--------------------------------|-------------------------------------------------------|
| Multi-hazard frame             | Compound, cascading, or aggregate                     |
| Thematic area                  | Climate change, natural hazards, or risk              |
| Study setting                  | Urban/rural                                           |
| Location                       | Location of study site                                |
| Development context            | Country income level (World Bank statistics)          |
| Hazard/disaster stage          | Hazard/disaster stage on which study is focused       |
| Spatial scale                  | Spatial scale of the study: local/regional/national/ supranational |
| Temporal scale                 | Temporal scale of the study                           |
| Hazard type                    | Origin based classification: biological, hydrometeorological, geophysical |
| Hazard                         | Hazard/peril studied                                  |
| Social vulnerability drivers   | Social, institutional, and demographic characteristics considered |
| Hazard exposure                | Elements of hazard exposure considered by studies     |

4. Results

Our literature review of multi-hazard studies of social vulnerability found three major classes of ‘multi-hazard’: aggregate, cascading, and compound. A 4th classification also emerged, comparative assessment, which contrasts the effects of different hazards. Because comparative assessment was only applied in two publications, we included the comparative approach in our results tables, but excluded it from our analysis.

4.1. How do classifications of multi-hazard measure social vulnerability?

4.1.1. Multi-hazard class and determinants of social vulnerability

The multi-hazard classifications measured social vulnerability in dissimilar ways by placing emphasis on different determinants of social vulnerability. For each multi-hazard class, figure 3 shows the percentage of papers measuring the determinants of social vulnerability, illustrating where emphasis is placed in each class. In general, more variation was seen in the cascading and compound classifications of multi-hazards.

Within the aggregate class, analyses often privileged physical factors of the hazard, with social vulnerability a secondary element. The determinants of social vulnerability measured in this multi-hazard class reflect a bias towards the physical conditions which populations occupy and socioeconomic factors of their lives. Living condition was the most often measured driver of social vulnerability (figure 3); with indicators of population size, lifelines...
4.1.2. Statistical association of the determinants of social vulnerability varies across multi-hazard classes

The statistical relationships between determinants of social vulnerability varied across the classifications of multi-hazards, further suggesting the multi-hazard classes measure social vulnerability in differing ways. Figure 4 identifies statistical clusters of correlations among the determinants of social vulnerability for each multi-hazard class. Color intensity and the circle size are proportional to the correlation coefficients. The blue circles indicate that most determinants of social vulnerability were positively correlated. Negative correlations are represented in red shades. Determinants of social vulnerability within each cluster are more closely associated with each other than to those in other clusters. Land tenure, demographic characteristics and socioeconomic status were the most closely associated determinants of social vulnerability in multi-hazard studies. Studies which measure one of these determinants were highly likely to also consider the other two drivers of social vulnerability. In general exposure was most distantly related to the other determinants.

Hierarchical clustering revealed distinct associations of determinants of social vulnerability across the multi-hazard classes. Figure 4 shows within the aggregate frame exposure was weakly associated with all other determinants of social vulnerability, while demographic characteristics were less commonly measured in papers which investigated risk perception, coping capacity and exposure. The correlations and clustering suggest studies in the cascading multi-hazard class pull most evenly from all eight determinants of social vulnerability. Within this class we found the living conditions and exposure cluster distantly associated and negatively correlated with coping capacity and risk perception. In the compound class, figure 4 shows coping capacity and exposure were each weakly correlated, and had few occurrences with other determinants of social vulnerability. Risk perception was absent from sampled papers in this multi-hazard class.
4.1.3. Thematic area of research influences how social vulnerability is measured

The combination of social vulnerability determinants in each multi-hazard class was closely linked to the thematic areas of research (figure 5). Climate change had the fewest contributions to each determinant of social vulnerability, probably due to being completely absent in sampled papers of the cascading multi-hazard class. Where present, climate change papers predominantly measured living conditions and exposure, and were especially representative in the compound class. The natural hazards theme was the major source of papers covering coping capacity and risk perception (figure 5). This thematic area accounted for over half of those studies measuring demographics and socioeconomic status in the aggregate and compound classes but had a limited role in the cascading class. Risk was the major source
of papers on health, socioeconomic status, exposure, and demographics. However, it influenced different determinants of social vulnerability across the multi-hazard classes. In the aggregate class, risk was the majority contributor to papers investigating living conditions, exposure, coping capacity, and demographic indicators. For the cascading class, risk was the dominant theme (66% of papers), and accounted for all studies measuring indicators of health, land tenure and demographics. One third of cascading-class papers on risk assessed exposure. In the compound class, studies in the thematic area of risk mainly included measures of socioeconomic status, hazard exposure and living conditions.

### 4.2. How are classifications of ‘multi-hazard’ employed in studies measuring social vulnerability?

The structure of multi-hazard studies may have an indirect but important influence on how social vulnerability is explored within each multi-hazard class. Table 2 summarizes the conditions in which the multi-hazard classes were implemented in the social vulnerability literature. Totals may exceed the 91 articles covered because some articles included analyses in multiple settings, countries, disaster stage, scales of analysis, or hazard type.

#### 4.2.1. Dominance of the aggregate classification

The aggregate classification was by far the most common implementation of multi-hazards (table 2). Thematically, the aggregate class was most often applied in the domains of risk and natural hazards, but still accounted for 70% of publications on climate change. Studies were evenly split between urban and rural settings and mostly applied in middle income countries. The dominance of the aggregate class suggests it is how most researchers think of multi-hazards. This classification is highly adaptable and relatively easy to implement, with limited computational demands.

Table 2 shows more variation in the application of cascading and compound classifications. Cascading was the least applied, appearing in just 7% of publications and only in studies of risk and natural hazards. It was usually applied in middle income countries. The compound classification was relatively evenly applied across the thematic areas of climate change, natural hazards, and risk. Most often employed in rural settings and middle-income countries, the compound class was absent in studies from low-income countries.

#### 4.2.2. Focus on mitigation

There was an overwhelming focus on mitigation across all multi-hazard classes (table 3). In each class, mitigation represented at least two thirds of all publications assessed. Conversely, response and recovery were the least represented stages of the disaster cycle. The risk thematic area represented 40% of all mitigation related papers. This may reflect the focus on economic losses and greater attention given to the physical over social aspects of hazard events which we found in the risk theme. For cascading multi-hazards, risk accounted for most of the mitigation focused papers, while natural hazards had limited representation in the recovery stage. In the compound class, the response and recovery phases saw limited entries from climate change and natural hazards thematic areas.
4.2.3. Multi-hazard studies typically cover hazards of a single origin

Hydrometeorological hazards were the most common type studied, while biological hazards were the least (table 3). We found cases where anthropogenic hazards were analyzed along with natural hazards, though not in the form a natech cascade. Aggregate multi-hazards accounted for the bulk of studies covering hydrometeorological, geophysical, and those including anthropogenic events. However, this pattern likely reflects the share of the sample held by the aggregate class. The compound framing accounted for half of the studies on biological hazards though making up only 23% of the sample. In the aggregate frame flood/landslide and flood/drought were the most common hazard combinations assessed. Flood/landslide and earthquake/landslide were the most common hazard combinations in the cascading classification. In the compound classification, floods were the hazard most assessed in conjunction with other hazard types. This combination most commonly included hurricanes or drought.

4.2.4. Diversity in where and how studies were conducted

Our results show diversity in how multi-hazard research on social vulnerability was conducted across the world. Primary data from participatory and mixed methods surveys were dominant in low and middle income countries and the climate change thematic area. Secondary data were mainly used for indicator based statistical modeling, were dominant in high income countries and in the risk assessment thematic area. Only six studies included lower income countries and two of those were conducted in a supranational context. The majority of studies focused on Asia, with India (11), China (9) and Bangladesh (7) hosting the most studies in this region (figure 6). The US was the country with most studies (14).

5. Discussion

5.1. Differing aspects of social vulnerability are measured by studies implementing different multi-hazard classifications

Measures of social vulnerability are largely contingent on multi-hazard class and thematic area of study. This limits ability to generalize the leading characteristics of social vulnerability across classifications of ‘multi-hazard’.

5.1.1. Indicator relationships were distinct across multi-hazard classifications

The social and structural processes (such as access to power and resources, risk perception, marginalization, and poverty) which shape inequalities in multi-hazard exposure, susceptibility and coping remain occluded. The few papers investigating these processes were mainly qualitative, local scale, and reflected the compound classification of multi-hazards. Such studies illustrate the role of structural advantage/disadvantage at local levels, such as commercial decline (Shameem et al 2014, Thanh et al 2020), and responsiveness of local and national government institutions (Sternberg 2014) in executing policy appropriate adjustments. Gender, accrued wealth and social status are important contributors to resource access in some disaster situations (Ray-Bennett 2009, Panda 2017) but not others (Soto et al 2019). A generalized understanding of these interactions requires expanded analyses of how drivers of social vulnerability interact to produce dangerous social and physical conditions. Expanded use of the cascading and compound multi-hazard...
classifications is required, as the dominant aggregate multi-hazard approach does not meet this need.

There is a gap in knowledge concerning interactions among determinants of social vulnerability across the multi-hazard classes. We identified demographic characteristics, socioeconomic status, and to a lesser extent land tenure, as important drivers of multi-hazard social vulnerability (figure 4). These determinants are frequently measured together, but the form of their relationship remains unclear. Successful interventions for vulnerability reduction must identify how addressing a particular determinant of social vulnerability exacerbates/attenuates conditions of other determinants. The cascading and compound multi-hazard classifications often utilize qualitative measures which can describe the form of relationships among determinants of social vulnerability. Future research should therefore focus on these multi-hazard classifications. To support such work, further research must address limitations of qualitative data including limited applicability at higher spatial aggregations (Hinkel 2011) and ability to generate and inform salient quantitative data (Mayoux and Chambers 2005). Does changing spatial aggregation influence the form of interactions between determinants of social vulnerability? Does the form of interaction between determinants of social vulnerability substantially differ between multi-hazard classifications?

5.1.2. Multi-hazard classes may be complementary in their accounting of social vulnerability

Emphasis on different thematic areas suggests individual multi-hazard classes may poorly represent some segments of social vulnerability. Papers in the climate change, risk, and natural hazards thematic areas place different emphasis on the determinants of social vulnerability. Natural hazards was the dominant thematic area for papers in the aggregate and compound multi-hazard classes; demographics, living conditions, socioeconomic status and exposure were the largest components of these multi-hazard approaches. Conversely the increased prominence of health, risk perception, and coping capacity in cascading multi-hazards reflects the focal points of the risk thematic area which was by far the largest contributor to research articles in this class of multi-hazards.

The complexities of comparing spatial and temporal scales of hazard extent and impact (O’Brien et al 2004, Greiving 2006, Polsky et al 2007, Sekhri et al 2020) present a related hurdle for comparing social vulnerability across multi-hazard classes. Climate change research has concentrated on large geographic scales, specific economic sectors, and typically includes measures of adaptive capacity, see O’Brien et al (2004), Kok et al (2016). Conversely, natural hazard studies are more localized, with household and county scales more common, but typically ignore measures of coping (e.g. Tate et al 2010).

These thematic differences hinder a systematic approach for analyzing vulnerability to multiple stressors. This shortcoming has received much criticism, as management and response priorities can be distorted without a full view of the processes involved (O’Brien et al 2004, Greiving 2006, Polsky et al 2007, Sekhri et al 2020). Areas for future research include determining cumulative impact of multiple events, accounting for differences in hazard, intensity, and frequency, and identifying and assessing linkages between hazards and vulnerable people (Delmonaco et al 2006, Kappes et al 2012). Though a systematic approach would aid effective policymaking for vulnerability reduction (O’Brien et al 2004, Kok et al 2016), individual classes of multi-hazard prioritize different determinants of social vulnerability. As an example, knowledge gained from the aggregate classification may underestimate the importance of public-health conditions and risk perception. Similarly, understanding gleaned from the cascading class may downplay the role of socio-demographics. A full accounting of social vulnerability in multi-hazard environments may therefore need to combine knowledge from all the multi-hazard classes.

5.1.3. Multi-hazard classes reflect different perspectives of social vulnerability

Classifications of multi-hazards employ divergent views of social vulnerability as an outcome or preexisting condition. The choice of multi-hazard class therefore reflects specific perspectives on social vulnerability. We found social vulnerability in a multi-hazard context places varied emphasis on the social and structural drivers of vulnerability. Since the multi-hazard classes address different questions on social vulnerability, on their own each class may not adequately cover the breadth of social vulnerability, but they may be complementary in nature.

Social vulnerability as an outcome of hazard events was the perspective most often found in the multi-hazard literature. Such studies typically quantify the relationship between hazard and outcomes—of which social vulnerability is but one subset. Determinants of social vulnerability may be used as confounders which modify the relationship between hazards and a physical outcome, but these studies are limited in their assessment of the structure of social vulnerability. Factors of susceptibility were mainly assessed, with limited consideration given to exposure and coping capacity related determinants of social vulnerability.

Studies in the aggregate class predominantly view social vulnerability as an outcome of hazard events. In these cases, social vulnerability is often seen as a modifier of a hazard outcome and as a result, these studies often address a smaller subset of the determinants of social vulnerability and their representative
indicators. Further, because social vulnerability to each hazard is examined independently, the aggregate approach cannot reflect how interaction of social elements varies across multiple hazard events and is thus limited in what it reveals about how multi-hazard conditions affect social vulnerability.

Social vulnerability as a preexisting condition influencing the human-hazard interaction was far less often explored in the literature. These studies were more likely to explore the social, economic, and political structures which influence hazard exposure, susceptibility, and coping—see 5.2.1. Coping capacity and exposure are much more represented in this view of social vulnerability and therefore the multi-hazard classes exploring this area.

Studies in the cascading and particularly the compound classes, were far more likely to approach social vulnerability as a preexisting condition. In these cases, the emphasis is on the interaction of social conditions, with the hazards a modifying factor of these interactions. A wider representation of the determinants and associated indicators of social vulnerability are used. Such studies are far more focused on the interactive elements of vulnerability and hazards, and therefore better explain how conditions of social vulnerability evolve with hazard events.

These differences in the underlying assumptions of social vulnerability make it difficult to compare or aggregate knowledge from the different multi-hazard classes.

Few authors explicitly identified the theoretical models (hazard of place, pressure and release etc) on which their research was based. These theoretical constructs likely influence the underlying assumptions of social vulnerability as a preexisting condition or an outcome. This lack of clarity creates an additional layer of uncertainty which must be overcome to compare studies across different classifications of ‘multi-hazard’.

Researchers and practitioners must be cognizant of these underlying assumptions. Care must be taken to choose a multi-hazard classification which best fits the perspective of social vulnerability needed for a particular assessment. Conversely, multiple classifications may be employed as complimentary measures to develop the full picture multi-hazard social vulnerability.

5.2. Application of multi-hazards is conceptually narrow

The literature on social vulnerability in multi-hazard contexts is dominated by the aggregate classification of multi-hazards, mitigation disaster stage, and research in upper- and middle-income countries. Yet the actual disasters the world likely faces in a changing climate are much more complex than this narrow view of multi-hazards. For example, there are increasing instances of combinations of intense heat, drought, and wildfires in the western US, and sequences of major hurricanes in the Caribbean. The current literature on social vulnerability to multi-hazards is poor in its reflection of this reality.

5.2.1. Multi-hazard knowledge comes mainly from the aggregate classification

The vast majority of multi-hazard papers on social vulnerability adopt the aggregate approach. Therefore, empirical knowledge on social vulnerability to multi-hazards mainly assumes the effects of individual hazards can be separately assessed then later linearly combined. This is at odds with the origins of the generalized indicators currently used to represent conceptual determinants of social vulnerability, which were developed from the analysis of social vulnerability across multiple hazards (Cutter et al 2003, Flanagan et al 2011, Mustafa et al 2011). Assessing social vulnerability to each hazard separately (i.e. aggregate classification) rather than the interactive elements of multiple hazards and vulnerability (as in the compound and cascading classes) limits the knowledge gained in such studies. Consequently, the single classification focus sheds light on only some aspects of social vulnerability.

The primary focus of studies on aggregate multi-hazards was quantifying the impact of natural hazards on physical or economic outcomes, while controlling for social factors such as age or family structure. These studies showed demographic characteristics, living conditions and lower socioeconomic status as linked to inequity of hazard outcomes, examples include Ahsan and Warner (2014) and Asare-Kyei et al (2017). This reinforces current understanding that vulnerability is as much socially constructed as it is resultant from the physical aspects of natural hazards (O’Keefe et al 1976, Cutter 1996, Turner et al 2003, Birkmann et al 2015). The weight of attention given to these factors suggests that, at least for the aggregate view of multi-hazards, these social factors are even more important than the physical elements of exposure (figures 3 and 7). However, the aggregate classification leaves a significant gap on questions covering how the interaction of hazards affect social vulnerability, or on the production of social vulnerability as a precursor to hazard outcomes. While other multi-hazard approaches (particularly the compound class) may be more suited to address these types of questions, they comprise a much smaller subset of the multi-hazard landscape.

Studies in the aggregate multi-hazard class typically considered all assessed hazards as equally important. However, vulnerability and risk are often much greater than simple combination of individual components would suggest. Omitting interactions between social determinants and/or hazards can lead to underestimation of impacts (Zscheischler et al 2018). Several researchers including Greiving et al (2006), Kappes et al (2012), Nugraha et al (2017) have recognized this issue as an element of weighting
decisions which have important impacts on model outputs. Delmonaco et al. (2006), Saltelli (2007) and Tate (2013) describe the difficulty of accounting for the social aspects reflected in indicator selection and use. However, operationalizing such insight remains the exception rather than the norm. Direct aggregation of equally weighted indicators is the simplest computational approach and has been most widely employed, but this does not mean it best represents processes shaping who is socially vulnerable.

Additionally, due to an increasing reliance on hazard-exposed critical-infrastructure and intensification of social inequalities, climate change induced increases in hazard intensity will likely result in associated upsurges in cascading and compound hazards. Cutter (2021) notes that the persisting social inequalities which produce differential vulnerability mean that most of these impacts will accumulate on those at the bottom of political, power, economic, and social structures—i.e. the socially vulnerable. The intersectionality of these marginalization producing processes (Kuran et al. 2020) cannot be adequately interrogated via the aggregate lens of multi-hazards. Understanding how social vulnerability functions in cascading and compound lenses of multi-hazards is therefore imperative, as it is social inequalities which transform hazards into disasters and, cascading and compound events are likely to become a dominant feature of the next century.

5.2.2. Multi-hazard studies focus on mitigation

More attention should be given to the potentially significant differences in determinants of social vulnerability active at different stages of disaster. Eighty-four percent of studies in our meta-analysis examined the mitigation phase of the disaster cycle, yet the literature shows that importance of social vulnerability determinants can vary across disaster stages (Zhang and Peacock 2009, Peacock et al. 2014, Meyer et al. 2018). It is often difficult to define where one stage of the disaster cycle ends and another begins, and even more so for multi-hazards where events may not be temporally aligned. Particularly where multiple hazards are concerned, actions to mitigate effects of one hazard may hamper activities of preparedness or recovery for other events—such as damage in the 2010 Haiti earthquake being closely associated with that society’s focus on hurricanes (Hou and Shi 2011). The temporal context of social vulnerability therefore remains obscured. Who is most affected across different stages of disasters remains poorly understood.

Similarly obscure is the shifting relevance of vulnerability determinants through subsequent events, or from one hazard type to another. Rufat et al. (2015) argued for attention to be paid across phases of disaster to build the contextual validity of social vulnerability indicators. Expanding beyond mitigation should reduce the current opacity of selection, weighting, and aggregation of indicators of social vulnerability; the importance of which are exponentially higher with the complexity of multi-hazard
interactions. Broader representation improves understanding of which indicators of social vulnerability are important to particular hazard types (selection), the relative importance of these indicators within determinants of social vulnerability, events and across event types (weighting), and the combined effect of these indicators on outcomes across multiple hazard experiences (aggregation).

5.2.3. Most multi-hazard studies are hydrometeorological

The multi-hazard literature concentrates on hydrometeorological events, likely due to the high frequency of hydrometeorological hazards. Yet it is important to also understand the factors influencing outcomes from hazards of less frequent origin. In particular, the limited assessment of social vulnerability to biological hazards is a concern. The combination of climate change, expanding populations, and rising resource demands increases hazard exposures of marginalized populations. If public health systems are unable to keep pace, biological hazards will continue to be a major global burden (Ario et al 2019, Thomas et al 2020). Public health systems need to be guided by information on determinants of social vulnerability. The public health literature’s contributions on the social determinants of health are significant in this area. Yet this literature seldom focuses on the influence of natural hazards and, pays even less attention to multiple hazard interactions producing dangerous conditions of biological hazards.

Multi-hazard studies remain bounded within origin-based classifications with limited assessments across hazards of different origins. Those incorporating hazards of multiple origins usually combine a hydrometeorological event such as cyclones with mass movement (geophysical) events such as landslides. Studies from the climate change thematic area are more apt to include assessment across origin classifications. As the effects of global change intensify, studies of hazards of multiple origins are increasingly necessary, particularly for low lying coastal areas and Small Island Developing States (Mortsch 2010, IPCC 2012a). However, the social vulnerability literature in this area has so far been focused on multi-hazards in high income countries in the Mediterranean basin (e.g. Gallina et al 2020 and Mavromatidi et al 2018). If society is to better prepare for future hazardous conditions, it is imperative that the social vulnerability research broadens its representation of potential hazard interactions.

5.2.4. Lower income nations are poorly represented

There is very little representation from studies in lower income countries, resulting in a lack of developmental context in the multi-hazard literature on social vulnerability. Significant differences in exposure, susceptibility, and coping between high- and low-income countries, result in very different impacts (Peduzzi et al 2009, IPCC 2012a). Scientific understanding gained from middle- and high-income countries may therefore not be directly transferable to lower income nations. Applying models and concepts from higher income places may significantly underestimate the capacities of people in lower income settings.

Studies conducted in lower income countries tend to be restricted to local spatial scales and qualitative in design. Such research is often better suited to answer questions on the interactions that drive multi-hazard social vulnerability in the local areas, but less equipped to identify factors of social vulnerability across large areas. Resource constraints often require comparative measures for prioritized community distribution of resources at national or state levels. Such constraints are often more acute in lower income countries where there are few multi-hazard studies of social vulnerability at this resolution. A balanced view of social vulnerability in multi-hazards settings therefore requires expanded representation of research in lower income countries. Sustainable, impactful interventions will only be achieved with fuller understanding of the unique attributes of socially vulnerable conditions in these places.

6. Conclusion

Our study interrogates the state of knowledge on social vulnerability in multi-hazard contexts and, is among the first assessments of social vulnerability based on a stratification of ways multi-hazards are classified. The multi-hazard approach remains the most promising for untangling the contextual characteristics of social vulnerability. However, we found multi-hazard classes focus on different elements of social vulnerability. Additionally, what is known of social vulnerability in the multi-hazard context comes from a limited contextual subset of the field: the aggregate classification and mitigation phase of the disaster cycle.

It is apparent that the multi-hazard classes may derive from different perspectives of social vulnerability itself. Social vulnerability research on multi-hazards primarily examines the impact of social vulnerability on hazard outcomes and, is structured on the aggregate fame of multi-hazards. There continues to be limited attention paid to the how these interactions develop to produce the unique social and structural circumstances shaping the perilous conditions in which populations exist. Overall, there is need for additional research on how relationships between the determinants of social vulnerability evolve across disaster stages and across events. The paucity of such research is striking, particularly given the stark impacts of multi-hazard events in the 21st century. The advantages of greater focus on local scale, and temporal flexibility across disaster stage offered by the compound and cascading multi-hazard classes can
be advantageous to addressing this shortcoming; yet these framings are employed infrequently.

The difference in perspectives of social vulnerability covered, and resultant inconsistency in coverage of determinants of social vulnerability produce significant knowledge gaps across classifications of multi-hazards. These gaps limit cross-conceptual comparisons and comprehensiveness of findings. Researchers need to understand the underlying assumptions of these multi-hazard classifications when considering study design and assessing findings. It may be intrinsically more difficult to observe the full impact of some determinants of social vulnerability when using a particular multi-hazard classification. By explicitly identifying the different ways multi-hazards are framed and how these framings are applied to social vulnerability, we provide new knowledge on social vulnerability in multi-hazard settings.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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## Appendix

### Table A1. Indicators of social vulnerability—adapted from Rufat et al (2015) (inputs from Cutter et al 2000, Clark et al 1998).

| Thematic indicators | Specific indicators | Description (does the study consider…) |
|---------------------|---------------------|----------------------------------------|
| **Coping capacity** | Individual capacity | Ability of the individual to withstand the impact of hazard losses using available resources |
| Ability/ resources to resist effects hazard impacts | Household capacity | Ability of household unit to withstand hazard impacts using collective resources |
| Social/societal capacity | Institutional capacity | Ability of public institutions to withstand hazard related disruptions |
| **Demographic characteristics** | Age | Dependents (those below and above working age) |
| (population characteristics determining the degree to which a group is positively or negatively affected by (susceptibility to) hazard impacts) | Race and ethnicity | Reduced access to resources often linked to marginalization of minority populations |
| Family structure | Female headed households, multigenerational families |
| Gender | Male–female ratios, females as part of the workforce |
| Disabilities/special needs | Populations requiring special accommodations |
| Language proficiency | Persons not proficient in the official or main language(s) of the area |
| **Land tenure** | Owners | Homeowners/owners of agricultural land |
| (security of living spaces) | Renters | Renters/tenant farmers |
| Squatters | Persons illegally occupying land |
| **Living conditions** | Lifeline disruption | Damage to lifeline facilities (health care, transportation, communications, etc) |
| (determinants of the conditions under which living and livelihoods occur) | Population density | # People per unit of measure |
| Housing | Identifiers of housing quality/condition (e.g. building materials, temporary roofs) |
| Resource dependency | Populations highly dependent on specific natural resources prone to suffer disruption from hazard events (e.g. agriculture, mining, logging, fishing) |
| **Socioeconomic status** | Income | Increasing wages and salaries often linked to greater ability to secure resources/coping |
| Wealth | Accrued affluence |
| Education | Level of education received |
| Occupation | Some occupations are both more marginalized and more susceptible to hazard impacts |
| Employment | Unemployed seen as more susceptible and having lower coping capacity |
| **Risk perception** | Awareness | Are they aware of the hazard, do persons have access to information, sources of information on hazards |
| (local views of likeliness to suffer specific losses due to identified events) | Prior experience | Have population experienced the hazard before |
| Risk denial/acceptance | Do population see hazards as nonexistent, unpreventable acts of God |
| Trust in officials | View of the veracity of information from officials, intent of officials |
| **Health** | Access to healthcare/facilities | Physical and economic access to health facilities |
| Caloric intake/food (in)security | Indicators of food security, having enough to eat |
| Disease burden/morbidity | Indicators of disease prevalence, lost workdays due to illness, etc |
| Mortality | Deaths due to hazard impacts |
| Sanitation | Indicators of community hygiene and waste removal infrastructure |
| **Exposure** | # of events | # of hazard events faced |
| (likelihood of experiencing a hazard event, duration and/or extent to which a system is subject to disturbance by a hazard) | Hazard extent | Geographical boundaries of hazard exposed area |
| Exposed population | # or % of population extant in hazard exposed area |
| Exposed facilities | Lifeline facilities exposed to one or more hazards |
ORCID iDs

Oronde Drakes 🔗 https://orcid.org/0000-0002-1047-1389
Eric Tate 🔗 https://orcid.org/0000-0002-9587-3028

References

Adlekan I, Johnson C, Manda M, Matyas D, Mberu B U, Parnell S, Pelling M, Satterthwaite D and Vivekananda J 2015 Disaster risk and its reduction: an agenda for urban Africa Int. Dev. Plann. Rev. 37 33–43
AghaKouchak A, Chiang F, Huning I, S, Love C A, Mallakpour I, Madiyason O, Motifakhari H, Papalexiou S M, Ragno E and Sadeq M 2020 Climate extremes and compound hazards in a warming world Annu. Rev. Earth Planet. Sci. 48 519–48
Ahsan M N and Warner J 2014 The socioeconomic vulnerability index: a pragmatic approach for assessing climate change led risks—a case study in the south-western Bangladesh Int. J. Disaster Risk Reduct. 8 32–49
Ario A R, Makumbi I, Bulage L, Kyazze S, Kayiwa J, Wetaka M M, Kasule J N and Orom F 2019 The logic model for Uganda’s health sector preparedness for public health threats and emergencies Glob. Health Action 12 1664103
Asare-Kyei D, Renaud F G, Kloos J, Walz Y and Rhynner J 2017 Development and validation of risk profiles of West African rural communities facing multiple natural hazards PlaS One 12 e0171921
Balch J K et al 2020 Social-environmental extremes: rethinking extraordinary events as outcomes of interacting biophysical and social systems Earths Future 8 e2019EF001319
Birkmann J et al 2015 Scenarios for vulnerability: opportunities and constraints in the contest of climate change and disaster risk Clim. Change 133 53–68
Buck K D and Summers J K 2020 Application of a multi-hazard risk assessment for local planning Geomat. Nat. Hazards Risk 11 2038–78
Burton C G, Rufat S and Tate E 2018 Social vulnerability Vulnerability and Resilience to Natural Hazards eds S Fuchs and T Thaler (Cambridge: Cambridge University Press) pp 53–81
Clark G E, Moser S C, Ratick S J, Dow K, Meyer W B, Emani S, Jin W, Kaspersson J X, Kaspersson R E and Schwartz H E 1998 Assessing the vulnerability of coastal communities to extreme storms: the case of Revere, Ma., USA Mitigation Adapt. Strategies Global Change 3 59–82
Cutler S L 2021 The changing nature of hazard and disaster risk in the anthropocene Annu. Am. Assoc. Geogr. 111 819–27
Cutler S L, Mitchell J T and Scott M S 2000 Revealing the vulnerability of people and places: a case study of Georgetown County, South Carolina Annu. Am. Assoc. Geogr. 90 713–39
Cutler S 1996 Vulnerability to environmental hazards Prog. Hum. Geogr. 20 329–39
Cutler S, Boruff B and Shirley L 2003 Social vulnerability to environmental hazards Soc. Sci. Q. 84 242–61
Dawson R J 2015 Handling interdependencies in climate change risk assessment Climatic 3 1079–96
Delmonaco G, Margotti C and Spizzichino D 2006 New Methodology for Multi-risk Assessment and the Harmonisation of Different Natural Risk Maps European Community H.R.707 - 106th Congress (1999–2000): Disaster Mitigation Act of 2000. (2000, October 30) US congress (available at: https://www.congress.gov/bill/106th-congress/house-bill/707)
Flanagan B E, Gregory E W, Hallsey E J, Heitgerd J L and Lewis B 2011 A social vulnerability index for disaster management J. Homel. Secur. Emerg. Manage. 1 8

Gallina V, Torresan S, Zaho A, Critto A, Glade T and Marcomini A 2020 A multi-risk methodology for the assessment of climate change impacts in coastal zones Sustainability 12 3697
Geist H J and Lambin E F 2001 What drives tropical deforestation LUCC Report series 4 (University of Louvain) p 116
Gill J C and Malamud B D 2014 Reviewing and visualizing the interactions of natural hazards Rev. Geophys. 52 680–722
Gill J C and Malamud B D 2016 Hazard interactions and interaction networks (cascades) within multi-hazard methodologies Earth Syst. Dyn. 7 659–79
Gill J C and Malamud B D 2017 Anthropogenic processes, natural hazards, and interactions in a multi-hazard framework Earth Sci. Rev. 166 246–69
Girgin S, Necci A and Kraussmann E 2019 Dealing with cascading multi-hazard risks in national risk assessment: the case of Natech accidents Int. J. Disaster Risk Reduct. 35
Greiving S 2006 Integrated risk assessment of multi-hazards: a new methodology Special Paper-Geological Survey of Finland vol 42 p 75–82
Greiving S, Fleischhauer M and Lückenköttter J 2006 A Methodology for an integrated risk assessment of spatially relevant hazards J. Environ. Plann. Manage. 49 1–19
Hewitt K and Burton I 1971 The Hazardousness of A Place: A Regional Ecology of Damaging Events (Toronto: University of Toronto)
Hinkel J 2011 ‘Indicators of vulnerability and adaptive capacity’: towards a classification of the science-policy interface Glob. Environ. Change 21 198–208
Hou L and Shi P 2011 Haiti 2010 earthquake—how to explain such huge losses? Int. J. Disaster Risk Sci. 2 25–33
IPCC 2012b Summary for policymakers Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change eds C B Field, V Barros, T F Stocker, D Qin, D J Dokken, K L Ebi, M D Mastrandrea, K J Mach, G-K Plattner, S K Allen, M Tignor and P M Midgley (Cambridge: Cambridge University Press) p 20
IPCC 2012a Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change Field C B et al (Cambridge: Cambridge University Press) p 582
IPCC 2021 Summary for policymakers Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change eds V Masson-Delmotte, P Zhai, A Pirani, S L Connors, C Pean, S Berger, N Caud, Y Chen, J Goldfarb, M J Gomis, M Huang, K Leitzell, E Lonnoy, J B Matthews, T K Maycock, T Waterfield, O Yelecki, R Yu and B Zhou (Cambridge: Cambridge University Press) p 41
Kappes M S, Keiler M, von Elverfeldt K and Glade T 2012 Challenges of analyzing multi-hazard risk: a review Nat. Hazards 64 1925–58
Kok M, Ludeke M, Lucas P, Sterzel T, Walther C, Janssen P, Sietz D and de Sopra Y 2016 A new method for analyzing social ecological patterns of vulnerability Reg. Environ. Change 16 229–43
Kraussmann E, Koppe K E, Fendler R, Cruz A M, Girgin S, Kraussmann E, Cruz A M and Salzano E 2017 Qualitative and Semiqualitative Methods for Natech Risk Assessment Natech Risk Assessment and Management: Reducing the Risk of Natural-Hazard Impact on Hazardous Installations eds E Kraussmann, A M Cruz and E Salzano (Cambridge: Elsevier) p 53
Kuran C H A et al 2020 Vulnerability and vulnerable groups from an intersectionality perspective Int. J. Disaster Risk Reduct. 50 101826
Leondar M, Westra S, Phatak A, Lambert M, van den Hurk B, Mclnnes K, Risby J, Schuster S, Jakob D and Stafford-Smith M 2014 A compound event framework for
understanding extreme impacts: a compound event framework Wiley Interdiscip. Rev. Clim. Change 5 113–28
Liu B Y, Siu Y. L. and Mitchell G 2016 Hazard interaction analysis for multi-hazard risk assessment: a systematic classification based on hazard-forming environment Nat. Hazards Earth Syst. Sci. 16 629–42
Mavromatidis A, Briche E and Claes C 2018 Mapping and analyzing socio-environmental vulnerability to coastal hazards induced by climate change: an application to coastal Mediterranean cities in France Cities 72 189–200
Mayou X. and Chambers R 2005 Reversing the paradigm: quantification, participatory methods and pro-poor impact assessment J. Int. Dev. 17 271–98
McCarthy J J, Canziani O F, Leary N A, Dokken D J and White K S 2001 Climate Change 2001: Impacts, Adaptation, and Vulnerability: Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change eds J J McCarthy, O F Canziani, N A Leary, D J Dokken and K S White (Cambridge: Intergovernmental Panel on Climate Change)
Meyer M A, Mitchell B, Purdum J C, Breen K and Iles R J 2018 Previous hurricane evacuation decisions and future evacuation intentions among residents of southeast Louisiana Int. J. Disaster Risk Reduct. 31 1231–44
Misseumphon A A 2005 What drives food security in Southern Africa? A meta analysis of household economy studies Glob. Environ. Change 15 33–43
Mortsch L D 2010 Multiple dimensions of vulnerability and its influence on adaptation planning and decision making Climate: Global Change and Local Adaptation (Dordrecht: Springer) eds I Linkov and T S Bridges pp 67–88
Mustafa D, Ahmed S, Saroch E and Bell H 2011 Pinning down vulnerability: from narratives to numbers Disasters 35 62–86
Naiithani S, Champati Ray P K and Joshi R C 2019 A multi-parametric micro-level vulnerability assessment model for mountain habitat: a case example from biliganga block, Uttarakhand Himalaya, India Geoinformation for Disaster Management (Int. Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences—ISPRS Archives) (3–6 September 2019, Prague) 42 267–74
Nugraha A L, Hanti’ah and Pratiwi R D 2017 Assessment of multi hazards in Semarang city AIP Conf. Proc. 1857 100006
O’Brien K et al 2004 Mapping vulnerability to multiple stressors: climate change and globalization in India Glob. Environ. Change 14 303–13
O’Keefe F, Westgate K and Wisner B 1976 Taking the naturalness out of natural disasters Nature 260 566–7
Panda A 2017 Vulnerability to climate variability and drought among small and marginal farmers: a case study in Odisha, India Int. J. Clim. Change 9 605–17
Peacock W G, van Zandt S, Zhang Y and Highfield W E 2014 Inequities in long-term housing recovery after disasters J. Am. Plann. Assoc. 80 336–71
Peduzzi P, Dao H, Herold C and Mouton F 2009 Assessing global exposure and vulnerability towards natural hazards: the Disaster Risk Index Nat. Hazards Earth Syst. Sci. 9 1149–59
Polsky C, Neff R and Yarnal B 2007 Building comparable global change vulnerability assessments: the vulnerability-scoping diagram Glob. Environ. Change 17 472–85
Qie Z J and Rong L L 2017 An integrated relative risk assessment model for urban disaster loss in view of disaster system theory Nat. Hazards 88 165–90
Ray-Bennett N S 2009 Coping with multiple disasters and diminishing livelihood resources caste, class, and gender perspectives: the case from Orissa, India Reg. Dev. Dialogue 30 108–20
Romero-Lankao P, Qin H and Dickinson K 2012 Urban vulnerability to temperature-related hazards: a meta-analysis and meta-knowledge approach Glob. Environ. Change 22 670–83
Rufat S, Tate B, Burton C G and Maroof A S 2015 Social vulnerability to floods: review of case studies and implications for measurement Int. J. Disaster Risk Reduct. 14 470–86
Saltelli A 2007 Composite indicators between analysis and advocacy Soc. Indic. Res. 81 65–77
Sekhri S, Kumari R, Füest C and Pandey R 2020 Mountain specific multi-hazard risk management framework (MSMRMF): assessment and mitigation of multi-hazard and climate change risk in the Indian Himalayan Region Ecol. Indic. 118 106700
Shameem I M, Montzal S and Rauscher S 2014 Vulnerability of rural livelihoods to multiple stressors: a case study from the southwest coastal region of Bangladesh Ozone Coast. Manage. 102 79–87
Soto M V, Arratia P, Cabello M, Moreno R and Whyndam K 2019 Natural hazards and exposure of strategic connectivity in extreme territories. Comau Fjord, North Patagonia, Chile Revista De Geografía Norte Grande 73 57–75
Sternberg T 2014 Transboundary hazard risk: the Gobi desert paradigm Nat. Hazards 72 533–48
Tate E 2013 Uncertainty analysis for a social vulnerability index Ann. Am. Assoc. Geogr. 103 526–43
Tate E, Cutter S L and Berry M 2010 Integrated multihazard mapping Environ. Plann. B 37 646–63
Thanh H T, Tschakert P and Hipsey M R 2020 Tracing environmental and livelihood dynamics in a tropical coastal lagoon through the lens of multiple adaptive cycles Ecol. Soc. 25 31
Thomas D S K, Jang S and Scandlyn J 2020 The CHASMS conceptual model of cascading disasters and social vulnerability; the COVID-19 case example Int. J. Disaster Risk Reduct. 51 101828
Tilloy A, Malamud B D, Winter H and Joly-Laulig A 2019 A review of quantification methodologies for multi-hazard interrelationships Earth Sci. Rev. 196 102881
Turner B L et al 2003 A framework for vulnerability analysis in sustainability science Proc. Natl Acad. Sci. USA 100 8074–9
UN 2002 Johannesburg declaration on sustainable development, plan of implementation of the world summit on sustainable development (World Summit on Sustainable Development (UN))
UNDRR, CRED 2020 Human Cost of Disasters: An Overview of the Last 20 Years 2000–2019 UN Office of Disaster Risk Reduction (UNDRR)
UNISDR 2015 The Sendai Framework for Disaster Risk Reduction 2015–2030 (Sendai: United Nations Office for Disaster Risk Reduction)
Wisner B, Blaikie P, Cannon T and Davis I 2004 At Risk: Natural Hazards, People’s Vulnerability and Disasters (New York: Routledge)
Wolf S, Hinkel J, Hallier M, Bisaro A, Lincke D, Ionescu C and Sternberg T 2014 Transboundary hazard risk: the Gobi desert paradigm Nat. Hazards 72 533–48
Zhang Y and Peacock W G 2009 Planning for housing recovery? Lessons learned from Hurricane Andrew J. Am. Plann. Assoc. 76 54–25
Zou L-L and Wei Y-M 2010 Driving factors for social vulnerability: the COVID-19 case example Int. J. Disaster Risk Reduct. 101828
Zscheischler J et al 2018 Future climate risk from compound events Nat. Clim. Change 8 605–17
Zscheischler J and Seneviratne S I 2017 Dependence of drivers affects risks associated with compound events Sci. Adv. 3 e1700263