International Journal of Disaster Risk Reduction 108 (2024) 104535

Contents lists available at ScienceDirect

International Journal of Disaster Risk Reduction

journal homepage: www.elsevier.com/locate/ijdrr

VulneraCity–drivers and dynamics of urban vulnerability based on a global systematic literature review

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ARTICLE INFO

Keywords:
Vulnerability drivers
Urban vulnerability
Urban disaster risk
Vulnerability dynamics

ABSTRACT

Globally, urban disaster risk is being affected by changing patterns of natural hazards due to climate change and rapid urbanization. While we have a relatively good understanding of the hazard and exposure in cities, we know little about their vulnerability. In this study, we investigate the drivers and dynamics of urban vulnerability for six different natural hazards by conducting a systematic literature review on the peer-reviewed scientific literature. Out of an initial set of 3168 studies, we included 462 studies for in-depth analysis. We present VulneraCity, the urban vulnerability drivers database, in which we record the drivers and classify them based on topic and acquisition method. Overall, we list 1460 unique drivers of vulnerability in VulneraCity, of which 37.3 % are empirically acquired in the source studies. Other drivers are either modeled (7.9 %), theorized (22.9 %), adopted (27.0 %), or acquired with an unknown method (5.0 %). Furthermore, the relationships between drivers and impact are often assumed to be linear, but we identify six types of directional dynamics - one-directional, bidirectional, transferable, asynergies, conditional, and compound - which describe the complexities in these relationships to show that the linearity assumption is regularly violated. These results shed light on the necessary drivers that should be taken into account in urban vulnerability assessments. VulneraCity can facilitate discussions in local-scale vulnerability analyses, but could also provide input for larger-scale comparative studies of cities. We recommend further research into multi-hazard (instead of multiple hazards') vulnerability and vulnerability dynamics as next steps towards more comprehensive urban disaster risk studies.

1. Introduction

1.1. Research gaps and aim

Over the past decades, many cities globally have grown rapidly in size and population [1,2]; over 50 % of the world's population now lives in cities, and this is projected to increase to around 67 % by 2050 [3]. This trend increases cities' risk to natural hazards, as the expanding concentration of people, assets, and economic activities enlarges the pool of potentially exposed elements that may be affected when hazards occur [4]. The potential impacts of natural hazards in several cities are further aggravated by anthropogenic climate change, which increases the frequency and impact of several meteorological, hydrological, and other climate-related hazards such as flooding, droughts, and heatwaves [5,6].

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https://doi.org/10.1016/j.ijdrr.2024.104535
Received 25 August 2023; Received in revised form 3 May 2024; Accepted 4 May 2024
Available online 7 May 2024
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At present, research into natural hazard disaster risk in cities is often fragmented into different case studies [7–10]. Reasons for this are ambiguous urban boundaries in analyses, missing quantitative and qualitative data [8], and sturdy monodisciplinary urban sciences [9]. We thus need a more comprehensive global overview of urban disaster risk, especially in the concurrent context of climate change. Much research is being carried out to provide this comprehensive view [8], yet significant challenges remain. While major challenges apply for both global hazard and exposure modeling [11–13], vulnerability arguably remains the most difficult risk component to assess [14]. We define vulnerability as the characteristics of the exposed urban elements that influence their susceptibility to harm from natural hazards [4,5,15]. It is difficult to assess because vulnerability as a whole is an intangible concept and - especially in cities – highly dynamic [16–19]. It requires a diverse set of disciplines to uncover it completely [20]. Moreover, the term "vulnerability" covers a wide range of concepts, from physical vulnerabilities to social vulnerabilities, which need to be translated into measurable variables to make vulnerability operationable [18].

To quantify vulnerability, researchers have often used proxies or indicators of vulnerability [7,21], which are often summarized into a vulnerability index (e.g., Ref. [22–26]). However, the applicability of indicators and indexes depends on our understanding of the local context of the system/location that is being studied [18], which is often missing due to a lack of data [16,27]. Savelberg [28] even show that two different vulnerability assessment methods within the same local context can lead to spatially different outcomes. Likewise, but on a more fundamental note, empirical evidence on vulnerability-impact causal pathways is often lacking as well [27,29]. This is an important research gap that Kuhlicke et al. [29] already started to address in a recent literature review of social vulnerability, resilience, and adaptation assessments. They found that 85 % of the papers they reviewed did not explicitly mention the theory on which their assessment is built. In other words, there is a lot of uncertainty surrounding vulnerability drivers, which are often not being addressed sufficiently to advance the field.

Note that we here use the term vulnerability driver to describe a feature that could alter the vulnerability of an urban area to a natural hazard. This is different from a vulnerability indicator, which is a measure to operationalize vulnerability [18]. For instance, poverty would be a driver of vulnerability, of which an indicator could be the number of people below the poverty line. Hence, vulnerability drivers are the conceptual description of vulnerability on which vulnerability indicators are built. We want to emphasize that, in some instances, a driver is directly operational (e.g., soil type underneath buildings) and thus indistinguishable from an indicator. In the current study, we focus solely on vulnerability drivers.

Another research gap is the uni-directional nature of most vulnerability assessments. Indicators and indexes usually give the impression that a certain characteristic of the (urban) environment always results in more or less vulnerability, whereas in reality there may be compounding intersectionality effects between vulnerability drivers [27,30,31]. In recent years, researchers have given more attention to the dynamics of vulnerability, which refers to dynamics in time, interactions between vulnerability drivers, or the way in which we manage vulnerability [16,27,30–32], demonstrating that the uni-directionality assumption may not hold for many real-world situations.

The aim of this study is to address both the empirical evidence gap and the uni-directionality issue by taking an inventory of vulnerability drivers within the urban context. Our goal is to create a (non-spatially-explicit) database that cities from across the globe can use as an evidence-based source for their local-scale vulnerability assessments. For this, we conduct a systematic literature review based on 3168 peer-reviewed journal articles to find the vulnerability drivers for six different hazards: pluvial flooding, coastal flooding, drought, earthquakes, heatwaves, and waterborne diseases. These drivers are subsequently categorized according to vulnerability type and acquisition method. Note that we do not look at multi-hazard vulnerability, but rather at the differences and commonalities between the six hazards (although we do discuss multi-hazard vulnerability in Section 4.2). Based on our review, we also discuss the dynamics in directionality of vulnerability in cities with several examples from the reviewed articles and develop several overarching types of vulnerability dynamics. The results can be used as a reference for selecting empirical urban vulnerability drivers in local-scale assessments, to further the efforts of conducting a global-scale urban vulnerability assessment, and to gain new insights in the field of vulnerability dynamics.

1.2. Concepts of 'vulnerability' and 'urban'

1.2.1. Vulnerability

The term vulnerability is extensively discussed in the academic literature, mostly because of its conceptual ambiguity [33,34] and neighboring concepts like resilience and susceptibility [35,36]. The latent character of vulnerability [37,38] and the large variety of underlying concepts [34,39,40] make it difficult to come to a deliberate and commonly-accepted definition. For extensive reviews on these conceptual discussions we refer to the following articles: [41]; Otto et al. [39], Jurgilevich et al. [33], Lankao & Qin [42].

Hence, the many understandings of vulnerability require us to clearly state the definitions used here in order to make our results interpretable for researchers from a variety of fields. We follow the definitions provided by the UNDRR [4] and the IPCC [5]. First of all, we look at the UNDRR's [4] definition: "Vulnerability is the conditions determined by physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, community, assets or systems to the impacts of hazards." We compare this with the IPCC's [5] definition: Vulnerability is "the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt." Both definitions refer to characteristics that make the people or elements subject to harm more or less likely to be impacted. In our study, these subjects are both cities and their citizens. The definitions are distinctly different from exposure, which is referred to as "the presence of people; livelihoods; species or ecosystems; environmental functions, services and resources; infrastructure; or economic, social or cultural assets in places and settings that could be adversely affected" [5].

Notice that the UNDRR's definition of vulnerability refers to the elements of exposure by mentioning "an individual, community, assets or systems". In other words, exposure is embedded in vulnerability, but in some cases there is also some apparent overlap. For instance, "hospitals in flood-prone areas" is at face value an indicator for exposure (of the hospital). However, if a hospital cannot function during an emergency (because it is flooded) it will have consequences for the broader community, making it a vulnerability at the community level.

1.2.2. Urban

Similar to vulnerability, the term 'urban' or 'city' has different meanings from country to country. To exemplify: a settlement with at least 200 people is considered a city in Iceland, but would be a small village in Japan, where it requires at least 50,000 people to be called a city [2]. To ensure a globally consistent selection criterion, we take a colloquial understanding of urban as being settlements of any size exceeding villages, hence including towns, cities, metropolises, and their urban agglomerations, etc. This criterion further avoids arbitrary subdivisions of built-up land and population densities.

2. Methods

2.1. Overview

We conducted a systematic literature review to determine the urban vulnerability drivers to six natural hazards. Our findings are summarized in VulneraCity [43], an open-access database of unique urban vulnerability drivers for each hazard, providing descriptions, classifications, and sources. The flowchart in Fig. 1 contains the main steps of this research. We started by identifying and defining our hazards (Fig. 1A), after which we created a search query for each hazard to find relevant literature on vulnerability drivers (Appendix A). We then gathered the relevant papers from the initial set of papers that came out of each search query (Fig. 1B). Next, we classified the drivers according to topic and acquisition method (Fig. 1C) and stored all the information in a database (Fig. 1D). From there, we collected several examples of vulnerability dynamics (Fig. 1E). Our methodology follows the PRISMA 2020 statement for systematic literature reviews [44] wherever it is applicable.

It should be emphasized that we aim to provide a comprehensive overview of drivers, even though not all drivers might be relevant in all locations, globally. In line with that, the strength and even direction of influence of a driver might differ across the globe, as a result of local conditions. This – and the fact that we cannot directly compare the different reviewed articles – also means that we did not assign any weighting in our database.

2.2. Hazard selection and definitions

We included six urban-relevant and globally-omnipresent hazards in this study: pluvial flooding, coastal flooding, droughts, heatwaves, earthquakes, and waterborne diseases (see Table 1). We expect that the chosen hazards are distinctly different from each other, such that we have covered a range of different vulnerability drivers. Nonetheless, we have an overrepresentation of hydrometeorological hazards. This is first of all because we wanted to include a range of slow to fast onset hazards [45,46]. This is the reason why we included drought, as it is one of the most distinctive slow-onset hazards [47]. Second, we looked at two types of flooding because they are among the most frequently occurring, damaging, and fatal hazards in the world [48,49], and because this allowed us to explore whether or not they share the same vulnerability drivers. Lastly, we included heatwaves as they are a well-known hazard that is especially pertinent to cities due to the urban heat island effect [50,51].

It is important to clearly define these hazards as this determines what characteristics in the urban system are vulnerable to these hazards and thus which vulnerability drivers we include in the VulneraCity database. Our definitions were based on those compiled in the Hazard Information Profiles [45], developed by UNDRR and the International Science Council, and slightly altered to fit the urban context or to enable a wider view on vulnerability drivers for that hazard (i.e., including more vulnerability drivers than with the definitions in Murray et al. [45]; Table 1).

2.3. Systematic literature review

For each hazard, we posed the question "*What vulnerability drivers are known for *hazard*, based on empirical evidence?*". We focused our literature search on empirical evidence to narrow down the number of studies to review, but did not exclude other types of evidence (e.g., modeled or theoretical) in our analysis. Appendix A shows the queries that we used to obtain papers from the Web of Science literature database. The queries contain several synonyms for the hazard under consideration and for the terms "vulnerability", "urban", and "empirical" to cover for differences in definitions between fields or authors (see Section 1.2). For instance, we consider "susceptibility", "sensitivity", and "resilience" (and their potential plural and adjective forms) as alternate forms for "vulnerability". Also, in an attempt to reduce the number of irrelevant papers beforehand, we added several search terms that exclude papers with a sole focus on the rural context (see Supplementary Table A1).

Our queries resulted in an initial set of 3168 papers, of which 3104 English-language papers (search conducted in September and October 2022). The screening, a first selection based on titles and abstract, left 1418 papers, of which 1383 were accessible for a more in-depth review – in which we read the full articles (Fig. 1B). Inclusion criteria for the screening are listed in Table 3. To speed-up the screening process, we developed the open-access tool Pinder [52], which lets the reviewer efficiently - with just one click - include or exclude a sequence of studies based on their title and abstract. The tool automatically saves all accepted and rejected studies in one file that can be imported in a reference manager. During the in-depth review, we applied the same inclusion criteria as during the screening, but with some additional criteria that we could not check for in the screening process (e.g., if two papers present duplicate information; Table 2). To give insight in our thought process during the article selection, we provide several examples of excluded articles and our reasons for exclusion in Appendix A. The final number of papers that contain information on urban vulnerability drivers is 462 (Fig. 1B)). All included references can be found in the VulneraCity database [43].

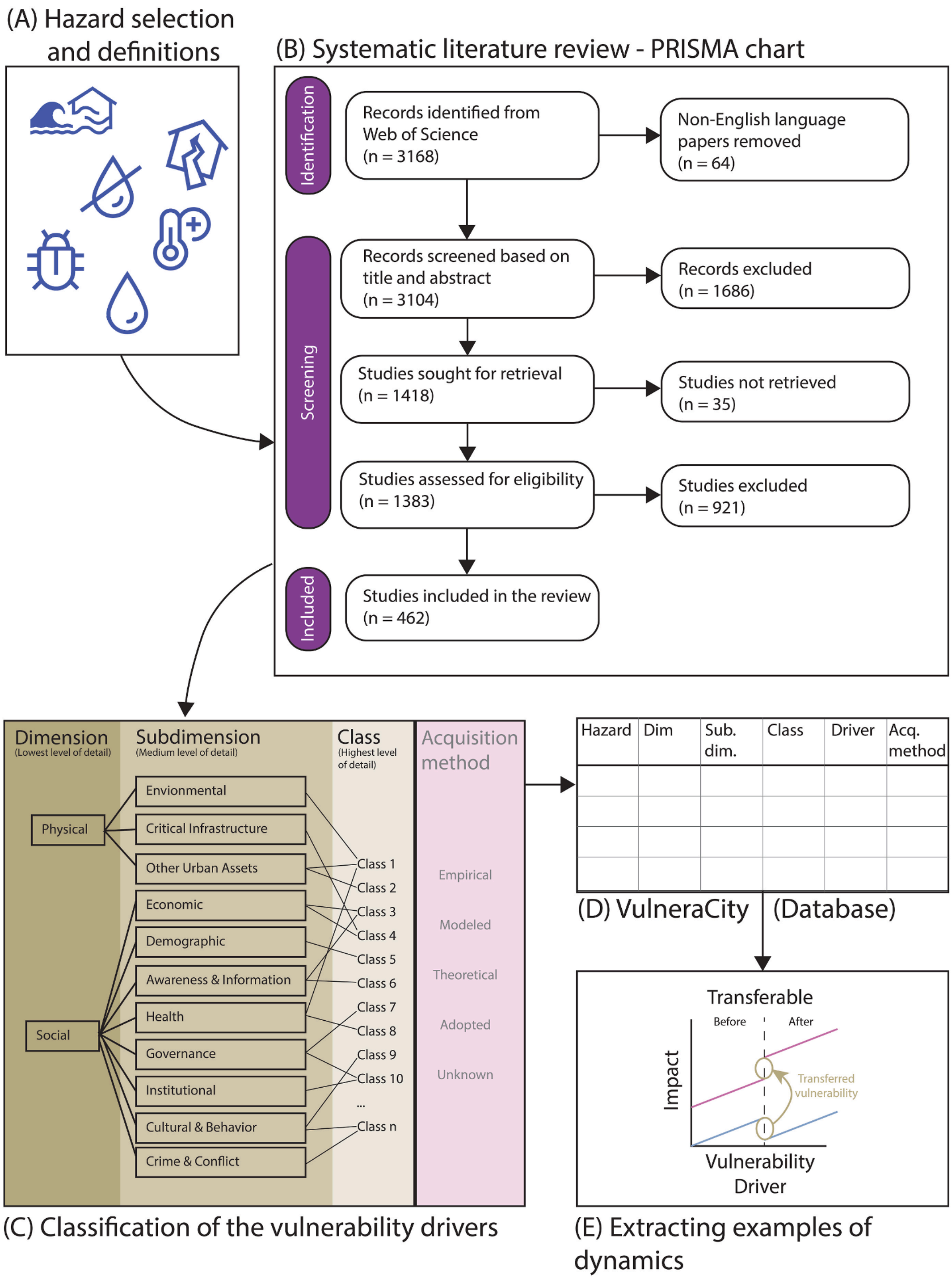

Fig. 1. Flowchart with the main steps of this research.

The screening process was carried out by the lead author and validated by two co-authors to check for selection biases. For this validation process, we created random samples of 60 studies per hazard. Each sample had exactly 30 included and 30 excluded studies by the lead author - which the two co-authors did not know about beforehand. On average, there was a 74 % agreement on the selected studies. We do not expect that these inconsistencies significantly affected the final database, since our goal is not to count the occurrence of vulnerability drivers, but rather to create a complete overview of drivers. In fact, the difference becomes much smaller if we also consider the in-depth analysis: only 5 out of 147 studies that were excluded by the two co-authors, but not by the lead au-

Table 1
The hazards considered in this study, their category, onset pace, and definition.

Hazard	Category	Onset pace	Definition
Pluvial flooding	Hydrometeorological	Fast	An excessive amount of precipitation in an urban area that exceeds a local hazardous threshold. Note that this hazard has several alternative names in different fields: urban flooding, drainage flooding, sewer flooding, or cloudbursts.
Coastal flooding	Hydrometeorological	Medium	Flooding in cities from the sea/ocean due to storm surges or combinations of high tides, waves, and strong winds. Excluded are: tsunamis, groundwater flooding due to rising sea levels, and fluvial flooding during high tide.
Drought	Hydrometeorological	Slow	The temporary lack and/or scarcity of water in an urban context relative to the normal climatic/hydrological situation. Water in the urban context includes for instance potable water, water for urban landscapes, and manufacturing/industrial water.
Heatwaves	Hydrometeorological	Medium	An unusual positive anomaly in the atmospheric condition around a city compared to the normal climatic situation. It manifests as thermal conditions above threshold x for period y.
Earthquakes	Geological/geophysical	Fast	Ground shaking in urban areas, caused by fault slips or other similar stresses in the Earth's interior.
Waterborne diseases	Biological	Medium	Diseases (e.g., viruses, pathogens, bacteria) that originate in and are transmitted by water and spread amongst urban residents.

Table 2
Vulnerability sub-dimensions and definitions.

Dimension	Sub-dimension	Sub-dimension definition
Physical	Critical Infrastructure	Characteristics of those physical assets in a city that are essential in maintaining business as usual. Drivers in this sub-dimension are for instance elevated roads, structural quality of bridges, and reliability of electricity networks.
	Environmental	Relates to the characteristics of (semi-)natural areas and phenomena in and around a city. Drivers in this sub-dimension are for instance presence of urban vegetation, and soil types.
	General Urban Assets	These are the characteristics of all the physical assets within a city that do not belong to the Environmental or Critical Infrastructure sub-dimensions. Drivers in this sub-dimension are for instance about building characteristics of - mostly residential - buildings (e.g., roof material, or the presence of a basement), presence of emergency shelters, and urban form (i.e., the large-scale morphological characteristics of the urban area).
Social	Awareness & Information	This relates to personal awareness about hazards, as well as to information provisions about these hazards. Drivers in this sub-dimension are for instance about gathering/conveying information, risk perception, and preparedness.
	Crime & Conflict	Illegal activities and small to large-scale conflicts within the urban area. Drivers in this sub-dimension are for instance about fear of crime, collaboration with gangs, and breaking regulations.
	Cultural & Behavior	Cultural beliefs and practices, as well as (culturally-influenced) behavior of citizens. Drivers in this sub-dimension are for instance about health-affecting behavior, social support, and adaptive behavior.
	Demographic	This refers to the demographic characteristics of the citizens in a city. Drivers in this sub-dimension are for instance about age, education, and minorities.
	Economic	Relate to the economy and economic system of a city. Drivers in this sub-dimension are for instance about poverty, occupation, and insurance.
	Governance	Organization - but not the execution - of urban development. Drivers in this sub-dimension are for instance planning, empowerment, and (stakeholder) collaboration.
	Health	This refers to health, patients, and medical support in cities. Drivers in this sub-dimension are for instance about pre-existing medical conditions, medical equipment, and water treatment.
	Institutional	The practical execution by institutions of what is determined by the urban authorities. Drivers in this sub-dimension are for instance about knowledge & expertise, resource allocation, and aid & intervention.

Table 3
Inclusion criteria applied to the selection of relevant articles.

Selection phase	Inclusion criteria
Selection based on general characteristics	Article is written in English.
Selection based on title & abstract and the in-depth review	• The article is about the hazard under consideration. We did not consider other hazards that are triggered by the hazard under consideration (e.g., articles about liquefaction from earthquakes are excluded). • The article considers vulnerability drivers conform the definition that we stated in the introduction. Note that the article does not necessarily need to adopt this definition nor does it specifically have to call a vulnerability driver as such. • The article has a clear urban context. An article that describes just one specific micro-element within a city in great detail (e.g., one single building that is hit by an earthquake) is excluded as it may not be representative for the city/urban context as a whole. • The article discusses cases from after the year 1900.
Selection based on in-depth review only	Articles need to provide unique information about vulnerability drivers. From articles that provide duplicate information, we select the one that explains the driver the most extensively or presents it in the clearest way. Two or more articles on the same driver that complement each other are all included.

thor (during screening) ended up in the final selection of studies. Furthermore, just 8 out of 66 studies that were accepted by the two co-authors but rejected by the lead author were found to be arguably relevant.

2.4. Classification of the vulnerability drivers - topic and acquisition method

During the in-depth analysis, we classified the vulnerability drivers based on topic and acquisition method (Fig. 1C), which made it possible to summarize the results and to compare urban vulnerability drivers between hazards. For the topic, we applied a three-layered hierarchical classification. We grouped each vulnerability driver in: (1) a vulnerability *dimension* (category with the least amount of detail); (2) a vulnerability *sub-dimension* (category with a medium amount of detail); and (3) a vulnerability *class* (category with the most amount of detail; Fig. 1C). Each driver belongs to one of 2 dimensions, one of 11 sub-dimensions, and one of 113 classes. For the dimensions and sub-dimensions, we adopted the common distinction of physical and social vulnerability dimensions [22,53], which we subsequently subdivided into 11 sub-dimensions (Table 2), based on those used in Hagenlocher et al. [54], Meza et al. [55], Depietri [56], Carrão et al. [57], Herslund et al. [58], and Birkmann et al. [59]. We differentiated between governance and institutional by defining governance vulnerability as the processes in management and law/decision making that alter the vulnerability of cities and their citizens, whereas institutional vulnerability refers to the execution of these laws and decisions by official institutions.

Note that the selection of (sub-)dimensions is semi-arbitrary as there is no consensus in what constitutes as the 'correct' or 'complete' set of vulnerability (sub-)dimensions. The references on which we base our selection approach it either in the same way – by referring to other studies that used (sub-)dimensions – or do not present a reason for their selection at all (except for Depietri [56]). This also means that our sub-dimension definitions can deviate from other studies. For instance, Papathoma-Köhle et al. [60] yields a broader definition of Institutional vulnerability than we do – encompassing a combination of what we call Institutional, Governance, and Cultural & Behavior vulnerability. Nevertheless, the sub-dimensions that we include here are commonly accepted in the literature as categories of vulnerability and distinctively different from one another, which is sufficient for our scope. Moreover, we have added definitions to our sub-dimensions to reduce ambiguity, which is an improvement from the studies referred to above. Whereas the vulnerability dimensions and sub-dimensions are pre-determined categories, the vulnerability classes are created ex-post by topically linking the found vulnerability drivers. Classes can be shared between sub-dimensions and hazards, which allows us to compare similarities and differences in the topics of vulnerability drivers between hazards.

We also classify the vulnerability drivers based on their acquisition method in the corresponding literature. We distinguish the following options.

- Empirical - vulnerability drivers are empirically obtained by field research. Note that we classify regression analyses with empirically-derived survey data as modeled and not as empirical, because they are often restricted to and led by a small amount of available and measurable data, whereas we want to look beyond this.
- Modeled - vulnerability drivers are implicitly derived from a modeling exercise.
- Theoretical - the authors argue why a certain urban characteristic alters the city's vulnerability.
- Adopted - the authors adopted vulnerability drivers from another study with or without a clear statement on the underlying causal pathways that lead to impact.
- Unknown - a statement about vulnerability is made without explaining the underlying causal pathway that leads to impact, nor does it refer to another source.

We searched for unique vulnerability drivers in each hazard, and we therefore removed duplicate information. However, a vulnerability driver can still be described by multiple sources in a complementary way. In those cases, we still assigned only one acquisition method, based on the hierarchical order of the list above. Hence, an empirically derived driver has priority over a modeled driver, which has priority over a theoretically derived driver, and so on. Note that we did not give a definitive direction for any driver-impact relationship, which means that we do not claim that any driver always increases or decreases a city's or citizen's vulnerability. We may give some examples as provided in the source article(s) of each driver (*comments* column in VulneraCity), but a different situation may apply for a different location.

2.5. Extracting examples of vulnerability dynamics

During the in-depth review, we encountered several dynamics of vulnerability in terms of directionality (i.e., does the driver always increase/decrease the vulnerability, or are there other variations?). These deviate from the standard one-directionality assumption that is often seen in vulnerability assessments. After completion of the first draft, we went through the entire database to identify six overarching types of directional vulnerability dynamics, based on the examples that we found in the literature. We also compared these types with the existing literature on vulnerability dynamics (Section 4). Note that we did not assign every driver a dynamic-type, because it was (1) not always applicable, and (2) not our goal to create a comprehensive overview of potential vulnerability dynamics, but rather to find examples that help us conceptualize the dynamics.

3. Results

3.1. Vulnerability drivers

3.1.1. General overview

Out of our final selection of 462 papers, we find 1460 urban vulnerability drivers, with 495 and 965 drivers in the physical and social vulnerability dimensions respectively. In total, 37.3 % of the drivers are empirically derived, 27.0 % are adopted, 22.9 % are theoretical, 7.9 % are modeled, and 5.0 % have an unknown source. The sub-dimension with the largest number of drivers is General Urban Assets (n = 268; 18.4 %), whereas hardly any drivers are found in Crime & Conflict (n = 5; 0.3 %). We find the highest percentage of empirically derived drivers in Cultural & Behavior (53.4 %), followed by Institutional (44.9 %), and Health (42.3 %). Conversely, the lowest percentage of empirically derived drivers are found in Critical Infrastructure (28.9 %), Awareness & Information (26.7 %), and Demographic (21.3 %). Empirical research is the main source for most sub-dimensions, but not for Critical Infrastructure (adopted; 30.4 %), Awareness & Information (theoretical; 41.8 %), Crime & Conflict (adopted; 60.0 %), and Demographic (adopted; 32.0 %).

Fig. 2 shows the relationship between the sub-dimensions and classes of the vulnerability drivers. Although the classes are not necessarily linked to either the physical nor social vulnerability dimension, we can see a clear division in physically and socially-oriented classes. However, there are cases in which a social sub-dimension has drivers in one of the physically-oriented classes and vice versa (Supplementary Figure B1). For instance, the class Transport & Traffic relates mainly to road conditions, redundancy, or connectivity of different urban areas, which all refer to the physical form of cities. However, there are some occasions in which the accessibility to transport is limited by the economic situation (e.g., [61,62]) - hence a social sub-dimension. Next to these relationships, Fig. 2 also shows the classes with the most sub-dimensions, which are most prominently *Building Characteristics* and *Gathering/Conveying Information*. These classes are also shown in Fig. 3, which shows the top 10 classes - in terms of commonality - and how these classes' vulnerability drivers are distributed over the different hazards. In order to compensate for the unequal numbers of drivers per hazard, we normalized the classes by dividing the number of drivers per class per hazard by the total number of drivers for that hazard. We see a clear distinction between classes that are mainly important for one or a few hazards (e.g., building characteristics, water supply, or health-affecting behavior) and classes that exhibit a more all–round importance (e.g., poverty or preparedness). Overall, only eight classes are linked to all of the hazards: gathering/conveying information, preparedness, poverty, water supply, compromised health, education, sex and age. In comparison, there are 31 classes that only link back to one hazard.

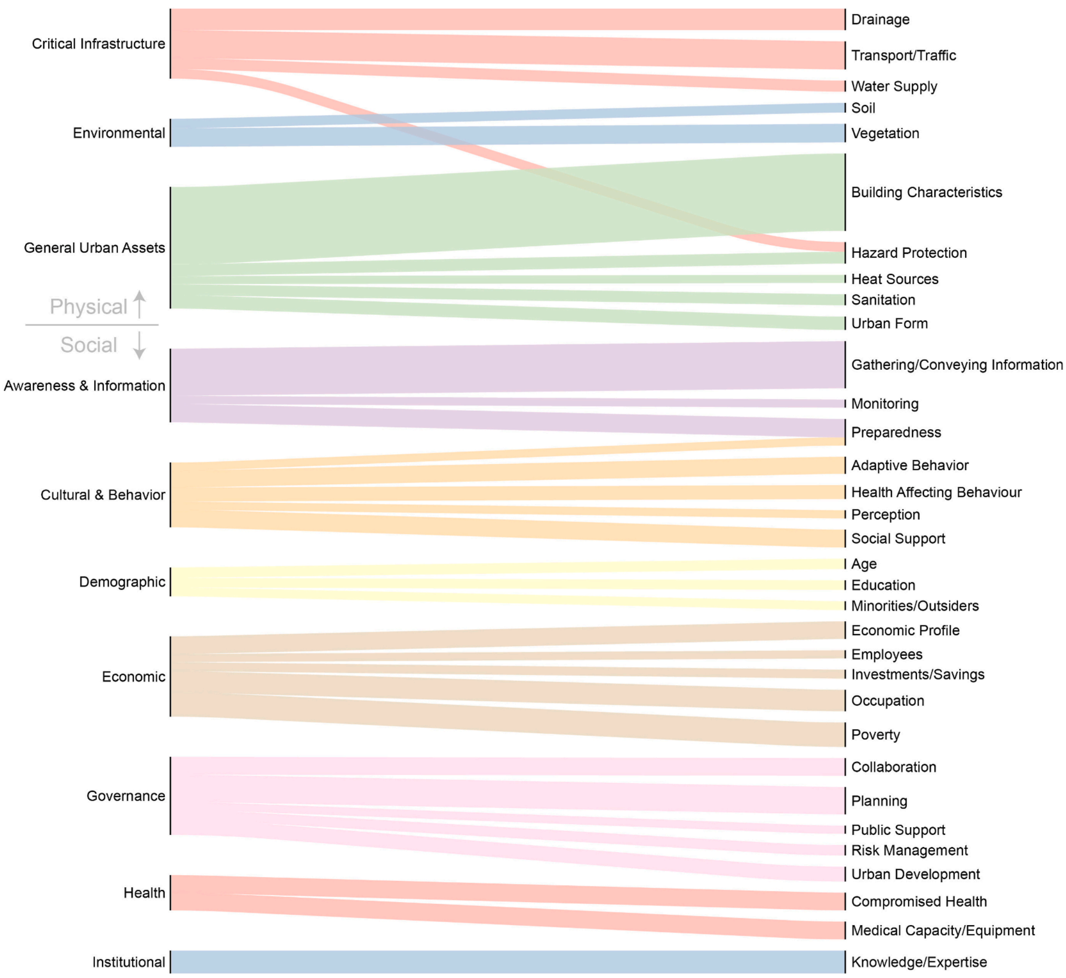

Fig. 2. Sankey Diagram showing the relationship of sub-dimensions and classes. Each line represents a number of drivers that flow from a sub-dimension into a class. For readability, we only display those sub-dimension – class combinations that contain at least 10 drivers.

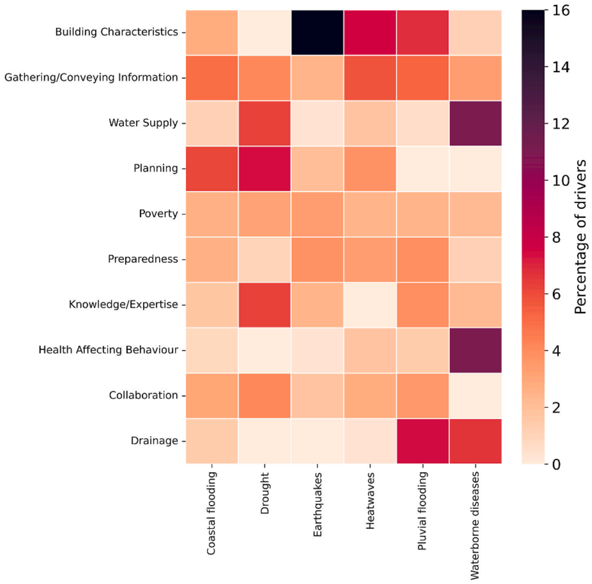

Fig. 3. Heatmap showing the percentage of vulnerability drivers in each class (rows) per hazard (columns), relative to the total number of vulnerability drivers for that hazard. This Figure only shows the 10 most common classes, which is determined by ranking the classes on the sum of the rows.

3.1.2. Overview per hazard

3.1.2.1. Coastal flooding. We found 356 vulnerability drivers for coastal flooding - the largest number for all our hazards - of which 33.4 % are empirically derived. Empirical research is also the most common acquisition method for this hazard. The majority of drivers are associated with the sub-dimensions Governance (54), Institutional (49), and General Urban Assets (43). Conversely, fewer drivers are linked to Demographic (18), Health (15), and Crime & Conflict (1). Supplementary Figure B2 presents which vulnerability classes are connected to each of the sub-dimensions, shedding light on the types of drivers that impact a city's vulnerability. For instance, we observe that Awareness & Information almost exclusively relates to the class of *gathering/conveying information*, which involves informing residents about coastal flood risks and appropriate measures to mitigate/adapt to them. Upon closer examination of the sub-dimensions with the highest number of drivers, it becomes apparent that *planning* emerges as a crucial class for Governance and Institutional. Firstly, retreat planning and urban planning in wetlands determine the retention and detention capacity of floodwater within and around the city [63,64]. Secondly, incorporating future developments into flood management plans and flexible scenarios allows cities to devise tailored strategies for coastal flood management, accounting for potential changes in climate, population, and urban development, thereby reducing vulnerability [65,66]. Thirdly, acknowledging vulnerable groups in coastal flood risk planning and integrating indigenous knowledge into flood response planning fosters a holistic and inclusive approach, leaving no residents behind and consequently addressing the vulnerability of all individuals [67,68]. For General Urban Assets, we see most of the drivers in the classes *hazard protection* and *building characteristics*. Drivers related to the first class show that urban vulnerability can be reduced through strategies such as barricading doors and deploying mobile floodwalls to safeguard individual or small clusters of assets [67,69,70], and by using barrier islands and revetments as preemptive water barriers [71,72]. The second class refers to the characteristics that determine a building's physical vulnerability, like its structural or foundational material [64], or the presence of basements [73] or openings in the building's ground floor [69].

3.1.2.2. Earthquakes. Here, we found 291 vulnerability drivers, of which 38.1 % are empirically derived. This makes the empirical method again the most common acquisition method for this hazard. The main sub-dimension for earthquakes is General Urban Assets (84 drivers) and this also contributes heavily to the number of empirically derived studies for this hazard (42/84 drivers). Other prominent sub-dimensions are Institutional (42 drivers) and Governance (39 drivers). We find the least drivers for earthquakes in Health (13), Environmental (8) and Crime & Conflict (1). A large part of General Urban Assets is related to the class *building characteristics* (49 drivers; Supplementary Figure B3), which contains primarily information on structural and non-structural components that make buildings prone to earthquakes. Examples are: chimney type, because mortar chimneys are easily dislodged during an earthquake and can cause serious injuries if they hit pedestrians [74]; or heavy overhanging floors that make a building unstable because it creates irregularities in the building's stiffness and mass distribution [75,76]. The interactions between neighboring buildings are also of interest. This has to do with aggregate (i.e., connected) buildings or with the pounding effect, which is the collision or hammering of adjacent buildings during an earthquake. Vulnerability is lower for (non-corner) buildings in an aggregate [77–80] - and for (non-)structurally-uniform adjacent buildings [78,81]. For the Institutional sub-dimension, we found that *knowledge/expertise* and *medical capacity/equipment* are important classes. In both classes, drivers link to post-earthquake rescue operations like the availability of rescue personnel [82] and of protective equipment for rescue workers [74]. Similar to coastal flooding, Governance is predominantly about planning. This time, it is mostly about developing an earthquake management plan [74,83,84] and potential obstructions to this process [85,86].

3.1.2.3. Pluvial flooding. Pluvial flooding has 335 drivers and the largest share in empirically derived ones (43.0 %). General Urban Assets is again the sub-dimension with the most drivers (61), followed by Critical Infrastructure (46), and Institutional (41). On the other end of the spectrum are Demographic and Environmental (18 each), Health (11), and Crime & Conflict (0). *Building characteristics* is an important class within General Urban Assets (Supplementary Figure B4). It contains drivers relating to building characteristics that make a building more vulnerable to pluvial flooding, but also several about adaptation measures that can be implemented to lower this vulnerability, such as raising the ground floor of buildings [87], or by using stepping stones at the front door [64]. The class *drainage* is important for Critical Infrastructure, because impact from pluvial flooding can be reduced with proper urban drainage. Several drivers in this class describe the availability or quality of the drainage system. One example of this is the need for some redundancy in the drainage system to cover for potential failure of parts of the system [88]. Furthermore, shared sewer systems may not be ideal during pluvial flooding, as its capacity will be reached faster than with separate systems [89]. Several studies also mention blockage or obstruction of drainage systems as an important driver of vulnerability. Dumping waste on the streets [87,90] or building directly on waterways/drainage channels [90] are examples of that. The main class in Institutional vulnerability is *knowledge/expertise*. Exchanging flood risk information [89] and emergency plans [91] between authorities and citizens, as well as high turnover rates at ministries [92] are some examples of drivers that relate to this class.

3.1.2.4. Heatwaves. There are 292 drivers for heatwaves, 38.7 % of which are empirically derived. This makes the empirical method again the most common one in our collection of vulnerability drivers for this hazard. General Urban Assets is the largest sub-dimension once more (64 drivers), but now followed by Economic (46 drivers) and Awareness & Information (38 drivers). Sub-dimensions with fewer drivers for heatwaves are Demographic (12 drivers), Institutional (10 drivers) and again Crime & Conflict (2 drivers). We see that the class *building characteristics*, and specifically ways to keep a building's indoor temperature low during heatwaves, makes up for most of the drivers in General Urban Assets (Supplementary Figure B5). Nonetheless, there are more classes that contribute to this sub-dimension. Firstly, heat sources, like vehicle heat emissions [93,94], or impervious surfaces [95] increase the urban temperature on top of atmospheric increases during a heatwave. Secondly, urban form determines how surfaces heat up and cool down, among others via urban canyons [96,97] or via differences in building heights and corresponding effects on wind speeds [94]. The economic sub-dimension is dominated by the class *occupation*, which relates to work location or intensity of citizens. For example, outdoor labor is often considered to be more dangerous than indoor labor because of the exposure to heat [98–100]. Awareness & Information links above all to (effectively) gathering and conveying information about the heatwave hazard and about measures to take to stay cool. Measures that we found in the literature are for instance heat helplines [101] or automated phone warnings [102]. Effective communication is bound to the literacy rate of the population [103] or identifying and communicating co-benefits of adaptation to broaden the consensus among the public about the necessity of adaptation [104]. We should mention that many of the reviewed studies discuss health-related vulnerabilities to heatwaves. However, Health does not show up as one of the biggest sub-dimensions, because we summarized most of the health-related issues into one driver in the database, which is "pre-existing medical conditions". Pre-existing medical conditions usually make a person more vulnerable to heatwaves [105]. Specific heat-vulnerable conditions are, among others, diabetes [106,107], cardiovascular impairment [103], metabolic diseases [108], hypertension [109], and cardiorespiratory diseases [100].

3.1.2.5. Drought. Drought has 96 drivers, of which most drivers (38.5 %) are empirically derived. The three sub-dimensions with the most drivers are: Governance (24), Economic (19), and Awareness & Information (12). Notably, General Urban Assets only has 3 drivers, which is just a bit more than Crime & Conflict (1) and Health (1). Governance is related primarily to the classes *water management policies* and *planning* (Supplementary Figure B6). More specifically, drivers in these classes mention the importance of water conservation [110] and augmentation [111] as well as the importance of the right (mix of) investment and planning strategies [112–115]. In economic terms, a city's economic profile determines for a large part its vulnerability to drought. A large dependency on agriculture or tourism makes a city vulnerable according to Zhang et al. [116] and diversification of income sources - either on a city level or on the household level - would be a good adaptation to reduce these water-dependencies [117,118]. Next to that, the city's share in and design of the water market determines for a large part how they can deal with drought [119]. For instance, Sapountzaki & Daskalakis [120] mention that water tanks are a very expensive source of water, and that subsidized water tariffs can also lead to water-wasting behavior by consumers. For Awareness and Information, we found that important drivers are about monitoring water use [113,115] and quality [121], as well as about gathering/conveying information by setting up media campaigns [113] and by organizing knowledge sharing sessions between scientists, policy makers, engineers, and the public [121].

3.1.2.6. Waterborne diseases. This hazard has the lowest number of drivers: 90, out of which only 22.2 % are empirically derived. It therefore is the only hazard for which we did not find mainly empirically derived drivers. Instead, there are many adopted (32.2 %) and theoretical (27.8 %) drivers. Most of the drivers reside in Cultural & Behavior (16), Critical Infrastructure (14), and Institutional (14). Conversely, there are only 5 drivers for Economic and Health, 2 drivers for Governance, and none for Crime & Conflict. From a behavioral perspective, we found several activities that negatively influence health. For example, bathing or recreational activities in contaminated water can lead to contracting a waterborne disease [122,123]. Also, street vendors may sell water that they store in unsanitary containers [124]. Like with pluvial flooding, Critical Infrastructure is mainly related to drainage (Supplementary Figure B7) and more specifically to how the drainage system (does not) contribute to the spread of contaminated water. For instance, the misconnection of sewer pipes on surface water drainage channels can cause spillovers of contaminated water to the surface [125]. The type of sewerage is important too. For instance, the water-pipe material determines its resistance to cleaning [126], and a water-based sewerage does not work properly during droughts, causing blockages in the system which then overflows. From the institutional perspective, it is important to monitor water and waste systems [127,128], food consumers [129], and people in disease-prone areas [130].

3.1.3. Comparison between hazards

Fig. 4 shows per hazard the distribution of the vulnerability drivers over the different sub-dimensions. Arguably, pluvial and coastal flooding have the most similar profiles in terms of drivers, as they are similarly distributed over the sub-dimensions. However, we observe some minor differences: General Urban Assets is slightly more prominent in pluvial flooding than coastal flooding, whereas Environmental and Governance see more prominence in coastal flooding. Some of these differences can potentially be attributed to hazard characteristics. For instance, the additional Environmental drivers in coastal flooding relate among others to beaches, dunes, and wetlands that connect a city to the sea, which are solely relevant to coastal flooding. We can also find differences within a sub-dimension when we look into the vulnerability classes. We see that *drainage* is an important class for pluvial flooding, whereas it is almost absent in coastal flooding. Drainage also has a different role between the two types of flooding: it is important to get rid of rain water (reducing vulnerability for pluvial flooding), but acts as an amplifier for coastal flooding (increasing vulnerability). Such differences seem to be connected to the nature of the hazard and not so much to the differences in research topics between these hazards. Conversely, more hazard-independent classes - like *minorities/outsiders*, or *collaboration* - show more subtle differences.

Earthquakes has a similar profile to the two flooding hazards, although General Urban Assets is even more prominent here, which comes at the cost of fewer drivers in Environmental and Awareness & Information. Indeed, there is a detailed accounting of building characteristics in the reviewed earthquake literature. This is again related to the nature of the hazard and the large impact that it can have on buildings. The few environmental drivers in earthquakes are related to soil or suitability for construction - which are both indirectly related to the vulnerability of buildings as well.

Heatwaves show a slightly different distribution over the sub-dimensions: there is a bit more focus on Awareness & Information and Economic, whereas Institutional and Governance are less prominent here. Moreover, Institutional and Governance have fewer drivers than health, which is the opposite of what we see for coastal flooding, pluvial flooding and earthquakes. The lack of drivers in health follows from the focus on pre-existing medical conditions in the reviewed studies. In other words, most studies refer to similar

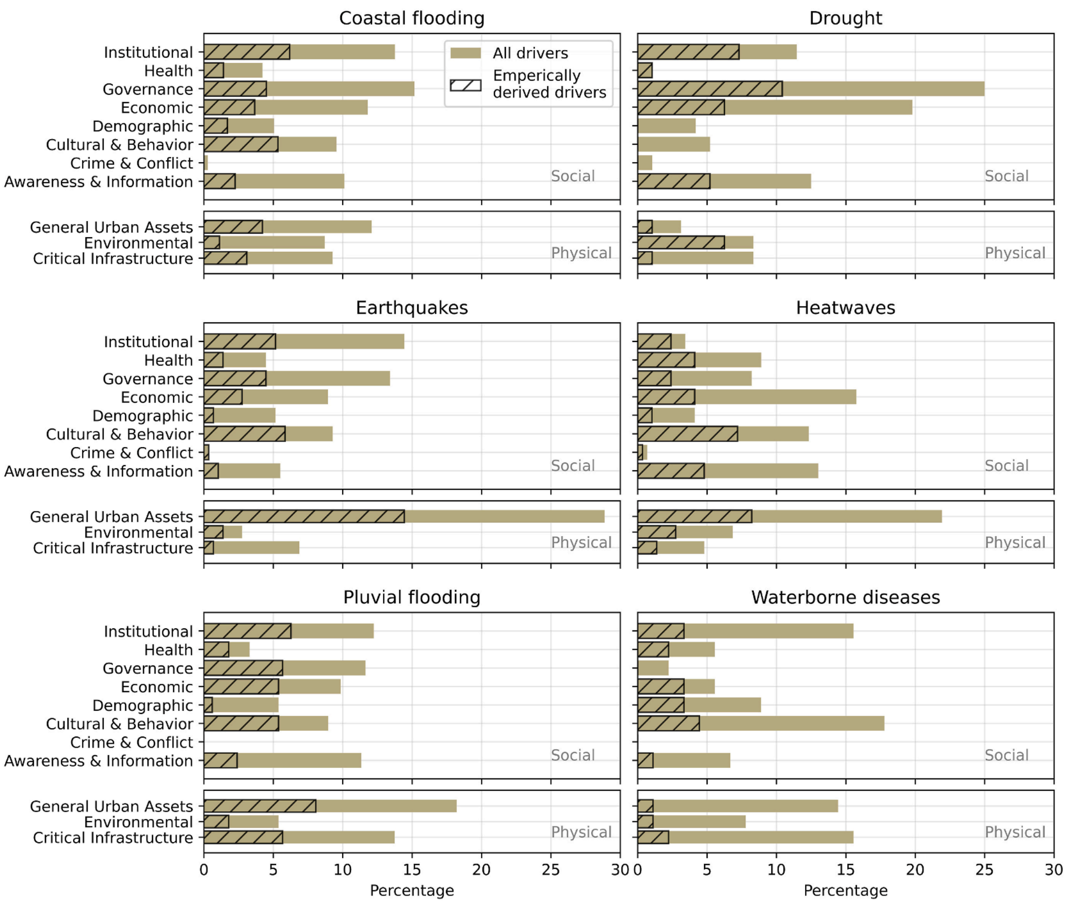

Fig. 4. Distribution of the vulnerability drivers over the different sub-dimension per hazard. hashed bars indicate the fraction that is empirically derived. Note that we split the social and physical sub-dimensions as indicated with text in the bottom right corner of each subplot.

drivers. Furthermore, many studies in Awareness & Information are also related to health impacts as they mention different modes of informing and warning citizens about the dangers of heat.

Drought shows a very different distribution of drivers compared to the aforementioned hazards. Most notable is the small share in General Urban Assets and the large shares in Economic and Governance. The lack of drivers in General Urban Assets can be explained by the fact that droughts do not generally impact buildings (unlike earthquakes or flooding), nor are building characteristics important for the level of exposure to droughts (unlike heatwaves, which can be escaped by residing in a cooled building). The vulnerability is instead more on a policy level, in which regulations, restrictions, savings and power dynamics determine how much water is available to a city in times of drought.

Waterborne diseases shows the largest differences on the social vulnerability side. Cultural & Behavior and Institutional have the highest share of drivers, and also Demographic is relatively important compared to its share of drivers in other hazards. For this hazard, behavior is especially important because it determines who is exposed to the hazard and who is not, whilst for most of the other hazards, this is often not a choice or a matter of behavior, but merely a given. For instance, earthquakes strike a certain area regardless of day-to-day choices that people make, but waterborne diseases are contracted during daily activities like bathing or drinking water.

3.2. Vulnerability dynamics

Among the drivers that we identified in the literature, we found several directional dynamics of vulnerability (Fig. 5). Below is a description of these dynamics, as well as some examples from the review to illustrate these dynamics in an urban setting. More examples can be found in VulneraCity, denoted in the "Dynamics" column [43].

3.2.1. One-directional vulnerability

A driver that always results in either an increase or decrease of a city/citizen's vulnerability to all hazards. **Example**: Disaster preparedness is generally considered as something that makes cities and citizens less vulnerable to all hazards, among others by: performing drills and thus becoming more skilled in dealing with disasters [131–134], storing emergency materials/supplies to increase survivability during disasters [135–137], and disaster training for medical personnel or city officials to improve reaction and recovery times [99,138].

3.2.2. Bi-directional vulnerability

A driver that can lead to both an increase and a decrease in vulnerability at the same time, or that simultaneously makes a city/citizen more and less vulnerable to a hazard. **Example**: A retired elderly person does not need to do heavy labor during a heatwave (less vulnerable than other citizens; [139]), but may have a weaker physique (more vulnerable than other citizens; [100,139,140]).

3.2.3. Asynergies

A driver that decreases vulnerability to one hazard but simultaneously increases the vulnerability to another hazard. **Example**: Urban drainage systems are important in times of pluvial flooding [87,88], but can also distribute the water more easily into the city during a coastal flood event [141]. Furthermore, if the drainage system gets rid of the water too fast, it impedes evaporative heat loss whilst this type of cooling can be beneficial in times of heatwaves [142].

3.2.4. Compounding vulnerability

Two vulnerability drivers that together have an amplifying effect on the total vulnerability, making the combined outcome worse than the sum of their individual parts. **Example**: Elderly migrants with neuro-cognitive conditions (e.g., dementia). Elderly people ex-

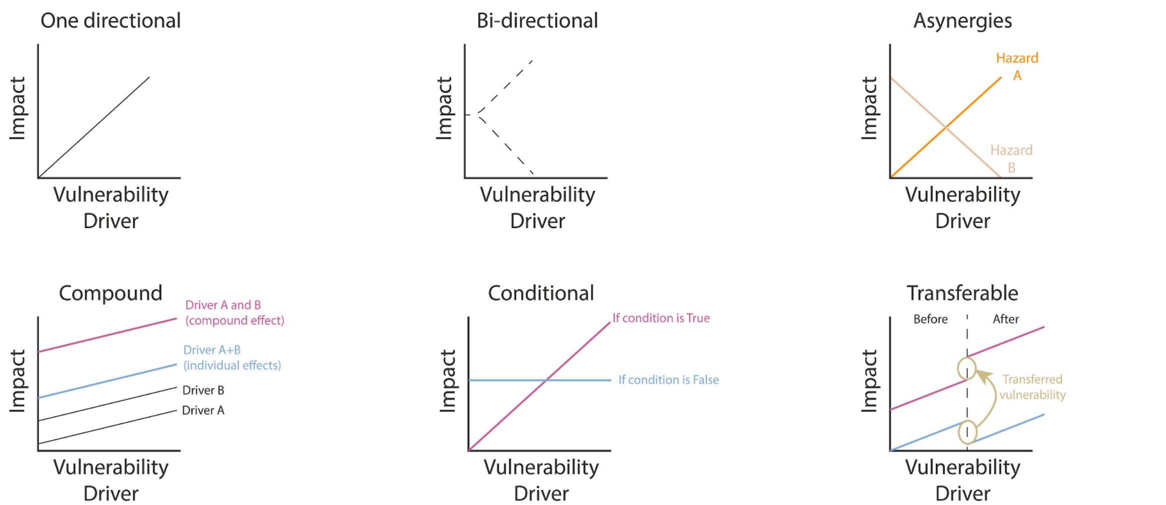

Fig. 5. Schematic drawings of the directional and driver-interaction dynamics of vulnerability.

perience an increased vulnerability to several hazards because age frequently comes with reduced physique [143], impeding mobility during a disaster [144]. This can be compounded by the fact that migrants may experience a language barrier in information dissemination [62,137], especially when they have a neuro-cognitive condition that may reduce their ability to understand a non-native language [62].

3.2.5. Conditional vulnerability

Drivers that change the vulnerability under certain conditions only. **Example**: In a patriarchal society, women in informal settlements are generally responsible for household tasks that bind them to home and which makes them more vulnerable to pluvial flooding than men [136,145,146]. But a woman in a more affluent community - in that same patriarchal society - may have resources to let servants do the heavy labor/repairments on her home after flooding, making her less vulnerable compared to men [146,147].

3.2.6. Transferable vulnerability

A driver that shifts vulnerability from one place/citizen to another, or which reduces the vulnerability of one place/citizen and increases the vulnerability of another. **Example**: Air conditioning lowers the temperature of the inside of a building, making its residents less vulnerable to heatwaves. However, it also increases the temperature outside of the building, worsening the urban heat island and therefore increasing the vulnerability of all that need to be outside (e.g., for work or transport; [93,94,148]). Air conditioning was also found to have detrimental effects on other - passive - cooling techniques [149].

4. Discussion

4.1. Empirical evidence of urban vulnerability drivers

We found that just over one-third of the vulnerability drivers in our literature review have been empirically derived. This fraction would have likely been even smaller if we had excluded the specific search terms to find empirical research from our queries. We have seen that empirical evidence is especially dire for the sub-dimensions: Critical Infrastructure, Awareness & Information, and Demographic. Reasons for this could be that (urban) empirical research can be labor intensive or expensive [8,150] - for instance in monitoring or testing the often sizable critical infrastructure - or that not all drivers are tangible and easily empirically measured [151] - like perception or gathering/conveying information in Awareness & Information. In such cases, modeling approaches could yield more value than the empirical method. Another limitation of the empirical approach is its localized nature and the corresponding difficulty to transfer results outside of the study area [23]. Note that our definition of empirical (see Section 2.4) is more restricted than most of the research in our review. In the case of Demographic, we classified many regression analyses as ‘modeled’, even if the study under consideration calls it an empirical research. Many of those regression analyses consider only a limited number of vulnerability drivers or indicators, usually determined by data availability, whereas our goal is to look beyond the data availability to the actual drivers of vulnerability.

Our results also suggest that the amount of empirical evidence differs per hazard. Most notably is waterborne diseases with only 22.2 % empirically derived drivers, even though this hazard has high shares in otherwise empirically-rich sub-dimensions like Institutional, Cultural & Behavior, and General Urban Assets. Looking at the nature of the drivers and the reviewed studies, we see no immediate reason for the lack of empirical drivers in this hazard. The presence of waterborne diseases is not unmeasurable (one could use microscopic analyses for example; [152]) and for several drivers, there is likely a set-up possible to investigate it empirically. Moreover, many studies that we used for the review on waterborne diseases are discussing a single disease outbreak or doing a local-scale case study, which are both suitable frames for empirical research. It could be that modeled and theorized methods are preferred by the field. The reason could also be methodological; other literature databases that are more tailored to health issues, like PubMed [153], may be more suitable to review for this hazard. Furthermore, it may help to search for research on specific waterborne diseases instead of generic disease terms like we did in this study.

Regardless of their acquisition method, our list of drivers can be used to inform both physical and social vulnerability theories. As we mentioned in the introduction, Kuhlicke et al. [29] found that social vulnerability research “seems to spin in circles”. Not many studies underpin their empirical (Kuhlicke et al.’s [29] definition is different from ours) study on social vulnerability with a clear theory. Using VulneraCity, researchers can now more easily identify possible drivers relevant for their study area and either deductively or inductively incorporate them into theory development. This may help in breaking the ‘circles’ in which we are ‘spinning’. The database can also be used to incorporate qualitative information into (quantitative) vulnerability assessments, something which is currently lacking in most vulnerability assessments in cities [7]. For instance, one could take the outcome of a physical vulnerability curve (e.g., one that shows how much damage a building undergoes from an earthquake) and then use the vulnerability drivers as a multiplier to correct for more qualitative vulnerability aspects (e.g., the capacity of the building's owners to recover from damage).

4.2. From multiple hazards’ vulnerability to multi-hazard vulnerability

With our current study, we have made a considerable step forward in terms of multi-risk research, by showing the most commonly shared vulnerability classes amongst the six hazards under consideration (Fig. 3). Only eight classes in VulneraCity are linked to all of the investigated hazards, whereas 31 classes link back to just one hazard. This suggests that there are either hazard-specific vulnerability drivers or that several relevant vulnerability drivers are not yet on the radar for some hazards. Future research should therefore take up these classes and test their applicability for other hazards. Furthermore, there are several other aspects we should consider when moving towards a comprehensive incorporation of vulnerability into multi-risk assessments.

First of all, the identified vulnerability drivers may be driven by a cascade of other vulnerability drivers [37] and in theory, we could dissect each vulnerability driver into its very fundamental building blocks. Bisaro & Hinkel [154] provide an example in which a lack of private investments in coastal adaptation (the driver) increases the vulnerability to coastal flooding. However, this lack of private investments is the result of an unfavorable investment climate because of high liability risks. The investment climate in turn is partly determined by uncertainties in a country's institutional environment. Hence, disentangling such cascades of drivers requires a lot of time and effort. Furthermore, Drakes & Tate [155] argue that the interaction of social vulnerability drivers may be divergent for different spatial scales and multi-hazard conceptualizations (e.g., compound or consecutive events). VulneraCity does not capture these driver entanglements and unavoidably overlooks some potentially important urban vulnerability drivers, like the one mentioned above, but it could provide starting points for methods that tackle these entanglements, like vulnerability chains [156] or vulnerability webs [157]. It is thus important to be aware of the multi-layered latent character of vulnerability and the many dependencies of each driver to other drivers [37,38]. Vulnerability is interwoven in each component of human society and isolating single-hazard vulnerability - even in a multi-risk setting - is therefore insufficient to understand the driving vulnerabilities of risks.

Second, multi-hazard vulnerability (i.e., vulnerability that comes forth out of the interaction between hazards) is hardly taken into account in multi-risk assessments [7,155,21,158]. Reasons for this are the epistemic and disciplinary differences between hazard-research fields [158] and - related to that - the lack of interdisciplinary knowledge and skills [21], high data requirements [159], differences in the development of knowledge on vulnerability for different disciplines/hazards [160], and a lack of validation of vulnerability drivers [16,54].

Third, the effect of a vulnerability driver can differ per hazard, like we saw with the effect of urban drainage systems for pluvial versus coastal flooding and heatwaves (Section 3.1.3). Another example between flooding and drought is the proximity to water bodies: living close to water decreases your vulnerability to heatwaves because of the water's evaporative cooling effect, but increases the chances that you are flooded [161]. Favorable building materials also differ per hazard: reinforced concrete is a strong material against earthquakes [162] and flooding [64], but a concrete roof also heats up buildings more rapidly, making it less suitable during heatwaves [163,164]. De Ruiter et al. [165] also show several conflicting effects of certain building practices between earthquakes and flooding. These examples are all related to physical vulnerability drivers. Indeed, most of these asynergies may take place in the physical dimension, and Julià & Ferreira [21] even go as far as claiming that social vulnerability is the same for all hazards. However, other studies have shown that the focus on one hazard (for example financially, politically, or in terms of awareness) takes away from the focus on another hazard [166,167]. Furthermore, some social vulnerability drivers may behave differently for climate-related hazards compared to non-climate related hazards. For instance, one of our drivers states that indigenous knowledge is beneficial only in stable or slowly changing systems, with time to build up knowledge about it. Climate-change induced fast-changing systems endanger the use of such knowledge [136].

4.3. Vulnerability dynamics

4.3.1. Beyond directional dynamics

We identified six types of directional vulnerability dynamics, which illustrated that the one-directionality assumption that is often seen in vulnerability assessments is regularly violated. Note that these six may not be a comprehensive list and other types may exist. Several of the directional dynamics have been found earlier. For instance, transferable vulnerability is discussed in Schipper [32], and asynergies is a term coined in de Ruiter et al. [165]. Still, this is the first time – to our knowledge – that directional dynamics are structurally defined. The borders between some of these dynamics are fuzzy and multiple directional dynamics can be at play simultaneously in any given situation, which illustrates once more the complexity of vulnerability.

We want to emphasize that vulnerability dynamics can be viewed through different lenses, which provide different ways to capture the complexities of vulnerability. Next to the directionality dynamics, the current literature also provides examples of spatial, temporal and management dynamics. Although this topic requires extensive further research, we can already shed some light on the differences and overlapping elements between these lenses.

4.4. Spatial dynamics

Space and location influence vulnerability in a variety of ways. Yet many vulnerability dynamics are related to space, but do not seem to be fundamentally caused by space. An example: the importance of vulnerability drivers changes from place to place as they are determined by the local physical, political, cultural, and sociological context. In this light, however, these apparent spatial dynamics are also closely related to conditional vulnerability (Section 3.2). In some instances, space may have a more direct influence: heat is experienced differently across space due to differences in climate and prevailing weather patterns. Someone may therefore become vulnerable to heatwaves in places where they are not acclimated to the type of heat [62]. Furthermore, different spatial scales call for different research methods of vulnerability, and in return also influence the outcome of such assessments [168].

4.5. Temporal dynamics

Temporal dynamics refer to the change of vulnerability drivers over time. De Ruiter & van Loon [16] identify three types of such dynamics: (1) changing underlying vulnerability conditions that are occurring at the moment that a disaster strikes; (2) changing dynamics during a long-lasting disaster like a drought – for instance because of maladaptation (see also Section 4.3.3); and (3) changing vulnerability in between consecutive events or owing to compound events. Assessing temporal dynamics requires long-term monitoring efforts to obtain the data, which makes it a time- and labor-intensive effort. In the past, this has been overcome by implicitly assessing vulnerability, using hazard-impact relationship data like the mortality/morbidity-heat relationship [169], but this does not account for any of the underlying drivers. In order to address vulnerability in (urban) planning, this information on the underlying drivers is essential.

4.6. Management dynamics

Management dynamics describe the vulnerability-adaptation relationship. It mostly manifests as maladaptation: usually adaptation measures that unintentionally reproduce and redistribute old vulnerability, and introduce new vulnerability [32,170]. Schipper [32] recognizes three subtypes of management or adaptation dynamics: (1) rebounding vulnerability - an adaptation measure that achieves the opposite effect of what it intended to (see e.g., Ref. [171]); (2) shifting vulnerability - similar to what we called transferable vulnerability; and (3) negative externalities - a measure that causes unwanted issues outside of the hazard it tried to address. Eriksen et al. [170] argue that maladaptation is mainly caused by a limited understanding of vulnerability, inequitable stakeholder participation in adaptation development, retrofitting adaptation into existing development agendas, and a lacking critical view on what is defined as "adaptation success". Underpinning all of this are power relations and – more importantly – imbalances.

All types of dynamics (directional, time, management) can occur simultaneously. They are sometimes even very similar: shifting vulnerability is the same thing as what we dubbed transferable vulnerability. It describes both how a certain adjustment causes unwanted consequences (management dynamics) as well as how the impact changes for both the adjuster as well as people around them (directional dynamics).

4.7. Use of the database: interpretation, limitation, and bias

Our database provides an extensive overview of vulnerability drivers for the six considered hazards, which can be used by researchers and practitioners for their vulnerability assessments. However, our methodological choices, along with the conceptual diversity between hazards and conceptual evolution of vulnerability [33,34], also come several limitations, which calls for a conscious interpretation of the results. Whilst our systematic review aimed at identifying a wide range of vulnerability drivers, it is important to emphasize that additional drivers and dynamics can potentially be found when utilizing other search queries, investigating other hazards, looking into other literature databases, and reviewing grey literature. For instance, caste is an important driver of vulnerability in countries like India or Nepal as mentioned by Arora [172], but we did not find any information on it in our review. In this particular case it is because Arora [172] is not written in an urban context and it therefore did not match our aim and search query. Regardless of such gaps, this database is, to our knowledge, the most comprehensive overview of urban vulnerability drivers to date and the structure of the database also allows for future additions of new vulnerability drivers. Researchers are invited to add to the database and to use it as a baseline to find more relevant drivers for their own studies.

The interpretation of the results in Figs. 3 and 4 also need to be discussed. In Fig. 3, we assigned prominence to our classes based on the number of drivers in each class, but this does not account for classes with only a few, yet important drivers like sex (all hazards; Section 3.2) or pre-existing medical conditions (heatwaves; Section 3.1.2). The overall importance of a class or driver is context dependent and therefore difficult to establish. By counting the drivers per class we get at least a general sense of the importance of a certain topic for the hazard. For Fig. 4, a different selection of sub-dimensions could alter the vulnerability profiles that we presented there. It is thus important to interpret them in the light of the definitions that we provided in Table 2. We should also note that some drivers are eligible for multiple sub-dimensions; "Decision makers that are aware of the public's risk awareness" could for instance be categorized as Awareness & Information (as it is now) or Institutional.

Although systematic literature reviews are meant as a method to summarize the existing literature in a way with the least amount of bias [173], some bias generally remains in building search queries and conducting the article selection [174]. Our selection of articles may be biased by personal traits and professional background, which we aimed to capture during the screening process (see Section 2.3). Another important source of potential bias comes from geographical causes, like (1) language barriers; (2) difficult-to-access areas for which there is limited research; and (3) popular research locations or cases – we saw for instance several studies on the 2015–2017 Cape Town drought or the 2011 Christchurch earthquake. It is therefore possible that additional drivers could arise from studying currently understudied regions or hazard events.

Screening of a random sample of 100 articles from our database reveals that there is a bias towards Global-North lead authors (73 compared to 27 Global-South lead authors). However, the number of unique locations of the lead authors is roughly equal between the Global South (13 countries) and North (15 countries) and the number of unique locations of the case studies is even skewed towards Global South areas (17, as compared to 10 in Global North). As such, the perspectives on vulnerability in our database is relatively balanced. In terms of continents, we see a bias towards the North American (30 out of 100) and European (28 out of 100) continents when it comes to lead author work stations, and towards North America (29 out of 100) and Asia (29 out of 100) for case study locations but also here we do have information from all continents. Considering our research aim to develop a general understanding of urban vulnerability, biases in terms of geographical representation are only relevant on a larger (i.e., continental to supranational) scales to gauge if we sufficiently include ideas from different parts of the world. From that perspective, we would argue that these biases do not substantially influence our results. See Appendices A and C for more details.

4.8. Outlook

Although researchers and practitioners could use the database independently of another, we suggest that the most use can be achieved when they work together. This advice is echoed by Scolobig et al. [175] who argue that collaboration between experts/scientists and local stakeholders is essential in multi-risk management - but only if we can prevent the science from becoming politically influenced. Another important addition is that vulnerability assessments are not only about marginalized communities within the city and through adaptation institutions, but also conducted together with the marginalized citizens and within the institutions [170].

Looking forward, we see merit in using VulneraCity in both theory/evidence-based local-scale assessments as well as more exploratory large-scale assessments of vulnerability. We suggest a workflow in which researchers and practitioners use the database to inform their (local) vulnerability assessments upfront. Although we do not give definite vulnerability-impact relationships - we do give suggestions or examples in most cases - they can use the database to find out what drivers have (empirically) proven to be important in other studies. They could for instance filter on the topics (e.g., classes or sub-dimensions) that are important for their field of study and then make a short list of likely important vulnerability drivers. Ideally, this shortlist is then discussed with local urban experts on these topics to validate these drivers' importance and to find appropriate indicators for them. The researchers and practitioners should also discuss their thoughts throughout the process with the marginalized citizens for which they develop their policy, as well as with the institutions that need to implement these policies.

5. Conclusions

We conducted a systematic literature review on urban vulnerability drivers and dynamics for six different hazards. We developed VulneraCity, the most comprehensive open-source database of urban vulnerability drivers to date, which can be used by researchers and practitioners alike - and preferably in collaboration with each other - to better inform their urban (multi-hazard) vulnerability assessments. With our main results, we first addressed the empirical evidence gap by showing that only around one-third of all the vulnerability drivers in our database have been empirically investigated. We did see substantial differences between vulnerability sub-dimensions as we found, for instance, that Cultural & Behavior consists of more than 50 % empirically-derived drivers, whereas Demographic only has around 20 % empirically-derived drivers. Furthermore, we see that the three most common classes of vulnerability among our hazards are *building characteristics* and *gathering/conveying information*. We also addressed the uni-directionality assumption within vulnerability research by describing six different types of directionality dynamics: uni-directional, bi-directional, asynergies, compounding, conditional, and transferable. This pallet of dynamics exemplifies that the uni-directionality assumption that is often used in vulnerability assessments may not be valid in many cases.

Although good progress is being made in the field of multi-risk assessments, there are still many challenges ahead in incorporating vulnerability beyond the data-driven indicator approach that is commonly used now. These manifest in different aspects related to (dynamics of) urban vulnerability to natural hazards: from the very fundamental theories underpinning the perceived vulnerability drivers, to ways in which to include them dynamically in vulnerability assessments, to management dynamics. Acknowledging these complexities, collaboration between scientists, urban practitioners and the subjects of vulnerability assessments should essentially work together on a local scale to understand vulnerability holistically and to prevent maladaptation. VulneraCity can be a guiding factor or as a lead up for discussion in these collaborations, as it provides an extensive set of potential vulnerability drivers and dynamics that may apply to the local context.

Funding

This work was supported by the EU Horizon-2020 project RECEIPT (Grant Agreement No. 820712); CoCliCo (Grant agreement No. 101003598); and MYRIAD-EU (Grant Agreement No. 101003276). Additionally MCdR received funding from the Netherlands Organisation for Scientific Research (NWO) (VENI; grant no. VI.Veni.222.169). The work reflects only the author's view and the agencies are not responsible for any use that may be made of the information it contains.

Data & software availability

VulneraCity v1.0.1, the dataset related to this article can be found at https://doi.org/10.5281/zenodo.11074142, hosted at Zenodo [43].

Pinder, the software related to this article can be found at https://doi.org/10.5281/zenodo.8181340, hosted at Zenodo [52].

CRediT authorship contribution statement

Tristian R. Stolte: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elco E. Koks:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Hans de Moel:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Conceptualization. **Lena Reimann:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Jasper van Vliet:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Marleen C. de Ruiter:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Funding acquisition, Conceptualization. **Philip J. Ward:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We have mentioned, described, and cited the used data and software in the article. DOIs are provided to ensure findability and quick access.

Acknowledgements

The authors would like to thank the MYRIAD-EU team for their constructive feedback and critical questions on this article. Furthermore, the authors want to thank the reviewers for their elaborate and constructive feedback from a wide range of perspectives. Lastly, the authors would also like to thank Sophie Buijs for proofreading.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2024.104535.

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