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Understanding human vulnerability to climate change: A global perspective on index validation for adaptation planning

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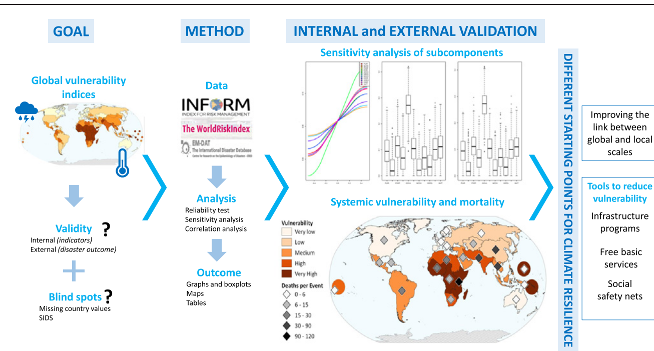
HIGHLIGHTS

- Internal and external validation is crucial for global vulnerability assessments.
- Vulnerability of WRI and INFORM index partially explains mortality and economic losses.
- Hazard mortality is 15 times higher in most compared to least vulnerable countries.
- Vulnerability shows different starting points towards climate resilient development.

GRAPHICAL ABSTRACT



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ABSTRACT

Climate change is a severe global threat. Research on climate change and vulnerability to natural hazards has made significant progress over the last decades. Most of the research has been devoted to improving the quality of climate information and hazard data, including exposure to specific phenomena, such as flooding or sea-level rise. Less attention has been given to the assessment of vulnerability and embedded social, economic and historical conditions that foster vulnerability of societies. A number of global vulnerability assessments based on

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indicators have been developed over the past years. Yet an essential question remains how to validate those assessments at the global scale. This paper examines different options to validate global vulnerability assessments in terms of their internal and external validity, focusing on two global vulnerability indicator systems used in the WorldRiskIndex and the INFORM index. The paper reviews these global index systems as best practices and at the same time presents new analysis and global results that show linkages between the level of vulnerability and disaster outcomes. Both the review and new analysis support each other and help to communicate the validity and the uncertainty of vulnerability assessments. Next to statistical validation methods, we discuss the importance of the appropriate link between indicators, data and the indicandum. We found that mortality per hazard event from floods, drought and storms is 15 times higher for countries ranked as highly vulnerable compared to those classified as low vulnerable. These findings highlight the different starting points of countries in their move towards climate resilient development. Priority should be given not just to those regions that are likely to face more severe climate hazards in the future but also to those confronted with high vulnerability already.

1. Introduction

The need and relevance to assess vulnerability to climate change and natural hazards is based on the assumption that climate risks and actual losses caused by hazard events such as storms, floods or droughts are not solely a result of the climate hazard, but also determined by societal and economic preconditions that shape the way in which people are prepared for or respond to such events (Birkmann, 2013; Cardona et al., 2012; Cutter et al., 2003; IPCC, 2012; UNDRR, 2019). The discourse about vulnerability within climate change and climate risk research encompasses various interpretations of the concept of vulnerability, such as vulnerability as a starting point versus vulnerability as an outcome (Füssel, 2007). Since the IPCC SREX report (IPCC, 2012) and within the newer conceptualization of climate risks in the fifth assessment report (IPCC, 2014b), there is an emerging consensus that vulnerability of societies or ecosystems is better framed as a starting point, rather than an outcome. Approaches that conceptualize vulnerability as an outcome often include hazard information and therewith do not sufficiently differentiate between vulnerability and risk. In this paper we use the term vulnerability to refer to the broader concept and systemic societal vulnerability to emphasise the vulnerability of societies and systemic barriers within societies in particular, as opposed to, for example, vulnerability of ecosystems.

Systemic societal vulnerability refers to characteristics of society or sub-systems of it (e.g. demographic groups or built infrastructures) and is largely independent of the specific climatic hazard. The term systemic refers to inherent barriers that people experience in terms of their ability to cope and adapt to climatic change and natural hazards. While there is still tension on how to precisely define risk, hazard or vulnerability (Garschagen et al., 2016; Hagenlocher et al., 2019), the scientific discourse (IPCC, 2014b; UNDRR, 2017) has reached a consensus that risks in the context of climate change result from the dynamic interaction of hazard, exposure and vulnerability of human and ecological systems. In contrast to climate and hazard information that often characterizes the physical phenomena—such as the mean temperature change, frequency or intensity of droughts, floods or storms—vulnerability is defined as the propensity and the predisposition of a system to be adversely affected by external shocks and thus is linked to the characteristics of a social-ecological system or community that determine their level of preparedness to anticipate or respond to risks (IPCC, 2014b; Sharma and Ravindranath, 2019). Systemic societal vulnerability acknowledges the significance of the vulnerability of individual elements – people, buildings, livelihoods – but aggregates, aiming to provide a comprehensive view of vulnerability of societies. Challenges of aggregation and data availability always exist in the assessment of systemic societal vulnerability at global scale and therefore the validation of such assessments (given their different methodologies) is crucial and lies at the heart of this paper.

Quantitative assessments of risk and vulnerability are often based on indicators that capture vulnerability as a hazard dependent or as a hazard independent phenomenon (EC-DRMKC, 2020; Peduzzi, 2013; Welle and Birkmann, 2015). While comparison of global scale vulnerability and risk assessments with national resolution underscores that different assessments of vulnerability show a relatively high agreement regarding global hotspots of vulnerability (see Birkmann et al., 2021; Hagenlocher et al., 2019; de Sherbinin et al., 2019; Feldmeyer et al., 2021; Garschagen et al., 2021), less attention has been given to the question of how to validate such assessments. This question is complex since vulnerability and systemic societal vulnerability in particular is not just an outcome of a specific event or a simple phenomenon, but rather a predisposition to be adversely affected that is often hidden until a concrete crises or hazard events reveals it.

Various researchers underscore significant knowledge gaps and uncertainty regarding the quantitative relationship between societal and/or social vulnerability measures and disaster outcomes (Bakkensen et al., 2017; Burton, 2010; Rufat et al., 2019; Schmidtlein et al., 2011). They conclude that because there is an increasing use of vulnerability metrics in planning and decision making, it is critical to better characterize and understand these relations between vulnerability or systemic societal vulnerability and disaster outcomes and in a broader sense to explore the validity of vulnerability assessments and models (Rufat et al., 2019). These studies often validate vulnerability indices at the subnational and local level with a focus on a specific hazard (Bakkensen et al., 2017; Rufat et al., 2019). While they stress the need to validate vulnerability assessments against their prognostic function to project areas where the highest fatalities and losses will occur or have occurred in the past due to natural or climate-induced hazards (Rufat et al., 2019), other authors argue that the validation needs careful assessment as social contexts and the perception of risk are specific (Fekete, 2009; Simpson et al., 2021). Other papers examine the validity of vulnerability assessments in terms of specific disaster outcomes observed in specific regions or with regard to a specific hazard event (Bakkensen et al., 2017; Rufat et al., 2019; Schmidtlein et al., 2011). While these studies are important, it is generally questionable whether or not a single hazard event and its outcomes can really be used to validate such assessments.

In this paper, we differentiate between internal validation methods that consist of reliability and sensitivity questions and external validation that explores whether and how vulnerability metrics can explain outcomes in the context of disasters or extreme events. Some vulnerability assessment approaches use their own reliability measures, such as the INFORM Risk Index (Marin-Ferrer et al., 2017, p. 16) that classifies reliability in terms of the availability and quality of data available for a specific country. We rather base our assessment on the relevance of indicators for explaining vulnerability. Such investigation has been rarely done or discussed in the literature (using most recent data) and therefore these results can increase the reliability and usability of vulnerability metrics by the broader research community. In addition, we explore the linkages between data, indicators and the underlying indicandum that need to be considered when assessing the appropriateness of indicators to measure very complex phenomena (e.g. inequality or response capacities) and dynamics (e.g. forced migration). Also, blind spots and limitations of global or national indicator based vulnerability assessments are examined and discussed.

Overall, the paper presents novel findings regarding internal and external validation options of indicator based vulnerability assessments focusing on the vulnerability components of the WorldRiskIndex (WRI) and the INFORM[1] index using national and regional boundaries. The WRI and the INFORM index are two approaches that cover issues of vulnerability more comprehensively compared to other approaches. We show that next to data quality issues and statistical validation of such indicator systems, the link between an indicator and the underlying indicandum is key, including the vision and goal. In this regard, the paper focuses on the following questions:

1. What has to be considered when assessing the validity of global comparative vulnerability indicator systems?
2. How statistically reliable are existing indicators and index approaches in capturing different aspects of vulnerability (internal validation)?
3. What is the quantitative relationship between these vulnerability assessments, their results and actual loss data from past disasters due to climate influenced hazards (external validation)?
4. What are blind spots and missing data within such global assessments?
5. To what extent and how can global vulnerability approaches be used to inform adaptation planning?
6. What are priority issues for further research and development to enhance such assessments and their linkages to sub-national or local context specific assessments?

2. Two approaches: the WorldRiskIndex and the INFORM Risk Index

The purpose of risk and vulnerability indicators and index systems is to capture the multidimensional phenomena and better understand the different components, spatial structures and levels of the risk and vulnerability, of countries and regions exposed to various climatic and natural hazards. These approaches aim to support decision making in terms of disaster prevention, preparedness and response (IPCC, 2019; UNDRR, 2019). The components and indicators of such index systems are based on specific assumptions about the relevance of each indicator for describing vulnerability and systemic societal vulnerability in particular. These assumptions need to be critically revisited.

The WorldRiskIndex (WRI) and the INFORM approaches are two prominent indices offering global assessments with national scale resolution, used in the context of climate change adaptation and disaster risk reduction to assess risks and vulnerabilities (Birkmann and Welle, 2016; EC-DRMKC, 2020; Welle and Birkmann, 2015). The paper examines the WRI and INFORM index since both indicator systems have global coverage and a comprehensive approach for assessing vulnerability quantitatively, including, for example, aspects of poverty, inequality and governance. Moreover, both indicator systems have been published over several years.

The key aim of WRI is to analyse and visualize the level of vulnerability and risk of a country to experience adverse consequences due to natural hazards and climate related events. It allows the comparison of 171 countries (Welle and Birkmann, 2016, 2015). The INFORM index focuses on risks and humanitarian crises by including present and projected conflict aspects as well as hazard and exposure aspects. A core component of the index is also the assessment of vulnerability. The INFORM index captures 191 countries (EC-DRMKC, 2020). Table 1 provides an overview of both indicator systems.

2.1. Selection of components, subcomponents and indicators

The components used in the WRI differentiate between the natural hazard sphere and the vulnerability sphere. The WRI is composed of exposure (natural hazard sphere), susceptibility, lack of coping capacity and lack of adaptive capacity (vulnerability sphere). These components are further sub-categorized, for example focusing on the availability of basic infrastructure, medical services, etc. The development and systematization of the different components and sub-categories were evaluated by scientists and practitioners during an international workshop as well as supported by international literature (see Buendnis Entwicklung Hilft, 2011; Birkmann et al., 2011; Welle and Birkmann, 2016, 2015). In 2019 some subcomponents of the index were modified, which on the one hand shows the ability to include new knowledge, on the other hand, these changes make a comparison of changes of vulnerability over time difficult.

The INFORM index consists of three components of risk, namely hazard and exposure, vulnerability and lack of coping capacity. Each of these components has additional sub-categories. Hazard dependent factors are captured in the exposure and hazard component while hazard independent factors are considered in the vulnerability and the lack of coping capacity dimension (see in detail EC-DRMKC, 2020). The development of these risk components is based on scientific literature and also the involvement of experts from over ten UN organizations (e.g. OCHA, UNDP, WFP or FAO), multiple other international organizations (such as IFRC or GFDRR) as well as scientists from universities and other research institutes. The Joint Research Centre (JRC) of

Table 1
Comparison of the WorldRiskIndex and the INFORM Risk Index.

Criteria	WorldRiskIndex	INFORM Risk Index
Main purpose/goal	Analysis of the risk level of countries to natural and climatic hazards	Assessment of risk of countries to inform disaster and humanitarian crisis responses
First published	2011	2012
Revision/update	Once per year	Once per year
Conceptualization	Risk is seen as a product of exposure and vulnerability, where vulnerability includes susceptibility and lack of coping and adaptive capacity	Risk is seen as a product of exposure, vulnerability (socioeconomic vulnerability and vulnerable group) and lack of coping capacity
Number of countries	171	191
Treatment of missing data	Missing values are estimated using various accounting techniques depending on the data available for each country	Systematic imputation of missing values using the data from the most recent year available within a 5 years timespan
Multicollinearity test	Pearson correlation matrix	Pearson correlation matrix
Transformation and normalization approach	Multiple approaches are applied depending on the data	Log transformation for some indicators and Min-max normalization [0–10] applied to all indicators
Aggregation method	Additive function for vulnerability subcomponents and multiplicative function for exposure and vulnerability	A mix of arithmetic and geometric means and minimum-, maximum aggregation
Validation (internal)	Reliability test Sensitivity analysis Factor analysis Uncertainty test	Index regarding the lack of reliability; it takes into account missing data, out-of-date data and conflict status.
Validation (external)	No	No
Key Source	Buendnis Entwicklung Hilft, 2011; Welle and Birkmann, 2015, 2016	EC-DRMKC, 2020

[1] For the INFORM index, not just the vulnerability component was considered but also the "Lack of Coping Capacity" component. These two components were considered in order to make the values comparable to the WRI vulnerability component, which does not only capture the fragility of a society, but also the differential capacities to cope and adapt to natural hazards and climate change. In order to underscore the fact that we focus on the vulnerability components of the WRI and INFORM, we use the abbreviation "WRI*v*" and "INFORM*v*" respectively in the paper.

the European Commission has been an important actor within this development process of the index, with close support, expert consultation and user validation of the different participating organizations (see Marin-Ferrer et al., 2017). The INFORM risk index has been published annually since 2012. Its data and results are fully accessible online (https://drmkc.jrc.ec.europa.eu/inform-index/) and have been widely used in the programming of the participating and other organizations. Next to yearly vulnerability scores and ranks, INFORM also provides results on vulnerability trends of each country. Vulnerability in the INFORM index is defined as a pre-existing vulnerability before a disaster and independent of a specific hazard (Marin-Ferrer et al., 2017).

Quality criteria used for the indicator selection were quite similar in both approaches. Both consider, for example, the availability of data and that the indicators should be statistically and analytically sound, reproducible, appropriate in scope, comparable and easy to interpret and understand (see Birkmann et al., 2011; Buendnis Entwicklung Hilft, 2017; EC-DRMKC, 2020).

The WRI is based on 28 indicators: 5 indicators assess hazard and exposure, 7 capture aspects of susceptibility, 5 indicators assess the lack of coping capacities and 11 the lack of adaptive capacity (Birkmann et al., 2011; Welle and Birkmann, 2016). The INFORM index is based on a larger number of indicators, encompassing 22 indicators for the assessment of hazard and exposure, 18 indicators to assess vulnerability and 14 indicators for measuring lack of coping capacity (see in detail Marin-Ferrer et al., 2017). The number of indicators used (see Tables 2 and 3), however, does not mean that each indicator can be calculated for all countries. In terms of internal validation, at first, statistical validation processes were undertaken in the development process of both indices. These internal validation methods within the construction process of the indicator system encompassed, for example, a multicollinearity analysis to explore redundancies among indicators. Next to statistical analysis (correlations), both index development processes also encompassed expert judgements and literature-based assessments on how the different indicators selected allow the visualization of core topics of societal vulnerability to natural hazards and climate change. INFORM further applies regular rounds of expert evaluation and validation among its core users.

2.2. Data collection and transformation

Both indicator systems—WRI and INFORM—are primarily based on indicators that can be calculated and visualized with global databases, such as poverty and inequality data or access to certain basic infrastructure stemming from the World Bank, the United Nations and other reputable international organizations. A list of the indicators is shown in Tables 2 and 3 while the data sources used by both indices for each indicator is shown in the Supplementary material (see Tables A and B). Data for each indicator was transformed in dimensionless rank levels between 0 and 1 for the WRI and between 0 and 10 for the INFORM index (see Welle and Birkmann, 2015 for WRI and Marin-Ferrer et al., 2017 for the INFORM index). Within the WRI, different transformation methods were used including min-max normalization and logarithm transformation, while for the INFORM index only min-max normalization was applied.

2.3. Weighting and aggregation methods

Weighting and aggregation methods are often a contested field, however, for a robust scientific methodology, it is most important that these weights and aggregation methods are transparent and clearly outlined for external readers and users (OECD, 2008). The scientific literature and also various disciplines use different methods to allocate weights to indicators or subcomponents for the index construction. The WRI approach uses weights for each subcomponent that were generated using the Analytic Hierarchy Process (AHP) as a statistical tool and these weights were further complemented with expert judgements as an additional input to weigh the importance of each indicator for the assessment (see weights for indicators and subcomponents in Supplementary material, Table-A). This approach keeps the option open to modify variables and weights of components in later years if expert knowledge changes, the risk context changes or additional data for different aspects of societal vulnerability become available. While indicators were weighted differently, each component (susceptibility, lack of coping capacity and lack of adaptive capacity) of the WRI was equally weighted. In terms of the INFORM approach, equal weights were assigned for the components and were justified with Pearson's correlation analysis (see Table-B in Supplement and Marin-Ferrer et al., 2017 for details).

In terms of the aggregation method for the components, the WRI used a multiplicative function for exposure and vulnerability for the final risk index while the vulnerability component is calculated using

Table 2
Overview of indicators used within the WorldRiskIndex (WRI) for measuring vulnerability including data sources and subcomponents.
(Source: Welle and Birkmann, 2015; Birkmann et al., 2021)

Subcomponents and their Indicators	Data source
Susceptibility	
Public Infrastructure (PUIR)	
Share of population without access to improved sanitation (Sus_A)	WHO/UNICEF Joint Monitoring Programme (JMP) and World, Development Indicators World Bank
Share of the population without access to an improved water source (Sus_B)	WHO/UNICEF Joint Monitoring Programme (JMP) and World, Development Indicators World Bank
Nutrition (NUTR)	
Share of under nourished population (Sus_C)	Millennium Development Goals Indicators Database based on FAO Statistics Division
Poverty and Dependencies (PVDP)	
Dependency ratio (Sus_D)	Human Development Index, UNDP
Extreme poverty (Sus_E)	Human Development Report, World Development Indicators
Economic capacity and Income distribution (ECID)	
GDP per capita (PPP) (Sus_F)	World Bank, World Development Indicators
GINI index (Sus_G)	World Bank and UN WIDER
Coping capacity	
Governance and Authorities (GOVA)	
Corruption perception index (LCC_A)	Transparency International
Good governance (Failed State Index) (LCC_B)	Foreign Policy
Medical Services (MEDS)	
Number of physicians per 10,000 inhabitants (LCC_C)	World Health Statistics
Number of hospital beds per 10,000 inhabitants (LCC_D)	World Health Statistics
Material Coverage (MCOV)	
Insurances (LCC_E)	Munich Re
Adaptive capacity	
Education and Research (EDRE)	
Adult literacy rate (LAC_A)	UNESCO Institute for Statistics
Combined gross school enrolment (LAC_B)	UNESCO Institute for Statistics
Gender equity (GDEQ)	
Gender parity in education (LAC_C)	UNESCO Institute for Statistics
Share of female representatives in the National Parliament (LAC_D)	Millennium Development Goals Indicators
Environmental Status/Ecosystem Protection (ESEP)	
Water resources (LAC_E)	Environmental Performance Index
Biodiversity and habitat protection (LAC_F)	Environmental Performance Index
Forest management (LAC_G)	Environmental Performance Index
Agricultural management (LAC_H)	Environmental Performance Index
Investment (INVT)	
Public health expenditure (LAC_I)	World Health Statistics
Life expectancy at birth (LAC_J)	Human Development Index, UNDP
Private health expenditure (LAC_K)	World Health Statistics

Table 3
Overview of indicators used within the INFORM index for measuring vulnerability and lack of coping capacity including data sources and subcomponents.
(Source: Marin-Ferrer et al., 2017; Birkmann et al., 2021)

Subcomponents and their indicators	Data source
Socioeconomic vulnerability	
Development and Deprivation (DEVP)	
Human Development Index (SEV1)	Human Development Report, UNDP
Multidimensional Poverty Index (SEV2)	Human Development Report, UNDP
Inequality (INQT)	
GINI Index (SEV3)	World Bank
Gender Inequality Distribution (SEV4)	Human Development Report, UNDP
Aid Dependency (AIDD)	
Public Aid per capita (SEV5)	OECD
Net ODA Received (SEV6)	World Bank
Vulnerable groups	
Uprooted People (UPPL)	
Number of refugees, returned refugees, internally displaced persons (absolute) (VG1)	UNHCR, IDMC
Number of refugees, returned refugees, internally displaced persons (relative) (VG2)	UNCHR, IDMC, World Bank
Other Vulnerable Groups (OTVG)	
Prevalence of HIV-AIDS above 15 years (VG3)	WHO
Tuberculosis prevalence (VG4)	WHO
Malaria mortality rate (VG5)	WHO
Children underweight (VG6)	Unicef, WHO
Child mortality (VG7)	Unicef, WHO
The relative number of affected populations by natural disasters in the last three years (VG8)	EM-DAT, CRED
Prevalence of undernourishment (VG9)	FAO
Average dietary energy supply adequacy (VG10)	FAO
Domestic Food Price Level Index (VG11)	FAO
Domestic Food Price Volatility Index (VG12)	FAO
Lack of coping capacity	
Institutional	
Disaster Risk Reduction (DRR)	
Hyogo Framework for Action self-assessment reports (LCC1)	UNISDR
Government effectiveness (LCC2)	World Bank
Corruption Perception Index (LCC3)	Transparency International
Infrastructure	
Communication (COMM)	
Access to electricity (LCC4)	World Bank
Internet users (LCC5)	World Bank
Mobile cellular subscriptions (LCC6)	World Bank
Adult literacy rate (LCC7)	UNESCO
Physical infrastructure (PINF)	
Roads density (LCC8)	OpenStreetMap
Access to an improved water source (LCC9)	WHO/Unicef
Access to improved sanitation facilities (LCC10)	WHO/Unicef
Access to health systems (AHLC)	
Physicians density (LCC11)	WHO
Health expenditure per capita (LCC12)	WHO
Measles immunisation coverage (LCC13)	WHO

additive function between susceptibility and lack of coping and adaptive capacity (see Table 1). For individual indicator aggregation within each subcomponent of the WRI, an additive function was used. The INFORM index applied a multiplicative function for calculating the risk index based on its core components (see Table 1) and for the individual aggregation of subcomponents a mix of arithmetic and geometric means were applied. In terms of the underlying methodological assumptions, an additive aggregation assumes certain substitutability between the indicators. That means an increase of one indicator can be counterbalanced by another, for example, a higher dependency ratio (due to a high number and percentage of elderly of the total population like in Japan) might make society more susceptible to heat stress, but at the same time, a good health care system or strong social networks might counterbalance this. In contrast to an additive aggregation, a multiplicative aggregation assumes non-linear substitutability and introduces a knock-out criterion in terms of the fact that if one of the indicators is zero, the entire equation will be zero. The results of the vulnerability assessment of the WRI and the INFORM index with a national scale resolution are shown in Fig. 1.

3. Methodology

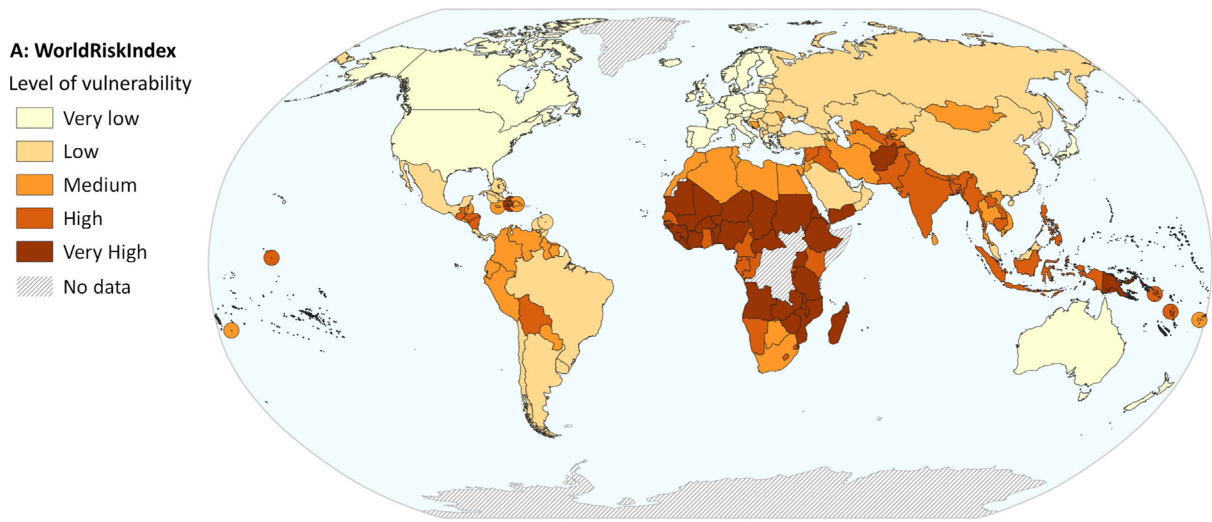
3.1. Index validation options

We examine index validity through internal and external analytical approaches. Validation is a broad term that contains a range of different methods for validating vulnerability indices. In scientific literature internal statistical validation (e.g. Tate, 2012; Sorg et al., 2018; Jamshed et al., 2020a), external statistical validation (e.g. Burton, 2010; Rufat et al., 2019; Bakkensen et al., 2017) and stakeholder/expert opinion based validation (e.g. Fekete, 2009) have been widely used particularly at the local scale. Our paper focuses on global comparative vulnerability index systems therefore opportunities to validate these with local participatory tools are limited. We differentiate between internal and external validation. Internal validation explores the inner coherence and reliability of the indicator systems based on actual data—often using statistical methods, such as sensitivity analysis. Internal validation also requires the assessment of indicator quality in relation to the underlying indicandum. External validation evaluates the relationship between calculated vulnerability and disaster outcomes or revealed vulnerability (e.g. fatalities, losses) within specific events. External validation investigates how well such indices explain losses and disaster outcomes of such events, even though it is important to note that vulnerability only represents one core determinant of overall risk (see IPCC, 2014b). We conduct this external validation at two spatial scales—national and regional scales (based on the regions defined by the United Nations Statistical Division, UNSD) to see whether and how validation values change with different spatial scales. Larger geographic regions cover a broader spectrum of hazard impacts and show a slightly different picture compared to results at the country level.

In addition to the analysis of the individual WRI and INFORM index systems, we combine the final vulnerability scores of the WRI*v* and INFORM*v* index to provide a presentation of a combined index. This combination requires transforming scales and taking an average. This transformation does not affect the actual index values or vulnerability ranking. Some of the indicators and subcomponents are similar in both indices (e.g. Gini-index, see also Table 1) which suggest there is an agreement between those indices. On the other hand, several indicators and subcomponents in both indices are different (e.g. development, disaster preparedness and environmental indicators; see also Table 1) but both indices still validate each other (in terms of the agreement) by identifying similar vulnerability hotspots and giving similar scores and rankings to countries for vulnerability and its subcomponents. This has been confirmed by recent studies (e.g. Garschagen et al., 2021, in review; Feldmeyer et al. 2021, in review), which provide new evidence and information about the agreement between the indices. We provide the results of each index system separately and also combined results that show the high agreement on spatial vulnerability hotspots at a global scale.

3.2. Data used in the analysis of the indices

In this analysis, we use the quantitative data from 2019 for both WRI*v* and INFORM*v* indices. The indices were constructed according to the method outlined above and documented for the WRI in Welle and Birkmann (2015) and for INFORM in Marin-Ferrer et al. (2017). In the INFORM index, lack of coping capacity is considered as an own component. However, for this analysis, we include this lack of coping capacity component, since vulnerability and systemic societal vulnerability in particular, according to widely accepted literature, should encompass



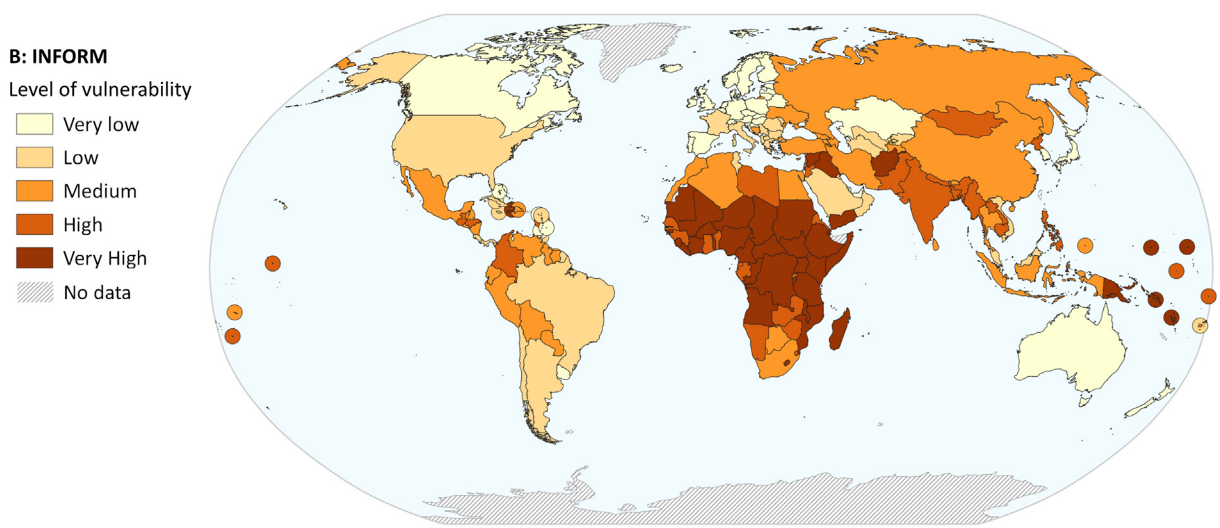


Fig. 1. Global vulnerability maps based on (A) WorldRiskIndex and (B) INFORM index. Fig. 1A shows the values for each country of the vulnerability component (with subcomponents susceptibility, lack of coping capacity and lack of adaptive capacity) of WorldRiskIndex. Fig. 1B shows the values for each country of the vulnerability component (with subcomponents socioeconomic vulnerability and lack of coping capacity). For both maps, the quantile classification method was used and Small Island Developing States are made visible at this scale using enlarged centroid dot symbols.

both susceptibility or fragility and capacities of countries or societies to cope and adapt (see e.g. Adger, 2006; Birkmann et al., 2013; Cardona et al., 2012; Cardona, 2001; IPCC, 2014a, 2014b; Jamshed et al., 2020b). Furthermore, a comparison of the INFORM vulnerability assessment results with and without the lack of coping capacity component found that there is no major difference in the resulting global picture of hotspots of vulnerability (see Figure-A in Supplement).

In a second comparison, we aggregate national data to the regional level. For the definition of regions, we use the geographic regions defined in the United Nations publication "Standard Country or Area Codes for Statistical Use" commonly referred to as the M49 standard (https://unstats.un.org/unsd/methodology/m49/). We use the smallest regions available for each country (i.e. the intermediate region or subregions). This aggregation allows us to examine the external validity of the indices at a different (smaller) spatial scale. For external validation, we use the number of events, mortality and economic loss data from the Emergency Events Database—EM-DAT (https://www.emdat.be/database) for climate-related hazards, namely storms, droughts and floods. The EM-DAT database encompasses also other natural hazards, such as tsunamis and earthquakes, however, these are excluded from the analysis since the focus is on selected climate influenced hazards.

3.3. Internal validation of the indices

Internal validation assesses the quality of the index based on the indicator, the data used and the overall index values in terms of reliability and sensitivity (Jamshed et al., 2020a; Welle and Birkmann, 2015). We conduct both sensitivity and reliability analyses. Reliability analysis measures the internal consistency of an index and describes the degree of accuracy of an index structure (OECD, 2008). It helps to increase the confidence in a composite index and has been used in natural hazard and climate change research (see for example Cutter et al., 2014; Welle and Birkmann, 2015; Sorg et al., 2018; Jamshed et al., 2020c). As quality measures, we apply the Cronbach's alpha and Guttmann lambda tests—commonly used in statistical validation for assessing the reliability and internal consistency (OECD, 2008). Secondly, we perform a sensitivity analysis to further increase the confidence in the index construction and its predictions by examining how the output variables (vulnerability index) respond to changes in the input variables (indicators or subcomponents) (see Oakley and O'Hagan, 2004). In this regard, we apply global sensitivity analysis which takes into account the measure of uncertainty in the output variable to the uncertainty in each input variable (Feldmeyer et al., 2020; Jamshed et al., 2020a;

Oakley and O'Hagan, 2004; Sorg et al., 2018). For conducting the sensitivity analysis, very few countries had to be excluded from the analysis due to their high number of missing values for various indicators. The sensitivity analysis was carried out in *Rstudio* using the *sensitivity* function in *tgp-package*.

Next to statistical methods to evaluate indicator systems, validation needs to be based on assessing the appropriateness of the indicator to represent and characterize the actual indicandum. Therefore, we assessed the quality of each indicator also in terms of its indicative function for the underlying subject of interest—the indicandum. In this regard, we conducted a literature research and assessed the relevance of the indicators used for the specific characteristic of systemic societal vulnerability they aim to measure and quantify (see Section 4.1). Besides these aspects, the applicability of any indicator requires that the indicator can be measured and visualized with data. Therefore, we also analysed the data sources used for each indicator (see Tables 2 and 3) and found both indices primarily use data from the known international organizations, however, small countries are underrepresented within global data (see also section on blind spots).

3.4. External validation of the indices

External validation is based on Pearson's correlation analysis of calculated vulnerability and observed disaster outcome data. That means the correlation explores the statistical relation between calculated vulnerability (vulnerability categories) and the observed severity (number of deaths per hazard event) of selected hazards – namely floods, droughts and storms - in the decade between 2010 and 2019 focusing on national and regional scales. This allows for the exploration of the differential consequences of hazards for most vulnerable versus least vulnerable countries, independent of the specific hazard intensity or exposure. It is likely that next to the general level of vulnerability of a country or region also the hazard intensity, exposure and specific circumstances within a single hazard event determine the overall loss outcome. Recent studies that explored specific outcomes of hazard events and vulnerability, such as Hurricane Sandy (Rufat et al., 2019), suggest there might be no significant quantitative relation, since other factors such as exposure or hazard specific characteristics largely determine loss levels due to a specific event. Therefore, external validation is a very open question and challenge.

4. Results: evaluating the validity and limitations of the WRI*v* and INFORM*v* index

4.1. Validation in terms of the indicandum and the link between indicators, goals and data

Since vulnerability indicators need to be evaluated also against the quality on how they represent different characteristics of vulnerability, we conducted an intensive literature analysis. The analysis revealed that all indicators used within the two assessments for assessing vulnerability (see overview Tables 2 and 3) can be justified in terms of their link to the overall indicandum—vulnerability—with evidence from scientific literature (see Tables A and B in Supplement). Several scientific papers and studies underscore the relevance of the respective indicator to assess and measure characteristics of vulnerability to climate change and natural hazards (e.g. Cardona et al., 2012; Cutter et al., 2003; Fekete, 2009; Sorg et al., 2018). Consequently, a close link between the indicators used within both assessments and aspects of the underlying indicandum is evident. However, it is important to note that specific goals for vulnerability reduction or for the development of capacities to cope and adapt were not found. Moreover, only a little information exists on whether or not the indicator-indicandum nexus is sufficiently valid for all countries. Tables 2 and 3 provide an overview of the subcomponents and indicators used to assess vulnerability and capacities in the WorldRiskIndex and the INFORM index. The Supplementary material (see Tables A and B) also contains more information about the supporting scientific literature for each indicator and the respective transformation rules applied to calculate it.

Furthermore, the conceptualization of risk within the Intergovernmental Panel on Climate Change (IPCC) differentiates hazard, exposure and vulnerability (IPCC 2014, 2019). Thus, in terms of the validation of the vulnerability indicators it is important to evaluate whether the indicators capture vulnerability or rather aspects of the hazard or exposure.

For example, the widely cited ND-Gain index to assess vulnerability to climate change differentiates exposure and sensitivity as well as adaptive capacities within the indicator system along different sectors (see Chen et al., 2015). The list of indicators to assess sensitivity in the context of climate risk includes among other indicators, the population living in areas where elevation is 5 m below sea-level (as % of the total population) based on data of the World Bank (Chen et al., 2015, p. 31). While this indicator is statistically valid, it is rather an indicator of exposure to the hazard of sea-level rise. About 59% of the total population in the Netherlands is living in areas where the elevation is 5 m below sea-level, while in Bangladesh it is about 9% (see The World Bank, 2021 [World Development Indicators; http://wdi.worldbank.org/table/3.11]).

However, the Netherlands has high financial and institutional capacities to protect people in low-lying coastal areas with large technical and infrastructure measures; the overall poverty is low and few people live in slums (housing poverty). In contrast, in Bangladesh, about 47% of the overall population live in informal settlements and slums (data from 2018) and approximately 14% of the population live in extreme poverty based on the assessment of the poverty headcount ratio at $US 1.9 a day (The World Bank, 2021, 2019). This example underscores that hazard, exposure and vulnerability indicators need to be differentiated, since their meaning and also measures to assess these aspects are quite different. Likewise, strategies to reduce vulnerability and exposure are not necessarily the same. For example, exposure reduction through relocation of inhabitants can lead to livelihood insecurity at the new location, thereby increasing vulnerability. Thus, the conceptual differentiation between exposure and susceptibility or exposure and vulnerability is quite important (IPCC, 2019, 2014b). Our analysis of the structure of the WRI and INFORM index revealed that both index systems have clearly differentiated exposure and vulnerability within their conceptualization. This differentiation is also documented in part in background studies and methodological guidelines.

4.2. Internal validation of WRIv and INFORMv index

A reliability test and sensitivity analysis were performed for internal validation of both index systems.

4.2.1. Reliability test

Cronbach's alpha and Guttmann Lambda were calculated based on the indicators in each subcomponent of vulnerability as well as considering all the indicators irrespective of their subcomponents. A Cronbach's Alpha and Lambda value of 0.7 is considered acceptable in terms of internal reliability as a threshold (Jamshed et al., 2020a; OECD, 2008; Sorg et al., 2018). Some authors use a 0.6 value as a cut-off line in the field of disaster risk and resilience research (for example, Cutter et al., 2014). The analysis revealed that the Cronbach's alpha and Guttman's Lambda for all indicators of the WRI*v* (all vulnerability components) were 0.949 and 0.965 respectively while for all vulnerability subcomponents these values were more than 0.850 suggesting that indicators or items are suitable and internally consistent to assess and characterize vulnerability. Table 4 provides an overview of the internal consistency and reliability values based on statistical validation using standard quality measures such as Cronbach's alpha and Guttman's Lambda (see Table 4).

For all vulnerability indicators (including lack of coping capacity) in INFORM*v* index, Cronbach's alpha and Guttman's Lambda values were

Table 4
Internal consistency and reliability of the vulnerability components in the WRI and the INFORM Risk Index.
Source: Own calculation.

Subcomponents	Cronbach's alpha	Guttman's Lambda
WRI		
Susceptibility	0.881	0.926
Lack of coping capacity	0.861	0.891
Lack of adaptive capacity	0.870	0.901
All indicators	0.949	0.965
INFORM Index		
Socioeconomic vulnerability	0.751	0.788
Vulnerable groups	0.790	0.851
Lack of coping capacity	0.933	0.940
All indicators	0.948	0.954

0.948 and 0.954 respectively. Moreover, each component showed a value of more than 0.75 (0.9 for lack of coping capacity) both for Cronbach's alpha and Guttman's Lambda (see Table 4). Overall, the reliability analysis for both indicator systems — WRI*v* and INFORM*v* — suggested a high level of inherent consistency among the indicators that characterize vulnerability. Nevertheless, it is still necessary to evaluate the logical link between the indicators used and the underlying indicandum (see Section 4.1).

4.2.2. Sensitivity analysis

Sensitivity analyses can be carried out for subcomponents or individual indicators (see Sorg et al., 2018; Jamshed et al., 2020a; Feldmeyer et al., 2020). In terms of sensitivity analysis with subcomponents, each subcomponent represents a specific number of indicators (sensitivity analyses for the complete set of indicators is provided in the Supplementary material, Figure-B). The analysis provided new insights into both the WRI*v* and the INFORM*v* index as shown in Fig. 2. Each figure (Fig. 2, A and B) contains three elements. The first part (left-hand side) shows curves that represent each subcomponent and its respective indicators. The x-axis depicts the original values of each subcomponent scaled between −0.5 and + 0.5 while the y-axis shows the variance of indicators representing subcomponents. The steeper the curve, the stronger the influence of the subcomponents and the respective indicators. Curves that are fully horizontal mean that the subcomponent has nearly no influence on the overall index result. The second part (in the middle—named "1st order sensitivity indices") shows boxplots with subcomponents on the x-axis and the sensitivity on the y-axis. The size of the box describes how a subcomponent (and its indicators) influences the index. A smaller boxplot size suggests a more precise influence on the index. The bold line in the boxplot shows the median. The higher scores on the y-axis imply the strength of influence of each subcomponent on the overall risk index. The third part of the figure (on the right— named "total effect sensitivity indices") also displays the boxplots and explains the total sensitivity effect. It shows how indicators in each vulnerability subcomponent change or interact if there is a change of one indicator. If the median of a subcomponent (and its indicators) in total sensitivity effect is above zero it means that the subcomponent is meaningful for and influences the vulnerability index.

Fig. 2 shows the differential influence of each indicator within the WRI*v* and the INFORM*v* index. Both figures clearly reveal that curves are steep and that the median values of all boxplots are above zero in both the first-order sensitivity (middle graphs) and the total sensitivity effect (right graphs) for WRI*v* and INFORM*v*. Consequently, it can be concluded that the indicators and the respective subcomponents are statistically meaningful and relevant for the overall assessment of vulnerability and their respective indices. The sensitivity analysis suggests that the index results are internally valid. In terms of the WRI*v* these results confirm the internal reliability evaluation done also within an earlier version of the WRI*v* (see Welle and Birkmann, 2015).

4.3. External validation: the quantitative relationship between vulnerability and loss of life

Understanding past disaster losses due to climate-related hazards, such as storms, droughts or floods can not only be explained in terms of the magnitude and frequency of hazards. Rather hazard intensity and frequency, exposure and vulnerability all play an important role. We argue that independent of the specific hazard, it is essential to reduce systemic societal vulnerability in order to close the adaptation gap – the difference between current levels of vulnerability and exposure and risk management capability. This is especially important given the increasing recognition that climate change hazards have emergent, indirect and cascading impacts—for example when a drought in one country leads to food insecurity in another country. In this regard, the assessment of vulnerability can also shift the prioritisation of countries for supporting the development of climate resilience and adaptive capacities. Developing vulnerability indicators independently of specific hazards and exposure means vulnerability reduction measures can be put in place even where there is no current climate hazard or exposure. Considering this, external validation of indices is imperative to examine their explanatory power by investigating how well they describe disaster or climatic event outcomes. This is one way of avoiding impacts from unexpected events.

There are several ways to measure the magnitude of impacts of hazard events, and the choice of metric results in different outcomes of which countries are most affected by disasters. Visser et al. (2020) show that if economic losses are considered as a disaster outcome then OCED countries are most affected by disasters. In contrast, if "number of people affected" is considered as the metric it is the "BRICS" countries (e.g. Brazil, Russia, India, China) that emerge as most impacted, and if "number of people killed" is considered it is developing countries that rank the most affected (Visser et al., 2020).

In our analysis, we use mortality per hazard event as the measure of disaster outcome as death is the most severe and irreversible impact. Mortality due to natural and climate-related hazards is captured in the EM-DAT database. The mortality (deaths per event) is likely to be underestimated in low income countries or remote areas due to incomplete reporting. Essential data sources for mortality are from vital registration or life insurance claims, neither of which are widely prevalent in poorer countries. Thus the difference that we present here in terms of mortality per hazard between high vulnerable versus low vulnerable countries is likely to be higher rather than lower.

As in Section 4.4.2 for vulnerability, we aggregated mortality per event (national EM-DAT data) to the regional level (Fig. 3) using the same UNSD regions as described in Section 3.2. Fig. 3B shows the average mortality per hazard event for each region as well as the number of hazard events per region. Significant spatial differences become visible for example in terms of the difference between South-East Asia and East-Africa.

Furthermore, we analysed how vulnerability in the WRI*v* and INFORM*v* indices and their combined values relate with hazard-induced losses of different types and thus investigated if vulnerability can statistically explain disaster outcomes or parts of it (see Table 5 and Fig. 4). Mortality per hazard event and the number of people affected per hazard event had a positive and significant correlation with vulnerability values of WRI*v*, INFORM*v* and the combined indices (see Table 5). The correlation coefficient of mortality per event ($r = 0.421$, $p = 0.05$) and people affected per event ($r = 0.434$, $p = 0.05$) at the regional level was found to be slightly higher than national level coefficients. Fig. 3 presents the maps of mortality per event at the national and regional levels. In terms of economic losses per event, a negative and significant correlation to vulnerability was found with a higher correlation coefficient at the regional level ($r = 0.500$, $p = 0.01$) than at the national level (see Table 5).

In short, the correlation analyses revealed that vulnerability at the national and regional levels does correlate with average mortality per

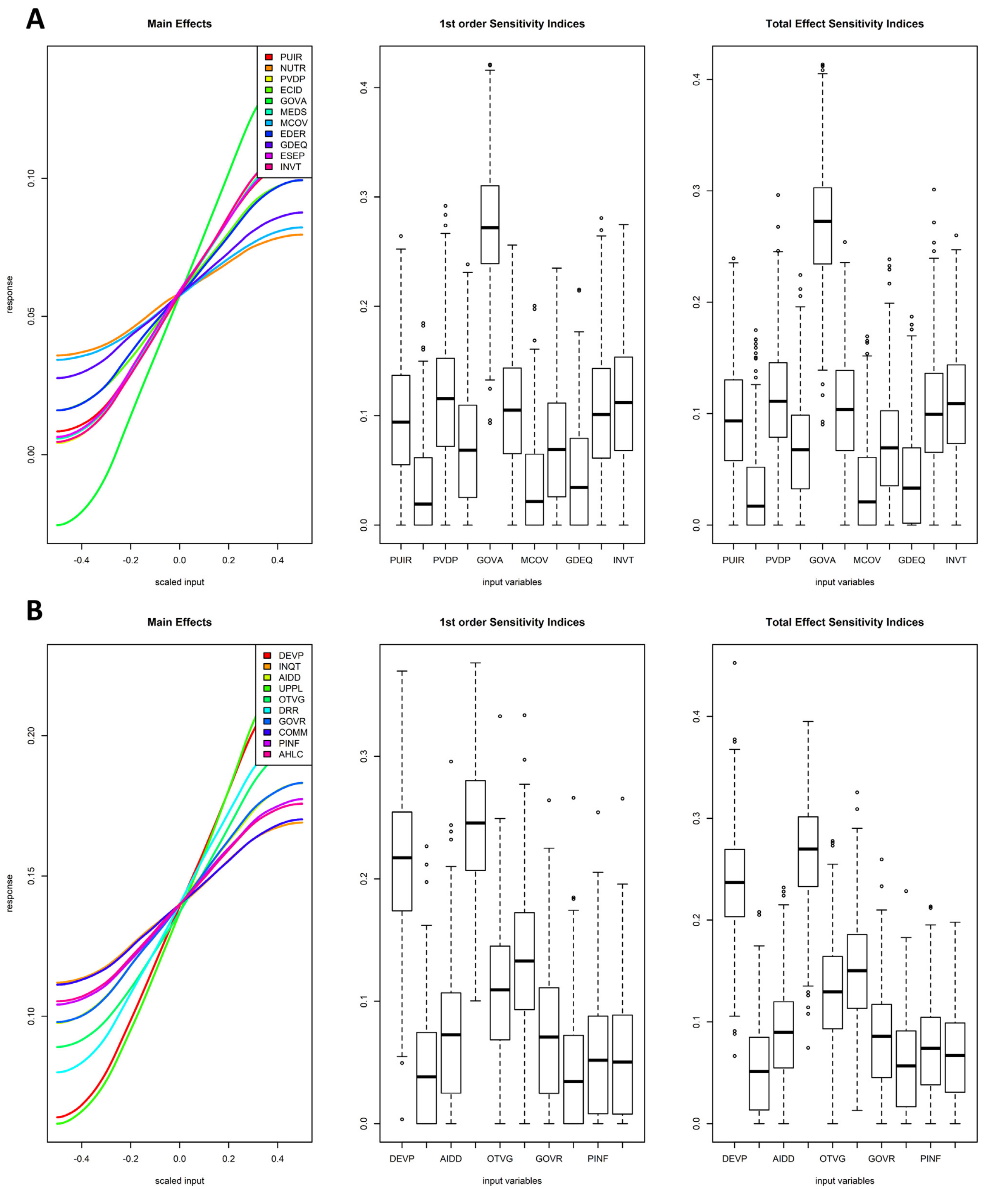


Fig. 2. Sensitivity analysis results for the vulnerability main components of the (A) WRI*v* and (B) INFORM*v* index.
In WRI: Public Infrastructure (PUIR); Nutrition (NUTR); Poverty and Dependencies (PVDP); Economic capacity and Income distribution (ECID); Governance and Authorities (GOVA); Medical Services (MEDS); Material Coverage (MCOV); Education and Research (EDRE); Gender equity (GDEQ); Environmental Status/Ecosystem Protection (ESEP); Investment (INVT). In INFORM Index: Development and Deprivation (DEVP); Inequality (INQT); Aid Dependency (AIDD); Uprooted People (UPPL); Other Vulnerable Groups (OTVG); Disaster Risk Reduction (DRR); Governance (GOVR); Communication (COMM); Physical infrastructure (PINF); Access to health systems (AHLC).
(Source: Own figure)

event, people affected and economic losses caused by each event. In other words, higher vulnerability means higher mortality and less economic loss per event. Overall, correlation results suggested that both the WRI*v* and INFORM*v* index, as well as their combined form, have explanatory power for disaster outcomes and thus are externally valid both at the national and regional levels.

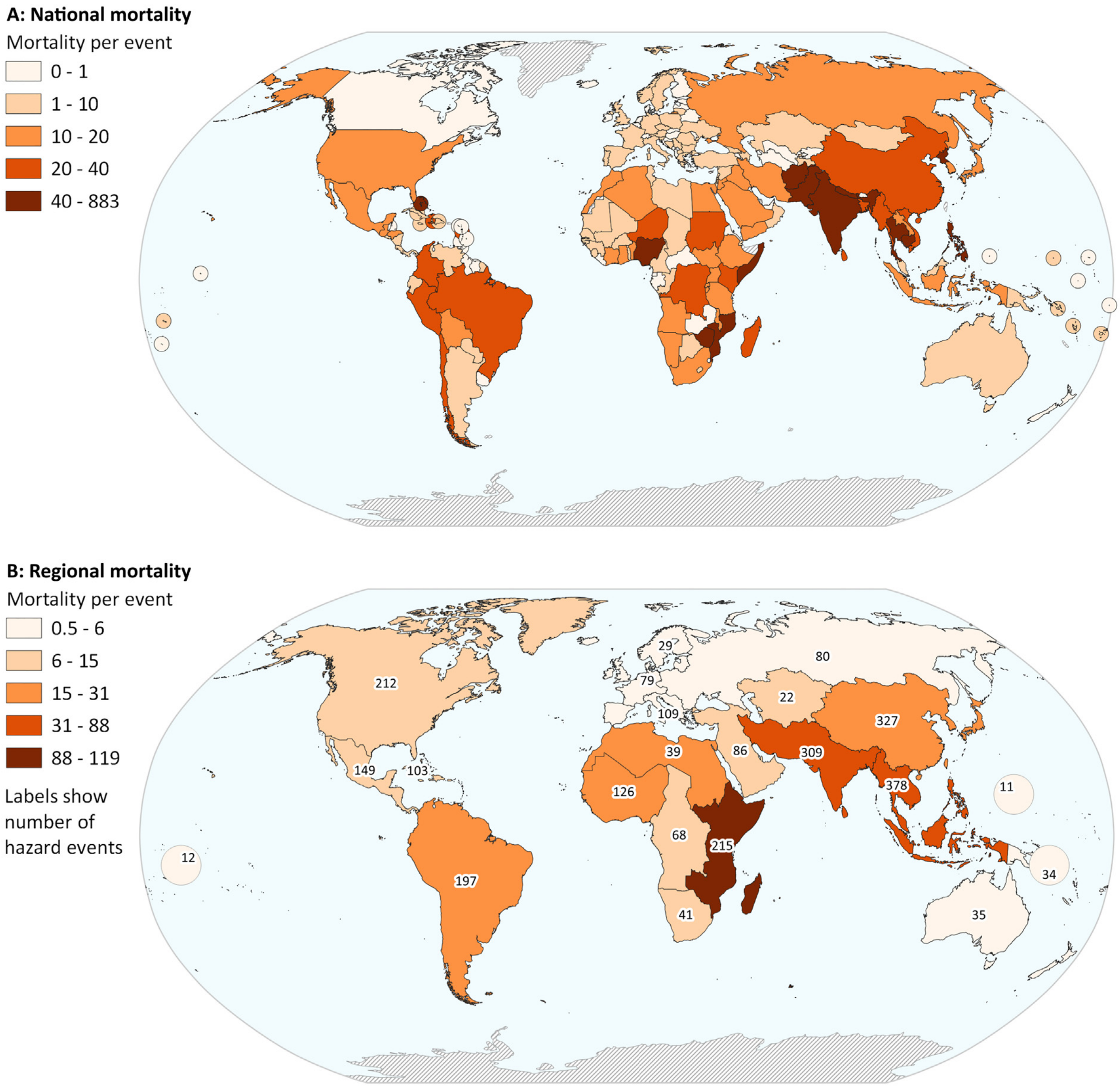


Fig. 3. Mortality per climate related hazard event (floods, storms and droughts) between 2010 and 2019 at the national (Fig. 3A) and regional level (Fig. 3B). Both maps are based on national scale data from the Emergency Events Database—EM-DAT (https://www.emdat.be/database) for storms, floods and droughts hazards. Fig. 3A was classified using a manually modified classification in order to account for extreme outliers (i.e. Somalia). Fig. 3B shows the average mortality per event for each UNSD region classified using the natural breaks method and labelled with the number of hazard events over the 10 year period for each region.

We further analysed the validity of these indices along vulnerability categories by exploring the magnitude of mortality and absolute economic losses. This analysis shows how many times higher or lower these impacts are in countries categorized as very highly vulnerable compared to countries in other vulnerability categories (see Fig. 4). Fig. 4 further underscores that mortality per hazard event in countries according to five vulnerability categories differs significantly as suggested by the nonparametric test.

Fig. 5A shows that loss of life per hazard event is 15 and 7 times higher in countries with very high vulnerability compared to countries with very low and low vulnerability, respectively, based on the combined index. In WRI*v* and INFORM*v* indices, mortality per event in

Table 5
Correlation of loss due to past disaster events (floods, droughts and storms) and vulnerability.

Hazard dependent variables	WRI vulnerability *(National level)*	INFORM vulnerability *(National level)*	Combined vulnerability[a] *(National level)*	Combined vulnerability[a] *(Regional level)*
Number of events	−0.002	0.040	0.041	0.048
Mortality per event	0.316**	0.274**	0.285**	0.421*
Economic losses per event	−0.278**	−0.211**	−0.230**	−0.500*
People affected per hazard event	0.260**	0.235**	0.255**	0.434*

**, * correlation is significant at the 0.01 and 0.05 levels, respectively.
[a] Combined vulnerability is calculated based on both WRI and INFORM index.

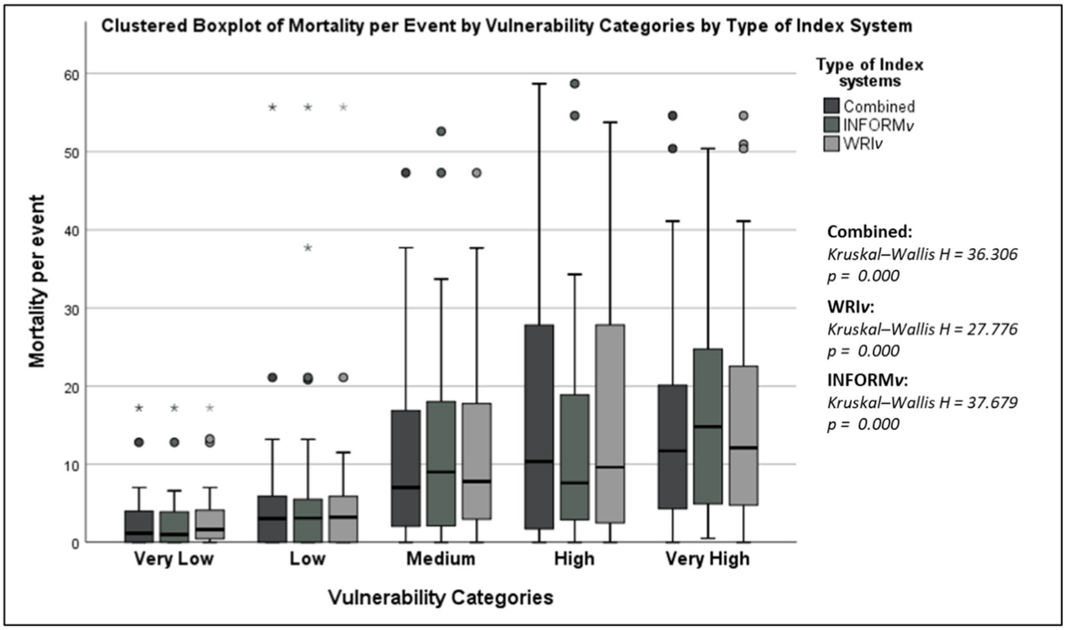


Fig. 4. Clustered boxplots of mortality per hazard event by vulnerability categories and type of index.

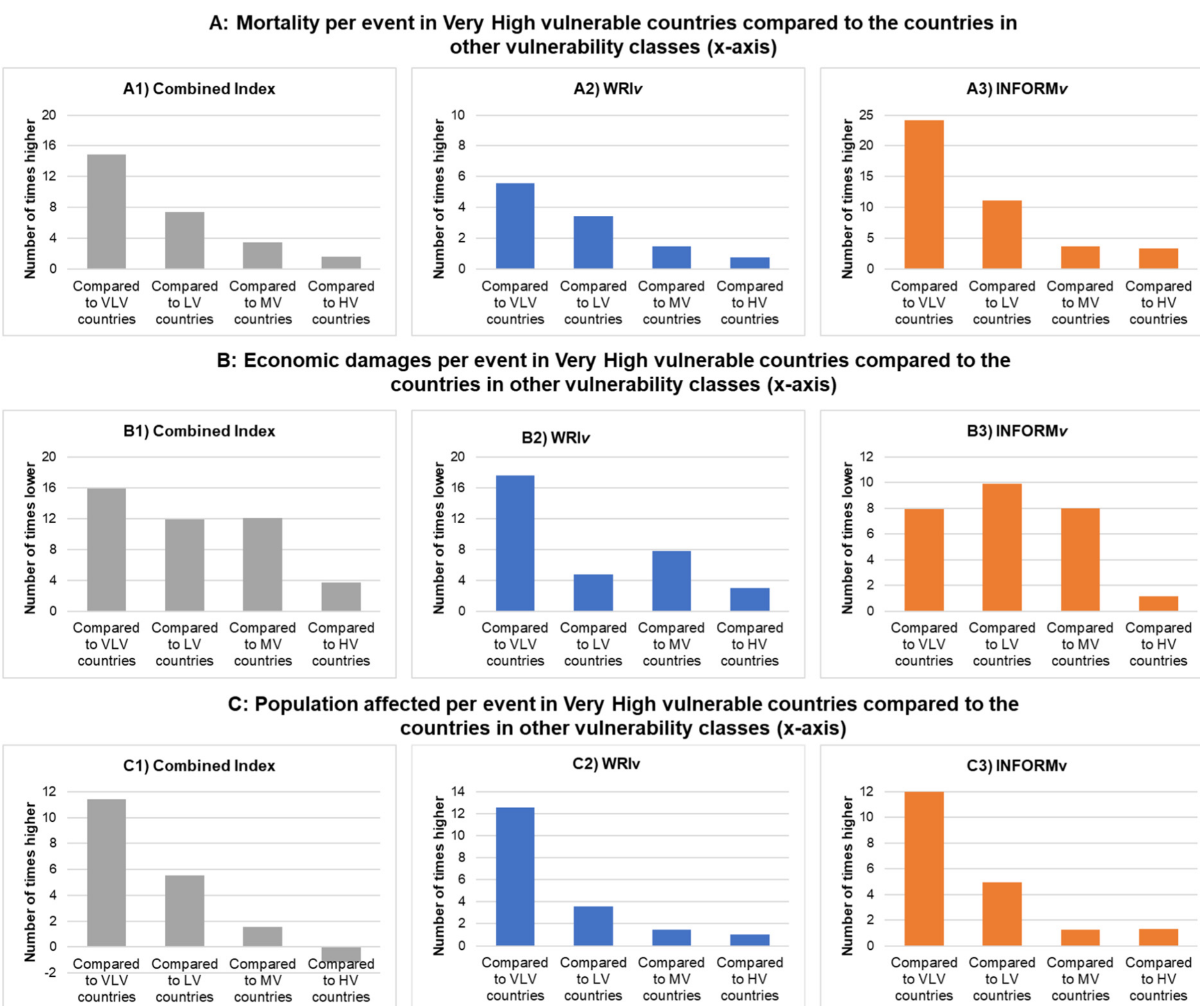


Fig. 5. Magnitude of (A) death per hazard event [*number of time higher*] and (B) economic losses per hazard* event [*number of times lower*] (C) population affected [*number of time higher*] in the past 10 years in countries categorized as very highly vulnerable compared to countries in other vulnerability categories. Only vulnerability components of WRI and INFORM are included in the analysis and represented with WRI*v* and INFORM*v*. [* selected hazards: floods, droughts, storms].

countries that are very highly vulnerable is 6 times and 24 times higher, respectively, than in countries with very low vulnerability. The significantly higher magnitude in the INFORM*v* index compared to the WRI*v* index is due to a greater number of countries (classified as highly vulnerable) included in the INFORM*v* index particularly Somalia, Dominica, the Democratic Republic of Congo and North Korea (see also Fig. 1A/B). We also examine the mortality per 100,000 inhabitants in the last ten years along different vulnerability classes. The results show that mortality per 100,000 inhabitants is higher in countries categorized as high and very high vulnerable compared to low and very low vulnerable. For the combined index and the INFORM*v* index, results show 3 to 5 deaths per 100,000 inhabitants in very high vulnerable countries while this number is below 1 in low and very low vulnerable countries (see Figure-C in Supplement). Thus, even though the specific numbers differ depending on the index used, it is evident that high and very high vulnerable countries in Africa (e.g. Somalia, Mozambique, Madagascar), Asia (e.g. Philippines, Nepal, Afghanistan, Pakistan) and the Small Island States (e.g. Haiti, Vanuatu, Micronesia) had a higher mortality per 100,000 inhabitants compared to other countries classified e.g. as low vulnerable.

In terms of economic damages, it was found that economic damages per event are higher in countries with low vulnerability than in very highly vulnerable countries (see Fig. 5B). The economic damages per event in countries categorized as very highly vulnerable in the combined index are 16 times lower compared to countries with very low vulnerability. In the WRI*v* and INFORM*v* indices, very highly vulnerable countries have 18 times and 8 times less economic damages per event to report compared to countries categorized as having very low vulnerability[2]. With regard to people affected, the quantitative analysis shows that the number of people affected per hazard event was significantly higher in very high vulnerable countries compared to low and very low vulnerable countries. The results of the combined index (see Fig. 5C) underscores that number of affected people per hazard event was about 11 times higher in countries categorized as very high vulnerable compared to very low vulnerable. In terms of WRI*v* and INFORM*v* indices, the population affected per hazard event was found to be about 12 times higher in very high vulnerable countries compared to very low vulnerable countries. Similar trends were observed for the affected population per 1000 people (see Figure-D in Supplement). The results underscore that the overall magnitude of mortality, economic losses and population affected differs significantly between all vulnerability categories regardless of the specific index used (see Table-D in Supplement).

Also, the regional level assessment of vulnerability and mortality (Fig. 4) reveals that large UN regions with a nearly similar number of hazard events in the last 10 years, such as North America compared to East Africa, faced significantly different mortality per event. It is very unlikely that this is primarily a result of hazard intensity or exposure.

Moreover, all three indices show a similar trend between all four vulnerability categories with respect to mortality and economic losses. Thus, this analysis also shows the validity of these indices in explaining disaster outcomes. The high mortality per hazard event in countries with very high and high vulnerability is associated with limited medical services and coverage, poverty and inequality, development deprivation, as well as governance issues (see Supplement, Table-E). The economic losses per event are higher in less vulnerable countries which are mainly high income countries. This finding is supported by other studies (UNDESA, 2020; Wallemacq and House, 2018). The main reason for this relationship is that countries with higher economic losses have more economic assets exposed and wealth to lose. For example, if a flood damages an expensive light-rail system in one country and washes away a dirt road in another, the residents of both may have restricted mobility and associated impacts to their lives but the economic loss in the first case will be much higher. However, the first country most likely has greater financial, technical and infrastructural resources and capacities to repair and recover without significant long-term consequences (Rentschler, 2013). For example, the analysis of the insurance coverage per region revealed that SIDS like Micronesia or Polynesia, but also various regions in Africa, such as Middle Africa and Western Africa have significantly lower insurance coverage compared to regions like Australia and New Zealand or Western Europe and North America (see Figure-E in Supplement). Thus, part of the losses in the latter countries might be compensated by insurance.

In summary, the highest absolute economic losses are found in countries with wealth and exposed capital assets, while BRICS countries (including South Africa) face the highest number of affected people particularly in absolute numbers (in part due to large populations sizes e.g. in China or India), however, the mortality per hazard event is lower compared to most vulnerable countries or least developed countries. When calculating the economic damage per country as a proportion of GDP along different country income groups, the disproportional high losses in low-income countries become visible (Wallemacq and House, 2018). However, the calculation of economic damages in proportion to the GDP for the vulnerability country classes is less clear or shows a more diverse picture also due to the fact that vulnerability classifications are not equal to income groups. We found that – even though economic losses (in the last ten years) as a percentage of GDP is higher in very high vulnerable countries compared to very low vulnerable countries as per INFORM*v* – there is not always a significant difference between very high, high, medium and low vulnerability country groups (see Figure-F in Supplement). Our analysis revealed that some countries that are categorized as very low or low vulnerable face relatively high economic losses as a percentage of GDP, such as Japan, USA, Oman, Kazakhstan, Cuba, Argentina and Serbia. The WRI*v* index provided different results also due to a lower number of countries (see also discussion in Section 4.4.1).

4.4. Blind spots, data gaps and limitations

4.4.1. Data gaps

Global indicator systems and indices, such as the WRI and INFORM, can only be as accurate as the available data. The INFORM approach calculates its own measure of the internal validity of the index (reliability index – see also Section 2) for each country based on the number of missing indicators, the recentness of the data available, and whether or not the country is experiencing violent conflict. The resulting "Lack of Reliability" value for each country was calculated in the INFORM Risk Index 2019. Our analysis of these values found that the lack of reliability is not significantly higher for countries with high levels of vulnerability according to INFORM. Out of the 50 countries most lacking reliable values in the INFORM assessment in 2019, 18 countries had high to very high vulnerability scores, 16 had low to very low vulnerability scores and 16 had medium vulnerability scores. That means next to instability within a country, it is also the size of the country that seems to influence data availability independent of the level of vulnerability. For example, there is also a lack of reliability for the scores of small countries with low vulnerability in Europe like Lichtenstein.

The WorldRiskIndex does not calculate reliability but instead does not calculate an index value for those countries for which there is a lack of recent data. This also largely explains why the WRI provides results for fewer countries compared to INFORM. The WRI omits 20 countries, 18 of which the INFORM index includes. Of these 20 countries missing from the WRI, 13 are Small Island Developing States (SIDS). SIDS and Antarctica are examples of blind spots of the indices due to limited data collection. In the case of Antarctica, an emerging place of investment, it is not a nation and thus data is missing from nation-based datasets.

While SIDS-dedicated vulnerability indices have been developed (Pelling and UITTO, 2001), missing data is a challenge when trying to

[2] Economic loss trends from EMDAT database must be interpreted with caution, since economic loss reporting is often underdeveloped and contains missing or underestimated data for many disasters. This leads to higher uncertainties of this impact data.

incorporate SIDS into wider indexing approaches. In the calculation of the Sustainable Development Goals (SDG) index and the Dashboards Report, 25 SIDS were omitted from analysis due to missing data (Gosling-Goldsmith et al., 2020; Nurse et al., 2014; Sachs et al., 2017). In the WRI, 34% of SIDS are omitted of the 38 SIDS that are United Nation Member States (see https://sustainabledevelopment.un.org/topics/sids/list). The INFORM Index includes all SIDS, however, 37% of the SIDS are in the top 25% of countries lacking reliable data based on the reliability index developed within the INFORM approach. Some of these data gaps could be addressed using data interpolation and training using machine learning techniques (see e.g. Jia and Ma, 2017; Mikhailiuk and Faul, 2018).

Our own analysis of SIDS data and vulnerability (see Fig. 6) found that the vulnerability rankings of various SIDS differ, for example, the SIDS in the Pacific have a higher vulnerability compared to the various SIDS in the Caribbean, even though all SIDS are highly exposed to climate threats like sea-level rise. The most vulnerable SIDS according to both INFORM*v* and WRI*v* are Haiti in the Caribbean (with a vulnerability value of 7.0 for INFORM*v* and 0.75 for WRI*v*) followed by Gineau-Bissau (5.6 for INFORM and 0.71 for WRI) in West Africa. INFORM rates the Pacific Islands of Micronesia (Federated States of Micronesia), Marshall Islands, Papua New Guinea and Tuvalu (all between 5.5 and 5.0) as the next most vulnerable. WRI*v* rates Papua New Guinea as the third most vulnerable, followed by Comoros in East Africa and the Solomon Islands and Timor-Leste in the Pacific (all between 0.60 and 0.68).

4.4.2. Regional aggregation

In a further analysis that highlights and differentiates the SIDS as well as landlocked countries, we calculated the average of the two indices (WRI and INFORM vulnerability components) and aggregated them to the level of regions (UNSD intermediate and subregions as described in Section 3.2). This regional classification includes four regions dominated by SIDS, namely Caribbean, Melanesia, Micronesia and Polynesia (see Figs. 6 and 7), the latter three being regions in the Pacific Ocean. This analysis shows that all three Pacific regions have a higher vulnerability compared to the average according to the combined indices. In addition, an analysis of landlocked vs non-landlocked countries was performed. In terms of landlocked countries, a clear difference in the level of vulnerability can be observed between landlocked and non-landlocked countries in Africa, Southern Asia and South America where landlocked countries have a higher average vulnerability compared to non-landlocked countries (see Figure-G in Supplement). However, landlocked countries for example in Europe (e.g. Austria, Switzerland, Lichtenstein) do not show such differences.

The boxplot in Fig. 6 shows a pattern of differentiated vulnerability not only between regions but also within regions. Countries of all regions of Northern America, Australia and New Zealand and Europe, except Eastern Europe, show limited variation in vulnerability. In contrast, all other regions show a higher variation of vulnerability within the region. For example, in Eastern Asia, Japan (19.89) and South Korea (20.84) were found to have a very low vulnerability, but China (39.6) and North Korea (53) had medium and high vulnerability respectively. Southern Asia has quite an even distribution of quartiles since countries had different vulnerability levels, for example, Afghanistan (very high), Pakistan, India, Nepal and Bangladesh (high), Iran and Bhutan (medium) and Maldives (low) (see Figure-H in Supplement). Landlocked countries in Southern Asia and Africa have overall a slightly higher vulnerability. In Eastern Africa, the higher position in the figure and smaller box size indicates that most of the countries have high vulnerability except Mauritius (31.8) and Seychelles (32.5) (which are represented with the '*' symbol). Similarly, Western and Middle Africa show a large distribution of vulnerability, but the majority of countries (except Cabo Verde and Sao Tome and Principe) have vulnerability values between 50 and 82 and are considered as high to very highly vulnerable. Overall, results suggested that the inner distribution of vulnerability differs significantly in the Global South particularly in regions of Asia and

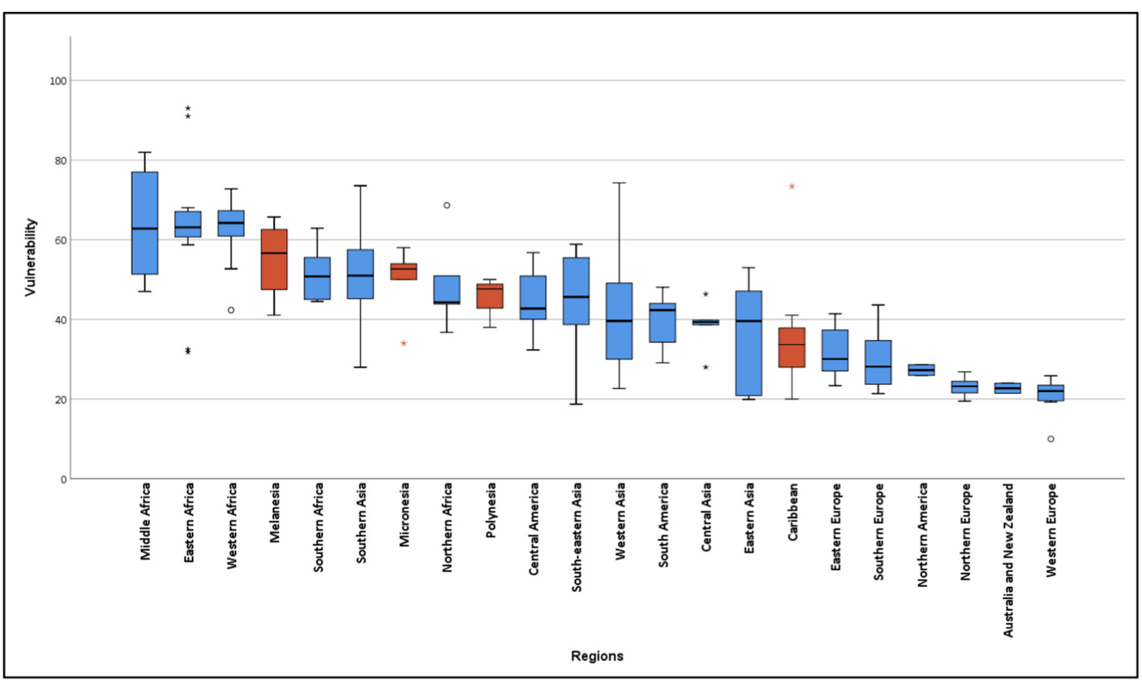


Fig. 6. Boxplots of the vulnerability of regions including SIDS (in brown). '°' represent mild outliers[2] and '*' extreme outliers (see Table-C in the Supplementary material for number of countries in each region).
Footnote 2. An outlier is defined as value with is numerically distant from the rest of the data (Schwertman et al. (2004). Mild outliers indicate the values which beyond the upper inner fence of the boxplot and calculated as {Third quartile or 75th percentile (Q3) + 1.5 × (Interquartile range)}. Extreme outliers indicate the values which beyond the upper outer fence of the boxplot and calculated as {Third quartile or 75th percentile (Q3)+3 × (Interquartile range)}. Interquartile range can be obtained by subtracting value of 75th percentile (Q3) and 25th percentile (Q1) i.e., Q3 - Q1. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Source: (Own figure based on WRI*v* and INFORM*v* index calculations using UNSD regions; the number of countries that fall into one of these regions is shown in Table-C of the Supplement).

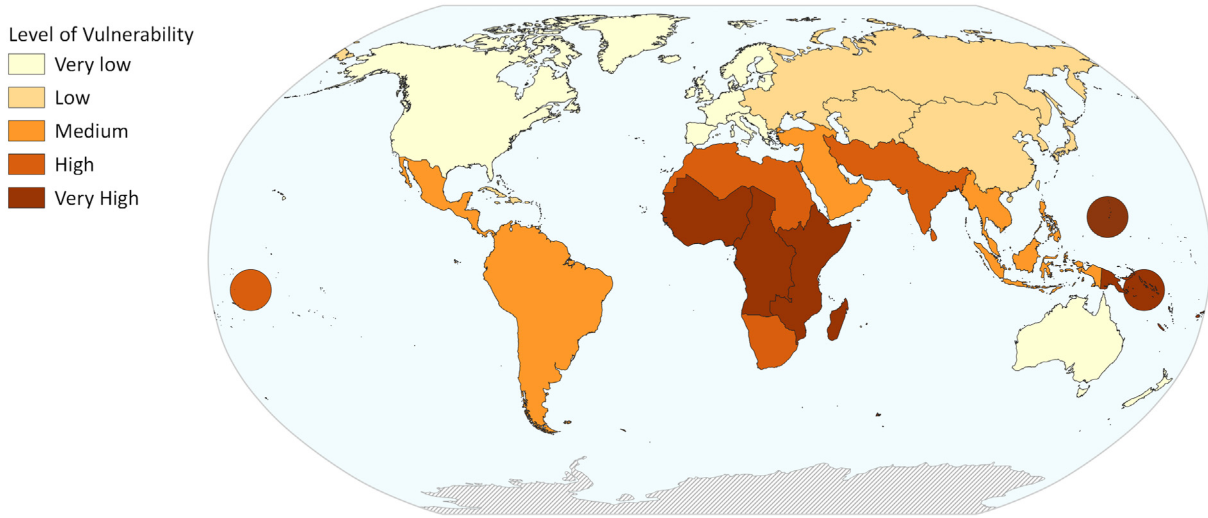


Fig. 7. Vulnerability at the regional level (based on UNSD intermediate regions and subregions). Level of vulnerability calculated by averaging the WorldRiskIndex vulnerability and INFORM vulnerability and lack of coping capacity values for each region. Regional averages classified into 5 classes (i.e. very low ≤ 28, Low 28 to 37, Medium 37 to 44, High 44 to 51, Very high >51) using the quantile method. For the region names see Table-C in Supplement.

Africa including their landlocked countries, unlike most high income regions where countries have more or less similar values as shown by the size of boxplots.

5. Discussion: different starting points, limits and levers for action

The results of the internal and external validation of the vulnerability indicators and components of the WRI*v* and INFORM*v* Index underscore that global vulnerability assessments can provide an important layer of information, linked to core characteristics of systemic societal vulnerability and explain (a part of) observed disaster impacts. The following section interprets core results of the analysis focused on three issues: 1) different starting points revealed through the assessment, 2) limitations and uncertainties and 3) how these results provide levers of action.

5.1. Vulnerability results reveal different starting points

The analysis presented here argues for a reframing of risk to climate change related hazards and to the policy responses taken to reduce risk through climate change adaptation and wider acts of climate sensitive development. To date, global assessments of climate change risk typically start with hazard analysis, then layer exposure (population distributions) and finally vulnerability. This is echoed for example in the logic of IPCC Assessment Review process with Working Group I (hazards) followed by Working Group II (Impacts, Adaptation and Vulnerability).

While people often assume that the mortality of storms, floods and droughts is mainly determined by hazard intensity, frequency and exposure, our analysis revealed the influence of vulnerability and systemic societal vulnerability in particular. The internal and external validation of the vulnerability assessments (INFORM*v* and WRI*v*) offers an additional argument for using vulnerability and systemic societal vulnerability (core focus on societal issues and barriers) as the entry point for adaptation planning. In contrast to many adaptation concepts that focus on climatic hazards or climate scenarios as the primary information basis, we argue that it is equally important to define goals for reducing vulnerability. The validation results showed that those countries suffering most in terms of human losses and severe impacts (people adversely affected) were also among the most vulnerable. Future national adaptation plans for example could take up some of this information to define goals for adaptation and vulnerability reduction, e.g. poverty reduction, reducing inequality or improving the access to basic services for most vulnerable groups (water and sanitation). Next to adaptation plans at a regional or national level, the quantitative vulnerability information could also be used to inform larger international adaptation projects (Muccione et al., 2017). For example, the International Climate Initiative (see BMU, 2021) finances projects to support vulnerable countries. All projects have to report on standard impact indicators, including the reduction of Green House Gas emissions, the number of people directly supported by the project to adapt to climate change, the number of improved policy frameworks developed, and the number of new or improved institutional structures and processes to address climate change and conserve biodiversity (see BMU, 2021). While these impact indicators are important, a stronger emphasis on aspects of systemic societal vulnerability could strengthen the overall intention to support vulnerable countries and to reduce vulnerability. Also, the question of what can be achieved in terms of strengthening adaptive capacities might need to be evaluated according to the level of vulnerability of a country or region. Thus, there is a need to acknowledge that countries have very different starting points in terms of their way towards climate resilience and these differences are also linked to the level of vulnerability.

5.1.1. Prioritizing countries

Interestingly, the external validation revealed that larger absolute economic losses per hazard event occur in less vulnerable countries. While this might be an argument for prioritizing less vulnerable countries as well, we observe that these countries that experience the highest absolute economic losses are often those that have wealth and measures that support recovery processes, such as higher levels of insurance coverage. In contrast, in poor communities, households whose houses and possessions have lower monetary value or who experience non-economic losses are not sufficiently visible within existing loss metrics. This is particularly true for informal economies, which make up a large proportion of the economic activity and value-adding in many of the most vulnerable countries. Consequently, our analysis underscores that there is a need to critically revisit whether economic damage as often used for the allocation of funding (after major events) is an appropriate indicator to assess the severity of impacts to climatic hazards.

While there is a need to account for the costs of climate change in terms of real estate losses or water costs, it is particularly the irreversible impact—like mortality or small scale chronic and irreversible losses—that require more attention. Moreover, a further disaggregation of mortality data by gender and other social categories would help global assessments to better account for these differences. Since this data is not available for most countries yet, it is recommendable to introduce and financially support such loss and damage reporting tools that also account for gender and social categories also in national adaptation strategies and through international adaptation funding. Only on the basis of a better understanding of societal impacts of climate influenced hazards, more specific adaptation and risk reduction goals can be formulated.

Even if in the past climatic hazard mortality has been relatively low in terms of absolute or relative numbers of fatalities per hazard event, it is essential to strengthen climate resilient development in these vulnerable regions. This is also crucial given the increasing number of affected people and economic damages due to natural hazards modified by climate change (Wallemacq and House, 2018) since it is likely that even smaller increases in hazard frequency and intensity will have adverse consequences.

5.2. Limitation and uncertainty

Despite improvements for example in terms of the representation of SIDS in global maps of vulnerability, the study shows clear limitations and constraints of the global vulnerability indicators and index approaches studied. Next to the uncertainty about the definition used for vulnerability or the data quality for the assessment (see Visser et al., 2020), indicator approaches only measure a part of the underlying indicandum—the phenomena of interest. Consequently, indicators are intentionally reductionist in that an indicator system can only focus on particular elements of the broader complex of vulnerability. For example, income inequality measured with the GINI index is just one aspect of inequality and there might be countries where such income differences are just one layer of inequality. Another example is that the adult literacy rate or the combined gross school enrolment is used as indicators for measuring adaptive capacity. The assumption is that a higher level of education allows one to be better prepared for livelihood transitions and future hazards and climate change. However, the quality of the schooling programme and the content of curricula are not captured in this assessment.

Gender parity in education or the share of female representatives in the national parliament are just two indicators that hint towards the relevance of the topic, but more specific structures of gender inequality cannot be captured with these global indicators and the present data. Issues of ethnicity are also often absent within global databases. The INFORM index uses the indicator "other vulnerable groups" to assess the vulnerability of specific marginalized groups, however, the aggregated indicator is also not in the position to include very local or context specific aspects, due to the intention of international comparison. That means global vulnerability assessment approaches have some limitations in considering local context and social diversity. Some flexibility can be used while implementing the assessment framework at subnational or local scale. For example, during the assessment indicators can be operationalized in a way that captures communities' priorities, values and aspirations.

Both the INFORM and WRI concepts assume that vulnerable groups do not just have deficiencies, but also different coping and adaptive capacities that need to be captured in the indicator list. Consequently, also the relationships between the indices and indicators are important and should receive more attention in the future. Furthermore, the rising importance of everyday risks and extensive impacts needs further attention in global datasets and assessments. In contrast to conventional risk assessments that often use absolute economic losses as a core focus, which means that high value physical assets and high hazard intensities are placed as a priority, we argue that vulnerability and systemic societal vulnerability in particular is a more appropriate metric since it points towards places where even a normal (non-extreme) storm, flood or drought are likely to result in ill health or damage to physical assets particularly for the poor. That means, even though these indicator based assessments provide only one layer of information and show a selected piece of a more complex picture, the findings underscore that we need to broaden our focus from the identification of how climate change causes physical impacts towards a perspective that accounts for the existing differences in vulnerability and thus better acknowledges the different starting points for climate resilient development.

5.3. Information for different levels for action

Promoting progress towards climate resilient development requires not only visions and tools for future development, but also the consideration of pre-existing adaptation gaps revealed when looking through the lens of different levels of vulnerability. The majority of the most vulnerable countries have contributed little to global greenhouse gas emissions but still face the major burden of climate change if we consider that human fatalities are key (see Fig. 5). Recent studies (Arnell et al., 2019; Tabari, 2020) that assess the future development direction of climatic hazards in different regions show, for example, that there is a high probability that droughts as well as flash floods, will increase, particularly in Africa. Various world regions are also likely to experience extreme heat events and coastal flooding and sea-level rise in the future (IPCC, 2018, 2014b).

5.3.1. Vulnerability assessments can also complement climate information

The newest IPCC AR6 report of the WG I (IPCC, 2021) includes, for example, synthesis of observed changes in agricultural and ecological droughts differentiating four types: increase (1), decrease (2), low agreement in the type of change (3) and limited data (4) (see Figure-I in Supplement). The assessment reveals for Africa that four climate zones are characterized by an increase of agricultural and ecological droughts, while for North Eastern Africa and South Eastern Africa solely "low agreement in the type of change" and for the Sahara "limited data" was found. While the assessment is of high quality, it is important to note that North Eastern and South Eastern Africa are areas that rank among the most vulnerable regions globally. The region of Eastern Africa (including North Eastern and South Eastern Africa) was exposed to over 200 hazard events (droughts, floods and storms) and faced more than 100 fatalities per event between 2010 and 2019. In contrast, Eastern Asia (e.g. encompassing China) faced more than 300 hazard events during the same period but had a mortality of 15 to 31 fatalities per event. Thus, vulnerability information and the external validation results can provide an important additional layer of information for defining adaptation needs and priorities. Thus, considering both – climate and vulnerability information can be highly relevant to inform adaptation policies since hazard information alone would point towards the urgent adaptation needs in Eastern Africa.

5.3.2. Vulnerability assessments can inform adaptation

Considering aforementioned discussion, adaptation measures for protecting communities from droughts or floods requires significant financial, institutional and human resources, the identified already existing adaptation gap has to be addressed as a priority, next to hazard specific adaptation projects. It is essential that we better understand the contributions that specific adaptation options can make to climate resilient development and vulnerability reduction.

Enhanced warning systems for drought risks are needed, alongside investments that address the existing vulnerability and adaptation gap, for example, in terms of access of most vulnerable people to basic infrastructure services, such as water, energy, sanitation and medical services. The correlation analysis (see Supplement, Table-E) underscored that significant but not very strong correlations exist between mortality per hazard event and vulnerability components such as inequality, vulnerable groups, infrastructure and development and deprivation in terms of INFORM*v* and governance, medical services, economic capacity and public infrastructure in terms of the WRI*v*. While indicators and indicator systems can only capture some elements of larger structures and systems, in this case, it can be argued that access to basic infrastructure and measures that reduce inequality and improve the access of vulnerable groups to basic infrastructure services is an important element of the solution space. Also, investments in improving medical infrastructure and access to it for most vulnerable groups within vulnerable countries are a valid resulting recommendation. Consequently, hazard specific adaptation programmes and local adaptation projects need to be complemented with larger scale infrastructure programmes at the national level if climate resilient development is to be achieved.

Increasingly recognized as fundamental for vulnerability reduction and adaptation are social insurances and infrastructure programmes as well as legislation that improves the access of poor and marginalized groups towards basic infrastructure services and basic security. Social insurance or protection programmes are not yet routinely included in indicator systems of vulnerability. The “free basic service programme” of the national government of South Africa (GovSA, 2021) is one example where the government of South Africa has committed itself to provide a basic amount of free water, electricity and sanitation to low income households, particularly indigent people such as those living in informal settlements or remote rural areas. This is an important measure for reducing systemic societal vulnerability since many countries that rank high in terms of vulnerability have a large proportion of people without access to such basic services. Coupled with incentives, for example in terms of a higher use of renewable energy (e.g. solar home systems in rural areas see GovSA, 2021) these investments can support vulnerability reduction and mitigation of greenhouse gas emissions. However, there is also a critique of the programme design and implementation (see Muller, 2008; Nel and Rogerson, 2005) as is witnessed by ongoing service delivery protests (Mutyambizi et al., 2020). The National Infrastructure Plan of South Africa also directs national investments into education, medical, water and sanitation infrastructure. These national plans address (in part) inequality and spatial disparities and might provide enabling conditions for local adaptation approaches.

Overall, the “free basic service programme” that targets particularly poor and most vulnerable groups shows that current national programmes can be linked to different aspects assessed within global vulnerability approaches. Hence, these indicators can, directly and indirectly, support the identification of levers for action. At the same time, it is important to acknowledge that drivers and root causes of systemic vulnerabilities and development challenges are not always new, and sometimes—for example in various countries in the Caribbean, Africa and Asia—can be linked to histories of imperialism, colonial structures, and subsequent development and governance contexts.

6. Conclusions

The most vulnerable countries and regions should become priority sites for climate resilient development since these regions and countries need support in reducing vulnerability and adapting the economic and social systems to a changing climate. The analysis and validation of vulnerability indicators of the WRI*v* and INFORM*v* index have revealed that the most vulnerable regions and countries have been suffering disproportionately already from climate-related hazards. While individual hazard events and local context conditions influence specific disaster outcomes it is important to note that the external validation clearly revealed that significant differences exist as to whether and how such natural phenomena (floods, droughts and storms) translate into disasters in most versus least vulnerable countries. Considering that the mortality per hazard event due to flood, storm or drought is already 15 times higher in the most vulnerable countries compared to countries with low vulnerability—based on the average of two global index systems (WRI*v* and INFORM*v*) and disaster impact data of the past 10 years– it is essential to acknowledge these facts when defining adaptation priorities. Past and existing climate impacts undermine resilience and sustainable development.

Our findings support calls for Loss and Damage policy to promote risk reduction through addressing inequalities that lie behind the vulnerability differences (Roberts and Pelling, 2020). In this regard, it is interesting to note that some regions that are highly vulnerable have not yet seen high mortality figures in the past 10 years. Climate change is likely to intensify particular climate hazards and modify their spatial occurrence so that places not yet exposed may be so in the future. Hence, the vulnerability information can be coupled with information on the future intensification of hazards and the spatial shift of hazards towards regions that have not been exposed in the past. This information would allow the identification of regions that might need to prepare for new or changing hazard patterns. Moreover, vulnerability and systemic societal vulnerability in particular is not static, rather it is dynamic and therefore monitoring tools are needed that are flexible (i.e. be able to integrate new topics and indicators), but at the same time also allow for longitudinal studies.

Our findings showed that the WRI*v* and INFORM*v* index can be validated in terms of the internal and external validation tests, however, clear limitations are also revealed. The first limitation is that the validation results apply to the sampled areas and the data available at this moment in time. Data limitations, especially due to missing data for some countries, could be addressed in future using machine learning techniques (e.g. Jia and Ma, 2017; Mikhailiuk and Faul, 2018). Consequently, the analysis of the internal and external reliability of the index systems might need to be repeated on a regular basis. Moreover, temporal dynamics of vulnerability should also receive more attention as shown by Feldmeyer et al. for the WRI (see in detail Feldmeyer et al., 2017).

Our internal validation confirms former studies (see Welle and Birkmann, 2015), however, it provides new insights in terms of the external validation and the link between indicators and the underlying indicandum. We have shown that at broader scales and within a time span of 10 years the vulnerability level of a country or region significantly influences disaster outcomes when focusing on mortality and economic losses due to floods, droughts and storms. The mortality associated with climate influenced hazards can also have other causes (e.g. malnutrition, no access to basic services like water, sanitation) which may be exacerbated due to climate change, and are not exclusively caused by it. These factors can be captured with assessments of vulnerability.

In terms of future improvement, there is a need to improve the linkages and capacities of assessing sub-national and more context specific vulnerability aspects. While global comparative approaches can account for some heterogeneity of countries in terms of the inclusion of specific indicators, the core of the assessments is still based on the development of an indicator set that allows the comparison of countries and regions with each other. Thus, most concepts focus on a relative vulnerability approach that means vulnerability does not appear when a specific threshold is reached, but rather these assessments measure the differences in terms of the vulnerability level between countries and regions. In order to promote stronger linkages between global assessments and sub-national or local assessments, the subcomponents of these global index systems should allow for flexibility. That means, themes and sub-components such as the access to basic services or gender inequality might need to be operationalized differently within a specific country or local context.

It is important to acknowledge that global comparative vulnerability assessment approaches like WRI and INFORM can provide one layer of aggregated overview information that needs to be complemented with more context specific information and additional methods at sub-national and local scales. Data available at the global level with national scale resolution, however, neither aims to provide nor would be able to deliver adequate knowledge for informing and guiding more local risk reduction, including the vast problems related to inner-country inequalities and disparities, both spatial and socioeconomic (Pelling and Garschagen, 2019).

Besides sub-national and local scales, also the regional scale needs more attention. A low variance of the level of vulnerability within a region (Fig. 6), points towards the fact that within this region it is not a single country or single community that is particularly vulnerable, but rather a cluster of countries that are characterized by a high level of vulnerability. This means local or national adaptation programmes need to be complemented with regional scale adaptation strategies, including incentives for transboundary cooperation.

Overall, there is a need to improve measurement tools to track and support climate resilient development at various scales, particularly in the most vulnerable countries. This should also include monitoring tools that account for interventions to reduce systemic societal vulnerability such as measures of social security and free basic services. It is important that the indicators and maps of a vulnerability assessment are valid and accurate (as discussed within this paper), however, it is similarly important to acknowledge that indicators do not replace the need for making informed decisions.

CRediT authorship contribution statement

Joern Birkmann: Conceptualization, Methodology, Writing – original draft, Supervision. **Ali Jamshed:** Formal analysis, Methodology, Writing – original draft, Visualization. **Joanna M. McMillan:** Visualization, Writing – original draft, Writing – review & editing. **Daniel Feldmeyer:** Formal analysis, Data curation. **Edmond Totin:** Formal analysis, Writing – review & editing. **William Solecki:** Writing – review & editing. **Zelina Zaiton Ibrahim:** Writing – review & editing. **Debra Roberts:** Writing – review & editing. **Rachel Bezner Kerr:** Writing – review & editing. **Hans-Otto Poertner:** Writing – review & editing. **Mark Pelling:** Writing – review & editing. **Riyanti Djalante:** Writing – review & editing. **Matthias Garschagen:** Writing – review & editing. **Walter Leal Filho:** Writing – review & editing. **Debarati Guha-Sapir:** Writing – review & editing. **Andrés Alegría:** Writing – review & editing.

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.

Appendix A. Supplementary data

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