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Vulnerability to climate change and its measurement: A survey

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Aggravating the intensity and frequency of hazardous events and causing more threats to human lives, climate change has become a foremost environmental issue. With the emphasis of IPCC on the scientific understanding of vulnerability to climate change, the measurement of vulnerability is important not only to knowing to what extent an area is vulnerable to climate change, but also to the government of policy formulation in order to mitigate the extent of vulnerability. Till date, different methods have been developed using both econometric and index based approaches to measure vulnerability to climate change. This paper summarizes different approaches to measure vulnerability to climate change and the data related issues of these methods. The paper also presents the nexus between different methods and their applicability based on the available socioeconomic environment and the type of data concerned. The discussion on the use of different available methods by the later researchers in the succeeding section further enlarges the scope of use of these methods. Finally, we wind up the paper with some possible suggestions on the methods used to assess vulnerability to climate change for the later scholars.

Introduction

Research on vulnerability due to climate change evolved and gained attention with the framework of the IPCC working group II (Birkmann 2013), which deals with the impact, adaptation and vulnerability to climate change (IPCC 2012a). Assessing vulnerability to hazards involves understanding the potential adverse impact on human livelihoods resulting from exposure to these hazards (Cutter *et al.* 2009). The goal of vulnerability assessment is not only to identify what and who is vulnerable to risks but also to identify the underlying factors and driving forces that shape vulnerability in a specific area (Hill and Cutter 2001). The methods that the vulnerability assessment analysis follows are qualitative or quantitative in nature. More people-centric methods, such as focused groups, in-depth interviews and participant observations are used in qualitative approaches. These methods emphasize the basic function of a researcher as an influencing interpreter of the situation (Massmann and Wehrhahn 2014). On the other hand, the quantitative approaches help the numerical estimation of vulnerability. With the advances on vulnerability science, the attention of vulnerability assessment has been diverted from the qualitative aspect to the quantitative or empirical measurement of the same (Cutter *et al.* 2009).

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Different quantitative approaches are being used to measure vulnerability to climate change. Although a number of methods have been used by various researchers, there is a lack of literature providing a comprehensive discussion regarding theses quantitative methods of vulnerability measurement, measurement issues and the suitable environment for using them. Such discussions are important for researchers to have a deep understanding about their respective research area and to carry out further research on their field depending upon the socioeconomic environment with the available data sources. The objective of this paper is to see the use of these quantitative approaches to measure vulnerability depending on different socioeconomic environments and their measurement-related issues. Therefore, the purpose of the paper is to establish a methodological foundation for measuring vulnerability to climate change and aiming to assist future researchers in selecting an appropriate method for vulnerability assessment. In this paper, the definition of vulnerability to climate change is taken from IPCC (2014, 2021) as "*the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt*".

Hazard, vulnerability and climate change: a background

Rich amounts of literature are available for studying hazards, disasters and risks (Cutter *et al.* 2009). In the 1980s, the importance of disaster risk reduction led to the emergence of a new research area in the field. (Rhyner 2013). Some of the prominent contributions towards this area include those by Burton *et al.* (1978), United Nations Disaster Relief Organization (UNDRO 1980), Susman *et al.* (1983) and Hewitt (1983). While studying different hazardous events, Burton *et al.* (1978) discussed the nature of adjustment adapted by individuals and social groups towards these extreme natural events. UNDRO Commission (1980) explained various natural hazards, risks associated with them, methods to study these risks and the use of regional planning to minimize the risks associated with those hazards. Susman *et al.* (1983) related the theory of marginalization with the disaster and illustrated how the process of marginalization develops with the hazards. Hewitt (1983), in his edited book, discussed the risks of hazards across different socio-cultural and environmental domain.

The risk due to a disaster may be explained as the damage or destruction caused by a given disaster and also the probability of injury or loss of life due to it during a particular period of time (Bouaakkaz *et al.* 2023). The UNDRR (2019) recognized the disaster risk as an outcome of "*the interaction between a hazard and the characteristics that make an area (population and places) vulnerable and exposed*" (Bouaakkaz *et al.* 2023). According to the definitions given by UNDRR (2019), hazard is "*the probability of experiencing a certain intensity of hazard (e.g., earthquake, cyclone, flooding, etc.) at a specific location and is usually determined by a historical or user-defined scenario, probabilistic hazard assessment, or other methods*". And exposure is "*the stock of property and infrastructure exposed to a hazard, and it can include socioeconomic factors*". Over the years, the focus on the impact of shocks in terms of loss of human life and physical infrastructure, disaster risk reduction has become a major concern for researchers and policy makers. One of such example is the Sendai Framework (2015), which was introduced in the World Conference on Disaster Risk Reduction held in Sendai, Japan. The prime objective of this framework is to reduce substantially the risks and losses in lives due to disasters as well as the disaster induced losses in the form of health, livelihood, people's economic condition, and social, cultural, physical and environmental assets. Moreover, climate change magnifies the intensity of disaster and risks, making people's lives and livelihood more vulnerable; predicting more occurrences of hazards on the one hand while indicating the importance of resilience of individuals on the other (IPCC 2001). As a result, the environmental, economic, social and cultural impacts disasters are considerably increasing; indicating the importance of emergence of more inclusive studies integrating various aspects of it, its management and

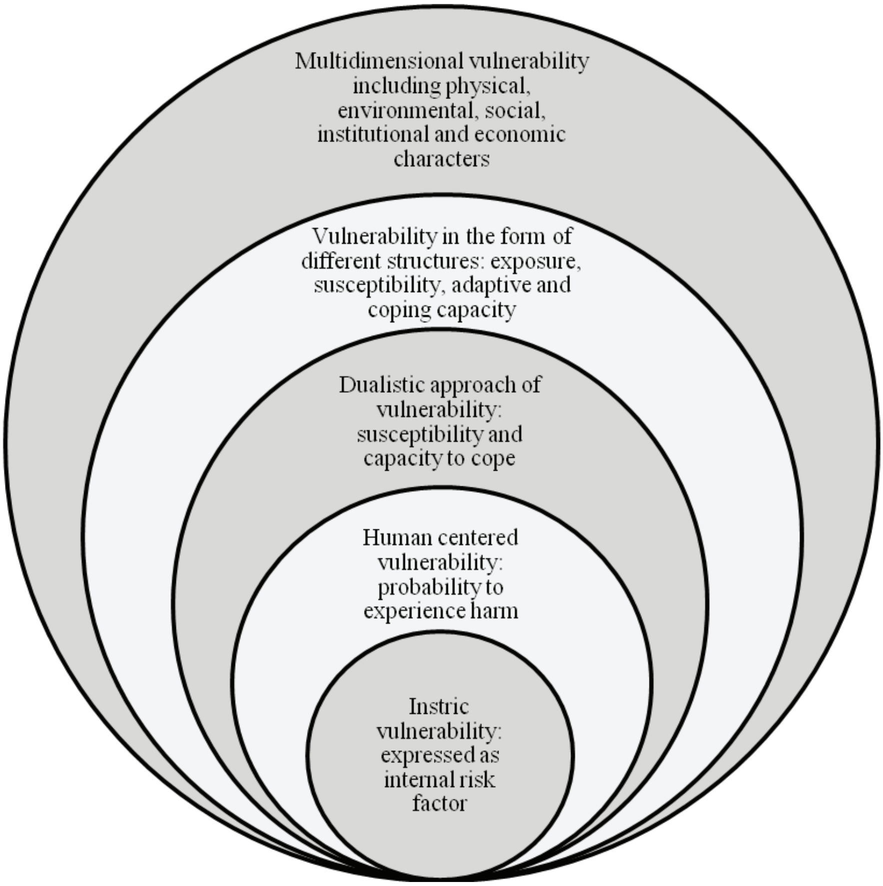

Fig. 1. Key Shapes of Vulnerability. Source: Birkmann (2005, 2013).

mitigation (Miranda and Ferreira 2019, Das *et al.* 2023). Amongst different types of natural disasters over the past two decades, the most frequently observed one across the globe is flooding caused by hydrological disasters (Caris *et al.* 2018). Over time, the field of disaster risk reduction has undergone significant development and has embraced different perspectives, ultimately emphasizing the concept of vulnerability as well as the identification of different core factors of vulnerability (Birkmann 2013).

The idea of vulnerability is a recent concept in comparison with the concepts like hazard, natural disaster and disaster risk management (Bouaakkaz *et al.* 2023). United Nations (UN), in the Yokohama Conference, adapted vulnerability as a basic concept. Vulnerability to hazards is an enormous concept covering physical, social and economic dimensions. The physical dimension talks about damages by hazards and the extent of exposure to hazard (Werren 2013), while the social dimension deals with the resilience of the society or human individuals and its ability to cope with (Reghezza 2006). The comprehensive social, physical and economic dimension is about the degree of influence to which a societal system, community, household or individual is affected by a dangerous hazard and at the same time the ability of them in mitigating the effect of hazard and recovering from the same (Mileti 1999, UNDRR 2019, Cutter *et al.* 2000, Cutter 2001, Cutter *et al.* 2003, ISDR 2004, Adger *et al.* 2009, Blaikie *et al.* 2014, Hewitt 2014, Bouaakkaz *et al.* 2023, ISDR 2009). Considering all the above dimensions, Birkmann (2013) gives a more comprehensive definition of vulnerability (Fig. 1).

Changes and variability in climate lead to changes in the intensity, frequency, duration, spatial extent and timing of extreme climatic and weather conditions, and can also lead to unpredictable extreme situations (IPCC 2012). Studies have revealed that global climate change has a great impact on precipitation: under the situation of global warming, the intensity as well as frequency of rainfall and flood are mostly expected to increase (Christensen and Christensen 2007, Nikulin *et al.* 2011, Whitfield 2012, Pendergrass and Hartmann 2014, Coppola *et al.* 2021, Ojeda *et al.* 2022). It is often believed that climate change aggravates the hazardous events causing harmful impact on the living communities and their socioeconomic development (Islam *et al.* 2015, Panthai *et al.* 2016, Simotwo *et al.* 2018). Looking at the aggravated climate change impacts, for many of the developing countries, natural hazards are not only the issues related to the environmental aspects but also stands as vital development issue (Ashley *et al.* 2000).

The study and the assessment of vulnerability to climate change taking the human perspective is important (Birkmann *et al.* 2022). The importance lies on the ground that chances of losses due to various hazardous events, such as droughts, storms or floods, are not the result of climatic hazards alone, but are also influenced and determined by the anthropogenic factors, such as coping and adaptation at both individual and societal level (Cutter *et al.* 2003, Cardona *et al.* 2012, IPCC 2012a, IPCC 2012b, Birkmann 2013, UNDRR 2019). Research on vulnerability in relation with climate change and climatic risks involve different paths to interpret vulnerability. Researchers may express vulnerability as a starting point, or as an outcome of an event such as hazard (Füssel 2007). The reports of IPCC (2012b, 2014b) are giving clear indications that the study of vulnerability to climate change from the perspective of ecosystem and society is a better representation of a starting point of vulnerability rather than the vulnerability as an outcome. On the other hand, the studies of vulnerability as an outcome mostly include the information of hazard, and as a result these are unable to differentiate risk and vulnerability in a sufficient manner (IPCC 2012, 2014b). The information on hazard and climatic situation talks about the physical phenomenon like the changes in mean temperature, intensity and frequency of storms, floods, droughts etc. and, on the other hand, vulnerability explains "*the propensity or predisposition of a system to be adversely affected by external shocks*" (IPCC 2001) and therefore the concept of vulnerability is associated with the nature of a community or a social system that how much they are prepared to speculate or react to the unforeseen risks (IPCC 2014b, Sharma and Ravindranath 2019).

Methods to measure vulnerability

In literature about vulnerability, there are two ways to measure or study vulnerability: econometric analysis and indicator-based method (Deressa *et al.* 2008). Econometric approaches are deductive in nature and provide better realism compared with an inductive approach. Establishing a causal relationship among the variables, the econometric approach helps the researchers to understand the significance of the different relevant variables in relation with the happening of the vulnerable situation (Noy and Yonson 2018). Indices or indicator-based approaches are basically known as the inductive approach of measurement, which reduces a large set of indicators to smaller values helping the researchers to present an overall view and idea on the concerned issue (Burton *et al.* 2018).

Econometric Approach

According to Noy and Yonson (2018), the econometric methods of assessing vulnerability explain two strands. First, they try to find out the factors having direct and significance impact on people and their assets due to the occurrence of a disaster. Second, these methods aim to measure the economic impacts of vulnerability typically either in the short-run or in the long-run. In the econometric approaches of vulnerability, the dependent variables are the direct impact of disaster on people or assets, and therefore these methods study the direct damage or cost from disaster (Lazzaroni and Berheijk 2014). Economists in general talk about three econometric methods to study about vulnerability: vulnerability as expected poverty (VEP), vulnerability as low expected utility (VEU) and vulnerability as uninsured exposure to risk (VER). These methods use the socioeconomic survey data collected from the individual household in order to analyze vulnerability on different grounds.

The vulnerability as expected poverty (VEP) method is based upon the probability estimation of the households to have a below-the-minimum level of consumption (for example: consumption poverty line) in the coming days (Chaudhuri *et al.* 2002, Deressa *et al.* 2008). Or in other words, the VEP framework studies the probability of a person to become poor in the coming days if this person is not poor currently, or the probability of the continuation of the person being poor if this person is already under the poverty (Christiaensen and Subbarao 2004). Under this framework, consumption (income) is considered as a proxy for well being and the idea of vulnerability is studied as an expected poverty (Deressa *et al.* 2008). VEP as proposed by Chaudhuri *et al.* (2002) of a household "*a*" at period "*t*" is the probability that *a*'s consumption per capita in the next period "t + 1" will go down below the poverty line at period "*t*" and the basic formula is given as:

$$V_{at} = \Pr\,(C_{a,t+1} < Z), \tag{1}$$

where Pr means the probability, V_{at} represents the vulnerability index of a^{th} household at time period t and $C_{a,t+1}$ is its consumption per capita at time period $t + 1$ and the socially defined poverty line is indicated by Z.

Ligon and Schecter (2002, 2003) introduced the method of vulnerability as low expected utility (VEU). To define vulnerability in a risky environment, they use a utilitarian approach. They decompose the utilitarian measure of vulnerability into distinct measures of aggregate risk, idiosyncratic risk and poverty. Vulnerability is expressed as a measure of loss in utility. The loss in utility is the difference between the level of utility that the households may derive from some certainty-equivalent level of consumption where the households do not consider themselves as vulnerable and the expected utility from the actual level of consumption expenditure. Using this view, the vulnerability of a household "*b*" can be expressed as:

$$V_b = U_b(X) - \mathrm{EU}(C_b). \tag{2}$$

Here, $U_b(X)$ is the utility of the household b from X, where X is the certainty-equivalent consumption level and consumption level above or equal to this level indicated that the individual is not vulnerable. EU is the expected utility from consumption of the household b (C_b).

Vulnerability as uninsured Exposure to Risk (VER) method is useful in accessing the change in the consumption of households as a result of shock (Deressa *et al.* 2008). Therefore, this model is based on the ex-post assessment of vulnerability, which means that VER examines the extent of welfare loss caused by the occurrence of negative shocks (Hoddinott and Quisumbing 2003). The VER model used by Endalew (2021) is given by:

$$\mathrm{Hloss}_i = \propto + \Sigma\beta_j(\mathrm{CV})_{ij}, \tag{3}$$

where Hloss_i is the total income loss of i^{th} household, $\propto$ is the intercept term, $(\mathrm{CV})_{ij}$ is the value of j^{th} characteristics of the components of vulnerability to climate change of i^{th} household, and β_j is the coefficient of $(\mathrm{CV})_{ij}$.

The three methods described above have the same characteristics in that they measure the loss of welfare due to shocks (Deressa *et al.* 2008, Narayanan and Sahu 2016). Apart from taking consumption as the dependent variable, several other welfare indicators can also be used in these three approaches (Hoddinott and Quisumbing 2003). The VER model is an ex-post-facto analysis of vulnerability, whereas the other two methods (VEP and VEU) are more concerned about estimating the likelihood of the occurrence of negative impacts on households as a result of given shocks (Deressa *et al.* 2008). Looking at the econometric models from the vulnerability literature, Hoddinott and Quisumbing (2003) argued that both VEP and VEU determine a benchmark of welfare (which may be poverty or utility) and measure the likelihood of falling below the determined level of welfare. Both of the methods try to give a future prospect of the vulnerability situation by calculating vulnerability at the individual levels. The sum total of vulnerability of all households or individuals will facilitate the measurement of aggregate vulnerability. On the other hand, the VER model does not construct probability, hence it does not measure vulnerability; rather it tries to focus on the issue that if the observed shock leads to the generation of welfare loss to the society. Therefore, the VER method will study the nature of impact of different factors and dimensions associated with vulnerability on economic well being. Hence, the VER model can be considered as useful to study the post effects on the economic well being after the occurrence of hazards (Saikia and Mahanta 2023).

Again, in addition to the VER model, some scholars like Mazumder *et al.* (2022) and Atiglo (2022) used a logistic regression, another form of econometric analysis, to see how different social and biophysical characteristics are related to a spatial exposure to flood risk. Another econometric model is that by Langill *et al.* (2022), where they used the Ordinary Least Square (OLS) method to find out the main factors contributing to flood vulnerability in the form of impact, exposure and response. For the regression, they integrated the vulnerability to flood across impact, exposure and response to construct the outcome variable.

Indicator-based approach

The vulnerability and risk measuring indices and indicators aim at capturing the phenomenon of different dimensions and better understanding of spatial structures and levels as well as different components of risks and vulnerability of the societies of different regions which are exposed to natural and climatic hazards (Birkmann *et al.* 2022). Another purpose of these approaches is also to support the individuals', households' or society's decision making in relation with the disaster prevention, their responses to disaster and preparedness for the same (IPCC 2019, UNDRR 2019). The vulnerability to climate change can be broadly divided into two aspects: the social or socioeconomic aspect and the physical aspect (Cutter *et al.* 2009). Social vulnerability is the result of various social factors shaping the susceptibility of a community to be adversely affected by hazards and determining their ability to respond to it (Cutter *et al.* 2003). Socioeconomic aspects are linked with those social and economic factors that contribute people's livelihood activities, sensitivity and their ability to adapt in response to the disturbances caused by the physical environment (Hahn *et al.* 2009). On the other hand, the idea of physical vulnerability captures the geophysical conditions associated with the occurrence of a given hazard (Findoeno *et al.* 2020). To study vulnerability of different aspects, indices are widely used. An advantage of using indices is that they can incorporate a wide range of variables into one single value, providing the researchers a scope for clearer presentation of the situation (Vincent 2004). Various indices have been developed and used to study vulnerability to climate change and other natural hazards by various researchers. This section of the paper presents a review on the indices used to study vulnerability concerned with the natural hazards and climatic shocks and stress.

Researchers believe that the socioeconomic status of a community or an individual has the potential to influence absorption of losses due to the hazards (Peacock *et al.* 2000, Cutter *et al.* 2009). Under the social vulnerability indices, the social factors that can increase or decrease impacts of natural hazards on the local population were carefully studied. Cutter *et al.* (2003) considered a socioeconomic dimension and introduced the Social Vulnerability Index (SoVI) to measure social vulnerability to climate change in the counties of United States. A total of 42 independent variables were studied in the SoVI. Data were collected from a secondary source. An additive method was used in the construction of the index with the assumption that all the factors have equal contributions to the country's vulnerability. Therefore, the assignment of same weight may be considered as a drawback of the SoVI. As an improvement over the methodological drawback of the SoVI, Vincent (2004) developed the Social Vulnerability Index (SVI). The

SVI is a weighted average of the subcomponents used to study social vulnerability, and it is used to measure vulnerability at a national level. The calculation of the SVI is based upon secondary sources of data. The SVI uses the same weight for all the countries. However, according to Ahsan and Warner (2014), it is important to have different weights of subcomponents for different countries. Vincent (2004), for the calculation of the SVI, used a wide range of indicators, such as economic well-being and stability, demographic structure, institutional stability and strength of public infrastructure, global in-connectivity and natural resource dependence. In the later phases as well, different indices were developed on the basis of the socioeconomic dimensions of vulnerability taking different social indicators. Like Vincent (2004), Ge *et al.* (2013) used a total of nine different indicators to develop the Social Vulnerability Index (SVI). However, Ge *et al.* (2013) used Projection Pursuit Cluster (PPC) to assign weigh against the different indicators under the calculation of the SVI. An important limitation of this method is related to the use of PPC: since there is no algebraic solution for PPC, it cannot derive a global optimal situation (Ge *et al.* 2013). Due to the presence of these difficulties in weight assignment among different methods of vulnerability measurement, another index Social Vulnerability was developed by Lee (2014). Here, in the index of social vulnerability, Lee (2014) used human capital, social capital, public security and provision of public resources as indicators to measure the value of the index. However, the method was further criticized on the ground that it considers only a single hazard, flood, and vulnerability is expressed as a positive function of the considered variables (Ahsan and Warner 2014).

According to Deressa *et al.* (2008), the socioeconomic approach of vulnerability basically concentrates on the variations within the society only. However, in a real world it may be that environmental conditions along with socioeconomic conditions influence the vulnerability situation of the society. As an alternative, a biophysical approach basically studies the level of damage due to a given environmental stress on social and biological systems. Though the biophysical approach is much informative in nature, it focuses on accessing the physical damages only. For example, Physical Vulnerability to Climate Change Index (PVCCI) developed by Findoeno *et al.* (2020) is completely based on the physical dimension of vulnerability. Through this index, the extent of physical vulnerability of the countries is measured. In a general sense, the biophysical approach basically only concentrates on the sensitivity aspect of a given hazard (Deressa *et al.* 2008). Therefore, it is important to have a method that envelops both biophysical and socioeconomic dimensions of vulnerability to bring out a clearer and better picture of the situation. Deressa *et al.* (2008) hence used the indicator-based method to quantify vulnerability in the form of developing index combining the socioeconomic and biophysical aspects of vulnerability. The vulnerability index by Deressa *et al.* (2008) was based upon the IPCC (2001) definition on vulnerability. This index is expressed as the addition of the weighted values of the variables and for the assignment of weights, and Principal Component Analysis (PCA) is used. The study was based on secondary data. A proper weighing mechanism was used to assign weights against the indicators under the three main dimensions of probability, and once the value of each dimension was measured, the vulnerability index was obtained by taking the average of the three dimensions of vulnerability. In the vulnerability research, the issue of missing data is always a serious one when the research is based on secondary information (Hahn *et al.* 2009). Therefore, in order to avoid such data related issues, Hahn *et al.* (2009) introduced the Livelihood Vulnerability Index (LVI) based on primary data and the concept of vulnerability proposed by IPCC (2001). The LVI is a combination of both biophysical and socioeconomic approach of measuring vulnerability and is useful for a region-specific comparison of vulnerability. Hahn *et al.* (2009) developed another index, the LVI-IPCC, which is also based upon primary and secondary data, being suitable for region, community, culture, gender and other social component-specific comparative analyses. The only difference between the LVI and LVI-IPCC is the method of calculating the final index. Apart from this, both the indices use the same variables and weighting technique.

Another vulnerability index, the Household Vulnerability Index (HVI), was used by Ehsan *et al.* (2022) to study climate change vulnerability in the Selangor coast of Malaysia. The HVI is more or less similar to the LVI and is also based upon primary data. The only difference in the calculation of the index is that the HVI assumes equal weighing techniques when calculating the indices of exposure, sensitivity and adaptive capacity separately. Ehsan *et al.* (2022) also studied the sensitivity index, exposure index and adaptive capacity index separately in different locations of the respective study area. Pandey and Jha (2012) introduced the Climate Vulnerability Index (CVI) to measure the vulnerability to climate change of different communities. The CVI was constructed on the basis of the LVI by Hahn *et al.* (2009) and was used in the lower Himalaya regions of India to measure the vulnerability to climate change of the communities residing here. In a similar manner, using the definition of IPCC (2001) where vulnerability is given as a function of sensitivity, exposure and adaptive capacity, Ahsan and Warner (2014) introduced the Socioeconomic Vulnerability Index (SeVI). The SeVI is based on a combination of primary and secondary data. Another index based upon the concept of vulnerability by IPCC (2001) is the Livelihood Effect Index (LEI) developed by Urothody and Larsen (2010). A major issue associated with the measurement of the LEI is the complexity of the indicators used, being technical and complicated in nature. As a result, for an illiterate or less literate respondent, it may not be possible to understand the questions properly, which may lead to incomplete information to the scholars.

Looking into some other recent use of vulnerability indices, Das *et al.* (2021) used the Social Vulnerability Index (SVI), the calculation and weighing involving the Principle Component Analysis (PCA). Birkmann *et al.* (2022), in their study of vulnerability, used the WRI and INFORM indices and stated, "*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*". Both the indices are based on a secondary source of data and have been vastly used to measure vulnerability across the countries of the world. The WRI was introduced by Welle and Birkmann (2015, 2016) whose prime purpose was to study and display the risk and vulnerability of a country to face the negative effects emerged due to climatic factors or due to the occurrence of natural hazards. The WRI made it possible to have a comparison of about 173 countries of the world in terms of their vulnerability status. By incorporating the present and expected aspects of conflict, hazard and exposure, the INFORM index tries to study the humanitarian crisis and risks and its main component is primarily related with the vulnerability assessment (Birkmann *et al.* 2022). The INFORM index was created by the European Commission- Disaster Risk Management Knowledge Center in 2020 (EC-DRMKS 2020), and the index has been able to cover 191 countries. The calculation and visualization in case of both WRI and INFORM is possible through the available global database, including the data on inequality, infrastructure, poverty etc. of the countries, which are easily available in the various authentic sources of the respective countries as well as in the database of the World Bank (Welle and Birkmann 2015, 2016, EC-DRMKS 2020, Birkmann *et al.* 2022). Table 1 in the appendix section gives a clearer picture about the methods discussed in this section and their probable limitations.

Data-related measurement issues

A number of methods of vulnerability measurement in relation with climate change have been emerged and used till date. Some of those methods were discussed in the previous section of this paper and also presented in Supplementary Information Table S1. Econometric methods generally require panel data for vulnerability measurements (Deressa *et al.* 2008). However, the availability and authenticity of panel data are important issues in developing countries (Hoddinott and Quisumbing 2003). In an econometric analysis to measure vulnerability, differences in measurements may occur due to the non-availability of panel data (Das and Mahanta 2015). Moreover, Hoddinott and Quisumbing (2003) argued that if cross-section data are collected carefully with the strength of community and qualitative fieldwork and with the use of secondary sources, then they can also reveal much information regarding risk and vulnerability.

The method of vulnerability measurement may be different for developing nations compared with the developed ones (Das and Mahanta 2015). One of the most important reasons for such differences is the unavailability of secondary data in developing countries (Hahn *et al.* 2009). Due to this issue of data unavailability, it may not be viable for the researchers of the developing countries with lack of secondary data to use the methods that are completely based of secondary information. Moreover, also primary data have the potential to reflect the vulnerability status of people or community based on the available information in its surroundings.

Some of the indices, such as the SoVI, SVI, PVCCI and Social Vulnerability, as discussed in the previous section of this paper, are calculated based on secondary data (Cutter *et al.* 2003, Vincent 2004, Deressa *et al.* 2008, Ge *et al.* 2013, Lee 2014, Findoeno *et al.* 2020), whereas other indices, such as the LVI, LVI-IPCC, CVI, LEI and SeVI, are calculated on the basis of primary data (Hahn *et al.* 2009, Urothody and Larsen 2010, Pandey and Jha 2012, Ahsan and Warner 2014). Primary data for all these indices were collected from household surveys. Different secondary sources were used to collect data for the measurement of vulnerability indices developed by different researchers. Cutter *et al.* (2003) collected data on 3141 counties of United States for the year 1990 from City and County Data Book for 1994 and 1998 under U.S. Census. Similarly, Vincent (2004) collected data from six different sources: World Bank (2001, 2002), UN (2001, 2002), UNAIDS and WHO (2002), International Telecommunications Union (ITU 2002), and Transparency International (Hodess 2003). Deressa *et al.* (2008) collected data from Ethiopia's Central Statistical Agency (CSA, 2006) to cover the socioeconomic aspect of vulnerability, while data on environment and disasters were collected from International Water Management Institute and International Disaster Data Base. In a similar manner, the SVI developed by Ge *et al.* (2013) covered 140 counties under 16 municipalities of Yangtze River delta of China. Ge *et al.* (2013) collected data from 1995 to 2009 at the interval of five years from Statistical Year Books and socioeconomic data developed by five research institutions working on the respective region. In the Index of Social Vulnerability, Lee (2014) collected data from Taiwan's National Geographic Information System (NGIS) for a social vulnerability aspect. The data on potential flood were collected from the Water Resource Agency, Taiwan Ministry of Economic Affairs. Findoeno *et al.* (2020) for the calculation of PVCCI collected secondary data from all the 191 member counties of United Nations.

Discussion and conclusions

In the field of climate change research, the concept of vulnerability to climate change and natural hazards is receiving significant attention. In the case of quantitative analysis of vulnerability, researchers have generally used either the indicator-based method or the econometric method. With the use of econometric methods in vulnerability literature, Hoddinott and Quisumbing (2003) argues that both VEP and VEU determine a benchmark of welfare (which may be poverty or utility) and measure the likelihood of falling below the determined level of welfare. Both methods give future indication of the vulnerability situation by calculating vulnerability at individual levels. The sum total of all households or individuals will facilitate the measurement of aggregate vulnerability. On the other hand, the VER model does not construct probability, hence it does not measure vulnerability, but rather focuses on the issue that whether the observed shock leads to the generation of welfare loss to the society. Therefore, the VER method studies the nature of impact of different factors and dimensions associated with vulnerability on economic well being. The VER model can be considered useful in studying post effects on economic well being after the occurrence of hazards. Both biophysical and socioeconomic factors are covered under the VER model, and it studies the impact of these factors on welfare loss in the form of reduction in consumption (Narayanan and Sahu 2016).

From the point of view of index based vulnerability assessment, some indices present vulnerability to climate change from the socioeconomic aspect, such as the SoVI (Cutter *et al.* 2003), SVI (Vincent 2004), SVI (Ge *et al.* 2013) and Index of Social Vulnerability (Lee 2014), whereas some others present the same from physical or biophysical aspect, such as the PVCCI (Findoeno *et al.* 2020). The sensitivity component of vulnerability is covered by the biophysical aspect of vulnerability, while the socioeconomic aspect of vulnerability covers the component of adaptive capacity. However, it may not be appropriate to calculate the sensitivity and adaptive capacity separately as a measure of vulnerability because both are interlinked with each other (Deressa *et al.* 2008). Therefore, a method comprising both the aspects of vulnerability in one index may be considered as more appropriate in knowing the vulnerability status of the society (Hahn *et al.* 2009). Indices, such as the Vulnerability index by Deressa *et al.* (2008), LVI and LVI-IPCC by Hahn *et al.* (2009), LEI by Urothody and Larsen (2010), CVI by Pandey and Jha (2012) and SeVI developed by Ahsan and Warner (2014), are some example of such indices.

For a quantitative assessment of vulnerability in both micro and macro levels, some of the methods discussed in the previous section of this paper are widely accepted by the researchers. Table S2 in Supplementary Information presents researchers using different indices and econometric approaches in different parts of the world and their findings. It is clearly visible that two of the indices, namely the LVI and LVI-IPCC constructed by Hahn *et al.* (2009), are mostly used by various researchers to deal with primary data in region-specific studies, followed by the CVI by Pandey and Jha (2012). The main reason behind gaining popularity among the researchers by these two indices by Hahn *et al.* (2009) may be the simplicity and flexibility nature of the indices. New variables can be incorporated, and variables with no use in the specific region can also be dropped out from the calculation of the LVI and LVI-IPCC (Hahn *et al.* 2009). As a result, the indices are found to be used in many areas of the world that are geographically as well as climatically different in nature. Another reason for the popularity of these indices is that they can use primary data. It is often seen that there is a lack of proper secondary data to facilitate the researchers with the needed information on the variable that they consider for study. This issue is more prominent in the developing countries (Hahn *et al.* 2009, Pandey and Jha 2012). Another index, the SoVI by Cutter *et al.* (2003), is also used by researchers dealing with the macroeconomic studies making use of secondary data. The use of some econometric methods by researchers in some of the recent studies is also visible in Table S2 in Supplementary Information. However, the econometric approaches of vulnerability to climate change are not seemed to be widely used in this field. Moreover, as both the indicator-based and econometric approaches have their own pros, it can be suggested that in order to have a better understanding, both approaches should be used together to study vulnerability to climate change. An example of such approach is seen in Table 2 from Endalew (2021), where the author uses the index LVI-IPCC and econometric model VER to study the vulnerability to climate change in Ethiopia.

Supplementary Information: The supplementary information related to this article is available online at: http://www.borenv.net/BER/archive/pdfs/ber28/ber28-111-124-supplement.pdf

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