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Indicator-based assessment of climate-change impacts on coasts: a review of concepts, methodological approaches and vulnerability indices

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Indicator-based assessment of climate-change impacts on coasts: a review of concepts, methodological approaches and vulnerability indices

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Abstract

Increasing human pressures on coastlines and associated threats posed by sea-level rise have stimulated development of a range of different concepts and methodological approaches to assess coastal vulnerability. The first section of this paper summarizes the concepts associated with vulnerability, natural hazards and climate change. The most widely adopted analytical approaches to vulnerability assessment are described, including spatial scales, the need for hybrid approaches comprising both biophysical and social dimensions of vulnerability, and the gradual incorporation of resilience aspects into such methodologies. In particular, the development and application of vulnerability indices is examined, based on a review of more than 50 studies that applied such indices across a range of hazards. The analytical procedures, proposed typologies, and most commonly selected variables are discussed. This overview demonstrates the breadth of vulnerability studies. This leads inevitably to lack of standardization of concepts and assumptions, which results in limited comparability between outputs for coasts from different areas. However, the widespread demand for vulnerability assessment as a component of decision-making in integrated management of the coast justifies pursuing indicator-based vulnerability assessments. In some cases these will explicitly adopt a consistent methodology that enables comparison between sites, whereas alternatively, metrics may be developed that are designed around particular system components and the site-specific functions for which they are valued.

Keywords

Sea-level rise, coastal hazards, risk, vulnerability assessment, indices, resilience

1. Introduction

Sea-level rise associated with climate change is globally considered to be a serious threat, especially for low-lying and densely populated areas (Bindoff *et al.*, 2007, Bigano *et al.*, 2008). The coast is one of the most vulnerable areas to potential impacts of climate change, particularly because of anticipated future sea-level rise (Wong *et al.*, 2014). The coastal zone is an important natural resource system, which provides space, as well as living and non-living resources for human activities, and has since the early days of civilisation. Past fluctuations of sea level have been significant factors in the evolution of cultures on a historical time scale and civilisations have founded or expanded as relative sea levels have shifted. The coastal zone is currently a focal point in many national economies with a large number of social and economic activities concentrated near the shoreline.

The importance of the coastal zone will further intensify in future, due to the ever-increasing number of people who live there. Adger *et al*. (2005) indicate that 1.2 billion people, which accounts for 23% of the world's population, now live within 100 km of the coast, and about 50% of the world's population are likely to do so by 2030 (Neumann *et al.*, 2015). While living near the coast is advantageous, it also exposes the inhabitants to an increasing number of detrimental impacts which are exacerbated by climate change, with elevated water levels becoming more frequent and severe due to intensively aggregated human activities. There is a need, therefore, to assess coastal vulnerability to impacts of climate change. Methodologies for assessing vulnerability, as widely suggested by the Intergovernmental Panel on Climate Change (IPCC) since their initial common methodology report in 1991 (IPCC, 1991), need to consider both biophysical and social aspects, and their mutual interaction, to adequately set up relevant adaptation policies for sustainable development. Such methodologies have been widely used both in academic research (e.g. Abuodha & Woodroffe, 2006, Sudha Rani *et al.*, 2015) as well as for management purposes (e.g. Pendleton *et al.*, 2005).

In this paper a broad range of literature on vulnerability to hazards is reviewed. Specifically, more than fifty studies that applied vulnerability indices for a range of hazards were assessed to identify fundamental concepts that could be applied to coastal risk analysis. The most widely adopted analytical approaches are described, and their integration into coastal vulnerability indices is summarized. This overview demonstrates the breadth of vulnerability studies and the lack of standardization of concepts, scales, simplifications and selected parameters adopted in the development of indices for identification of vulnerable areas.

2. The conceptualization of vulnerability

The initial scientific use of "*vulnerability*" has its roots in geography and natural hazards research, but now this term is a central concept in a variety of research contexts related to natural impacts, such as salinity incursion, drought, bushfire, flooding and inundation, erosion and sedimentation, as well as social effects, such as poverty, famine, and landuse change (Füssel, 2007, Toan, 2014, Li *et al.*, 2015). Adger (1999) and O'Brien and Leichenko (2001) indicate that vulnerability is not an outcome, but rather a state or condition of being, and a very dynamic one at that, moderated by existing inequities in resource distribution and access, the control individuals can exert over choices and opportunities, and historical patterns of social domination and marginalisation.

2.1 Defining vulnerability

White (1974) indicated that "v*ulnerability is the degree to which a system, sub-system, or component is likely to experience harm due to exposure to a hazard, either a perturbation or stress*". Later, Timmermann (1981) hypothesized that "*vulnerability is a term of such broad use as to be almost useless for careful description at the present, except as a rhetorical indicator of areas of greatest concern*". Liverman (1990) noted that vulnerability *"has been related or equated to concepts such as resilience, marginality, susceptibility, adaptability, fragility, and risk"*. Other concepts such as exposure, sensitivity, coping capacity, criticality, and robustness could also be added to this list (Füssel, 2007, Wolters & Kuenzer, 2015). It is apparent that there is no single optimal definition of vulnerability that would fit all assessment contexts. It is important to note that the diversity of definitions can be considered as a primary consequence of the term "*vulnerability*" being used in different policy contexts, referring to different systems exposed to different impacts.

Accordingly several authors have emphasized that the term "*vulnerability*" can only be considered meaningfully with reference to a specific vulnerable situation (Brooks, 2003, Luers *et al.*, 2003, Downing & Patwardhan, 2004, Metzger *et al.*, 2005, Füssel, 2007, Hinkel & Klein, 2007). Fundamental dimensions of a *vulnerable situation* include: the *system* that is subject to analysis, such as an integrated human-environment system, a population group, an economic sector, a geographical region, or a natural system; the valued *attributes of concern*, which might include for example human lives and health, the existence, income and cultural identity of a community, and the biodiversity, carbon sequestration potential and timber productivity of a forest ecosystem; the *hazard*, which refers to a potentially damaging influence on the system; and a *temporal reference*, which refers to the point in time or time period of interest, (e.g., current vs. future vs. dynamic) (Füssel, 2007).

A clear description of the vulnerable situation is an important first step to avoid confusion concerning vulnerability. A clear description is important as different classifications of vulnerability by scientists from different disciplines or with varying perceptions produces different interpretations of the term "*vulnerability*".

2.2 Biophysical and socio-economic aspects of vulnerability

Several researchers distinguish biophysical or natural vulnerability from social or socio-economic vulnerability, (e.g., biophysical vs. social), even though there is little agreement on the meaning of these terms (Cutter, 1996, Adger, 1999, Klein & Nicholls, 1999, McLaughlin *et al.*, 2002, Brooks, 2003, Cutter *et al.*, 2003, Meur-Férec *et al*., 2008, McLaughlin & Cooper, 2010, Soares *et al.*, 2012, Sudha Rani *et al*., 2015). Other classifications have been proposed; for example, Moss *et al*. (2001) suggest including physical-environmental, socio-economic, and external assistance dimensions; the United Nations (2004) suggest including physical, economic, social, and environmental factors; and Fekete *et al*. (2009) suggest including ecological, social, economic, political and technological aspects.

In general, vulnerability approaches to biophysical conditions are largely based on natural hazards and focus on distribution of hazardous conditions, human occupancy within hazardous areas (Muler & Bonetti, 2014), maladaptation (Cooper & Pilkey, 2012, Bernatchez & Fraser, 2012), and the degree of loss associated with a specific hazardous event (Cutter, 1996, Dow, 1992). These approaches, also known as risk-hazard or impact-driven studies, focus on the degree of risk and exposure to hazard, which together determine the level of vulnerability, and issues such as magnitude and duration of the hazardous event (Eakin & Luers, 2006, Ford *et al.*, 2010, Turner *et al.*, 2003). They consider vulnerability as an "end-point", (i.e., the outcome of climate-change impacts minus adaptation) and the studies consider exposure to the hazard and sensitivity of the subject of analysis (but not adaptive capacity), in order to understand climate-change impacts and inform decision-making regarding costs of adaptation or mitigation (O'Brien *et al.*, 2007). However, the focus on physical processes generating exposure neglects social, economic, political and cultural factors which other approaches would include in estimations of vulnerability (Cardona, 2004).

In contrast, the social perspective conceives vulnerability as a socially-constructed phenomenon within the context of particular social, political, historical and economic processes and structures that influence social systems, (i.e., individuals, communities, groups) which make them vulnerable (Liverman, 1990, Cutter, 1996, Adger, 1999, Brooks, 2003, Kunte *et al.*, 2014, Mahapatra *et al*., 2015). Vulnerability is conceptualized as a pre-existing condition and is regarded as a “starting-point” of analysis. Exposure (to climate change) is considered as an external element, and social vulnerability focuses on “sensitivity” and “adaptive capacity” (Gallopin, 2006).

2.3 Integrated approaches to vulnerability

Soares *et al*. (2012) describe integrated approaches to vulnerability, also known as synthetic or hybrid approaches, in which exposure to climate change is addressed as an internal component of vulnerability (Gallopin, 2006). These are an amalgamation that aims to address both biophysical and social dimensions of vulnerability. Although designed to provide a more comprehensive understanding of the multiplicity of processes and dynamics affecting vulnerability of coupled biophysical and social systems by merging concepts from different views of vulnerability (Newell *et al.*, 2005), it can be problematic because it requires combining different ways of framing and performing vulnerability analysis (Soares *et al.*, 2012). This approach is particularly important in the context of policy-driven assessments that provide measures to inform adaptation policy (Füssel & Klein, 2006).

Numerous researchers distinguish an internal and an external aspect to vulnerability to environmental hazards (Chamber, 1983, Chambers, 1989, Blaikie *et al.*, 1994, Watson *et al.*, 1996, Ellis, 2000, Kasperson *et al.*, 2000, Bohle, 2001, Sanchez-Rodriguez, 2002, Pielke & Bravo de Guenni, 2003, Turner *et al.*, 2003). In terms of social vulnerability, studies are concentrated on social dimensions following the tradition of analysis of vulnerability to hazards, such as population, poverty, and food insecurity. This is in contrast to the predominant views on vulnerability to the impacts of climate change which emphasize the physical dimensions of the issue (Cutter, 1996, Adger, 1999). Studies on social or contextual vulnerability consider that there are two sides: an external side encompassing the perturbations and shocks to which the system is subjected, and an internal side that includes the system's own capacity to cope and respond to hazardous events (Chambers, 1989, 2006). They focus on issues such as resilience, sensitivity, resistance, and coping capacity, perceiving vulnerability as the "starting-point" of the analysis (O'Brien *et al.*, 2007). Cardona (2004) considered that some such studies neglected the impact and damage of the hazard, overemphasising social and political processes generating the vulnerability.

There are common issues with natural hazard assessments and climate-change vulnerability assessments. Recently, Romieu *et al*. (2010) attempted to differentiate vulnerability in the contexts of climate change from use of the same term in respect of natural hazards, exploring divergences in terminology. They indicated that issues arising from the inconsistent use of the term vulnerability for climate change and natural hazard risk assessments relate to numerous factors: climate change is commonly considered a "stress", whereas natural hazards might be considered a "shock"; individual or societal behaviour while facing these different processes is associated with different institutional, social, and psychological mechanisms (Turner *et al.*, 2003); scale-dependence, including both temporal, (e.g., static vs. dynamic) and spatial scales, (e.g., local vs. global) (Birkmann & Von Teichman, 2009); function (e.g., different institutions); assessment approach (e.g., statistical); and levels of uncertainty and efforts to synthesize gaps and common issues between vulnerability in the contexts of climate change and natural hazards (see Table 1).

According to Soares *et al*. (2012), vulnerability assessments are considered "second generation" as compared to climate impact assessments, because they also address relevant non-climatic drivers (e.g., economic, demographic), and the adaptive capacity of the system under analysis (Füssel & Klein, 2006). This resulted in the appearance of new vulnerability-driven methodologies characterized by "bottom-up" approaches (e.g., study-site to globe scale) that were more aligned with social and integrated perspectives on vulnerability. In analytical terms, a focus on current climate variability alongside adaptation and non-climatic factors or drivers marks the shift from climate impact assessment to vulnerability assessments (Füssel & Klein, 2006). This shift is also associated with new approaches to stakeholder involvement, more sophisticated socio-economic scenarios, and the consideration of adaptation measures, decision-support tools and enhancement of adaptive capacity as ways of reducing vulnerability to climate change (UNFCCC, 2005).

2.4 Exposure, sensitivity and adaptive capacity

The conventional concept of vulnerability, since the second assessment report of the IPCC (1995), identifies three key components: exposure, sensitivity, and adaptive capacity. In the scope of this paper, the definition of vulnerability proposed by in the fifth assessment report of the IPCC (2014) is preferred. The glossaries of the third, fourth and fifth assessment reports of the IPCC define "*contextual vulnerability (starting-point vulnerability)*" as *"a present inability to cope with external pressures or changes, such as changing climate conditions; it is a characteristic of social and ecological systems generated by multiple factors and processes"*, whereas "*outcome vulnerability (end-point vulnerability)"* defines vulnerability as *"the end point of a sequence of analyses beginning with projections of future emission trends, moving on to the development of climate scenarios, and concluding with biophysical impact studies and the identification of adaptive options. Any residual consequences that remain after adaptation has taken place define the levels of vulnerability"*. According to these reports, *"vulnerability"* is considered as a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity (IPCC, 2007). Moreover, vulnerability index refers to "*a metric characterising the vulnerability of a system, which is typically derived by combining, with or without weighting, several indicators assumed to represent vulnerability*" (IPCC, 2014).

Climate change refers to any change in climate for extended periods, typically decades or longer, whether due to natural variability or as a result of human activity (IPCC, 2007). A useful shorthand definition is that the vulnerability to climate change is a "measure of possible future harm" (Hinkel, 2011) and includes a number of components. "*Exposure"* refers to the presence of people, livelihoods, species or ecosystems, environmental functions, services and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected; whereas, *"sensitivity"* refers to the degree to which a system or species is affected, either adversely or beneficially, by climate variability or change. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise). The combination of exposure and sensitivity defines the degree of the potential impacts of climate change to a system. *"Adaptive capacity"* refers to the ability of systems, institutions, humans, and other organisms to adjust to potential damage, to take advantage of opportunities, or to respond to consequences. Measuring the adaptive capacity of a system enables policy makers to adopt suitable strategies in order to enhance the adaptive capacity or resilience of this system to the impacts of climate change. Integration of the potential impact and the adaptive capacities involved defines the vulnerability of a system. A system is anticipated to be vulnerable if it is exposed to climate-change impacts, if it is sensitive to those impacts, and if it has a low capacity to cope with those impacts.

Limitations of these definitions have been described by many researchers, who have indicated that they are not accurately defined, that there is considerable overlap between the concepts of sensitivity and adaptive capacity; the concepts are not easily separated, since future sensitivity depends on current adaptive capacities and measures (Vincent, 2004, Brooks *et al.*, 2005), and lack of transparency as to how the defining concepts are combined or that they are not operational concepts (Patt *et al.*, 2008). These definitions have been widely adopted as an appropriate starting point to explore possibilities for vulnerability assessment. Making a theoretical concept operational consists of providing a method (an operation) for mapping it to observable concepts; and that method is then called the operational definition (Bernard, 2000, Copi & Cohen, 2005). Measurement, therefore, is based on notions of comparative or quantitative concepts; that is concepts that can take on different values. These concepts are often called variables (Bernard, 2000). It is worth noting that comparability is key to the notion of vulnerability (Barnett *et al.*, 2008, Ionescu *et al.*, 2009). However, Hinkel (2011) argued that it is more accurate to speak about making the concept operational or practical instead of measuring it, since vulnerability is a theoretical concept that has been further developed by the IPCC.

To deal with those limitations, an extended definition of vulnerability and related components, which is developed by European Environment Agency, can also be considered. Figure 1 illustrates the three key components for climate-change vulnerability assessment, all of which have a spatial aspect that is generally mapped in GIS to show *where* there is vulnerability. In Figure 1, exposure and sensitivity (or susceptibility, as preferred by some authors) are viewed as determining the potential impact, as initially proposed by Schauser *et al*. (2010). The potential impact may be ameliorated by aspects of adaptive capacity to give overall vulnerability in this stepwise fashion.

Exposure, in a climate-change context, comprises those hazardous aspects of climate that pose a threat, which clearly has a spatial dimension. It can be combined with social or biophysical aspects to indicate primarily *where* the potential impacts will be experienced (e.g., the area most likely to be affected by climate change). The social information indicates *who* is sensitive and could be affected (e.g., how population density is affected or groups of the population, such as the elderly or another group could be the most sensitive). When this is combined with the biophysical information, it indicates *what* is sensitive and could be affected (e.g., which landuse is most likely to be affected by climate change). The *who* and *what* information may also be appropriate in terms of adaptive capacity, recognizing that natural systems may have resilience to impacts, but that components of society also have adaptive capacity.

Not all combinations are similarly important for all threats. For some threats (e.g., heat) the "*What (is sensitive)*" information is of little interest, except that it influences the "*Who (is sensitive)*" information. The relations between *the who* and *the what* are not yet integrated in any variable, therefore, the vulnerability of people and landuse should be dealt with as two separate strands, two different metrics according to the different risk or hazard types. This framework, developed by the European Environment Agency (EEA, 2010, ETC/ACC, 2010), cannot simultaneously deal with all limitations; however, it allows identification of cross-space dimensions *where* the potential impacts will be, and *who* and *what* is sensitive and could be affected regarding social, and biophysical, factors, and then combining *who* and *what* information with appropriate adaptive capacity information.

In summary, a climate-change vulnerability assessment needs to define dimensions as clearly as possible. These include location (or space) of analysis (e.g., geographical region), the system of analysis (e.g., natural system, and human system), the valued attributes of concern (e.g., income, poverty, education, and health), the hazard/ potential impact, (e.g., flood risk, erosion, and saltwater incursion), and a temporal reference, (e.g., current, future, and dynamic) with regard to the three components: exposure, sensitivity, and adaptive capacity.

3. Approaches used to assess coastal vulnerability

A *Common Methodology* for vulnerability assessment was developed by the IPCC in 1991 (IPCC, 1991). Many approaches for assessing coastal vulnerability to climate change have evolved since, based on that common methodology (Abuodha & Woodroffe, 2006, McFadden, 2007, Harvey & Woodroffe, 2008, Abuodha & Woodroffe, 2010a, Mcleod *et al.*, 2010). Table 2 presents numerous methods for assessing coastal vulnerability to climate change.

The majority of coastal hazard studies have focused on physical factors associated with coastal vulnerability, such as geo-physical dynamics (e.g., geomorphological processes), or physical impacts (e.g., sea-level rise, flooding and inundation) rather than socio-economic factors of coastal vulnerability, such as poverty (Abuodha & Woodroffe, 2006, Eakin & Luers, 2006, Nicholls *et al.*, 2008). Harvey and Woodroffe (2008) also indicate that the concept of coastal vulnerability developed from the IPCC needs to be expanded from biophysical impact reduction to vulnerability reduction or resilience enhancement. Several approaches to evaluate coastal vulnerabilities in Australia were summarized by Harvey and Woodroffe (2008) who remarked that there has been little consistency or uniformity in the way in which Australian researchers have assessed the vulnerability of the Australian coast to the impacts of climate change. Kay *et al*. (1993, 1996), as a result of criticisms of the IPCC Common Methodology (1991), proposed four key stages in alternative approaches to assess coastal vulnerabilities. The first stage focused on the biophysical condition of the study area and delineated those areas of potential future coastal hazard. The second stage considered the notion of the susceptibility to stress, shock and damage caused by climate change while recognising the importance of resilience of the natural coastal system. The third stage focused on the inter-relationship between the condition of the study area and connected systems; and the final stage considered the possible policy options and plans determined by governments to reduce coastal vulnerabilities.

A number of factors, accordingly, need to be determined in the context of climate change and coastal vulnerability assessment, such as objectives of the research or policy questions addressed, the urgency of the threat, the geographical and temporal scope of the analysis, the reliability of future climate impact projections, the level of previous knowledge, and the availability of data, expertise, and other relevant resources. This is necessary in order to select a proper assessment approach to be used in a specific vulnerable situation, location (e.g., regional or local area), or sector (e.g., agricultural sector) (Eakin & Luers, 2006).

Vulnerability is scale-dependent, across both space and time. First, vulnerability is spatially scale-dependent, depending on whether it is national, regional or local. Yoo *et al*. (2011) claimed that the spatial scale of climate-change vulnerability assessments is often either too broad when focused on the national or regional scale (Thieler & Hammer-Klose, 1999, 2000a, 2000b, Bryan *et al.*, 2001, Dominguez *et al.*, 2005, Mokrech *et al.*, 2008, Dawson *et al.*, 2009,) or too narrow when focused on coastal segments (Pendleton *et al.*, 2005). Abuodha and Woodroffe (2006) summarize numerous approaches based on segmentation techniques that rank sections of the coastline according to a semi-quantitative assessment of variables. These are useful to determine high priority areas for vulnerability reduction; however, most lack incorporation of socio-economic aspects of vulnerability. Harvey and Woodroffe (2008) also indicate that awareness in terms of impacts of climate change, particularly sea-level rise, has come from a global or national scale, but there is need for specific impact assessments and adaptation strategies that are local. A preferred approach is identification of coastal segments with higher or lower propensity to be affected by coastal hazards, through spatial analysis of multivariate data (Bonetti *et al.*, 2013).

Torresan *et al*. (2008) advocate a more detailed approach at the local and regional scale requiring detailed description of coastal systems and their dynamics, together with more complex and data-intensive models which incorporate site-specific metrics. This should enable better identification of specific vulnerable areas and sectors to support policy and decision-making for comprehensive adaptation strategies. Romieu *et al*. (2010) also emphasize that local assessments provide more bottom-up and locally contextualized views of vulnerability, but are difficult to relate to climate-change projections because these are not yet available with sufficient spatial resolution.

Coastal zone processes operate over time scales that span from hours for tidal variations, to days for storm surges, to years for El Niño phenomena, and decades to millennia in the case of vertical tectonic land movements. Climate-change related pressures (e.g., sea-level rise) add further long-term coastal challenges that will continue for centuries. Nicholls *et al*. (2007) show that reactive and standalone efforts to reduce climate-related risks to coastal systems are less effective than measures that are part of integrated coastal zone management. Proactive adaptation to climate change aims to reduce a system's vulnerability by minimising risk and/or enhancing resilience of the system. Nicholls and Klein (2005) identify five objectives of proactive adaptation for coastal zones, including increasing robustness of infrastructural designs and long-term investments; increasing flexibility of vulnerable managed systems; enhancing adaptability of vulnerable natural systems; reversing maladaptive trends; and improving societal awareness and preparedness.

It is rather difficult to differentiate current and future vulnerability because, as Schauser *et al*. (2010) point out, there is a lack of data for projections of sensitivity and adaptive capacity. On the one hand, for many socio-economic sectors, only past data from the last census, that might be up to 10 or 20 years old, are available. On the other hand, future vulnerability depends on past actions, adaptation and societal adjustments. Most existing variables are somehow measuring actual vulnerability, not taking into account future adaptation strategies. Therefore, until these are available, it will be necessary to focus on current (+/- 10 years) vulnerability. In most cases, particularly at the local scale, the future aspects relate primarily to climate projections and may only include population dynamics if projection data is available.

Coastal assessments have adopted a series of future scenarios. Most have concentrated on the set of Special Report on Emissions Scenarios (SRES) prepared by Nakicenovic and Swart (2000) which incorporate population projections for the future as well as alternative economic and environmental pathways (see Nicholls, 2004). More recently, Representative Concentration Pathways (RCP) (van Vuuren *et al.*, 2011) have been adopted within the Fifth Assessment Report of the IPCC (IPCC, 2014). Assessment of the influence of non-climatic environmental change or socio-economic change is less well developed despite the overwhelming evidence that anthropogenic impacts have been the overriding cause of degradation of coastlines throughout the 20th century (Nicholls *et al.*, 2011). Further consideration of these climate and non-climate drivers and their incorporation into scenarios for the future is beyond the scope of this review.

4. The development of vulnerability indices

Vulnerability indices can help identify and prioritise vulnerable regions, sectors or population groups, raise awareness, and can be part of a monitoring strategy. Several researchers indicate that the analysis of vulnerability often relies on the use and aggregation of indicators (Cutter *et al.*, 2000, Moss *et al.*, 2001, Yohe & Tol, 2002, Vincent, 2007, Abuodha and Woodroffe, 2010a). Generally, vulnerability index development involves sequential stages including the selection of indicators, normalization of indicators to a common scale, and aggregation to a final value. First, the goal of indicator selection is to choose proxy variables for the underlying theoretical dimensions of vulnerability comprising physical and social factors related to the components of vulnerability assessments: exposure, sensitivity, and adaptive capacity. Second, it is important to note that normalization of data to a common (comparable) unitless scale and subsequent summation of the normalized data is generally used to overcome issues of incommensurability when combining multiple indicators. Finally, the aggregation stage refers to the way it is used to combine transformed, normalized, and weighted indicators into the final index used; common options include multi-criteria analysis (Tate, 2013).

4.1 The objectives of vulnerability indexation

In order to make theoretical concepts operational in the context of climate change and vulnerability assessment, there have been three approaches used for a great diversity of different systems, as well as spatial and temporal scales; these are: 1) participatory; 2) simulation-model-based; and 3) indicator-based approaches. In relation to this review, indicator-based approaches are the principal focus in terms of their usage and limitations in the climate-change vulnerability assessment. Moreover, they have been used to develop a final composite/summary coastal vulnerability index, comprising the three variables of exposure, sensitivity, and adaptive capacity, respectively. A vulnerability index generally aims to simplify a number of complex and interacting parameters, represented by diverse data types, to a form that is more easily understood and has much greater utility as a management tool.

Hinkel (2011), however, notes two requirements for the development of vulnerability indices: defining the vulnerable system and the forward-looking aspect of vulnerability. It is difficult to exactly define the boundaries of the system, because often this is very large, for example an entire country. Within a nation there are different regions, economic sectors and social groups, and the assessment may be considering all climate-related hazards (e.g., both primary and secondary ones) and possibly other hazards. Even local assessments, focusing on individuals or communities, need to take into account broad political, institutional, economic and social contexts (O'Brien *et al.*, 2007).

Vulnerability assessments are highly context specific and require an understanding of how multiple, often interdependent, indicators of vulnerability vary in relation to each other (Füssel, 2009, Yohe & Tol, 2002). Population density, for example, as an indicator for social vulnerability assessment, may either increase or decrease vulnerability (Meyer *et al.*, 1998). High population density in agrarian communities can result in dependence on degraded or marginal land that rapidly becomes unproductive for food production and therefore increases vulnerability to food insecurity (Reycraft & Bawden, 2000). Conversely, high population density in locations with high quality agricultural land may allow intensified production and investment in infrastructure, increasing food supplies (Boserup, 1965). Using population density alone as a key vulnerability indicator could lead to development of inappropriate policy without appropriate consideration of its capacity for agricultural production or how it interacts with the environmental system.

The second challenge relates to the forward-looking aspect of vulnerability. Hinkel (2011) stresses that vulnerability indices must indicate a possibility, (i.e. some state that might or might not come about in the future (Patt *et al.*, 2008, Ionescu *et al.*, 2009)). Indices, such as UNDP’s Human Development Index 2006 for example, tend to indicate a state and not the potentiality of a future state. Developing a vulnerability index involves building a predictive model, based on an observed present state, which provides insights into possible future states. Whereas in the indicator-based approach, the index is, by definition, simple and time-independent, providing no information on when in the future harm will occur, the simulation-model-based approach is more complex and time-dependent, representing a dynamical system that is iterated over time including feedbacks and non-linearity. Hinkel (2011) distinguishes between harm indices, which evaluate the state of a system based on normative judgments of what constitutes a good or bad state, and vulnerability indices, which are indices of possible future harm, including both the forward-looking aspect as well as the normative aspect of defining harm.

Despite these challenges in the development of vulnerability indices, Füssel & Klein (2006) and Eakin & Luers (2006) indicate that vulnerability indices have been applied for many scientific purposes (e.g., for identifying causal processes and explaining attributes of vulnerable systems, for linking system attributes to vulnerability outcomes, and for mapping, ranking and comparing vulnerability across regions), at many scales (from local to global), and with different policy objectives (e.g., more realistic assessment of climate-change risks, aiding the allocation of resources across regions, monitoring the progress in reducing vulnerability over time, and identifying suitable entry points for interventions).

4.2 Different approaches to vulnerability indexation

Different decision contexts and scales generally require different kinds of information. For example, an index developed to describe household vulnerability to natural hazards in Mozambique may be largely irrelevant in Germany, or outright inapplicable if used in German studies (Vincent, 2007); additionally institutions such as the United Nations Environmental Programme (UNEP, 2006) and the UK's Department of International Development (Thornton *et al.*, 2008) have recently undertaken broad scale (multi-national to continental scale) vulnerability mapping exercises in Africa. Nevertheless, quantifying and communicating the multiple drivers of socio-natural vulnerability is problematic, particularly when seeking to explicitly map vulnerability across broad spatial scales (Eakin & Luers, 2006, Füssel, 2009, Van Velthuizen *et al.*, 2007). It can be clearly seen that there have been implicit uncertainties in these broad scale vulnerability assessments.

There are three broad approaches for developing vulnerability indices, according to Harvey *et al*. (2009b) and Hinkel (2011). Most vulnerability methodologies make use of a combination of theory-driven, data-driven, and normative approaches. Theory-driven approaches, also known as deductive approaches, are based on existing scientific knowledge in the form of conceptual frameworks, theories or models about the system considered to identify relevant variables, and determine their relationships, and generate a list of components (Moss *et al.*, 2001, Schröter, 2004a, Adger & Vincent, 2005, Schröter *et al.*, 2005, Yohe *et al.*, 2006b, Mahendra *et al.*, 2011). Data-driven approaches, or inductive approaches, select vulnerability variables based on their statistical relationship with observed vulnerability outcomes (e.g., mortality due to natural hazards) (Briguglio, 1995, Peduzzi *et al.*, 2002, Brooks *et al.*, 2005, Dilley *et al.*, 2005, Eriksen & Kelly, 2007, Tol & Yohe, 2007). Normative approaches are based on subjective individual or collective expert opinion (e.g., the Delphi method); and have been widely applied for the development of variables for various purposes (Kienberger *et al.*, 2009); the most prominent example is the selection of variable components for the Human Development Indicator (HDI) (Schauser *et al.*, 2010).

Indicator-based approaches can be divided into two different types. These are index- and variable-based approaches, although a sharp distinction is not always evident. A comprehensible explanation of the adopted approaches is essential to support the proper uses. Ramieri *et al*. (2011) have attempted to distinguish the two types. Index-based approaches express coastal vulnerability by a one dimensional, and generally unitless, risk or vulnerability index. These approaches are not immediately transparent since the final index does not enable the understanding of assumptions and aggregations that led to its calculation. Variable-based approaches express the vulnerability of the coast by a set of fairly independent variables. In many cases, variables are combined into a final composite index that characterizes key coastal issues, such as coastal drivers, risk, hazard, exposure, sensitivity, impacts, adaptive capacity, and damage. Moreover, these approaches allow the evaluation of different aspects related to coastal vulnerability to produce evaluated variables corresponding at those steps within a completely consistent assessment context.

4.3 Context within which vulnerability is assessed

According to Fisher (1922), the use of indices as policy tools started in 1920. Gallopin (1997) considered that an indicator is an utility from observable variables, called indicating variables or theoretical variables. Indices or variables are a kind of measure - they are generally sets of information used to determine the status quo or changes of a characteristic of a system (Sullivan, 2002). Variables should be measurable, accessible, transferable, easy to be applied in practice, and not redundant (Lane *et al.*, 1999, Birkmann, 2006). Depending on the context and the purpose of the envisaged vulnerability assessment, these variables may be of quantitative character, but they may also embrace qualitative criteria or broader assessment approaches to allow for the integration of aspects, such as the institutional or cultural vulnerability (Birkmann, 2006).

Several researchers indicate that variable- and index-based approaches could be considered as appropriate methodologies only at local scales because systems of analysis can be narrowly defined (Barnett *et al.*, 2008, Hinkel, 2011). Consequently, three steps in development of vulnerability indices have been proposed (Birkmann, 2006, Kienberger *et al.*, 2009, Hinkel, 2011). The first step is definition of what is to be indicated; and in the case of climate-change vulnerability indices, this would be the vulnerability of a system to climate change. A wide range of different systems (e.g., individuals, households, communities, ecosystems, regions, economic sectors and countries) may be considered. Often these systems can be conceptualized as natural systems (Judge *et al.*, 2003) and integrated with social systems (Boruff *et al.*, 2005, Birkmann & Fernando, 2008), because vulnerability is determined by the interaction of bio-geophysical (or natural environment) and social/ or socio-economic (or human) sub-systems. Defining the system needs to include defining the system's boundaries. The next step is the selection of the indicator variables, which includes defining the domain of the index function itself, involving some aggregation of multiple sub-indicators to produce a single index. The final step is aggregation of all indicator variables, including defining the indicator function itself. Aggregation can obscure deficiencies in data, implying that the formulation of the index is very important and needs to be transparent (Bossel, 1999).

4.4 Aggregation of variables

A common approach to holistic vulnerability mapping is to aggregate (i.e., where the same units are used), or to composite (i.e., where different units are used) (Schauser *et al.*, 2010, Abson *et al.*, 2012), capturing the multiple aspects of biophysical and social vulnerability and adaptive capacity into a single index, or small number of spatially explicit vulnerability indices, termed a vulnerability "*score*", reducing the amount and complexity of information that must be communicated, and acting as powerful visual tools to identify those areas most vulnerable to climate-change effects. The study by Preston *et al*. (2008) on vulnerability variables for the Sydney Coastal Councils Group region in Australia can be identified as an example of good practice (see Appendix), indicating that it is often necessary to integrate datasets from many different sources that vary in format, scale and by their methods of acquisition due to the strong socio-economic component of vulnerability. Indeed, an integrated quantitative model that represents all the linkages and relationships between such data, combining them in a meaningful way, is strongly recommended.

The complex structure of vulnerability assessment frameworks is often described by hierarchical aggregation (Schröter *et al.*, 2005, Hiete & Merz, 2009), and aggregated vulnerability indices are computed using the mathematics of index construction (Moss *et al.*, 2001, Schmidtlein *et al.*, 2008). However, the combination of multiple variables of aspects of vulnerability into aggregated vulnerability indices must overcome the incommensurability of the units in which the individual indicators are measured (Sullivan & Meigh, 2005). Before aggregating, indicating variables must be normalized to create a common measurement unit. Common normalization methods include min-max, standardization, and ranking methods (Schauser *et al.*, 2010).

Weighting methods, also known as ranking methods, express the contribution and relative importance of the individual variables in the system. Using weighting methods can be considered as a supporting tool for a more objective (Wang *et al.*, 2011) and consistent decision processes (Saaty, 1980, 1994). This helps avoid over-estimation of the contribution or importance of variables in terms of vulnerability (Yoo & Kim, 2008), and can identify more accurately the most vulnerable areas on the map (Kubal *et al.*, 2009, Wang *et al.*, 2011). However, there have not been many studies that used weighting methods. This is because of lack of a comprehensive understanding of the theoretical vulnerability framework (Hiete & Merz, 2009) and a lack of knowledge about the effective relative importance of each descriptor. Weighting methods when used in studies can be based on expert opinions, or stakeholder involvements (qualitative data), rather than quantitative and qualitative data (Schauser *et al.*, 2010), and both can be a source of contention.

5. Synthesis of vulnerability studies

A synthesis of 53 studies that generated a vulnerability index, summarized in the Appendix, indicates that there is little consistency between approaches, particularly between those that have incorporated social variables into coastal vulnerability indices. From the analysis of the selected studies, the diversity of approaches that have been adopted by different authors is evident, differences being related to: the scale of analysis, the selection of variables, and their ranking. In particular, the adoption of adaptive capacity as one of the dimensions of vulnerability and the choice of associated descriptors seems poorly resolved when compared to the representation of exposure and sensitivity. This is especially true when comparing studies related to typical coastal hazards (sea-level rise, inundation due to storms and erosion) with ones that focus more on economical and health issues, such as higher temperatures, droughts, wild fires and urban floods (see Appendix). The choices made by those undertaking the assessments, considering spatial and temporal scale of study, the components of the systems and the threats to them, data availability and selection, and methods used to combine indicators, all influence the outcome, as noted by Wolters and Kuenzer (2015) in their summary of the vulnerability of deltas.

An example of a highly detailed assessment is the study by Mackey and Russell (2011), which examined the western part of the Mekong River Delta in Vietnam, adopting a standard vulnerability and risk assessment methodology and framework to identify the comparative vulnerability and adaptive capacity of natural and human systems, among particularly vulnerable geographic hotspots (a district boundary). By contrast Yusuf and Francisco (2009) conducted assessments for sub-national areas, regions, provinces, and districts for southeast Asia, in which climatic hazard maps for five climate-related risks, tropical cyclones, floods, landslides, droughts, and sea-level rise, were generated. Population density was used as the proxy for human sensitivity to climate hazard exposure, and an index of adaptive capacity was also created, as a function of socio-economic factors, technology, and infrastructure. On the other hand, Preston *et al*. (2008) conducted a vulnerability assessment throughout the Sydney Coastal Councils Group region, which incorporated five areas of potential climate-change impacts, such as extreme heat and human health effects, sea-level rise and coastal hazards, extreme rainfall and urban storm water management, bushfire, and natural ecosystems and assets. Whereas Yoo *et al*. (2011, 2014) developed a method for local vulnerability assessment with application to coastal cities; their framework corresponds to the second stage of an alternative method proposed by Kay *et al*. (1993, 1996) for the assessment of climate change on a local scale by incorporating statistical data and expert opinions into GIS.

The compilation in the Appendix indicates variables categorized into three components of vulnerability: exposure (87% of cases), sensitivity (85% of cases), and adaptive capacity (74% of cases). Those incorporated into exposure consist of biophysical hazards or threats due to climate change, (e.g., sea-level rise and coastal hazards, extreme rainfall and urban storm water management, extreme heat and human health effects). A broader suite of variables are included in sensitivity, reflecting the system's potential to be affected by changes; these can be categorized into two main sub-components: human or population sensitivity (e.g., population density, gender, race and ethnicity), adopted in 75% of cases, and landuse sensitivity factors (e.g., agricultural landuse, protected land area), adopted in 47% of cases.

Adaptive capacity describes the system's ability to adjust to climate change (including climate variability and extremes), to moderate potential damages, to take advantage of opportunities, or to cope with the consequences. A wide range of information and datasets have been used for this, including: 1) socio-economic indicators (e.g., poverty, income, education, health care services), adopted in 34% of cases; 2) technology indicators (e.g., availability of irrigation, electricity coverage), adopted in 13% of cases; 3) infrastructure (e.g., road density, access to information (radio, internet), and intervention tools (early warning system)), adopted in 22% of cases; and 4) institutional capacity (e.g., awareness, governance, policy foundation), adopted in 19% of cases. Only a small proportion (about 9% of cases) considered the index in the context of public policy. Generally, sensitivity and adaptive capacity components are not easily differentiated; they cannot be separated in many cases. This may be because future sensitivity depends on current adaptive capacities and measures. About of a third of the studies considered were conducted at a local scale.

Table 3 summarizes the physical and social variables, and their ranges, that have been used in coastal vulnerability studies. Since there is no indication that a standard methodology will be widely adopted for vulnerability mapping in the near future, a key need is implementation of strategies to facilitate comparability between outputs for coasts from different areas. This could be accomplished, in upcoming studies, by: 1) clearer identification of processes that are dominant in the area under investigation, their scale dependence and representativeness to express exposure to a target hazard; 2) specification of the assumptions adopted in ranking of variables, weighting and also an indication of their overall range of variation over the adopted scale; and 3) adoption of some calibration procedures in order to test the efficiency of the model, as attempts at validation have been particularly lacking (Wolters & Kuenzer, 2015).

It is clear that there will continue to be a demand for assessments into the threats that coastal processes pose as a component that underpins decision-making in integrated coastal management. In order for vulnerability assessments to lead to practical outcomes in political/institutional contexts rather than academic/scientific ones, it will be important that stakeholders are involved both during conception and during the assessment, if the results are to be used in management plans. However, it is easy to over-anticipate the applicability of indicator-based models to solve policy problems, creating a gap between the expectations of planners and the real applicability of vulnerability indices.

According to Hinkel (2011), vulnerability indicators cannot be used to identify mitigation targets, raise awareness of climate change, allocate adaptation funds, or monitor adaptation policy. However, the indicator-based approach to vulnerability may be appropriate to identify vulnerable people, communities, or regions, when systems are narrowly defined at local scales, using only a few variables based on observed harm. Consistency in the adoption and application of the metrics on which the index is based will be essential if comparison over a wide geographical range is intended (Hinkel, 2011). However, the process of index development is subjective, and the actual selection of metrics to apply for a given vulnerability assessment depends on many factors, primarily the purpose and scale of the vulnerability assessment, and data availability. Walmsley et al. (2105) have recently proposed an alternative approach for identifying and comprehensively defining meaningful metrics to enable assessment of vulnerability for a wide range of systems and hazards at multiple scales. Their approach includes five steps: identify the purpose of the assessment, create a vulnerability profile, define system components and valued functions, link factors to functions, and establish metrics. Following this procedure, the metrics and the weighting assigned to them, will be site-specific and depend not only on what has been identified as important to measure but also on the spatial scale of the vulnerability assessment and data availability.

By adopting a consistent methodology, Pendleton *et al*. (2010) were able to compare vulnerability to sea-level (or lake-level) rise across 22 National Park Service sites in a variety of geological and physical settings along the U.S. Atlantic, Pacific, Gulf of Mexico, Gulf of Alaska, Caribbean, and Great Lakes shorelines. However, by contrast, similar indicator-based approaches have been attempted by researchers around the coast of India, but different studies have varied the assessment method to suit particular regions (Sudha Rani *et al*., 2015). The former studies focus on rates of erosion of the shoreline which are inferred to be related to the physical variables upon which the vulnerability index is based, whereas studies of the Indian coastline go beyond consideration simply of erosion, and incorporate other impacts such as the effects of extreme storms, coastal inundation and saltwater intrusion. Socio-economic variables also need to be integrated into vulnerability assessments of the

Indian coast which explains the greater diversity of parameters considered within the sub-continent (see Table 6 in Sudha Rani *et al.*, 2015, Mani Murali *et al*., 2013).

The literature also shows that there is little consensus in the selection of socio-economic indicators for exposure and adaptive capacity in comparison with biophysical descriptors used for sensitivity. This may be due to lack of data for many areas, its heterogeneity, and also to the strong variation of spatial scales at which demographic information is available, usually derived from censuses. More effort needs to be directed towards identification and selection of types of indices or strategies to be adopted in different contexts (scientific vs. political). For example, although different geospatial data models have already been tested (points, segments, raster, fuzzy), it has not been widely discussed which one is the best to cartographically represent coastal vulnerability for practical use in any particular coastal setting. Moreover, it is not clear which variables are the best to represent the capacity of a community to cope with the effects of a hazard. Most socio-economic databases present more than thirty variables, which have a very high degree of correlation and redundancy (for example "education level" and "household income"). It appears that the selection of descriptors is primarily based on common sense instead of a more accurate analysis strategy. Analytical frameworks for the evaluation of human sensitivity and adaptive capacity, including identification of relevant data metrics based on demographics, still require more development. This can include statistical tools such as correspondence analysis or other exploratory multivariate data compression techniques.

6. Summary

The coast supports millions of people and is considered one of the most vulnerable areas to the impacts of climate change, particularly sea-level rise. Accordingly, there is an urgent need to undertake actions to respond to those threats that are becoming more severe. The definitions of vulnerability and other related concepts provided by the IPCC represent a starting point to explore possibilities for vulnerability assessment, but there remains a diversity of different conceptualisations of vulnerability across disciplines. Concepts of vulnerability can be distinguished into two types (i.e., biophysical vs. social). Vulnerability is the "end-point" of analysis from the biophysical perspective, and is conceptualized and analysed based on two components: exposure and sensitivity, with adaptive capacity generally not accounted for in such analyses. In contrast, vulnerability is regarded as a "starting-point" of analysis from the social perspective, or is conceptualized as a pre-existing condition. Integrated approaches to vulnerability are needed to address both the biophysical and social dimensions of vulnerability, and consider the scale dependence of parameters.

In addition, several researchers indicate that vulnerability assessments have been considered as "second generation" assessments that address relevant non-climatic drivers (i.e., economic, demographic), and the adaptive capacity of the system under analysis. This resulted in the appearance of new vulnerability driven methodologies characterized by "bottom-up" approaches, and more aligned with social and integrated perspectives on vulnerability. Currently, coastal vulnerability assessments have produced more consistent outcomes where they are focused on biophysical factors rather than socio-economic effects, although very few have been validated against observed changes.

There have been three methodological approaches, termed participatory, simulation-model-based, and indicator-based approaches. Most attempts at coastal vulnerability assessments to the impacts of climate change lack consistency and are either too broad, (i.e., they are national or regional), or too narrow, (i.e., they are focused on a particular segment of the coast). Until now, there seems to have been no convincing framework or methodology focused on how to quantify and compare vulnerability to climate change at spatially-dependent scales using selected indicator variables, with respect to the three main components of vulnerability (exposure, sensitivity and adaptive capacity), and aggregated or combined into a composite vulnerability index.

This paper demonstrates that a wide range of variables that have been considered in such analyses, and consideration is needed of the time and space scales at which coastal processes operate. Moreover, each variable can be categorized into different intervals and ranked to represent varying degrees of vulnerability. It is often difficult to compare results obtained for different sites. Variables have generally been inappropriately ranked in terms of their suitability for determination of vulnerability. Inter-comparison of studies from geographically diverse areas is possible, as Hinkel (2011) indicates, but only when a consistent methodology has been used. On the other hand, more detailed analyses at individual locations are likely to benefit by the adoption of metrics designed to capture the principal factors at those sites. Above all, the rapid increase of settlements on the coast, and their comparative wealth, increases the assets that are at risk in the face of current and future hazards.

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Figure Caption

Figure 1 Combination of the three key components in assessments of climate-change vulnerability (modified from AGC, 2005 and Schauser *et al*., 2010).

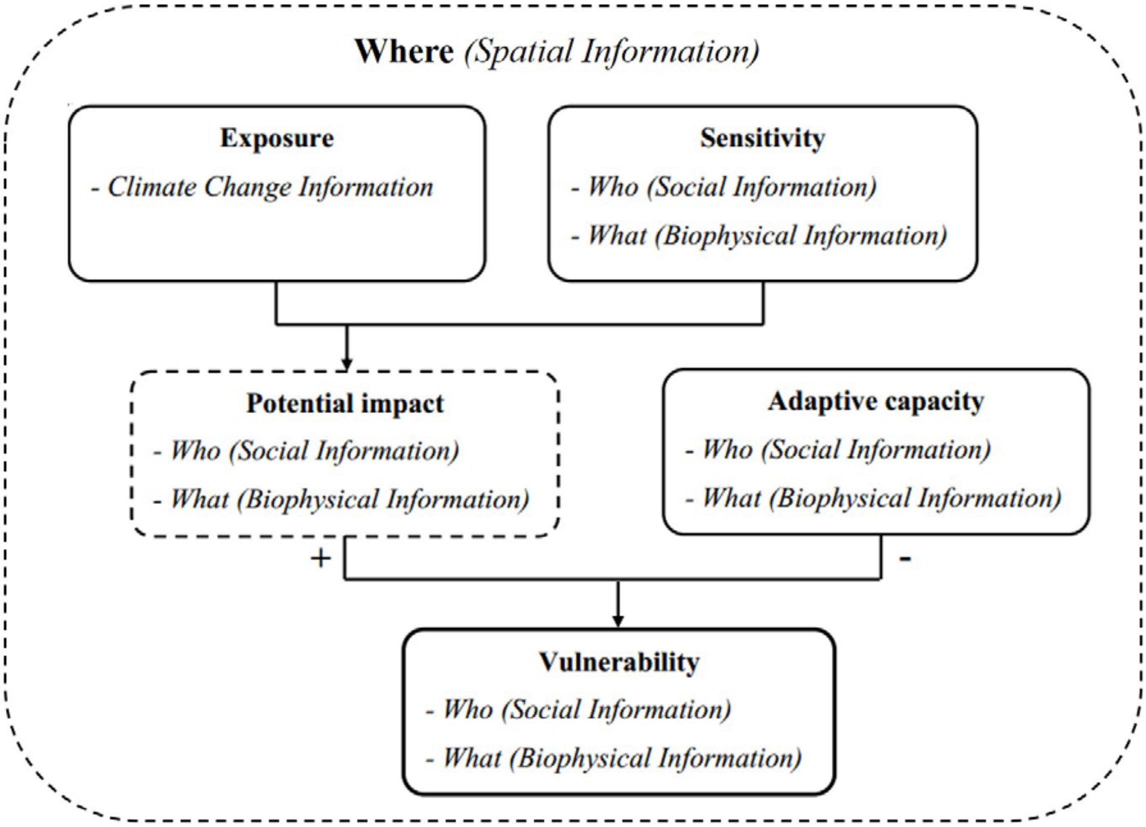

Table 1 Synthesis of common issues and differences between vulnerability assessment related to climate change and natural hazards (based on Romieu *et al*., 2010).

Issues	**Natural hazard**	**Climate change**
Objective	Identify risk reduction measures Reduce probability of damage	Develop strategies to manage: adaptation
Process	Natural hazards as "*shock*"	Progressive & irreversible- "*stress*"
Time scale	Event-scale (before/during/after), discrete events, static processes	Long-term and progressive, discrete or continuous, dynamic processes
Spatial scale	Local to global	Global awareness to local need
Functional scale	Local to regional jurisdictions	Local to global
Simplified formulation	Risk = Hazard x Vulnerability	Vulnerability = (Exposure + Sensitivity) - Adaptation = Impacts - Adaptation
Vulnerability assessment	Step within risk assessment	End in itself
	Risk is associated with a notion of probability of occurrence at any time	Prospective scenarios until a given time
Level of uncertainty	Low to medium	Medium to very high
Common issues	Define a focus, wider than physical environment itself	
	Find a convergence between ''*impact-based*'' and ''*human-based*'' approaches	
	Take into account dynamics & interactions of the socio-environmental system	

Table 2 Methods for assessing coastal vulnerability (based on Abuodha & Woodroffe, 2010a).

Methods	Application
Common methodology (IPCC, 1991)	Applied to coastal countries and includes 7 steps: delineate the case study area; inventory study area characteristics; classify the relevant socio-economic development factors; assess the physical changes; frame response strategies; assess the vulnerability profile; and classify future requirements.
Synthesis and Upscaling of sea-level Rise Vulnerability Assessment Studies (SURVAS, 2004)	Deploys activities that contributed to the DINAS-COAST project and DIVA tool, including: reviewing potential impacts of human induced sea-level rise at the national, sub-national scales; and holding workshops using coastal vulnerability experts to identify tools available for assessing the physical susceptibility and socio-economic vulnerability.
Dynamic and interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to sea-level rise project (DIVA-COAST) and Dynamic & Interactive Vulnerability Assessment (DIVA) Tool	Integrates information on physical, ecological and socio-economic characteristics to analyse a range of mitigation and adaptation scenarios. Decomposes the world's shoreline into a series of 1-dimensional coastal segments, failing to capture the multidimensional complexity of extensive low-lying areas such as deltas (David *et al.*, 2008, Hinkel & Klein, 2007, Vafeidis *et al.*, 2004, Woodroffe, 2010).
Simulator of CLIMate Change Risks and Adaptation Initiatives (SimCLIM)	Applied from global to local scales to assess coastal flood risk from tropical cyclones and river flooding, effects of rainfall change, the risks of climate variability and change in domestic water supply tank systems (Chowdhury & Hameed, 2005, Warrick, 2007, Warrick, 2009, Warrick *et al.*, 2005). Links to other models such as hydrological and DSSAT crop models (Warrick & Cox, 2007).
Community Vulnerability Assessment Tool (Flax *et al.*, 2002, Mazumder *et al.*, 2006)	Supports linking of environmental, social and economic data to build an effective strategy in response to hazards, both at macro & micro levels based on systematic evaluation of vulnerability. Risk and Vulnerability Assessment Tool (RVAT) is an extension of the CVAT methodology, supporting communities to identify risks and vulnerabilities to coastal storms to create effective hazard mitigation strategies and reduce impacts (Russell, 2003). Consists of 7 steps: hazard identification and prioritisation; hazard analysis; critical facilities analysis; social analysis; economic analysis; environmental analysis; and mitigation opportunities analysis.
Coastal Vulnerability Indices such as coastal vulnerability index (CVI)	CVI includes physical parameters to assess the vulnerability of a coastal area to anticipated sea-level rise: relief, rock type, landform, vertical (tectonic) movement, shoreline displacement, tidal range, and wave height (Gornitz *et al.*, 1994, Pendleton *et al.*, 2010).
Coastal social vulnerability index (CSoVi)	Hybrid approach that integrates a socio vulnerability index (SoVI) with socio-economic variables developed by Cutter *et al*. (2003) into a CVI to produce the coastal social vulnerability index (Boruff *et al.*, 2005). CSoVI includes socio-related parameters: poverty, population, development, ethnicity, age, and urbanisation.
Place vulnerability index (PVI)	Developed by Boruff and his colleagues (2005) by applying the hazard of place model of vulnerability (Cutter, 1996) to derive the place vulnerability index (PVI) for each of the USA counties. Achieved by adding CVI and CSoVI scores and classifying PVI scores into low, medium and high classes.
Decision-making indicators	Vulnerability has been examined by considering exposure to risk, management of risk, remembrance of risk, and perception of risk, by Meur-Férec *et al*. (2008), evaluating hazard, stakes, events,

Table 3 Physical and social vulnerability ranges used for coastal vulnerability indices.

Physical variable	**Rank**					**References**
	Very low	**Low**	**Moderate**	**High**	**Very high**	
Relief, m	≥ 30.1	20.1- 30.0	10.1- 20.0	5.1- 10.0	0-5.0	Gornitz (1991)
Sea-level rise, mm/year	≤ -1.1	-1.0- 0.99	1.0- 2.0	2.1- 4.0	≥ 4.1	Gornitz (1991)
	< 1	1 - 2	2 - 5	5 - 7	7 – ≥ 9	Özyurt and Ergin (2010)
Tidal range (mean), m	≤ 0.99	1.0- 1.9	2.0- 4.0	4.1- 6.0	≥ 6.1	Gornitz (1991)
	< 0.5	0.5- 2	2- 4	4- 6	> 6	Özyurt and Ergin (2010)
Wave height (max), m	0- 2.9	3.0 - 4.9	5.0- 5.9	6.0- 6.9	≥ 7.0	Gornitz (1991)
Flood depth, m	< 0.5	0.5 – 1.0	1.0 – 1.5	1.5 – 2.0	2.0 – ≥ 2.5	Kafle *et al*. (2007)
		0 - 1	1 - 3	3 - 6	> 6	Bormudoi *et al*. (2008)
	< 0.8	0.8 – 1.2	1.2 – 2	2 – 4	> 4	Le *et al*. (2009)
	≤ 1	2	3	4 - 5	> 5	Özyurt and Ergin (2010)
	< 0.5	0.5 – 1.2	1.2 – 2.0	2.0 – 3.0	> 3.0	Dang *et al*. (2011)
	< 0.25	0.25 – 0.5	0.5 - 1	1 – 1.5	> 1.5	Mackey and Russell (2011)
	0 – 0.2	0.2 – 0.5	0.5 – 1.0	1.0 – 2.0	> 2.0	Dinh *et al*. (2012); Tingsanchali and Karim (2005)
	≤ 0.5	>0.5- ≤1.0	>1.0- ≤1.5	> 1.5- ≤ 2	> 2	Balica *et al*. (2013)
Salinity, ppt	< 1	1 - < 2.5	2.5 – 3	3 - 4	> 4	Grattan *et al*. (2002)
	< 1	1 - < 4	4	> 4		Mackey and Russell (2011)
		< 4	4	> 4		Hoang *et al*. (2012)
		< 4	4 - 8	> 8		Le (2003)
Shoreline displacement, m/year	≥ 2.1	1.0 – 2.0	-1.0 – 1.0	-1.1 - -2.0	≤ -2.0	Gornitz and Kanciruk (1989)
	≥ 2.1	1.0 – 2.0	-1.0 – 1.0	-1.1 - -2.0	< -2.0	Gornitz (1991)
	> 2.0	1.0 – 2.0	-1.0 – 1.0	-1.1 - -2.0	< -2.0	Gornitz *et al*. (1994)
		> - 5.0	-15.0 - -5.0	- 30.0 - -15.0	< -30.0	Pham *et al*. (2005)
	> 15.0	5.0 – 15.0	-5.0 – 5.0	-15.0 - -5.0	< -15.0	Dwarakish *et al*. (2009)
	> 2.0	1.0 – 2.0	-1.0 – 1.0	-1.0 - -2.0	< -2.0	Pendleton *et al*. (2010)
	> 2.0	1.0 – 1.9	-0.9 – 0.9	-1.0 - -1.9	< -2.0	Abuodha and Woodroffe (2010b)
	0.3- 0.5	0 – 0.3	-1- 0	-1.0 - -2.0	-2.0 - -4.0	Nguyen (2012)
Social variable	**Rank**					**References**
	Very low	**Low**	**Moderate**	**High**	**Very high**	
Population density, inhabitants/ km^2		1-750	750 - 1 500	1 500 - 2 250		Kafle *et al*. (2007)
		< 500	500 - 1 000	> 1 000		Dang *et al*. (2011)
		66 - 168	196 - 333	339- 2 190		Mackey and Russell (2011), whereas those in Kien Giang [268]
	< 250	250 - 500	500 - 1 000	1 000 - 2 500	> 2 500	Average in other regions in Vietnam [260]
Landuse patterns	Water	Minimal use, nature conservation, potential agriculture	Livestock grazing, irrigated horticulture, woodland	Residential	Transport & Communication	Preston *et al*. (2008)
	Protected area	Unclaimed	Settlement	Industrial	Agricultural	Özyurt and Ergin (2010)
	Rocky cliffs	Scrub	Beach, sand dunes, forest, rough	Agricultural land, Tee boxes, fairways, amenity grass	Urban, residential, car parks, greens	McLaughlin and Cooper (2010)
	Forest, sea (Limited used)	Agricultural land (Low-impact used)	Living and tourism (Middle-impact used)	Industry and transport (High-impact used)		Liu (1996) and Huang *et al*. (2012)
		The bare land	Water/wetland, grassland	Forest, farmland	Built-up	Yin *et al*. (2012)
Local income level, mil.VND/capita/yr		> 6.0 million VND (US$ 375)/capita/yr	2.4 – 6.0 million VND (US$ 150 - 375)/capita/yr	< 2.4 million VND (US$ 150)/capita/yr		Dang *et al*. (2011)

Appendix. A review of vulnerability indices used to assess vulnerability to impacts of climate change.

Name of indicator	Purpose	Scale (spatial/ temporal)	Methods/ Tools (Aggregation)	Exposure	Sensitivity	Adaptive Capacity	Reference
Overall vulnerability							
An overall vulnerability indicator	Estimate & compare overall vulnerability of very different cities	Cities observed trend & projections for 2050s	City experts	1. Temperature 2. Precipitation 3. Sea-level 4. Tropical cyclone 5. Drought 6. Heat waves	1. Population 2. Density 3. Percent slum population 4. Percent of urban area susceptible to flooding 5. City % of national GDP	*Institutions and Governance* 1. Urban governance (corruption index ranking for city) 2. City leadership is willing to address climate change *Information and Resources* 3. Comprehensive analysis of climate risks for the city 4. Administrative unit assigned to address climate change 5. Balance between adaptation & mitigation	(Mehrotra *et al.*, 2009)
Climatic threat/ issue: Heat wave: Higher temperatures, heat wave and health problems							
Heat vulnerability indicator	Neighbourhood level heat vulnerability assessment for the city of Toronto to assess cartographic design decisions in creating heat vulnerability maps	City, Toronto, Canada	Aggregation by specific multi criteria & cluster analysis methods	1. Surface temperature	19 components (related to dwellings, income, specific population groups, age classes)	Partly included in S	(Rinner *et al.*, 2010)
Heat waves	Components	European	Not aggregated	1. Warm spell	1. Age classes	1. GDP	(Harvey *et al.*,

vulnerability index	influencing the vulnerability of European populations to heat waves	Regions		duration index 2. Tropical nights	2. Age > 65 yrs	2. Education level	2009a)
Cumulative heat vulnerability index	Cumulative heat vulnerability index for the USA to create maps for comparison & to give guidance at regional (county) & national scales for further analysis & intervention	At regional (county) & national, USA	Aggregated by principal component analysis	None	1. Race 2. Age ≥ 65 3. Living alone & age ≥ 65, 4. Diabetes 5. Area without vegetation	1. Poor 2. Education level 3. Living alone 4. Without central 5. Any air conditioning	(Reid *et al.*, 2009)
Vulnerability Indicators for Extreme Heat and Human Health	Vulnerability Indicators for Extreme Heat & Human Health for the region to initiate a dialogue among researchers & stakeholders & a bottom-up assessment of local governments	Regional, Sydney Coastal Councils Groups in 2030	Aggregation by summation of components values for each element, scoring, weighting based on expert values & summation of the elements values for vulnerability indicator	1. Present average January maximum temperature 2. Present average January minimum Temperature 3. Present # Days > 30^{o}C 4. Projected change in average DJF maximum temperature in 2030 5. Land cover 6. Population density 7. Road density	1. % population≥65 years of age 2. % population≥65 years of age & living alone 3. % population≤4 years of age 4. % of housing as multiunit dwellings 5. Projected population growth to 2019	1. % population completing year 12 2. % population that speaks language other than English 3. Median home loan repayment 4. % home ownership 5. Median household income 6. % households requiring financial assistance 7. % population with internet access 8. Current ratios 9. Per capita business rates 10. Per capita residential rates 11. Per capita community service	(Preston *et al.*, 2008)

						expenses 12. Per capita environment & health expenses	
Indicator for heat related risk	Heat related risk assessment & a generic framework for risk management	Local, Greater Manchester & Lewes	Normalized in classes, aggregated by unweighted addition	1. Daily max. & min. temperatures	1. Urban Morphology Types 2. Age > 75 3. Age < 4, 4. Population health 5. Residence dependency	None	(Lindley *et al.*, 2006)
Climatic threat/ issue: Decreased precipitation, water scarcity and drought							
Indicators of vulnerability to climate change	Indicators of vulnerability to climate change to inform the pertinent political debate on international adaptation funding within the framework of the UNFCCC	Global	No aggregation suggested	3 variables (median & standard deviation of projected change in precipitation, median of the projected change in runoff)	3 variables (current population weighted precipitation, renewable water resources per person, water use ratio)	2 variables (households with improved water supply or with improved sanitation)	(Füssel, 2010)
The social vulnerability index for water availability	The social vulnerability index for countries in Africa is an aggregate index of human vulnerability to climate-change-induced changes in water availability	Africa (country level) / water availability	Weights are applied to the indicators in forming the sub-indices, & then when aggregating the sub-indices to form the aggregate index, in keeping with the theory-driven nature of the index, & based on expert		Natural resources sensitive to water stress & water availability	1. Economic well-being & stability 2. Demographic structure 3. Institutional stability 4. Strength of public infrastructure 5. Global interconnectivity & dependence	(Adger & Vincent, 2005)

			judgment				
Drought vulnerability index	To assess vulnerability index to agricultural drought in Nebraska	In Nebraska	Each factor a relative weight was given between 1 & 5, & 5 is the most significant. 4 classes of vulnerability: low, low-to-moderate, moderate & high	1. biophysical: soil & climate	1. social: landuse & irrigation		(Wilhelmi & Wilhite, 2002)
Indicators for water resources	Indicators for water resources to investigate the integrated impacts of potential global warming	National, USA	Only graphical aggregation as percentage of thresholds	2 variables (Climate & economic scenarios, runoff ratio)	3 variables (Storage vulnerability, hydropower, water quality, coefficient of variation, dependence ratio)	5 variables (consumptive use, relative poverty, import demand ratio, withdrawal ratio)	(Lane *et al.*, 1999)
Climatic threat/ issue: Wild fires							
Vulnerability Indicators for Bush Fires	Vulnerability Indicators for Bush Fires for the region to initiate a dialogue among researchers & stakeholders & a bottom up assessment of local governments	Regional, Sydney Coastal Councils Groups in 2030	Aggregation by summation of components values for each element, scoring, weighting based on expert values & summation of the elements values for vulnerability indicator	1. Present average maximum January temperature 2. Present # Days > 30^{o}C 3. Projected change in average maximum DJF temperature in 2030 4. Present average annual rainfall 5. Present average annual 10th percentile rainfall 6. Projected average	1. Annual primary production 2. Land cover 3. Slope 4. Aspect 5. Population density 6. Road density	1. % population completing year 12 2. % population that speaks language other than English 3. Median home loan repayment 4. % home ownership 5. Median household income 6. % households requiring financial assistance 7. % population with internet access & Current ratios 8. Per capita business rates	(Preston *et al.*, 2008)

				annual rainfall change in 2030		9. Per capita residential rates 10. Per capita community service expenses	
Climatic threat/ issue: Fluvial floods, flood claims and health effects of flooding							
Flood Vulnerability Index (FVI) for river basins	To use 11 indicators (out of 40 indicators) divided in 4 components, 2 sub-indices, as a tool for assessing flood risk due to climate change in relation to underlying socio-economic conditions & management policies	River basins	Acknowledged by a group of over 50 participants to the Asian Development Bank Water Week of 2004 in Manila	1. Frequency of heavy rainfall (I1) belonging to climate component (C) 2. Average slope (I2), urbanized area rational (I3) belonging to hydro-geological component (H)	The human index, which corresponds to the social effects of floods & the material which covers the economic effects of floods: 1. TV penetration rate (I4), literacy rate (I5), population rate under poverty (I6), years sustaining healthy life (I7), population in flooded area (I8), infant mortality rate (I9) belonging to socio-economic component (S) 2. Investment amount for structural measures (I10), investment amount for non-structural measures (I11) belonging to countermeasures component (M)		(Connor & Hiroki, 2005, Quinn *et al.*, 2010)
Flood Vulnerability Index (FVI)	To develop a Flood Vulnerability Index methodology, based on 3 factors of vulnerability: exposure, susceptibility & resilience; these factors are interlinked with the three components, using 19	Coastal cities		1. Hydro-geological (sea level rise, storm surge, number of cyclones, river discharge, foreshore slope, soil subsidence, coastal line)		1. Socio-economic (cultural heritage, population close to coastal line, growing coastal population, shelters, awareness/ preparedness, disable people, km of drainage, recovery time) 2. Politico-administrative (uncontrolled planning zones, flood hazard maps, institutional	(Balica & Wright, 2009, Balica & Wright, 2010, Balica *et al.*, 2009)

	indicators					organizations & flood protection)	
Indicator for river flooding vulnerability	Components influencing vulnerability of European urban areas to river flooding to raise awareness of river flooding risk & to identify hotspots for more detailed analysis	European urban areas	No aggregation suggested	1. River flows 2. River floods	1. Population density	1. GDP 2. Education level 3. Money spend on flood protection	(Harvey *et al.*, 2009a)
Social vulnerability index in context to river-floods	Social vulnerability index in context to river-floods in Germany to generate information about people potentially flooded	Elbe & Rhine river valleys, Germany	Aggregation by component analysis & regression analysis to derive 3 most sensitive parameters (fragility, region, socio-economic conditions), which were combined to an index	None	1. Age >65 yrs 2. Population density 3. Housing type	1. Living space per person 2. Unemployment ratio 3. Education level	(Fekete, 2009)
Indicator for flood vulnerability	Integrated urban flood risk assessment	Leipzig	Aggregation by multi criteria assessment to derive different risks (social, economic, land value, ecologic)	1. Depth of inundation	11 variables (landuse, classification of buildings, land values, affected population & special population groups per building, social hot spots, contaminated sites, soil erodibility, oligotrophic biotopes, protected biotopes, vulnerable trees)	None	(Kubal *et al.*, 2009, Meyer *et al.*, 2009)

Spatial vulnerability based on flood modeling	Spatial vulnerability units for socio-economic flood modeling	Regional, urban areas	Aggregation based on multiple criterion analysis & on expert opinion (weights)	None	6 variables (with more sub-variables) (households & building uses, infrastructure length, assets, sensitive land covers age distribution, employments)	7 variables (with more sub-variables) (workforce in different economy sectors, size of companies/ workplaces, ecosystem integrity of sensitive areas, distance to health facilities & roads, early warning system available, origin of population, education level)	(Kienberger *et al.*, 2009)
Social Flood Vulnerability Index	Social Flood Vulnerability Index for communities	Communitie s, i.e., Manchester & Maidenhead	Aggregation by simple weighting & summation the components in an index. The index was classified in 5 bands	None	3 variables (long-term sick, single parents elderly > 75 yrs)	4 variables (unemployment, overcrowding, non-car ownership, non-home ownership)	(Tapsell *et al.*, 2002)
Climatic threat/ issue: Intensive precipitation and urban drainage floods							
Vulnerability Indicators for Extreme Rainfall and Storm water Management	Vulnerability Indicators for Extreme Rainfall & Storm water management for the region to initiate a dialogue among researchers & stakeholders & a bottom up assessment of local governments	Sydney Coastal Councils Groups in 2030	Aggregation by summation of components values for each element, scoring, weighting based on expert values & summation of the elements values for vulnerability indicator	1. Present average annual rainfall 2. Present average 90th percentile annual rainfall 3. Projected change in extreme rainfall events in 2030	1. Land cover 2. Elevation 3. Slope 4. Drainage 5. Average soil water holding capacity 6. Population density 7. Road density 8. Projected population growth to 2019	1. % population completing year 12 2. % population that speaks language other than English 3. Median home loan repayment 4. % home ownership 5. Median household income 6. % households requiring financial assistance 7. % population with	(Preston *et al.*, 2008)

						internet access 8. Current ratios 9. Per capita business rates 10. Per capita residential rates 11. Per capita community service expenses	
Climatic threat/ issue: Sea level rise and storm surge-driven flooding							
The coastal vulnerability index	The coastal vulnerability index to identify areas at risk of erosion &/or extreme climatic events	Coastal areas	Aggregation based on classification & ranking into one indicator	1. Average swell 2. Relative sea-level change tax 3. Average tidal range	1. Geology resistance 2. Erosion tax 3. Coastal slope	None	(Gornitz, 1991)
A multi-scale coastal vulnerability index: a tool for coastal managers	A multi-scale coastal vulnerability index based on coastal characteristics, coastal forcing, socio-economic factors	A multi-scale			1. Coastal characteristics (solid geology, drift geology, shoreline type, elevation, river mouths, orientation, inland buffer) 2. Coastal forcing (significant wave height, tidal range, difference in storm & modal wave height, storm frequently)	1. Socio-economic: (population, cultural heritage, roads, railways, landuse & conservation status)	(McLaughlin & Cooper, 2010)
Coastal sensitivity index	Coastal sensitivity index (CSI) to assess & characterise susceptibility	Coastal areas	Aggregation based on classification & ranking into one indicator		1. Relative sea-level rise 2. Mean wave height 3. Mean tidal range 4. Rock type 5. Coastal slope 6. Geomorphology 7. Barrier type	None	(Abuodha & Woodroffe, 2010b)

					8. Shoreline exposure 9. Shoreline change		
Indicator for storm surge-driven flooding vulnerability	Components influencing the vulnerability of European urban coastal areas to storm surge-driven flooding to raise awareness of the potential increase in flooding events	European urban coastal area	No aggregation suggested	1. Sea-level rise projection 2. Change in height of storm surges)	1. Flooded people 2. Population density 3. Elevation & slope 4. Sea defences	1. GDP 2. Education level	(Harvey *et al.*, 2009a)
Vulnerability Indicators for Sea-Level Rise and Coastal Management	Vulnerability Indicators for Sea-Level Rise & Coastal Management for the region to initiate a dialogue among Researchers & stakeholders & a bottom-up assessment of local governments	Sydney Coastal Councils Groups Up to 2019	Aggregation by summation of components values for each element, scoring, weighting based on expert values & summation of the elements values for vulnerability indicator	1. Distance to coastline 2. Present relative storm surge along Sydney Coastal Councils Groups coast 3. SEPP 71-defined sensitive coastal locations 4. Coastal elevation 5. Slope	1. Land cover 2. Population density 3. Road density 4. Projected population growth to 2019 5. Acid sulphate soils	1. % population completing year 12 2. % population that speaks language other than English 3. Median home loan repayment 4. % home ownership 5. Median household income 6. % households requiring financial assistance 7. % population with internet access 8. Current ratios 9. Per capita business rates 10. Per capita residential rates 11. Per capita community service expenses	(Preston *et al.*, 2008)
Indicators for	Indicators for	Regional,	Aggregation by	None	1. Administrative units	None	(Torresan *et al.*,

coastal vulnerability assessment	coastal vulnerability assessment at the regional scale to understand & manage the complexities of a specific study area	coastal areas	classification & GIS overlay to derive homogeneous units		2. Location of rivers 3. Geo-morphological characteristics 4. Wetland migratory potential 5. Coastal population density		2008)
Physical & social Vulnerability to sea level rise & storm-surge flooding	Physical & social vulnerability to sea-level rise & storm-surge flooding for local planners at a region to understand how sea-level rise will increase the vulnerability of people & infrastructure to hurricane storm surge flooding over the next century	Hampton Roads, metropolitan, Counties, cities, southeastern Virginia Next century	Aggregation by combination of statistical methods & combination of physical & social vulnerability	maximum surge heights, elevation	S, AC: different approaches: 1. 3 variables based on principal component analysis (current poverty, income, old age/ disabilities) 2. current spatial distribution of critical features 3. projected spatial distribution of population density Combination of current & future physical (based on storm-surge model) & social vulnerability (based on different approaches)		(Kleinosky *et al.*, 2007)
Climatic threat/ issue: Erosion							
Spatial & numerical methodologies on Coastal Erosion and Flooding Risk Assessment	Spatial and numerical analysis in local scales.	The 3 case studies of beaches with historical sensibility to erosion & storm surge flooding presented a	GIS: CVI with data obtained from historical aero-photos, satellite images, topographic maps and wave statistics.	GIS 1.backshore landforms 2.backshore altitude 3.shoreline displacement 4.shoreline exposure to wave	GIS 1. man-made structures at risk		(Bonetti *et al.*, 2013)

		very good correlation with reality in southern Brazil	Processed with the Digital Shoreline Analysis System - DSAS, the Wind Fetch Model (ArcGIS extension tools) and integrated in a GIS system. Numerical modelling: Used for inundation level and erosional hotspot calculations.	incidence Numerical Modelling: 1. Wave run-up 2. Longshore sediment transport rate			
To produce a social vulnerability index in terms of erosion hazard vulnerability	To use socio-economic data from US-Census database in order to produce a social vulnerability index in terms of erosion hazard vulnerability	213 US coastal counties: socio-economic variables (SoVI) placed in a principal components analysis (PCA) & physical variables (CVI)	An analysis of variance (ANOVA) for regional differences in the overall place (PVI), SoVI, & CVI (at the 95% confidence level)		6 physical variables (CVI)	39 availability data out of 42 socio-economic variables (SoVI)	(Boruff *et al.*, 2005, Cutter *et al.*, 2003, Thieler & Hammer-Klose, 1999, Thieler & Hammer-Klose, 2000a, Thieler & Hammer-Klose, 2000b)
Social/ ecological vulnerability							
Social Vulnerability Index (SoVI) to environmental hazards	To define a robust set of variables that capture the characteristics of social	US counties Spatial: all 3,141 U.S. counties Temporal: 1990 data	After all the computations & normalization of data (to percentages, per capita, or	None	1. Personal wealth (per capita income, % of households earning > $75,000/ year, median house values, & median rents)	None	(Cutter *et al.*, 2003)

	vulnerability of counties, which then allows us to monitor changes in social vulnerability geographically & over time.		density functions), 42 independent variables used, reduce to 11 independent components (76% of the variance). These components were placed in an additive model which equal weights to compute a summary score - the SoVI		2. Age (median age) 3. Density of the built environment (No. commercial establishments/mi^2) 4. Single-sector economic dependence (employed in extractive industries) 5. Housing stock & tenancy (housing units that are mobile homes) 6. Race-African American (African American) 7. Ethnicity-Hispanic (Hispanic) 8. Ethnicity-Native American (Native American) 9. Race-Asian (Asian) 10. Occupation (employed in service occupations) 11. Infrastructure dependence (employed in transportation, communication, & public utilities)		
To examine the vulnerability to climate change	Citizen participation in emergency response following the Loma Prieta Earthquake			Earthquake	1. The structure & health of the population: Age is an important consideration as to be inherently more susceptible to environmental risk & hazard exposure		(O'Brien & Mileti, 1992)
To study the	Societal				1. Human population	1. Institutional	(Handmer *et al.*,

coping mechanisms to environmental shock/ or hazard by biophysical vulnerability	Vulnerability to Climate Change and Variability					stability 2. Strength of public infrastructure	1999)
To construct vulnerability resilience variables to climate change	To identify 10 proxies for 5 sectors of climate sensitivities & 7 proxies for 3 sectors of coping/or adaptive capacity	US	Proxies aggregated into sectoral variables, sensitivity variables & coping/ or adaptive capacity variables to finally construct vulnerability resilience variables to climate change		1. Settlement sensitivity 2. Food security 3. Human health sensitivity 4. Ecosystem sensitivity 5. Water availability	1. Economic capacity 2. Human resources 3. Environmental /or natural resources capacity	(Moss *et al.*, 2001)
Socio-economic indicators of Community vulnerability to natural hazards	To use socio-economic indicators of Community vulnerability to natural hazards/ disasters in Northern Australia & address limitations: ageing of the data, the arbitrary nature of boundaries, problems of weighting indicators, &	In Northern Australia		1. Tropical cyclones 2. Floods	1. Land data 2. Demographic indicators	1. Socio-economic indicators	(King, 2001)

	categorisation of vulnerability				
The environmental vulnerability index (EnVI)	50 smart indicators used to capture a large number of elements in a complex interactive system while simultaneously showing how the value obtained relates to some ideal condition	Country level	Country experts, international experts, interest groups & other agencies judgments	The indicators are classified into 5 classes: 1. M = Meteorological 2. G = Geological 3. B = Biological 4. C = Country Characteristics 5. A = Anthropogenic classified into a range of sub-indices including: hazards, resistance, damage, climate change, biodiversity, water, agriculture & fisheries, human health aspects, desertification, & exposure to natural disasters; grouped into three sub-indices namely: REI = Exposure to human & natural risks per hazards; EDI = Environmental Degradation Index; measures the present position of the "health" of the environment. IRI = Intrinsic Resilience Index; values are rated on a scale of 1 to 7, with 7 representing high vulnerability, an overall average of all is calculated to generate a country's EnVI	(Peduzzi *et al.*, 2003, Peduzzi *et al.*, 2001)
The Climate Vulnerability Index (CVI) for assessing Water Poverty Index		Country-level	Every component is made up of subcomponents; the components are joint using a composite index structure. The index ranges between 0 to 100	6 major categories/components: Resource (R), Access (A), Capacity (C), Use (U), Environment (E) & Geospatial (G). There are different vulnerabilities to climate change, some of the studied are vulnerability to climate related mortality, social vulnerability to climate change, even some countries have defined their vulnerability to climate change using different indicators; for example: Canada, Peru, USA etc. Mortality from climate-related disasters can be quantified via emergency actions database data set, statistical relations between mortality & select likely proxies for vulnerability are used to spot key vulnerability indicators. Other CVI use 11 indicators: literacy rate; literacy rate, > 15 yrs; population with access to sanitation; maternal mortality; life expectancy at birth; 15-25 yrs; calorific intake; civil liberties & political rights; voice & accountability; government effectiveness literacy ratio (female or male). The indicators can be separated in three categories: Governance; Health status & Education. Almost 100 possible indicators were examined for climate-change report in Canada; 2 groups (Nature: sea-level rise, sea ice, river & lake ice, glaciers, polar bears, plant development & People: traditional	(Sullivan, 2002, Sullivan *et al.*, 2003)

				way of life, drought, great lakes, frost & frost free season, heating & cooling, extreme weather)			
The Composite Vulnerability Index	The Composite Vulnerability Index for Small Island States	Country Level focusing On developing Small island states/ hazard	Point out the intrinsic vulnerability of small island states in comparison to large countries which possess several advantages associated with their large scale Application of weighted least square (determination of weights through regression) routines to integrate the basic indicators				(Briguglio, 2003, Briguglio, 2004)
Advanced Terrestrial Ecosystem Analysis and Modelling (ATEAM)	To assess potential impacts of global change on ecosystem sensitivity to climate change in Europe, & to translate these impacts into maps of our vulnerability; the sectors: agriculture, forestry, carbon storage, water,	European data sets at regional scale 10' x 10' grid resolution over EU15 plus Norway & Switzerland, baseline 1990, future time slices 2020, 2050,	Fuzzy inference rules were applied to aggregate the individual indicator values into one generic measure of adaptive capacity per spatial unit. The resulting generic index captures one of many dimensions of	A consistent set of multiple, spatially explicit global change scenarios for A1F, A2, B1 & B2. 1. Past & future climate change scenarios for monthly values of five different climatic variables (monthly temperature, diurnal temperature	A range of state of the art ecosystem models that represent the sensitivity of the human- environment system were used. *Agriculture sensitivity indicators:* 1. Agricultural land area (Farmer livelihood) 2. Soil organic carbon content 3. Nitrate leaching 4. Suitability of crops	Spatially explicit & quantitative generic index of adaptive capacity (macro-scale: provincial level). This index is based on 6 determinants identified by the IPCC TAR 2001 (power, flexibility, freedom, motivation, knowledge & urgency) categorized into 12 indicators,	(Schröter, 2004b, Schröter, 2004a)

	nature conservation & mountain tourism in the 21st century were mapped	2080	adaptive capacity	range, precipitation, vapour pressure & cloud cover)	5. Biomass energy yield *Forestry sensitivity indicators:* 6. Forest area 7. Tree productivity: growing stock, increment, age class distribution 8. Tree species suitability *Carbon storage sensitivity indicators:* 9. Net biome exchange 10. Carbon off-set by fossil fuel substitution *Water sensitivity indicators:* 11. Runoff quantity 12. Runoff seasonality 13. Water resources per capita 14. "Drought runoff" (the annual runoff that is exceeded in 9 years out of 10) 15. "Flood runoff" (the mean maximum monthly runoff) *Biodiversity & nature conservation sensitivity indicators:* 16. Species richness & turnover (plants, mammals, birds, reptiles, amphibian) 17. Shifts in suitable habitats *Mountains sensitivity*	such as: 1. GDP 2. Female activity rate 3. Age structure 4. Literacy index 5. Urbanisation, etc	

					indicators: 18. Elevation of reliable snow cover 19. Number of heat days		
Vulnerability Index to climate change	Vulnerability Index to climate change in Africa	Africa (country level) / water availability	Expert weighted index of five indicators; however the indicators are not directly related to "water availability" Draws from the global climate change research community who align social vulnerability with adaptation capacity		1. Economic well-being & stability (Standard of living/poverty, Change in % urban population) 2. Demographic structure (Dependent population, Proportion of the working population with HIV/AIDS) 3. Institutional stability & strength of public infrastructure (Health expenditure as a proportion of GDP, Telephones, Corruption) 4. Global interconnectivity (Trade balance) 5. Natural resource dependence (Rural population)		(Vincent, 2004)
Mapping vulnerability to multiple stressors: climate change & globalization	Mapping vulnerability to multiple stressors: climate change & globalization in India	India	To measure adaptive capacity, significant biophysical, socio-economic, & technological components that influence agricultural	1. Biophysical (soil conditions (quality & depth), ground water availability)	None	1. Socio-economic (levels of human & social capital, presence or lack of alternative economic activities) 2. Technological (availability of irrigation & quality of infrastructure)	(O'Brien *et al.*, 2004)

			production were identified. To measure sensitivity under exposure to climate change in regard to dryness & monsoon dependence, they constructed a climate sensitivity index				
Predictive Indicators of Vulnerability	Predictive Indicators of Vulnerability	Global	Set of 11 indicators based on correlations with decadal hazard mortality; unweighted combination within an index (no ranking, classification of different vulnerabilities)	Selection of social vulnerability indicators guided by historic hazard mortality	1. Population with access to sanitation 2. Literacy rate, 15-24 year olds 3. Maternal mortality 4. Literacy rate, > 15 yrs 5. Calorie intake 6. Voice & accountability 7. Civil liberties 8. Political rights 9. Government effectiveness 10. Literacy ratio (female to male) 11. Life expectancy at birth	None	(Adger *et al.*, 2004)
Indicators for vulnerability	National level indicators of vulnerability & capacity to adapt to climate hazards to support policy	Spatial: national data Temporal: averaged, decadal data for past damages & system	Adaptive capacity variables were selected by correlation analysis with the exposure component.	None	1. Numbers of people killed by climate related disasters per decade as percentage of national population	1. Population with access to sanitation 2. Literacy rate (15-24 yrs) 3. Maternal mortality 4. Literacy rate > 15 yrs	(Brooks *et al.*, 2005)

		characteristics	Standardisation based on ranges (quintiles) & scores between 1 & 5. Different weightings of the indicators based on expert interviews			5. Calorific intake 6. Voice & accountability 7. Civil liberties 8. Political rights 9. Government effectiveness 10. Literacy ratio (female to male) 11. Life expectancy at birth	
The climate vulnerability index (CVI)	Assessment of human vulnerability to develop adaptation strategies	Variable	Composite index as weighted average of all components. The weighs should be assigned by participatory consultation & expert opinion. Here they were all given the value 1	1. Different scenarios	1. Resource factor, i.e., evaluation of water storage capacity 2. Access factor 3. Environment factor 4. Geospatial factor	1. Capacity factor 2. Use factor	(Sullivan & Meigh, 2005)
Indicators for country- level adaptive capacity	To suggest 8 determinants of country- level adaptive capacity; To develop a set of indices of (aggregated outcome) vulnerability to climate change; The indices endure from fundamental	country- level		None	Climate sensitivity	1. The availability of technological options for adaptation 2. The availability of resources and their distribution 3. The structure of critical institutions 4. The stocks of human and social capital 5. Access to risk spreading mechanisms	(Yohe *et al.*, 2006a, Yohe & Tol, 2002)

	methodological & conceptual limitations. The project website displays 144 global vulnerability maps					6. The ability of decision-makers to manage risks and information 7. The public's perceived attribution of the source of the stress 8. The significance of exposure to its local manifestations	
A case study of coastal assessment of climate-change vulnerabilities	A case study of assessment of climate-change vulnerabilities in the Canada's most sensitive coast, Graham Island.	Coastal vulnerability assessment at a case study in Graham Island (Canada)	Based on a qualitative statement: Local & traditional knowledge is the key to research design & implementation & allows for locally relevant outcomes that could aid in more effective decision making, planning & management in remote coastal regions	1. Biophysical impacts: extreme climate variability	1. Sensitive landscape 2. Restricted natural resources	1. Socio-economic capacity: access to and distribution of wealth, technology, and information, risk perception & awareness, social capital & critical institutional frameworks	(Dolan & Walker, 2006)
Vulnerability concepts in hazard & risk assessment	Vulnerability concepts in hazard & risk assessment	Regional	The indicators were weighted in a way that the overall regional vulnerability is 100%. Integrated	None	1. Damage potential: GDP/capita; population density; tourism; culturally significant sites; significant natural areas; fragmented	1. Coping capacity: education rate; dependency ratio; risk perception; level of mitigation; medical infrastructure	(Kumpulainen, 2006)

			vulnerability index: regional GDP/capita 30%, population density 30%, fragmented natural areas 10% (only 10% because this component only depicts one aspect of ecological vulnerability), national GDP/capita 30%.		natural areas		
To evaluate impacts of natural disasters across income Groups (social vulnerability)	Distribution of impacts of natural disasters across income groups: A case study of New Orleans	A case study of New Orleans (USA) impacted differently by Hurricane Katrina		1. Elevation 2. Flood levels	1. Population characteristics: gender, race & ethnicity, age, residential property, renters, education, health status, social dependence, special-needs populations (infirm, institutionalized, transient, & homeless)	1. Socio-economic status (income, savings, employment, access to communication channels and information, insurance influences, political power, prestige) 2. Transport	(Cutter *et al.*, 2001, Masozera *et al.*, 2007)
To select indicators and methods to measure revealed and emergent vulnerability of coastal communities at the local scale	To focus on the social dimension of vulnerability to select indicators & methods to measure revealed & emergent vulnerability of coastal	Coastal communities at local scale in the examples of Batticaloa & Galle tsunami-affected in Sri Lanka	A meta-framework to structure the questionnaire survey & the analysis of the tsunami census data Not mention about the aggregation		1. Impact of tsunami on household members & their assets 2. Structure of household (age, gender, education & income, etc) 3. Housing conditions & impact of tsunami 4. Direct loss of possessions	1. Social networks 2. Knowledge of coastal hazards & tsunami 3. Financial support from formal & informal organisations 4. Access to information (radio) 5. Intervention tools	(Birkmann & Fernando, 2008)

	communities at the local scale: susceptibility & degree of exposure, coping capacities, & intervention tools				5. Activity & occupation of household members	(Relocation of housing & infrastructure to inland; Early warning system; 100-metre 'buffer zone' (implemented by government)	
The new Climate Change Vulnerability Index (CCVI)	A new global ranking, calculating the vulnerability of 170 countries to the impacts of climate change over the next 30 years	National-scale, 42 indicators categorized into 3 areas: social, economic, & environmental factors		Exposure to climate-related natural disasters & sea-level rise	Human sensitivity, in terms of population patterns, development, natural resources, agricultural dependency & conflicts	The future vulnerability index assessed by considering the adaptive capacity of a country's government & infrastructure to combat climate change	(Maplecroft, 2010)
Human vulnerability to climate change		Central America, central South America, the Arabian Peninsula, Southeast Asia, & much of Africa			1. Population density is one of indices of human vulnerability to climate change 2. Agriculture sector		(Samson *et al.*, 2011)
Assess the impacts of climate change	Assess the impacts of climate change based on 5 climate hazard crossed 4 sectoral effects for western part of the Mekong river delta in	District level for 2 provinces in the western part of the Mekong river delta in Vietnam	No aggregation	1. Sea-level rise 2. Flood 3. Typhoon 4. Storm surge 5. Heat wave		1. Energy & industry 2. Urban planning & transportation 3. Livelihood & agriculture 4. Socio-economic pattern	(Mackey & Russell, 2011)

	Vietnam (Kien Giang, Ca Mau)						
Intergrated vulnerability assessment							
A conventional methodology to assess vulnerability to climate change	A general methodology to assess vulnerability to climate change followed the conceptual framework provided by IPCC	Coastal cities in South Korea	Synthesizing by standardized using a dimension index method (MIN-MAX), expert suggestions for weighting	1. Sea-level rise 2. Heavy rain-storm 3. Heat wave	1. Population density (with more sub-variables: age at 65yrs & >65yrs or < 5 yrs) 2. Land cover (with more sub-variables: flooded area, ratio between flooded area & total area in each county): agricultural land, forest/ wetland/ grassland, commercial area, residential area, industrial area, & recreational & other urbanized parts.	1. Economic capability: financial independence) 2. Infra-structure (green area, state support for health, water resource accessibility) 3. Institutional capability (awareness, governance, policy foundation)	(Yoo *et al.*, 2011)
An index of the climate-change vulnerability	Construct an index of the climate-change vulnerability	Sub-national areas, regions, provinces, districts for South East Asia	Synthesizing by standardized using a dimension index method (MIN-MAX), expert suggestions for weighting	1. Tropical cyclones 2. Floods 3. Landslides 4. Droughts 5. Sea-level rise	1. Population density *(Human sensitivity)* 2. Percentage of protected areas *(Ecological sensitivity)*	1. Socio-economic factors (HDI: Standard of living, longevity, education; poverty incidence, income inequality) 2. Technology (electricity coverage, extent of irrigation) 3. Infra-structure (road density, communication) 4. Policy & institutions	(Yusuf & Francisco, 2009)
Vulnerability Indicators for Ecosystems & Natural Resources	Vulnerability Indicators for Ecosystems & Natural Resources for	Regional, Sydney Coastal Councils Groups	Aggregation by summation of components values for each element, scoring,	1. Projected change in annual average temperature in 2030	1. Elevation 2. Land cover 3. % Native vegetation 4. Water condition 5. Land condition	1. % population completing year 12 2. % population that speaks language other than English	(Preston *et al.*, 2008)

	the region to initiate a dialogue among researchers & stakeholders & a bottom-up assessment of local governments	in 2030	weighting based on expert values & summation of the elements values for vulnerability indicator	2. Projected change in average DJF maximum temperature in 2030 3. Projected change in annual average JJA minimum temperature in 2030 4. Projected change in average annual rainfall in 2030	6. Population density 7. Road density 8. Projected population growth to 2019 9. SEPP 14 wetland areas	3. Median home loan repayment 4. % home ownership 5. Median household income 6. % households requiring financial assistance 7. % population with internet access 8. Current ratios 9. Per capita business rates 10. Per capita residential rates 11. Per capita community service expenses 12. Per capita environment & health expenses 13. Per capita annual recycling	