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Original Article

Nonlinearity, fuzziness and incommensurability in indicator-based assessments of vulnerability to climate change: A new mathematical framework

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ABSTRACT

The earth's climate system is highly nonlinear and the vulnerability of a community to a climate hazard is no exception. While this fact is widely accepted, indicator-based vulnerability assessments (IBVA) hardly ever take such nonlinearities into account. This is mainly due to the fact that the majority of assessment studies use methods based on Multiple Attribute Utility Theory (MAUT) (e.g. simple additive weight or multiplicative aggregation) to aggregate indicators. These methods convert all indicators into a global utility function and produce only a linear, threshold-free scaling of the effects of an indicator on vulnerability. In a previous paper, we showed that outranking procedures developed in decision-making science offer a more theoretically-sound approach to aggregation because they allow the analyst to incorporate the incommensurability, fuzziness and uncertainty associated with indicators. In this paper, we develop a new mathematical framework for vulnerability in order to clearly identify various sources of nonlinearity and incommensurability in vulnerability assessments. We then propose a new outranking formulation which can accommodate both and can be used to conduct assessments at different scales. We do so by introducing the concept of *harm criterion* as a mediator between an indicator and the vulnerability it represents. The new assessment approach can aggregate a mix of indicators with various degrees of subjectivity and non-linearity, without converting them into a single utility function and without requiring them to be mutually compensating.

We illustrate the proposed approach by applying it to a simplified model of urban vulnerability to heat, focusing on the non-linear relationship between mortality and temperature above a 'comfort temperature', long evidenced in the epidemiological literature. We compare vulnerability rankings yielded by linear and non-linear characterizations of the relationship between temperature and mortality and find that the incorporation of non-linearity can have a significant impact on the rankings.

1. Introduction

As global average temperatures increase and changes to the hydrological cycle become more evident, anthropogenic climate change presents significant threats to cities, economic sectors and infrastructure systems (IPCC, 2014). Climate risk assessment and climate change adaptation are becoming a central concern for policymakers, planners and engineers. Risk and vulnerability assessments aim at identifying hotspots, understanding processes generating vulnerability and helping policymakers to prioritize, allocate resources and develop better adaptation planning.

Vulnerability assessment is a complex form of risk appraisal, which considers both bio-physical and socio-economic components of the environmental hazard. The most commonly used framework of vulnerability is the one proposed by the Intergovernmental Panel on Climate Change (IPCC) in its Third Assessment Report which recognises three dimensions of vulnerability, namely exposure, sensitivity and adaptive capacity, with the first generally reflecting, as the name indicates, the extent to which a socio-ecological system (SES) (e.g., locality, region, community, infrastructure system) is exposed to the hazard in question, the second its propensity to be damaged by that exposure and the third its ability to cope with, and recover from, that damage. In other words, while exposure focuses on the degree of contact between hazard and SES, sensitivity and adaptive capacity are concerned with the complex ramifications of the hazard in human societies (Eriksen and Kelly, 2007; Parry et al., 2007). However, this

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framework has come under criticism especially for the ambiguity of its concepts and its lack of specificity concerning the relationship between them (e.g., Ionescu et al., 2009).

The literature on climate-change vulnerability assessment falls broadly into three categories. A number of papers over the last ten years have engaged with theoretical and semantic aspects of vulnerability in order to negotiate a multiplicity of definitions and some confusion surrounding the concept (e.g., Adger, 2006; Adger and Kelly, 1999; Cutter et al., 2003). This has led to a level of agreement about the need for precision in defining processes generating vulnerability, the importance of scale and the place-specific nature of assessments. For example, Füssel and Klein (2006), showed that vulnerability assessments have evolved over the years from an impact assessment focusing only on exposure and sensitivity of a system to a more complex form of evaluation which account for important place specific non-climatic factors and acknowledge the potential for adaptation measures at appropriate scale to reduce potential climate impacts.

A second, albeit small, set of studies proposed specific methodologies (as opposed to conceptual frameworks) to guide practitioners in conducting assessments (e.g., Füssel, 2007; Füssel and Klein, 2006; Luers et al., 2003; Tonmoy et al., 2014; El-Zein and Tonmoy, 2015), while a third, and by far the largest, reports actual assessment studies (Hahn et al., 2009; Duriyapong and Nakhapakorn, 2011; Brenkert and Malone, 2005; Preston et al., 2008). To our knowledge, no paper, including methodological ones, has tackled specifically the various nonlinearities present in relationships describing vulnerability, nor has there been a formal attempt at incorporating them in assessment studies.

Broadly, two approaches have been used in climate change quantitative impact studies in the literature (Tonmoy et al., 2014). Scenario-based analyses downscale predictions of Global Circulation Models (GCM) then combine them with mechanistic biophysical or biochemical models (e.g., hydrological, epidemiological, atmospheric) in order to derive GCM's implications at regional and local scales. The advantage of this approach is that it is usually based on robust climate science and sound understanding of the dynamics of the system in question and can represent threshold effects and nonlinearities. However, restrictions on the spatial resolution of GCMs and the complexity of incorporating the social, economic and institutional components of risk, limit the scope of this approach.

In the second approach, indicators offer an attractive and relatively simple way of quantifying different components of the risk, biophysical, institutional and socio-economic (Füssel, 2007; Hinkel, 2011). The challenge of indicator-based vulnerability assessments (IBVA) lies in identifying and selecting measurable indicators that can represent all significant processes generating vulnerability and then combining these indicators, using sound aggregation principles, in order to produce a proxy measure of vulnerability. While indicators can usually be identified with relative ease, the exact relationship they hold to vulnerability is either difficult or impossible to determine with precision. This relationship usually turns out to be more complex than the linear association that is assumed in most analyses. One partial way out of this impasse is to combine impacts studies simulating the biophysical components of the hazard with indicators representing its socio-economic and institutional components. However, another difficulty facing IBVA lies in developing aggregation principles that can take into account the different types of indicators (continuous, discrete and ordinal variables); different types of relationships between indicators and vulnerability (linear and non-linear, deterministic and stochastic, dichotomous and fuzzy); as well as different possible relationships of compensation and non-compensation *between* the indicators (Tonmoy et al., 2012; Tonmoy and El-Zein, 2013a; El-Zein and Tonmoy, 2015). To date, the vast majority of the IBVA literature has used simple aggregation approaches whose validity is in serious doubt (Tonmoy and El-Zein, 2013; Tonmoy et al., 2014). For example, most IBVA studies use Multiple Attribute Utility Theory (MAUT) based methods such as simple additive weight or multiplicative weight for aggregation of indicators which assume a linear relationship between indicators and vulnerability and complete compensation between indicators based on allocated weights.

This paper has two objectives:

a) to present a new mathematical framework for vulnerability which allows us to clearly define different forms of nonlinearity and incommensurability in vulnerability assessments;
b) to propose a new indicator-based approach which can accommodate non-linear relationships between an indicator and the vulnerability it represents, as well as different degrees of compensation between indicators (from total compensation to complete incommensurability).

We build on our previous work on vulnerability assessments in which we showed that outranking procedures first developed in decision-making science by Roy (1968) offer a more theoretically sound approach to aggregation than MAUT-based ones because they allow the analyst to incorporate incommensurability, uncertainty and multiple subjectivities in vulnerability models (El-Zein and Tonmoy, 2015). In this paper, we are not particularly concerned with semantic aspects of vulnerability, though we acknowledge their importance. Instead, we start from a definition of vulnerability (generally accepted in the literature and presented at the beginning of the next section) and abide by it throughout. First, we present the new vulnerability framework and definitions attached to it, and elicit the different forms of nonlinearity present in relationships of vulnerability. Second, based on this framework, we formulate a new outranking approach to aggregation which incorporates nonlinearity. Finally, we illustrate the new approach by applying it to a simplified model of vulnerability to heat stress and show that the incorporation of nonlinearity and partial compensation can have a significant impact on the ranking of vulnerabilities.

The goal of the paper is to propose a method that can be used by practitioners in assessment studies. Therefore, although we are proposing a mathematical formalism for the sake of precision and conceptual clarity, we will mostly use vulnerability terminology that is familiar to researchers in this field.

2. Vulnerability to climate change: from conceptual framework to assessment

2.1. Vulnerability framework and definitions

The aim of vulnerability assessment is to develop some measure, quantitative or qualitative, of the susceptibility to damage of, or damage likely to be inflicted on, a valued attribute of an SES, as a result of its exposure to one or more climate stresses. For the purpose of the discussion below, at any point in time, we denote damage by D(t), vulnerability by V(t) and the magnitude of the climate stress in question by M(t), where t is time. It is reasonable to assume that, as the magnitude M of the climate stress increases, so does the damage D. In the remainder of the paper, we refer to D(t), V(t) and M(t) for simplicity, as D,V and M, respectively, with the understanding that they are functions of time. We define vulnerability as the ratio of damage to magnitude:

$$D = \mathbf{V}M \tag{1}$$

where D, V and M are positive numbers (for clarity, we represent D and M in italics and the slope connecting them, i.e. vulnerability, in bold-faced font, throughout). In some cases, V is largely independent of M and Eq (1) simply reflects a linear relationship between D and M. For example, within a given range, the extent of physical damage inflicted on houses in a "do nothing" scenario may be roughly proportional to the level of sea rise causing it, i.e. V does not depend on M. In reality, such relationships are seldom linear. More often than not, D is a non-