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Research Paper

Assessing urban flooding vulnerability with an emergy approach

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HIGHLIGHTS

- A systems approach is required for assessing vulnerability.
- Emergy can be used to evaluate exposure, sensitivity, and adaptive capacity.
- Mapping emergy indices revealed the spatial vulnerability to flooding.

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ABSTRACT

Under the context of climate change adaption research, vulnerability assessment should take into consideration the interaction among natural processes, socio-economic conditions, and the mechanisms of response of the integrated ecological economic system. Pressure from urban development, land use and land cover change along the western coast of Taiwan not only has caused the loss of ecosystem services in peri-urban environments, but has also resulted in an increase in urban flooding vulnerability. This paper develops a framework, which incorporates the interaction among exposure, sensitivity, and adaptive capacity for assessing the vulnerability to flooding. To achieve this aim, this research interprets urban flooding vulnerability based on emergy concepts and develops emergy indices to assess the spatiality of urban flooding vulnerability in Taiwan's western coastal plain via GIS. Based on the results of the emergy evaluation of the three components of vulnerability and five emergy indices for urban flooding vulnerability, the areas with intense urbanization are characterized with high potential impact to flood. However, cities with higher potential impact do not necessarily lead to higher vulnerability for urban flooding because adaptive capacity can also mitigate the vulnerability of cities to extreme climate events. Using the framework developed by this research we show that the emergy concept can effectively provide a common measuring unit for evaluating exposure, sensitivity and adaptive capacity of urban flooding vulnerability.

1. Introduction

Vulnerability has in recent years become a central focus of the global environmental change and sustainability science research communities (Füssel, 2007; GLP, 2005; McCarthy, Canziani, Leary, Dokken, & White, 2001; Turner et al., 2003; UGEC, 2005). Vulnerability is defined by the Third Assessment Report of IPCC as the degree to which a system is susceptible to adverse effects of climate variability or extremes (McCarthy, Canziani, Leary, Dokken & White, 2001). Turner et al. (2003) further defined vulnerability as "the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress/stressor". Vulnerability has generally been conceptualized as being constituted by three interrelated components: (1) exposure to perturbation; (2) sensitivity of the system to perturbation; and (3) system's capacity to adapt (Adger, 2006). The exposure and sensitivity of a system are affected by the interaction of environmental and social forces, while adaptive capacity is shaped by socio-economic, cultural, and political forces (Smit & Wandel, 2006). A growing number of studies have positioned vulnerability assessment as an important element for developing and implementing adaptation strategies to policy (Adger, 2006; Brooks, Adger, & Kelly, 2005; Füssel & Klein, 2006; Hinkel, 2011). The framework of vulnerability assessment by Turner et al. (2003) can be regarded as an important turning point inspiring subsequent vulnerability assessment research with specific concerns for the social and biophysical dimensions of climate change or natural disasters related vulnerability.

To assess the degree of vulnerability to extreme climate events, indicators have been frequently developed. Brooks et al. (2005)

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developed national-level indicators, via a Delphi survey, to assess vulnerability to climate hazards. Szlafsztein and Sterr (2007) created a composite vulnerability index (CVI), which includes 16 variables of both natural and socio-economic conditions. Ozcan and Musaoglu (2010) used an analytic hierarchy process (AHP) to assign scores for attributes of DTM, slope, aspect, land use, and geology to derive a vulnerability map. Ouma and Tateishi (2014) also used AHP to assign weights to decision parameters (e.g. rainfall, elevation, slope, drainage, land use, etc.) for creating a flood vulnerability map. In these studies, the relationships between indicators representing exposure, sensitivity, and adaptive capacity for assessing vulnerability were often assumed independent and weighted and ranked separately, then combined and aggregated to derive an overall measure of vulnerability. In assessing vulnerability, exposure is the primary factor of concern that makes people or places vulnerable to natural hazards. Socio-economic conditions were always regarded as the major factor, which affects the system's ability to adapt to extreme climate events. Cutter, Boruff, and Shirley (2003) used principle component analysis to aggregate county-level socio-economic data to assess the social vulnerability of different municipalities in US. In the vulnerability assessment of the ATEAM (Advanced Terrestrial Ecosystem Analysis and Modelling) land use scenarios, Metzger, Rounsevell, Acosta-Michlik, Leemans, and Schröter (2006) aggregated 12 socio-economic indicators to three components of awareness, ability and action, and then combined them into an index of adaptive capacity. In order to incorporate geographic characteristics of study areas, Geographic Information System (GIS) techniques have been applied to most of the place-based studies to evaluate the spatial heterogeneity of vulnerability (Metzger et al., 2006; O'Brien et al., 2004; Ouma & Tateishi, 2014; Ozcan & Musaoglu, 2010; Szlafsztein & Sterr, 2007).

From a biophysical systems perspective, this research suggested using emergy synthesis to highlight the fact that the three constituents of vulnerability are inseparable entities. This also allows for the use of emergy as a common unit to integrate the energetic flows between natural and human society for vulnerability assessment. The properties of exposure, sensitivity, and adaptive capacity are interrelated and overlapping, meaning that in each assessment of vulnerability no single property must be emphasized over the others. The major challenges of incorporating emergy evaluation for vulnerability assessment include: linking biophysical and social realms and their mutual interactions; taking into account the interactive characteristics among the three components of vulnerability; and evaluating these three components with comparable emergy units. On the basis of emergy concepts, the purpose of this paper is to develop a systemic evaluation framework that will help us to interpret the three components of urban vulnerability to flooding from emergy concepts; develop emergy indices to assess urban vulnerability to flooding; and exhibit the spatial heterogeneity of urban vulnerability to flooding via GIS. The proposed framework is applied to study Taiwan's western coastal plain area. The remainder of this paper will first describe our study design and methodology of how emergy concept is used to interpret the three components of vulnerability and the development of emergy indices for assessing urban flooding vulnerability. The framework of emergy evaluation and indices is applied to the study area to reveal the spatiality of exposure, sensitivity and adaptive capacity. The advantages and limitations of using emergy evaluation to assess vulnerability are also discussed.

2. Framework of emergy evaluation for assessing urban vulnerability to flooding

From a systems perspective, cause–effect relationships between exposure, sensitivity, and adaptive capacity for assessing vulnerability are linked through energy and material flows between natural and social systems (Huang, Chang, & Yeh, 2011). In this section, the concepts of exposure, sensitivity, and adaptive capacity are redefined from an ecological energetic viewpoint. Emergy evaluation and indices for vulnerability assessments are also proposed.

2.1. Emergy basis for vulnerability assessment

On the basis of general system theory and the laws of thermodynamics, Odum (1983, 1996) developed the emergy concept to account for the different energy qualities inherent in energy and material flows of complex ecological economic systems. Emergy is defined as "all the available energy that is used in the work of making a product and expressed in units of one type of energy" (Odum, 1996). The emergy value of a flow of storage can be derived by multiplying its energy content or mass by its transformity:

$$\text{Emergy (sej)} = \text{energy (J)} \times \text{solar transformity (sej/J)} \quad (1)$$

Emergy indices can also be developed and calculated by aggregating resource flows to synthesize system performance and to measure sustainability. In this research, emergy is incorporated to evaluate the contribution of energy and resource flows with a common emergy unit for vulnerability assessment.

The emergy values of the constituents of vulnerability were interpreted as follows (Chang & Huang, 2011; Huang, Chang, & Yeh, 2011):

Exposure is the total emergy of the extreme climate events acting upon the area.

Sensitivity is the amount of stored emergy that is likely to be affected by an extreme climate event.

Adaptive capacity is the system's ability to attract emergy inflows to recover and to adjust from the impacts of hazards.

Exposure and sensitivity can be combined into potential impact, which can also be regarded as the emergy value of the potential damage and loss caused by an event.

The energy system diagram of urban flooding vulnerability (Fig. 1) shows the different energy and material flows between ecological and urban economic systems, and represents the basis of cause–effect relationships among the components of vulnerability. The energy diagram consists of natural and agricultural systems and the urban system. Flows representing climatic events, economic inputs and urban responses interconnect system components. When an extreme climate event occurs, it brings rainfall over a short period of time. The amount of rainfall emergy ($J1$) can potentially contribute to the exposure of this area to the extreme climate event. Depending on the characteristics of land cover and soil properties, a proportion of the rainfall will become runoff emergy ($J2$), which can be regarded as the exposure of the area. $J3$ is the ratio of runoff ($J2$) to rainfall ($J1$), representing the intensity of exposure. The assets stored in natural and agriculture systems and the urban system can be regarded as the components of the sensitivity to vulnerability. $J4$ and $J5$ are the damages that result in the natural and agricultural systems and the urban system, respectively. The larger the stored assets the more likely flood damage will occur from an extreme climate event. $J6$ is the summation of total damage to both natural and agricultural systems and the urban system. The interaction of the intensity of exposure ($J3$) and sensitivity ($J6$) will represent the potential impacts ($J7$). Higher potential impact is likely to result in higher vulnerability. At the same time, when an extreme climate event occurs the urban system can adapt ($J10$) by attracting more emergy from outside sources in response to the event. Finally, vulnerability is assessed by dividing the emergy of potential impacts by the emergy of adaptive capacity ($J11$).