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# Integrated spatial ecosystem model for simulating land use change and assessing vulnerability to flooding

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ABSTRACT

Components of urban vulnerability (exposure, sensitivity, and adaptive capacity) to extreme climate events are directly related to urbanization. An indicator-based approach has frequently been used to assess urban vulnerability, but the interactions among indicators representing the components of vulnerability and the feedback interactions between vulnerability and urbanization have rarely been considered. To understand the interactive and dynamic relationships between urbanization and vulnerability, a study was undertaken that applied systems ecology theory to the development of a spatial model for the simulation of land use change and vulnerability to flooding in the Taipei metropolitan region. The study area was divided into grids of 1 km × 1 km, and each grid cell was represented by a system model comprising subsystems of natural area, agricultural area, and urban area. A model of vulnerability assessment was attached with the urban area subsystem to calculate the three components of vulnerability as a consequence of land use change and to show the bilateral relationship between urbanization and vulnerability. The simulation results showed that the spatial distribution of urban development in the Taipei metropolitan region and the components of vulnerability that were directly affected by urbanization. The simulation results suggested that *peri*-urban areas of the Taipei metropolitan region have higher vulnerability to flooding than the heavily urbanized areas in the Taipei basin. The simulation results also revealed that the pace of urban development would be slowed if the assessed vulnerability was used as feedback to subsequent urban development.



## 1. Introduction

Urbanization is an important issue of concern in response to global climate change. For the first time since the first assessment report (FAR) of the Intergovernmental Panel on Climate Change (IPCC) in 1990, a chapter on "Urban Areas" and "Human Settlement, Infrastructure, and Spatial Planning" were included in the output of Working Group II and Working Group III of IPCC AR5 respectively. Both of these additions were to assess the adaptation and mitigation of cities to climate change. Rapid urban development and uncontrolled growth are likely to increase urban vulnerability due to its sensitive characteristics to extreme climate events and lack of adaptive capacity to respond to climate change (Huang et al., 2011). Urban sprawl is also becoming a serious problem to local climate, and it also has caused impacts to social and economic development in cities (Emadodin et al., 2016).

The Third Assessment Report of the IPCC defined vulnerability as "The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity" (McCarthy et al., 2001). Vulnerability is also regarded as the susceptibility of a system to perturbations (Eakin and Luers, 2006), and the degree to which harm is caused by exceeding a damage threshold under exposure to a stressor (Turner et al., 2003). The assessment of vulnerability can be represented by a function of potential impact (including exposure and sensitivity) and adaptive capacity; both of which are affected by external driving forces, such as urbanization (El-Zein and Tonmoy, 2015). The three components of vulnerability (exposure, sensitivity and adaptive capacity) should be approached as interactive (Huang et al., 2011) and dynamic in response to various types of natural and social-economic shocks (Smit and Wandel, 2006).

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Vulnerability assessment to climate change has been applied by different disciplines to analyze problems in natural hazards, disaster management, ecology, public health, land use sustainability, and climate (McCarthy et al., 2001). There have been many studies on the concept and development of methods for vulnerability assessment. Cutter et al. (2003) used multivariate analysis to construct an index of social vulnerability to environmental hazards. Many studies have used the scoring and weighting of indicators as a tool to assess responses of regional environments to external impacts (O'Brien et al., 2004; Brooks et al., 2005; Metzger et al., 2006). Park et al. (2015) assessed flood vulnerability in South Korea by calculating the weightings of proxy variables. Li et al. (2016) and Varadan and Kumar (2015) both estimated agricultural vulnerability by using multiple indicators respectively in China and India. El-Zein and Tonmoy (2015) applied an outranking procedure, developed indicator-based vulnerability and multi-criteria decision analysis to assess vulnerability to heat stress in Sydney. Although the indicator-based approach can include a variety of affective aspects and estimate vulnerability quantitatively, the approach lacks consideration of the interactive relationships among natural, social and economic indicators (Huang et al., 2011).

From a system ecology perspective, components of vulnerability are characterized by cause and effect relationships. Huang et al. (2011) applied system ecology theory and emergy synthesis to analyze urban vulnerability in order to understand the extent of damage and the socioeconomic system's ability to cope with extreme events of typhoons. On the basis of this ecological energetic approach, exposure is defined as "the total emergy of the extreme event acting upon an area"; sensitivity is "the amount of stored emergy that is likely to be affected by the events"; and the adaptive capacity can be regarded as "the system's ability to attract emergy inflow to recover and to adjust from the impacts of hazards". Using these definitions, Chang and Huang (2015) further developed emergy indices to analyze the interactive characteristics of the three components of vulnerability to flooding. The results of vulnerability assessment using emergy approach also show the spatial difference of vulnerability to flooding along Taiwan's western coastal plain due to the different intensities of urbanization.

Vulnerability is dynamic, spatially variable and scale dependent (Srinivasan et al., 2013). A number of studies have considered both long-term changes and spatial differences in urban vulnerability. Qiu et al. (2015) assessed the vulnerability of ecosystem provisioning to urbanization in China from 1980 to 2010 by ranking indicators of vulnerability. Li et al. (2016) focused on spatial vulnerability in the coastal urban areas. Srinivasan et al. (2013) developed a human-environment system and simulated the link between urbanization and water vulnerability in India. Following Chang and Huang's (2015) assessment of the spatial variation of vulnerability to flooding in Taiwan's western coastal plain, this paper further raises the issue that the urban vulnerability in response to climate change impacts is characterized by its dynamic interaction with urban development. Due to spatial variations in the natural environment and land use intensity, there also are spatial differences in vulnerability caused by urbanization. During processes of urban transition, changes of land use will affect vulnerability, which in turn will then affect the process of urban development.

Using Odum's ecological energetic simulation, Huang (1998) developed an urban zonation model to represent the energy hierarchy of land use and to simulate the evolution of urban zones as a consequence of energy convergence from a rural landscape to an urban information center. Huang et al. (2007) advanced a land use model using an ecosystem modelling approach and employing a Geographic Information System (GIS) to reveal the pattern of spatial convergence and the energetic evolution of the urban landscape in the Taipei metropolitan region. Following a similar approach, Lee et al. (2009) employed Model Builder of ArcGIS to verify hypotheses and theories regarding socio-economic metabolism and land use change (SEMLUC). By integrating an ecosystem model with Multi-Objective Land Allocation (MOLA), Wang et al. (2012a) was able to mimic the interactions of human decision making in economic systems and potential material and energy flows in ecosystems with high spatial resolution. Wang et al. (2012b) also used ecosystem modelling to examine changes in the resilience of the socio-ecological system in response to typhoons and land cover change. On the basis of the previous spatial simulation methodology, this paper developed a spatial system model to simulate land use change, which also included the assessment of urban flooding vulnerability and the influence of urban development on vulnerability. Our primary purpose in developing this spatial simulation model is to show the bilateral relationships between urbanization and vulnerability by allowing for interaction between exposure, sensitivity, and adaptive capacity, and to have feedback into subsequent development using the Taipei metropolitan region as a case study.

## 2. Material and methodology

### 2.1. Study area

The Taipei metropolitan region, which includes Taipei City, New Taipei City and Keelung City, is the fastest growing urban area and major socio-economic center of Taiwan. The built-up areas of the Taipei metropolitan region are located in the central part of a flat basin. The major river in Taipei, the Tamsui River, is the natural boundary between southwestern Taipei City and New Taipei City. The Tamsui River is formed by three tributaries, the Keelung River from the northeast, the Xindian Creek from the southeast, and the Dahan Creek from the south, has sustained the livelihood of millions of people (Fig. 1).

The total area of the Taipei metropolitan region is 2457 $km^2$. There are 7 million in the region which makes this area the most heavily populated in Taiwan. In the early 1990s, urbanization in the Taipei basin had reached a threshold and since that time continuing economic development has caused *peri*-urbanization in New Taipei City and Keelung City. In 2015, the resident population in the urban planned districts is approximately 98% of the total population within the study area.

Due to the topographic characteristics of the floodplain, flooding has been a major threat in Taipei. Flooding has impacted urban living and the economy when extreme rainfall events (e.g. typhoon) have occurred during the past decades. The flood control in Taipei is still dominated by an engineering approach. Levees were constructed along the major rivers to protect the city from floods of a 200-year frequency (Chang et al., 2013). There are more than 80 pumping stations along the rivers with a capacity of over 2000 cubic meters per second (Fig. 1). Despite the increasing occurrence of intense storms and the low-lying topography of the Taipei area, the urban extent of the Taipei metropolitan region continues to expand. During the past two decades, the urban areas in New Taipei City have increased by 12% and population growth has increased by 16% and 8% for New Taipei City and Keelung City in 2000, respectively. Consequently, land use change due to urban development and a resulting integrated assessment of vulnerability to flooding as they relate to climate change is an important research theme in Taipei.

### 2.2. Methods

In order to incorporate the dynamic interaction between land use change and the three components of urban vulnerability, this paper used a systems ecology approach for the simulation of land