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Identifying the key catastrophic variables of urban social-environmental resilience and early warning signal

Yi Li[a], Yangfan Li[a,b,*], Martin Kappas[c], Mitchell Pavao-Zuckerman[d,e]

[a] Key Laboratory of Coastal and Wetland Ecosystems (Ministry of Education), College of the Environment and Ecology, Xiamen University, 361102 Xiamen, China
[b] Fujian Provincial Key Laboratory for Coastal Ecology and Environmental Studies, Xiamen University, 361102 Xiamen, China
[c] Department of Cartography, GIS and Remote Sensing, Institute of Geography, Georg-August University of Goettingen, 37077 Goettingen, Germany
[d] Department of Environmental Science and Technology, University of Maryland, College Park, MD 20742, USA
[e] Cluster for Sustainability in the Built Environment, University of Maryland, College Park, MD 20740, USA

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ABSTRACT

Pursuit of sustainability requires a systematic approach to understand a system's specific dynamics to adapt and enhance from disturbances in social-environmental systems. We developed a systematic resilience assessment of social-environmental systems by connecting catastrophe theory and probability distribution equilibrium. Catastrophe models were used to calculate resilience shifts between slow and fast variables; afterwards, two resilience transition modes ("Less resilient" or "More resilient") were addressed by using probability distribution equilibrium analysis. A tipping point that occurs in "Less resilient" system suggests that the critical resilience transition can be an early warning signal of approaching threshold. Catastrophic shifts were explored between the interacting social-environmental sub-systems of land use and energy (fast variables) and environmental pollution (slow variables), which also identifies the critical factors in maintaining the integrated social-environmental resilience. Furthermore, the early warning signals enable the adaptability of urban systems and their resilience to perturbations, and provide guidelines for urban social-environmental management.

1. Introduction

Resilience and sustainability have emerged in recent years as important paradigms for understanding threats to humanity and the environment (Brelsford et al., 2017; Little et al., 2016; Mooney et al., 2013). A numbers of terms in sustainability sciences have been developed for analyzing interconnected system, such as "Social-Ecological System (SES)", "Coupled Human and Natural Systems (CHANS)" or "Social-Environmental System (SES)". From the perspective of environmental management, these approaches use interdisciplinary research to assess and enhance the sustainability of social-environmental systems (Allington et al., 2017; Palmer et al., 2016; Turner II et al., 2016). The interactive social-environmental system provides vital information to help overcome the misalignment of scientific work and government management (Sayles and Baggio, 2017). This mismatch between science and governance can obscure both social and environmental concerns, which suggests the mismatch can be overcome through the linking of these two sub-systems in resilience assessment (Fiksel, 2003). However, a quantitative analysis of indicators of the sub-systems is rarely conducted in such coupled systems.

Resilience offers a unique perspective to detect system responses to natural stochastic or human perturbations (Adger et al., 2005; Downes et al., 2013; Folke, 2016). However, the resilience of coupled social and environmental systems in response to external disturbances is non-linear dramatic and sudden changes (Palmer et al., 2016). Catastrophe theory was proposed to explain the phenomenon of sudden change resulting from continuous changes within a stable equilibrium (Lin, 2013; Zeeman, 1976). According to catastrophe theory, the interactions between slow (control) and fast variables and systems trigger regime shifts of the resilience in social-environmental system (Walker and Salt, 2012). The slow variables are often environmental drivers; while the fast variables are social indicators that change faster than environmental variables, which are involved with anthropogenic stressors as land use change, economic structure adjustment (Walker and Salt, 2006).

The bifurcation of catastrophic shifts between slow and fast variables has revealed the existence of early-warning signals that indicate a system is approaching the boundary of thresholds (Scheffer et al., 2009; Steffen et al., 2015). Bifurcation signifies the probability of a forward and backward transition that separates two stable and resilient states

* Corresponding author at: Key Laboratory of Coastal and Wetland Ecosystems (Ministry of Education), College of the Environment and Ecology, Xiamen University, South XiangAn Road, Xiamen 361102, China.
E-mail address: yangf@xmu.edu.cn (Y. Li).

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(from an initial state to an alternative state) (Scheffer and Stephen, 2003). We developed an analysis of the probability distribution equilibrium (PDE) that describes the probability of a catastrophic transition over time (Perz et al., 2013; Scheffer et al., 2009). By extension, if a system shifts over time, a time series of PDE can be observed for the probability of regime shifts between different states. The changing states of PDE signify the transformation between high and relative low resilience states. Therefore, integrating regime shifts in terms of PDE with an analysis of catastrophic fluctuation enables the identification of threshold regarding to dramatic resilience changes in social-environmental systems.

Thus, in the context of catastrophic regime shifts, resilience addresses the capability of a system to adapt to catastrophic shifts or the transitions between equilibria in such system (Folke, 2016). We therefore propose a new multi-stage framework to assess catastrophic regime shifts of resilience in social-environmental systems that integrates catastrophe theory and PDE analysis. We applied this framework using a resilience assessment for a coastal city in China (Study area in Supporting information, Fig. S1), constructing the regime shifts of slow and fast variables based on catastrophe theory and the probability distribution equilibrium. The integrated framework addresses tipping points as the threshold of critical resilience change between social/fast and environmental/slow variables.

2. Methods

In comparison to conventional approaches to assess sustainability that deal with avoiding drastic changes (Singh et al., 2012), resilience of integrated social-environmental systems simultaneously represents sustainability while also considering the ability to adapt to external disturbances. Based on our previous work, Lianyungang city experienced a vulnerable period during 2000–2010, where Lianyungang experienced a vulnerable transformation after 2005 due to its rapid urbanization (Li et al., 2015; Perz et al., 2013), similar as other coastal cities, such as Xiamen (Lin et al., 2013). However, the transition trend of regional system is still an open question. We implement a resilience assessment framework of social-environmental systems and describe this approach in more detail in the sections below. Generally, we used catastrophe theory to calculate a resilience value by employing various indicators of the coupled social-environmental systems (Table 1 and below), and the integrated values from catastrophe models were divided by K-means cluster analysis into five resilience grades.

Table 1
Classification of indicators referring to essential characteristics.

	Sub-system	Indicators
Social (A1)	Production (B1)	GDP (C1) Industry structure (C2)
	Population and culture (B2)	Urbanization (C3) Educational institution (C4) Employee (C5)
Social-environmental (A2)	Land use (B_3)	Built-up area (C6) Arable area (C7)
	Energy (B_4)	Electric energy consumption (C8) Domestic water consumption (C9)
Environmental (A3)	Pollution (B5)	Volume of industrial waste gas emission (C10) Volume of industrial SO_2 emission (C11) Discharged industrial wastewater (C12)
	Treatment (B6)	Treated wastewater per GDP (C13) Industrial solid wastes utilization (C14)

Afterwards, resilience transitions of the social-environmental system were illustrated by the PDE with “More resilient” or “Less resilient” modes, combined with an analysis of the tipping points that are identified as thresholds. By integrating the mechanisms of catastrophic shifts and thresholds, we offer a theoretical framework to address the specific resilience dynamics in social-environmental systems.

2.1. Data collection and standardization

The resilience analysis was conducted in five areas of Lianyungang as Central, Ganyu, Donghai, Guannan and Guanyun districts. A series of indicators from 2000 to 2015 were selected from Statistics Year Book (2001–2016, Bureau of Statistics in Lianyungang) and Environmental Quality Report (2001–2016, Environmental Protection Agency). These indicators were selected following our previous research on indicators for urban environmental governance (Li et al., 2017), and is based on principles of integrity, simplicity, dynamic response, geographical accuracy, and data availability.

Considering the interlinkages of social-environmental systems, all collected indicators were assigned a representative initial characteristic referring to social, environmental, or social-environmental perspective. Indicators were classified into three sub-systems that were used in the hierarchical processing of the catastrophe model. The first sub-system was focused on human disturbances in relation to rapid urbanization (social sub-system), including economic data (average salary, income, retail sales, GDP), ratio of different production categories (agricultural, industrial and social services production), population, science and cultural indicators, etc.; the second sub-system focused on the environmental impacts of pollution/treatment (environmental sub-system), including major environmental pollution and waste treatment data (industrial solid wastes, air pollution and waste water); and the third represented coupling dynamics for the interconnected social-environmental sub-system holding both social and environmental characteristics, represented by land use and cover types and energy consumption data. Specifically, the linking sub-system connects the social and environmental sub-systems, as these indicators represent the combination of effects resulted from both social and environmental systems. In addition, to balance the contribution of different sub-systems to the overall system, we chose 2–3 critical indicators in each sub-system based on significance analysis (Pearson correlation) in SPSS. Then, a set of values uncorrelated variables were converted from collected indicators. The integrated resilience of social-environmental systems is a systematic interactive index, in contrast to one that would only be calculated from single sub-system. Ultimately, 14 indicators, as shown in Table 1, were generated with independent values for all five districts in each year (more detail information in Supporting information, Table S1).

Our selected indicators have different dimensions and distributions, thus, the original data should be made dimensionless through data normalization; this also meets the requirements of the catastrophe modeling approach (Scheffer and Stephen, 2003; Scheffer et al., 2009). Min-max normalization is one of common process of transforming raw value to a value between 0 and 1 (from low to high), and offers a practical way to compare values that are measured using different scales/units (Mohamad and Usman, 2013). In addition to normalization, all indicators were set to be either negative or positive to resilience before calculating with formula (1) or formula (2) in Supporting information, Box S1.

2.2. Catastrophe theory application-resilience calculation and transformation

Catastrophe theory is discussed as a comprehensive approach to explore gradual and abrupt changes to describe the nonlinear dynamics of different steady equilibria (Lignos et al., 2002). A catastrophic shift often occurs unannounced and results in a system's equilibrium shift or