Journal of Hydrology 536 (2016) 457–470

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Vulnerability assessment of urban ecosystems driven by water resources, human health and atmospheric environment

Jing Shen [a], Hongwei Lu [b,c], Yang Zhang [a], Xinshuang Song [a], Li He [b,c,*]

[a] Resources and Environmental Research Academy, North China Electric Power University, Beijing 102206, China
[b] School of Renewable Energy, North China Electric Power University, Beijing 102206, China
[c] State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China

ARTICLE INFO

Article history:
Received 10 January 2016
Received in revised form 2 March 2016
Accepted 3 March 2016
Available online 9 March 2016
This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
Vulnerability assessment
Ecosystem management
Multi-criteria decision analysis
Water resources
Human health
Atmospheric environment

SUMMARY

As ecosystem management is a hotspot and urgent topic with increasing population growth and resource depletion. This paper develops an urban ecosystem vulnerability assessment method representing a new vulnerability paradigm for decision makers and environmental managers, as it's an early warning system to identify and prioritize the undesirable environmental changes in terms of natural, human, economic and social elements. The whole idea is to decompose a complex problem into sub-problem, and analyze each sub-problem, and then aggregate all sub-problems to solve this problem. This method integrates spatial context of Geographic Information System (GIS) tool, multi-criteria decision analysis (MCDA) method, ordered weighted averaging (OWA) operators, and socio-economic elements. Decision makers can find out relevant urban ecosystem vulnerability assessment results with different vulnerable attitude. To test the potential of the vulnerability methodology, it has been applied to a case study area in Beijing, China, where it proved to be reliable and consistent with the Beijing City Master Plan. The results of urban ecosystem vulnerability assessment can support decision makers in evaluating the necessary of taking specific measures to preserve the quality of human health and environmental stressors for a city or multiple cities, with identifying the implications and consequences of their decisions.

1. Introduction

With increasing population growth and resource depletion, the relationship between natural resources and human society has come into an obviously disharmony status. Ecosystem management emerges as a comprehensive, inter-disciplinary process that aggregates ecological, social–cultural, economic and institutional structures (UNEP-IEMP, 2011). Ecosystem management may be defined as "an integrated process to conserve and improve ecosystem health that sustains ecosystem services for human well-being". The International Union for Conservation of Nature (IUCN) expanded the definition as "a process that integrates ecological, socio-economic, and institutional factors into comprehensive analysis and action in order to sustain and enhance the quality of the ecosystems to meet current and future needs" (Pirot et al., 2000). In the view of 'sustainable' and 'long-term', a sustainable water resource management is closely related to groundwater management, surface water management and land use. Long-term sustainable resources management is supported by the application of ecosystem management concept (Randhir and Hawes, 2009; Tuinstra and van Wensem, 2014; Yin et al., 2014; Tsai et al., 2015). Koundouri et al. (2016) applied Ecosystem Services Approach in an integrated framework that revolved around inland surface waters, transitional waters, coastal waters and ground waters. Rodríguez et al. (2015) evaluated ecosystem services for setting priorities and planning carbon and water resource management in Columbia. Five ecosystem services: water provision, regulation of water flow, carbon storage in the above-ground biomass and in the soil and finally landslide prevention had been evaluated in this study.

Traditional vulnerability assessment usually proposed ecological analysis of study sites with exposure index, sensitivity index, and capacity index (Smith, 2000; Morgan, 2011; Pandey and Bardsley, 2015; Qiu et al., 2015; Pisciotta et al., 2015). Preston et al. (2014) drew on five topography and hydrological indices within the vulnerability assessment of brine contamination in Williston Basin, America. The five parameters included date of the oldest oil well, percentage of surficial geology mapped as glacial outwash deposits, percentage of wetland cover, total length of stream reach, and total number of oil wells. Leichenko and Solecki (2013) applied climate risk assessment to identify key

* Corresponding author at: School of Renewable Energy, North China Electric Power University, Beijing 102206, China.

http://dx.doi.org/10.1016/j.jhydrol.2016.03.004
0022-1694/

vulnerabilities in a range of natural and economic resource indices and to examine how these vulnerabilities vary across different types of suburban communities. Infrastructure, ecological/natural resources and public health were considered as key sectoral climate vulnerabilities. Kazakis and Voudouris (2015) used a modified DRASTIC method to assess vulnerability of nitrate in porous aquifers. The DRASTIC method is a popular solution for vulnerability assessment considering with morphological, hydrological and hydrogeological indices. Nandy et al. (2015) selected 7 variables, including land use/land cover, forest canopy density, slope, aspect, distance to settlements, distance to roads, and elevation, as input parameters for environment vulnerability assessment in India Himalaya over three time periods (1990, 2000 and 2010). It can be seen that the vulnerability assessment were generally applied for assess surface water, groundwater, soil, and climate change on environment, separately. Meanwhile, social–cultural and economic elements should also be considered.

Multi Criteria Decision Analysis (MCDA) method is a modeling and methodological tool for dealing with complex problems. It has widespread applications in solution selection (Cinelli et al., 2014; Nwokoagbara et al., 2015; Cobuloglu and Büyüktahtakın, 2015), life-cycle assessment (Domingues et al., 2015), feasibility analysis (Matzen et al., 2015), data scoring (Isigonis et al., 2015), sites location evaluation (Tahri et al., 2015), watershed prioritization (Jaiswal et al., 2015), project design (Linnemann et al., 2015), municipal solid waste management (Soltani et al., 2015), sustainability assessment (Cinelli et al., 2014), vulnerability assessment (El-Zein and Tonmoy, 2015; Zabeo et al., 2011) and other fields. The MCDA has two branches: Multi Attribute Decision Making (MADM) and Multi Objective Decision Making (MODM). The MADM method can provide a powerful decision analysis approach on the basis of definition and normalization of multiple stressors that are relevant to the problem. Bohanec et al. (2007) addressed qualitative multi-attribute modeling that consisted of 34 attributes (hierarchically structured into eight levels) to assess impact of cropping systems on soil quality and crop management options. Bartolini et al. (2007) evaluated the impacts of agricultural and water policy scenarios on the sustainability of selected irrigated farming systems using multi attribute linear programming models. Sola and de Miranda Mota (2012) proposed a Multi Attribute Utility Theory (MAUT) to select the best portfolio of options based on the decision makers' utilities in industrial motor system.

The MCDA needs to aggregate data from multi resources. and many methods can be available for aggregation of the provided data (Cheng et al., 2006, 2014; Parisopoulos et al., 2009; Adiat et al., 2012; Moglia et al., 2012; Chen, 2013; Yang et al., 2013; Li et al., 2014; Zhang et al., 2014; Shi et al., 2014; Wang et al., 2015; Shen et al., 2015; Kadziński et al., 2015; Lu et al., 2015; Veisi et al., 2016; Bellu et al., 2016; Yu et al., 2016). One of the widely used aggregation methods in decision-making is the ordered weight averaging (OWA) operators developed by Yager (1988). It provides a general class of parametric aggregation operators and has shown to be useful for studying multi kinds of aggregation problems. Up to now, the OWA operators had been used in a wide range of applications (Liu et al., 2014; Gao et al., 2015; Suo et al., 2012; Peng et al., 2012; Liu, 2012). Four main challenges are involved in the development of a comprehensive urban ecosystem vulnerability assessment in terms of the above considerations:

(1) application of spatial analysis within multiple urban ecosystem stressors and sources;
(2) critical gaps of regional range data, as the relation between various attributes of stressors cannot be expressed by strict mathematical models;
(3) relationship between socio-economic drivers and environmental elements;
(4) transformation of the urban ecosystem vulnerability results to the decision-makers.

The developed urban ecosystem vulnerability assessment method represents a new vulnerability paradigm for environmental managers and decision makers, as it's an early warning system to identify and prioritize the undesirable environmental changes rather than exact predictions. The whole idea is to decompose a complex problem into sub-problem, and analyze each sub-problem, then aggregate all sub-problems to solve this problem. It integrates spatial context of Geographic Information System (GIS) tool, multi-criteria decision analysis (MCDA) method, ordered weighted averaging (OWA) operators, and socio-economic elements. This method can help resource managers to make resource decision at district unit. Decision makers can find out relevant urban ecosystem vulnerability assessment results with different vulnerable attitude. The results of urban ecosystem vulnerability assessment can support decision makers in evaluating the necessary of taking specific measures to preserve the quality of human health and environmental stressors for a city or multiple cities, with identifying the implications and consequences of their decisions.

2. Methods

The developed urban ecosystem vulnerability assessment method for estimating recipients in city range integrates spatial context of Geographic Information System (GIS), multi-criteria decision analysis (MCDA), ordered weighted averaging (OWA) operators, and socio-economic elements. More specifically, GIS can handle spatial analysis in regional range. The MCDA method can manage data from multiple stressors and sources and normalize all indices into a common numerical scale. The OWA operators are powerful operators to aggregate multiple input values obtained from multiple sources. Fig. 1 shows the flow chart of this developed method. The methods can be divided into four steps, as follows:

(1) definition of stressors and attributes selection in urban ecosystem;
(2) standardization of attribution values;
(3) assignment of weights for different classes of attributes;
(4) aggregation of urban ecosystem vulnerability with ordered weighted averaging (OWA) operators.

2.1. Definition of stressors and attributes selection in urban ecosystem

Due to data collection from multiple stressors and resources, urban ecosystem vulnerability is more complicated and intricate than vulnerability assessment in a specific contaminated site. In terms of the data availability from the estimated region, attributes selection is a very significant step in the urban ecosystem vulnerability assessment. In this paper, estimated multiple stressors are selected basing on Pettyjohn et al. (1991), EPA (2014) and MEP PRC (2002). Therefore, human health, groundwater, surface water, and atmospheric environment are chosen as regional range stressors. In the attribution selection process, nature, human, economic and social elements are taken into account. Inducing human elements, economic elements and social elements is to indicate the influence of human activities on nature resources. While, the nature elements contain quality class of groundwater and surface water, catchment area and runoff of surface water, and average annual concentrations of $PM_{2.5}$, PM_{10}, SO_2, and NO_2. The human elements embrace exploitable yield and exploitation degree of groundwater, land use. Gross Domestic Product (GDP) is involved