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Comprehensive assessment and hierarchical management of the sustainable utilization of urban water resources based on catastrophe theory

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ABSTRACT

Evaluation of sustainable utilization of urban water resources is a multi-criteria comprehensive assessment system that needs judgment of decision makers in making decision. To avoid subjectivity of decision makers in the assessment, evaluation method based on catastrophe theory was introduced in this study. A model for assessing sustainable utilization of urban water resources was developed using the method of catastrophe. The model integrated multiple assessment indices of sustainable utilization of water resources according to the inherent contradictions and relative importance of indices without calculating weighs. The model was applied by evaluating the sustainable utilization levels of the water resources of Dalian, China, from 2001 to 2011. Results showed that Dalian had its strongest sustainable level of water resources in 2005 (0.7705). The comprehensive sustainable utilization level in 2002 was the lowest among the 11assessed years (0.4481). The comprehensive sustainable utilization levels of Dalian from 2001 to 2011 were above the 'generally recognized as sustainable level'. Water resources per capita, seawater intrusion, urbanization, and per capita daily water consumption were the main factors for destroying the sustainable utilization of water resources in Dalian. Decision makers of water resources management should pay more attention to ground water management and adopt more appropriate measures to control water consumption. The model involves simple calculations and requires no index weighing, while at the same time providing a new technique for the comprehensive assessment and hierarchical management of the sustainable use of urban water resources.

1. Introduction

Water is the material basis for human survival and development, and an important strategic resource for the support of sustainable socioeconomic development. The 2011 World Water Day: "Water for Cities: Responding to Urban Challenges" was designed to draw international attention to the impacts of urbanization and industrialization, as well as the threats posed by climate change, conflict, and natural disasters for sustainable water management. For China, 21st century development will lead to severe shortages of water [1]. The pressure on water resources is increasing, especially in the northern cities of China. From the point of view of maintaining water resources for sustainable development, both to ensure the continuity and durability of development, and the efficient and equitable use of water resources, it is necessary to satisfy the demands of the societal, economic and ecological environments for water resources as fairly as possible. There will be no sustained, stable development of human society without the sustainable utilization of available water resources. Too a high demand for water from the development of human communities will adversely affect the level of water resources, and influence or even destroy the sustainability of the development and utilization of these resources. In this regard, there is considerable need for methods to diagnose the state of sustainable utilization of urban water resources for alleviating the water shortage problem, prompting water resources development, utilization, protection and management, and safeguarding social and economic sustainable development strategic goal.

Sustainable utilization is the application of sustainable development theory on the utilization of renewable resources. Sustainable utilization of water resources is one new mode of the utilization of water resources under the framework of sustainable development. In another word, on the condition of maintaining water sustainability and ecological system integrity, sustainable utilization of water resources is not only the whole procedure to support the population,

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resources, environment and economies coordinated development and meet the needs of generations, but also the most reasonable utilization mode of comprehensive development, utilization, protection, control and management of water resources [2]. These days, sustainable utilization of water resources has attracted a great deal of attention [3–5]. Many methods for assessing sustainable utilization of water resources have been proposed. Lawrence et al. constructed an International Water Poverty Index System that included resources, access, capacity, use, and environment [6]. The Policy Research Initiative developed the Canadian Water Sustainability Index (CWSI) with fifteen indicators [7]. Chaves and Alipaz proposed a Watershed Sustainability Index that can be specifically applied at the basin level [8]. Juwana et al. established the West Java Water Sustainability Index that benefits water stakeholders in West Java [9]. Deng and Qiu structured an evaluation index system based on three big functional processes of regional water resources: storing, consuming and regenerating [10]. Shu et al. established the evaluation model of a fuzzy four-element connection coefficient for the sustainable utilization of water resources and applied the model to evaluate the sustainable utilization of water resources in Yan'an city [11]. To meet the system demands for water, Fabricio et al. developed a model considering the possibility of using alternative water sources such as rainwater and reclaimed water to enhance the sustainability of natural water bodies [12]. Rojas-Torres et al. proposed a mathematical programming model for the sustainable design of macroscopic water systems involving the optimal planning and scheduling of the water storage and distribution system in a city and considering natural and alternative water resources [13]. Although consideration attention has been given from the scientific community and policy makers to evaluate the sustainable utilization of water resources [14–18], most related studies often have disadvantages in subjectivity and complexity associated with the determination procedure. Catastrophe theory, a mathematical model proposed by Thom, studies systems that, under particular conditions, show sudden changes in the steady equilibrium state as a consequence of small changes in the value of certain input parameters [19]. Catastrophe theory is a mathematical framework that deals with discontinuous transitions between the states of a system, given smooth variation of underlying parameters. It is derived mainly from the topological concept of stable structure, and developed on the mathematical theory basis, such as topological dynamics and singularity theory. Its characteristic is to combine catastrophe theory with fuzzy mathematics, and to only consider the relative importance of the indices. So the method avoids the subjective in weight decisions. Due to its dialectic characteristics and advantages as a simple mathematical construct with clear physical meaning, the catastrophe theory has been widely employed in multi-index comprehensive assessment studies, such as, coal and gas outburst prediction [20], water security [21, 22], land ecological security [23], rural information level [24], ground water potential zones [25], and insect pest control [26]. We argue that the change of utilization of water resources state can be considered as a particular catastrophic behavior, a small and gradual change in the steady equilibrium state of a sub-system can rapidly cause the whole system to reach the crush state. Following such idea, this paper aims to propose a catastrophe model for water resources utilization assessment with a case study in coastal city Dalian, China. Specifically, our objectives are to: (1) develop a catastrophe model for assessing the sustainable utilization of urban water, and apply the model to case study of Dalian; (2) find out the main influential factors of sustainable level of water resources in this region; (3) provide reference for decision makers of water resources management to promote the protection of water resources as well as to improve sustainable development in the region.

The paper is organized as follows. Section 2 describes the study area and methodology we use for assessing the sustainable utilization of urban water resources based on catastrophe theory. Section 3 presents the main results and discussions for evaluation of the sustainable utilization of urban water resources in Dalian, China. Section 4 gives the conclusions.

2. Material and methods

In this section, we first give an overview of the study area. Then, we briefly introduce the catastrophe theory used in the paper. Next, we apply this theory to the detailed study of a catastrophe assessment model, to show how the assessment is designed and performed.

2.1. Study area

Dalian is located on the southern tip of the Eastern Liaoning Peninsula, with the Yellow Sea to the east, the Bohai Sea to the west, and with Liaoning, Jilin and Heilongjiang (the three northeastern provinces) and part of Inner Mongolia Autonomous Region to the north (Fig. 1). Dalian is one of the fourteen open coastal cities in China. The city's total area is 12573.85 square kilometers, including an urban area of 2415 square kilometers, and it has a 1906-km-long coastline. The area has the characteristics of a warm temperate continental monsoon climate, with certain features of an oceanic climate [27]. Because of these climatic factors and the impact of natural and geographical conditions, the regional distribution of precipitation is very uneven, and interannual variability and distribution across the year are very different.

2.2. Catastrophe theory

Catastrophe Theory is a branch of dynamical systems theory that investigates discontinuous changes and catastrophes [28]. It can deal directly with discontinuity without linking any specific internal mechanisms; therefore, it is particularly applicable to studies of systems with unknown internal functions. Catastrophe theory is widely used, and one common application is the use of the catastrophe progression method derived from catastrophe theory to solve multiple criteria decision problems. In the multi-criteria evaluation method based on catastrophe theory, the dependency of state variables on control variables is determined by the catastrophe fuzzy membership functions, rather than weights assigned by the users, and different control variables have different impacts on state variables.

Catastrophe theory uses mathematical tools to describe system parameter regions in a stable or unstable state, as well as the parameter range of system catastrophes, for mathematical modeling of the catastrophe process. Catastrophe models are characterized by the classification of critical points according to the system potential

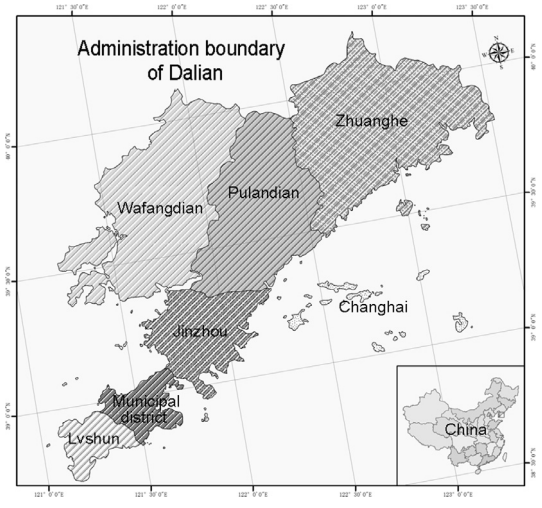

Fig. 1. Location of Dalian, China.