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Emergy analysis of regional water ecological–economic system

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ABSTRACT

The theoretical framework and methodology of a water ecological–economic system (WEES) assessment based on emergy synthesis are proposed in this paper. Through calculating ecological and economic inputs and outputs within and outside the complex system, this paper discusses the system's economic situation, water resources development and system sustainability based on a series of emergy indicators. Besides traditional indices, following the principle of system assessment, four new indices, water emergy ratio (WER), water emergy utilization ratio (WEUR), water emergy self-support ratio (WESR), and water emergy density (WED) are formulated to assess the state of water resources development quantitatively. Taking the Zhengzhou water ecological–economic system as a study area, through the comparison of the systematic indicators of Zhengzhou with those of the selected Chinese cities, the general status of the Zhengzhou water ecological–economic system in China is identified. The results also show that most indicators of Beijing are located at middle levels among the selected Chinese cities. In particular, the sustainability, expressed by the indicators emergy-based sustainability index (ESI) and water resources population carrying capacity (WPC) were 1.34 and 1.94 million, respectively, in Zhengzhou in 2005, which indicates that the Zhengzhou WEES is in heavy pressure of water resources and is located at low levels of sustainability.

1. Introduction

A water ecological–economic system (WEES) is crucial for social development, but rapid development due to human activities has had negative ecological consequences on ecosystem structures, processes, and functions (Western, 2001). For WEES, human activities can lead to loss of keystone species and functional groups, high nutrient turnover, and the loss of productivity; and similarly, water resources serving as a sink to absorb and recycle some of the waste products of economic activities and providing an irreplaceable life support function, so the deterioration of water ecosystem can lead to fall of standard of living. Therefore, the relationship between society and ecosystems should be harmonized, and the WEES should be treated as an integrated system.

To determine the ongoing human–nature interactions in order to develop policy for regional sustainable development, an interdisciplinary approach and system theory should be used (Boulanger and Brechet, 2005), and it is necessary for scientists to employ sound ecological principles and provide interdisciplinary ideas for decision makers (Naiman et al., 1998). Ecological economics provides an effective means to handle interdisciplinary problems with social, economic, and ecological dimensions (Shi and Gill, 2005). The paper "flow

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of water" is considered to be the systematic framework to integrate economic and ecological processes, and the emergy theory of ecological economics has been often used at the regional scale.

To include the complexities of ecosystems and social systems, economic or ecological theory alone cannot achieve good predictions. Thus, an integrated ecological–economic method has developed since the 1980s (Gao, 2003). Despite the differences between economic and ecological theory, they contain some commonalities in the methods of analysis and modeling procedures, such as systems analysis, information integration, modeling, and application (Campbell, 2001). Thus, ecological–economic method, which can be used to integrate social systems and ecosystems, has been widely applied in decision making (Costanza et al., 2002). Land-use changes and subsequent consequences for natural and social systems have been the focus of the previous studies (Camara et al., 1986; Suh, 2004). System dynamics (SD), the Delphi method, scenario analysis, input–output models, and landscape models have been commonly applied (Chappelle, 2001). The Patuxent landscape model by Costanza et al. (1997) is considered to be a successful application of ecological–economic method at the watershed scale. The method contains both economic and ecological systems, and the effects of interrelated ecological and economic factors on the watershed landscape are modeled (Voinov et al., 1999). Similar studies that have addressed the different economic and environmental implications of landscape design scenarios include that of the Walnut Creek watershed in Iowa (Coiner et al., 2001), the Delaware estuary model (Russell, 1995), and the integration of economic, environmental, and GIS modeling to target cost-effective land retirement in multiple watersheds (H. Yang et al., 2003; W. Yang et al., 2003).

Despite these achievements, the ecological–economic method of water ecological–economic system is rarely studied. Although watershed pressures have been considered in ecological models of water ecosystems in previous studies, they are often treated as external variables; the methods focused mainly on pollutants, and the effects of water resources and direct economic activities were largely ignored. Joint research to examine the water ecological–economic system is rare. As one of the efficient ecological economics approaches, emergy accounting offers some advantages to integrate various resources and proved an efficient method to assess the ecosystem situation. Emergy analysis with corresponding indices and ratios has been proved an effective tool to understand the resource flows supporting both the natural ecological system and the macro-economic system, and can be used to measure their sustainability.

As an application of emergy theory of ecological economics, we focused on developing a comprehensive evaluation of WEES and sought to apply the proposed method to decision making regarding Zhengzhou City in north China. Combining with the ecosystem service function of water resources, the theoretical framework and methodology of water ecological–economic system assessment based on emergy synthesis are proposed in this paper. Through calculating ecological and economic inputs and outputs within and outside the complex system this paper discusses the system's economic situation, water resources development and system sustainability based on a series of emergy indicators. Besides the traditional emergy indices, such as emergy yield ratio (EYR), emergy investment ratio (EIR), environmental load ratio (ELR), following the principle of system assessment, four new indices, water emergy ratio (WER), water emergy utilization ratio (WEUR), water emergy self-support ratio (WESR), and water emergy density (WED) were formulated to assess the state of water resources development quantitatively. Taking the Zhengzhou water ecological–economic system as a study area, through the comparison of the systematic indicators of Zhengzhou with those of the selected Chinese cities, the general status of the Zhengzhou water ecological–economic system in China is identified. We expect our results to aid not only scientists, engineers, and planners in understanding the complexity of WEES, but also to help local authorities manage the water environment in an effective and efficient way.

2. Water ecological–economic system

Water resources are vital for sustaining the life and health of people and ecosystems. One of the key factors for the economic and social development of a country is to ensure that water is sustainable (Pei et al., 2006). The development and utilization of water resources operates in both the ecological and the economic system. Now research has emphasized the fact that ecological and economic systems are jointly determined. The clear implication of this is that if we are to truly comprehend the many interdependencies between such systems, then we must study these systems jointly. With the same implication, water system is the coupling system of traditional water resource system and ecosystem, social economic system. So the evaluation of water resources must be based on water ecological–economic system.

The main difference between WEES and traditional water resource system is that the latter is an engineering technology system serving only the economic targets and ignoring the ecological system, while the WEES, larger in scope, serves the dual targets of nature and economy. In WEES, water flows from ecosystem into economic system, passes through production, becomes polluted, and returns to the ecological environment system. In WEES water flow is the link between the trinity of human actions, economic production, and ecosystems. Despite the significance of WEES, a number of issues relating to the functioning of jointly determined ecological–economic systems remain poorly understood (Wu, 2004). More study is needed.

3. Theory and method

3.1. *Emergy theory and method*

Emergy, specifically solar emergy, is 'the available solar energy used up directly and indirectly to make a service or product" (Odum, 1996). Emergy analysis considers all systems to be networks of energy flow and determines the emergy value of the streams and systems involved. Emergy analysis presents an energetic basis for quantification or valuation of ecosystems goods and services. A fundamental principle of emergy analy-