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River ecosystem assessment and application in ecological restorations: A mathematical approach based on evaluating its structure and function

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ABSTRACT

The river is an essential part of water resources, which has unique ecological structure and function. With the rapid socio-economic development, the improper use of water resources has led to a series of structural and functional decline of the river system, such as water pollution, environmental degradation and river shrinkage. How to restore damaged river ecosystems to an ecologically healthy status has become one of the important environmental issues, which is the key to achieve the goal of productivity improvement, ecosystem balance and sustainable development. And also, the structure and function of the river ecosystem should be pre-assessed before the restoration. In this paper, the Liangshui River, a tributary of Daling River in the arid region of western Liaoning Province, is selected as a study site. An assessment index system involving 21 defined indices on structure and function of river ecosystem is firstly established. A mathematical method for comprehensive assessing the structure and function of river ecosystem is proposed based on the Set Pair Analysis (SPA) and Quadrant Method. Then, the evaluation value is gained at the ecosystem level. The result shows that the assessment value of structure and function is −0.513 and −0.208, respectively, which means that the Liangshui River ecosystem is defective in structure and sub-healthy in function. It is necessary to choose potential development emphasized on the structurally rehabilitating of the Liangshui River ecosystem. Based on the above, ecological engineering measures and suggestions are recommended to preserve the health of river ecosystem.

1. Introduction

As an important resource and environment carrier, the river works as shelter and food source for an array of biological species, and aiding in flood management and ecological refuge development (Pinto and Maheshwari, 2011). With the rapid development of society, human disturbances on the river extend. Water conservancy projects bring great social benefits, but also lead to stress effect on the river ecosystem inevitably. Rivers have been channelized, diverted, straightened and corseted in levees, with little or no thought for river dynamics and biodiversity preservation (Poulard et al., 2010). Furthermore, a huge amount of industrial and agricultural pollutions from human activities were put into rivers. The emergence of series of structural and functional decline of river system, such as water environment deterioration, biodiversity loss and ecosystem degradation, has eventually resulted in the unbalance between natural features and socio-economic functions of rivers.

How to restore damaged river ecosystems has raised wide concern from hydrologists, stream ecologists and watershed managers. It is found that the assessment of river ecosystem defect is the prerequisite for ecological restoration, which could provide theoretical foundation for river management. There are a large number of empirical studies on assessment of river ecosystem health (Liu and Liu, 2009; Zhao and Yang, 2005), analysis of river service function (Xiao et al., 2006; Zhou and Xiao, 2010), discussion of ecosystem restoration (Li and Ju, 2005; Pei et al., 2013). The current research, however, rarely focuses on the holistic method and process of river ecosystem protection and restoration based on the assessment of its structure and function. Dong (2008) developed a conceptual model, describing the structure and function of river ecosystem. The assessment of river ecosystem was studied earlier

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abroad, and more research concentrated on a biological community via its features, changes and the feedback mechanisms to reflect the health of river ecosystem (National Research Council, 1992; Lansing et al., 1998; Lakly and McArthur, 2000; Bain et al., 2000; Gallardo et al., 2011; Ramos et al., 2012). There are a great amount of evaluation methods including fuzzy method, grey system theory, matter element analysis method, principal component analysis. Although these approaches have been applied to some extents in the comprehensive evaluation field, common defects exist such as their complexity, difficulties in the implementation and application. Along with the study and experiment of assessment for river ecosystem, it is necessary to find an appropriate technical method of simplicity and effectiveness. In this context, a mathematical method for comprehensively assessing the structure and function of river ecosystem is developed.

The northwest area of Liaoning Province is a representative region with serious water shortage. In order to completely solve this problem, a large scale of the water diversion project for northwest of Liaoning has been adopted. Water is transported to Baishi Reservoir, and then diverted to Chaoyang, Fuxin, Tieling, Jinzhou and Huludao City, which effectively supporting the strategy of “Breakthrough Northwest of Liaoning”. As an important direct inflow of Baishi Reservoir, the Liangshui River drains a broad area with large number of resident population and industrial enterprises. It has become a significant target to protect water quality and to preserve the drinking water source of the Baishi Reservoir. In this research, the Liangshui River, a tributary of Daling River, is selected as a study site. Based on the quantitative evaluation of the structure and function of Liangshui River, this paper proposes measures for the river ecological restoration. The main goal of this study is to provide basis on the comprehensive management of the Daling River. Meanwhile, it can not only be applied to small and midsize rivers for researchers, engineers and managers, but also to create a positive suggestion for protection and restoration of the local river ecosystem.

2. Methods

2.1. Set Pair Analysis (SPA)

The river ecosystem is a highly complex system with multitudinous influential factors, involving many aspects. It is not easy to estimate the status of river ecosystem for multiple and uncertain characteristics. Set Pair Analysis (SPA) is a system theory using a connection number to process the uncertainty caused by fuzzy, random and incomplete information uniformly. Considering symmetry information from identity, discrepancy and contrary, SPA is simple in concept and convenient to calculate. As a useful tool in uncertainty theory, SPA can analyze the inner relations of the research system, which has been widely applied in many fields (Wang et al., 2009; Su et al., 2009). This paper introduces SPA in the study to measure river ecosystem.

SPA was proposed by Zhao (1989) based on the point of view in unity and opposition. The core procedure of SPA is combining set A and B to construct a certain-uncertain system as a set pair whose properties are analyzed by means of identity, discrepancy and contrary. The connection degree of set pair could be established according to the three aspects. There are N characteristics can be obtained. S, P and F are the number of identical, contradictory and discrepant terms of characteristic. The connection degree of set A and B is defined as follows:

$$\mu_{AB} = \frac{S}{N} + \frac{F}{N}i + \frac{P}{N}j = a + bi + cj \quad (1)$$

where μ_{AB} is the connection degree; i is the uncertainty coefficient of discrepancy having different values in [−1,1] or sometimes as a marker of discrepancy only; j is the uncertainty coefficient of contradictory with the value of −1 or sometimes as a maker of contradictory only; S/N, F/N and P/N is called identity, discrepancy and contradictory degree, namely a, b, c and $a+b+c=1$.

According to an actual research demand, the connection degree can be extended from three elements to four or five and more. The expression of multi-element connection degree can be written as:

$$\mu_{AB} = a + b_1 i_1 + b_2 i_2 + \cdots + b_{k-2} i_{k-2} + cj \quad (2)$$

where b_1, b_2,···, b_{k-2} are called the components of discrepancy degree explained as the different grades of the discrepancy degree, and $a+b_1+b_2+\cdots+b_{k-2}+c=1$; i_1, i_2,···, i_{k-2} are uncertainty components coefficient of discrepancy degree.

A membership function is established to quantitatively describe the relationship from the three aspects of identity, discrepancy, and contrary. Assessment indices can be divided into cost-type and benefit-type. The connection degree formulas are represented as Eqs. (3) and (4), respectively:

Cost-type index:

$$\mu_l = \begin{cases} 1 + 0i_1 + 0i_2 + \cdots + 0i_{k-2} + 0j & (x_l \le s_1) \\ \dfrac{s_1 + s_2 - 2x_l}{s_2 - s_1} + \dfrac{2x_l - 2s_1}{s_2 - s_1} i_1 + 0i_2 + \cdots + 0i_{k-2} + 0j & \left(s_1 < x_l \le \dfrac{s_1 + s_2}{2}\right) \\ 0 + \dfrac{s_2 + s_3 - 2x_1}{s_3 - s_1} i_1 + \dfrac{2x_l - s_1 - s_2}{s_3 - s_1} i_2 + \cdots + 0i_{k-2} + 0j & \left(\dfrac{s_1 + s_2}{2} < x_1 \le \dfrac{s_2 + s_3}{2}\right) \\ \cdots & \\ 0 + 0i_1 + \cdots + \dfrac{2s_{k-1} - 2x_l}{s_{k-1} - s_{k-2}} i_{k-2} + \dfrac{2x_l - s_{k-2} - s_{k-1}}{s_{k-1} - s_{k-2}} j & \left(\dfrac{s_{k-2} + s_{k-1}}{2} < x_l \le s_{k-1}\right) \\ 0 + 0i_1 + 0i_2 + \cdots + 0i_{k-2} + j & (x_l > s_{k-1}) \end{cases} \quad (3)$$