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Short Communication

A combined model for river health evaluation based upon the physical, chemical, and biological elements

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ABSTRACT

Rivers provide many services to humans, however, globally, they have been historically impacted from over-exploitation for human needs. Such impacts are likely to increase into the future leading to poorer river health and the service functions provided by rivers are being lost. This study focused on the river health evaluation for river protection and sustainable water management. Eight indices were selected to structure an evaluation index system, consisting of physical, chemical, and biological elements, for river health evaluation. Among them, a new index, Ratio of Environmental flow to Streamflow (RES), was proposed to evaluate the satisfaction degree of environmental flow and to establish a common standard for the comparison of habitat quality among different rivers. A combined model consisted of fuzzy matter-element and projection pursuit models was established for the evaluation of river health, which was adopted to convert several indices in the evaluation index system to a comprehensive indicator. The Huai River Basin was selected as the case study area. The results showed that the river health of the whole Huai River was at the medium level. Four river reaches such as Reach I, II, IV and V were in the middle level, while only Reach III was at the sub-healthy level. This study is expected to provide scientific knowledge for the improvement of river health and water allocation.

1. Introduction

River deterioration is an important issue in river basin management and has adverse consequences on humans and aquatic organisms. River pollution occurs gradually due to natural and anthropogenic activities (Sundaray et al., 2006), such as climate change, uneven distribution of precipitation in time and space, agricultural, industrial and domestic wastewater emissions, excessive dam constructions, and floodgate constructions. Furthermore, in water resource allocation management, the social, economic and domestic water demand has often been prioritized over the environmental flow needs for rive ecosystem (Tharme, 2003). However, the importance of river health protection is critical for the sustainable utilization of rivers to satisfy social, economic, and domestic demands. Health of rivers has been widely studied with the aim of providing important knowledge for sustainable river management.

Biological monitoring and comprehensive indicator methods are the currently accepted methods for river health evaluation (Zhao and Yang, 2009). The biological monitoring method was explored since 1980s, and the underlying principle of it was that the biota was the ultimate integrator of all human actions. The biological monitoring method always uses biological monitoring technology with indicative species as the representative to evaluate the river health. Common biological monitoring methods include RIVPACS (Wright et al., 1984), IBI (Karr, 1981), AUSRIVAS (Simpson and Norris, 2000). Boulton (1999) indicated that biological monitoring methods cannot fully reflect the complexity of river ecosystem since they focus on assemblage structure of a broad taxonomic groups. So comprehensive indicator method came into being.

The fundamentals of comprehensive indicator method is that a suite of physical, chemical and biological variables should be sampled to obtain an integrative perspective of river health by using mathematical models. With the development of monitoring technique, a variety of parameters can be measured in monitoring programs within rivers including water quantity and quality, river structure, biological characteristics (Bunn et al., 2010). Traditional and early comprehensive indicator methods were based on a comparison of the studied river referenced to a healthy or natural river. Such methods include Rapid Bioassessment Protocols (RBPs) (Barbour et al., 1992), Riparian, Channel and Environmental Inventory (RCE) (Petersen, 1992), System

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for Evaluating Rivers for Conservation (SERCON) (Boon et al., 1998), and Index of Stream Condition (ISC) in Australia (Ladson et al., 1999). However, selection of natural reference points and the evaluation scores in these methods are inevitably subjective, and the data are difficult to obtain for some indices. Consequently, the comprehensive indicator method has been improved, such that it uses relevant mathematical models to convert several indices to a representative comprehensive indicator to evaluate river health (Zhao et al., 2009 & Sheldon et al., 2012). The mathematical models and indices can be chosen freely based on the actual situation of the evaluated river, resulting in increased flexibility. The common used mathematical models for multi-index conversion problem include analysis hierarchy process (Qin et al., 2014), Entropy model (Yang et al., 2016), fuzzy matter-element model (Deng et al., 2015; Pan et al., 2015), and so on.

This aim of this paper was to evaluate the health of the Huai River using the comprehensive indicator method to generate critical technical knowledge for river management and for river health improvement. The evaluation index system of river health was structured based on the physical, chemical and biological elements. Previous studies have primarily focused on the biological diversity without focusing on the habitat situation. This research proposes an index, ratio of environmental flow to streamflow (RES), for evaluating the habitat quality. The combined model was established, which was composed of fuzzy matter-element model and projection pursuit model. The fuzzy matter-element model was used to convert several indices in the evaluation index system of river health onto a comprehensive indicator (Zhang et al., 2011). In more cases, the weights used in the fuzzy matter-element model are decided by subjective opinions such as Delphi method (Linstone and Turoff, 1975). In this paper, fuzzy matter-element model was combined with the projection pursuit model. The weights obtained by projection pursuit model depended on the data structure of several indices which could effectively reduce the subjectivity and bias (Montanari et al., 2001). Particle swarm optimization is the common algorithm to solve the nonlinear optimization of projection pursuit model. In this paper, chaos algorithm was combined into particle swarm optimization to solve the particles clustering problem.

2. Materials and methods

2.1. Study area and data

The Huai River Basin (N30°55′-36°36′, E111°55′-121°25′), which is the sixth largest river basin in China, is in eastern China, between the Yangtze River Basin and the Yellow River Basin. It has a drainage area of 270,000 km^2 and the total length of about 1000 km (Fig. 1). Due to population growth and rapid economic development, the Huai River is significantly polluted, resulting in adverse health impacts on humans, aquatic organisms, and riparian plants. Since 1949, 38 large reservoirs, over 11,000 dams and floodgates have been constructed. Consequently, most rivers have been fragmented into independent water bodies, and the vertical or horizontal connectivity of some rivers have been restricted, causing the deterioration of aquatic ecosystem. In addition, the water quality of more than half of 86 national monitoring stations cannot reach the Grade III level of the national standard (Zhai et al., 2014). Therefore, ecological and environmental protection and restoration in the basin has attracted significant attention.

The actual and straight lengths of the five reaches were measured using the Google Earth images. The water quality data, ecological data in 2011, and historical daily runoff series of the five sections (23 years from 1988 to 2011) were collected from the monitoring center at the Huai River Water Resources Protection Bureau. The water quality of the five sections, namely Huaibin, Wangjiaba, Lutaizi, Bengbu, and Xiaoliuxiang was monitored once a week. Four field investigations of aquatic organisms such as benthic animals and fishes were carried out during March, June, September and November in 2011.

2.2. Evaluation index system

For comprehensive evaluation of the river health, various elements of the river health are required and several indices are needed to describe the characteristics of each element. In this study, eight indices were selected to develop the evaluation index system, which can describe the physical, chemical, and biological elements of river health.

2.2.1. Physical element

Urbanization has resulted in straightening of many river bends that are favorable for developing abundant and diverse habitats, and better biodiversity. Several countries realized the adverse effect of straightening of river bends, and advocated maintaining the natural form of river (Ladson et al., 1999; Barbour et al., 1999). The river sinuosity index, proposed by Leopold et al. (1964), was chosen to characterize the river physical form, because it is a widely-used index in river structure evaluation (Maddock, 1999; Aswathy et al., 2008; Zhu et al., 2015), and can effectively evaluate the comprehensive bending of a river reach. The data used in river sinuosity index can easily be extracted from the Google Earth, which is suitable for the regions with inadequate observational data. The river sinuosity index is calculated according to Eq. (1):

$$RC = La_i/Ls_i \tag{1}$$

where RC is river sinuosity, La_i is the actual length of the i-th reach and Ls_i is the straight length between the initial and end of the i-th reach.

2.2.2. Chemical elements

Three water quality indices, ammonium nitrogen (NH_3-N), permanganate index (COD_{Mn}) and dissolved oxygen (DO), were selected for water quality evaluation. The NH_3-N and COD_{Mn} are the major water quality evaluation indices in the Huai River Basin recommended by the government (Xia and Chen, 2015). The DO, which is a classic environmental variable, is frequently used to evaluate water quality and influenced by a combination of physical, chemical, and biological characteristics of river (Sanchez et al., 2007). The DO has a closer relationship to aquatic life and is critical to protect aquatic life (Simoes et al., 2008).

2.2.3. Biological elements

(1) Aquatic biodiversity

Aquatic biodiversity, which is the reflection of accumulative ecological effects along with time and space, is an important index for river health (Fryirs, 2003). Benthic animals and fishes are commonly used indicator taxa (Maxted et al., 2005; Lakra et al., 2010). In this research, the Shannon-Wiener index (H') was used to quantify the diversity of benthic animals and fishes and is based on communication theory and incorporates species richness (Grubb et al., 2006), calculated using Eq. (2):

$$H' = -\sum_{i=1}^{s}\left[\frac{N_i}{N}\times\ln\left(\frac{N_i}{N}\right)\right] \tag{2}$$

where, s is the number of species, N is the total number of individuals, and N_i is the number of individuals in the i-th species (i = 1 to s).

(2) Ratio of Environmental flow to Streamflow (RES)

The Indicators of Hydrologic Alteration (IHA) provided a statistical analysis of 33 ecologically relevant hydrological indicators to characterize the condition and variation of streamflow (Richter et al., 1996, 1997). The IHA method is applied to evaluate long series of historical flow condition using a combination of 33 indicators. Suitable flow condition is critical for encouraging suitable habitats. On this basis, the RES index was proposed to reflect the satisfaction degree of environmental flow to current streamflow and to establish a comparable common standard for different rivers. RES refers to the ratio of the environmental flow for an ecological target (base flow or optimum