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Original Articles

Health assessment and spatial variability analysis of the Naolihe Basin using a water-based system

Zhenxiang Xing, Yinan Wang, Yi Ji, Qiang Fu*, Heng Li, Ruizhuo Qu

School of Water Conservancy & Civil Engineering, Northeast Agricultural University, 150030, Harbin, China

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ABSTRACT

To determine the spatial distribution and variability in the health status of the Naolihe Basin, a water-based system was introduced, and 27 indexes were selected within the water-based system theoretical frame. The Naolihe watershed was divided into 12 subareas, and the health status of each subarea was evaluated using a fuzzy comprehensive evaluation method with weightings calculated using an improved combined entropy-weighting method and analytic hierarchy process. Three semi-variability models (spherical, exponential, and Gaussian) for the Kriging interpolation method were used to analyze the spatial variability of the basin's health status. The Kriging interpolation method with the Gaussian model delivered the highest accuracy. Spatial variability analysis showed that the health status of the Naolihe Basin was mainly affected by river direction, topography, and regional economic development level. The health state of the southern area of the Naolihe River was better than that of the northern area, and the health state gradually improved from east to west in the Naolihe Basin. In addition, the health statuses of several specific areas were slightly lower, which was caused by overdevelopment.

1. Introduction

Water is widely regarded as the most essential natural resource. A freshwater ecosystem in a basin, a subject of concern as highly vulnerable water systems in the world (David et al., 2014), are among the most threatened environments worldwide (Dudgeon et al., 2006). Globally, an estimated 65% of freshwater habitats are considered moderately to severely threatened (Schowe and Harding, 2014; Vörösmarty et al., 2010), and freshwater habitats are comprised of flowing (i.e., streams and rivers) and standing (i.e., lakes, ponds and wetlands) waters (EPA, 2017). Watershed health has been an important topic among the general public and patrons involved in basin planning and stabilization (Wen and Kai, 2011).

A prerequisite for basin health evaluation is the definition of the concept of basin health, but there is no universal definition of basin health at present. In the view of ecological definitions, a healthy basin should include a diverse range of biological species, a complex ecological structure, and an integrated ecological function (Barmuta et al., 1996; Schofiled and Davies, 1996 Scrimgeour and Dan, 1996) with the capacity for self-development. The structure and function of a healthy basin can remain in a relatively optimal steady state during interaction processes with the surroundings of the natural basin (Frappier and Eckert, 2007; Johnson et al., 2007).

A basin is a compound ecosystem composed of nature, society, and economics, and it supplies the development of a social economy (Hu, 2014). Thus, a basin has ecological integrity and a special contribution to human society and economic development. Therefore, a certain balance state of basin health is necessary to satisfy the requirements of ecosystem stability and human social and economic development (Cai et al., 2011b; Huang et al., 2014).

Over the past 20 years, many practical methods for evaluating basin health status have been constructed. In terms of evaluation theories, these methods are divided into prediction model methods and multi-index evaluation methods (Cai et al., 2009a; Wu et al., 2005). The prediction model is used to evaluate river health status by making a comparison between actual biological composition and theoretical biological composition under the assumption of no interference of the river. The examples are the River Invertebrate Prediction and Classification System, PIVRACS (Wright et al., 2000) and the Australian River Assessment System, AUSRIVAS (Smith et al., 1999). Multi-index evaluation methods are usually used to consider several factors influencing basin health with certain evaluation indicators that indicate the basic situation of a basin to assess basin health. For different study areas, the multi-index evaluation method can be used to construct an evaluation index system suited for basins of agricultural areas (Petersen et al., 1992), lakes (Zhang et al., 2016), or forests (Hepelwa, 2014). This index

* Corresponding author.
E-mail addresses: zxxing@neau.edu.cn (Z. Xing), fuqiang@neau.edu.cn (Q. Fu).

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system is then used to establish a method for evaluating basin health status. Examples of multi-index evaluation methods are the multi-level fuzzy comprehensive evaluation method (Wang et al., 2012) and the pressure-state-response method (Yi et al., 2015).

At present, studies on basin health mainly focus on the ecosystem health assessment in basins, and the factors related to the biodiversity and vitality of ecosystems are usually considered in selecting evaluation indexes. However, social and economic factors are often ignored. Social factors, such as population density, sewage treatment, and per-capita gross domestic product, have an important influence on basin health. Therefore, a water-based system theory (Huang et al., 2014; Liu, 2005; Liu and Guo zhi, 2005) has been adopted in the present study to consider the natural, social, and economic influences on basin health status.

The water-based system of a basin contains all elements influencing water resources of the basin. The water-based system consists of the water and all water-related factors of the basin within a certain time scale and range, including water quantity, water quality, engineering media containing reservoirs, water transfer projects (Cai et al., 2011a) and water pipelines, wading media containing river road direction and riverbed shape, and all the external factors influencing the water resource systems of the basin, i.e., socio-economy, ecological environment in the basin, etc. An evaluation index system for basin health was built, and an evaluation method using a water-based system for basin health with fuzzy comprehensive evaluation was established. Furthermore, to ensure the rationality of the evaluation result, the weightings for each index were determined by both subjective and objective weighting methods. Based on the evaluation result, the geostatistics method was used to evaluate the spatial distribution characteristics of health status, on which the influence factors were determined.

2. Methods

2.1. Study area

The Naolihe Basin is located at longitude 131°31′–134°10′ east and latitude 45°43′–47°35′ north in the northeast part of Heilongjiang Province in China. The Naolihe River, with a basin area of 24,863 km^2, is a major tributary of the Ussuri River. The Naolihe River originates from the north slope of the WanDan Mountains and flows through 3 administrative counties (Baoqing County, Fujin City, and Raohe County) and 9 state farms (No. 597 Farm, No. 852 Farm, No. 853 Farm, No. 859 Farm, Hongqiling Farm, Shengli Farm, Daxing Farm, Hongwei Farm, and Raohe Farm) (Fig. 1). The total arable land is 15,086.25 km^2, of which irrigated fields cover an area of 4898.77 km^2. The altitude of the Naolihe Basin gradually decreases from the southwest to the northeast. There are dense primeval forests and fragmented forests in the southwest, so the vegetation coverage is very high. In addition, there is a large plain area in the northeast, which is mainly cultivated for agricultural production.

2.2. Evaluation using a water-based system

A water-based system is carried out in a fundamental habitat and consists of water resources, media related to water, and water conservancy engineering at a certain hydrological scale and spatial range. For a basin, the water-based system includes not only these 3 parts but also the external factors impacting it, such as social economy, atmospheric circulation, and the ecological environment. The water-based system is an open multidimensional system that integrates all complex things related to water. Therefore, a basin health evaluation using a water-based system is a comprehensive assessment, which considers the situation for the water resources of development, utilization, carrying capacity, and environment.

Based on the domestic and foreign research on watershed health (Agency), a health evaluation index system, under the theoretical frame of the water-based system, was established as the basis for assessing the practical situation of the Naolihe Basin. There are 3 layers: the target layer, the criterion layer, and the index layer. Moreover, the criterion layer is classified into 3 categories (stability, harmony, and evolution rate, which are named characteristics of a water-based system). To categorize the 3 characteristic properties, 27 indexes were selected in the index layer. The selection of some indexes refers to numerous international studies (Cai et al., 2009b; Xu et al., 2011a; Jia et al., 2015; Nguyen-Truong and Le, 2015; Shear et al., 2005). The details of the evaluation index system are shown in Table 1. The specific meanings of the indexes are explained as follows:

N1 (Water resources development and utilization rate): a significant index to characterize the extent of the development and utilization of water resources, a ratio of water exploitation amount (WEA) to the amount of available water resources (AAWR) in watershed or region.

N2 (Water resources reuse rate): a ratio of the reuse amount of water (RAW) to the total water supply (TWS). RAW is the water amount after certain treatments of agricultural and industrial waste water.

N3 (Standard-reaching rate of **the** water quality of sources of drinking water): a ratio of the number of water sources (NWS) with water quality meeting the standard of drinking water to the total number of sources for drinking water (NTSDW).

N4 (Proportion of water area): a ratio of water area (WA) to the total watershed area (TWA). Water plays a critical role in the ecological function of a basin. The larger the water area is, the healthier the water-based system will be.

N5 (Irrigation and drainage capacity): an ability of the irrigation and drainage of projects for farmland, which is the amount of water supplied by irrigation and drainage engineering per second (m^3/s).

N6 (Effective irrigated area ratio): a ratio of irrigated area (IA) by project with supporting well facilities and technologies and water source guarantee to the total irrigated area (TIA). The study area is classified as an agricultural production zone by nation, so the larger the effective irrigated area is, the stronger the ecological function of basin and the healthier the water-based system will be.

N7 (Soil erosion intensity): a ratio of soil erosion area (SEA) to total land area (TLA) of the basin. Soil erosion causes a decrease in agricultural productivity and ecological collapse, both due to the loss of nutrient-rich upper soil layers. The stronger the soil erosion intensity is, the more the damage strength of water-based system will be.

N8 River meandering degree is a ratio of the central axis length (CAL) to the straight length (SL) between the two ends in a river reach. It is also described as the rate of stream channel slope to water level gradient in a river. Natural rivers are mostly bent, with shallow beaches and deep pools under the principle of minimum energy consumption, which is a pattern to maintain the momentum balance and stable hydraulic distribution within a river.

N9 (Per capita GPD): a measure to evaluate people's living standards. It is a ratio of total gross domestic product (TGDP) to the number of residents (NR) in a basin during a period (usually one year).

N10 (Natural population growth rate): a ratio of the net increase (decrease) of population (NIP or NDP) to the average annual population (AAP) in a region in a certain period (usually one year). It is generally expressed as permillage; however, it is taken as percentage for convenience.

N11 (Per capita green land area): i.e., the average public green land area (APGLA) for an urban population (UP). Green land plays a significant role in city purification. The bigger the N11 is, the stronger the self-purification function of the urban area and the healthier the water-based system will be.

M1 (Degree of urbanization): a ratio of the urban population (UP) to the total population in the basin (TP). The greater the index value is, the greater the number of people that transferred from rural to urban areas to live, and the worse the water-based system in a basin will be.

M2 (Population density): a ratio of the total population (TP) to the total area of a catchment (TAC). Its unit is usually taken as the number