Journal of Hydrology 551 (2017) 352–364

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Evaluation method for regional water cycle health based on nature-society water cycle theory

Shanghong Zhang [a,*], Weiwei Fan [a], Yujun Yi [b,*], Yong Zhao [c], Jiahong Liu [c]

[a] Renewable Energy School, North China Electric Power University, Beijing 102206, China
[b] School of Environment, Beijing Normal University, Beijing 100875, China
[c] China Institute of Water Resources and Hydropower Research, Beijing 100038, China

ARTICLE INFO

Article history:
Received 22 May 2017
Received in revised form 9 June 2017
Accepted 10 June 2017
Available online 13 June 2017

Keywords:
Dualistic water cycle
Healthy water cycle
AHP
Composite-index assessment
Fuzzy recognition assessment

ABSTRACT

Regional water cycles increasingly reflect the dual influences of natural and social processes, and are affected by global climate change and expanding human activities. Understanding how to maintain a healthy state of the water cycle has become an important proposition for sustainable development of human society. In this paper, natural-social attributes of the water cycle are synthesized and 19 evaluation indices are selected from four dimensions, i.e., water-based ecosystem integrity, water quality, water resource abundance and water resource use. A hierarchical water-cycle health evaluation system is established. An analytic hierarchy process is used to set the weight of the criteria layer and index layer, and the health threshold for each index is defined. Finally, a water-cycle health composite-index assessment model and fuzzy recognition model are constructed based on the comprehensive index method and fuzzy mathematics theory. The model is used to evaluate the state of health of the water cycle in Beijing during 2010–2014 and in the planning year (late 2014), considering the transfer of 1 billion m^3 of water by the South-to-North Water Diversion Project (SNWDP). The results show health scores for Beijing of 2.87, 3.10, 3.38, 3.11 and 3.02 during 2010–2014. The results of fuzzy recognition show that the sub-healthy grade accounted for 54%, 49%, 61% and 49% of the total score, and all years had a sub-healthy state. Results of the criteria layer analysis show that water ecosystem function, water quality and water use were all at the sub-healthy level and that water abundance was at the lowest, or sick, level. With the water transfer from the SNWDP, the health score of the water cycle in Beijing reached 4.04. The healthy grade accounted for 60% of the total score, and the water cycle system was generally in a healthy state. Beijing's water cycle health level is expected to further improve with increasing water diversion from the SNWDP and industrial restructuring.

1. Introduction

The water cycle underpins the formation of water resources and is the main driving force in the evolution of water environments and ecosystems. In recent years, the water cycle has been strongly influenced by global climate change and increasing human activities (Brown and Mitchell, 2010; Plummer et al., 2010). The driving force of the water cycle, its structure and parameters have gradually changed from a natural to a natural-social dualistic water cycle model, reflecting attributes of both nature and society (Wang et al., 2006; Wang and Jia, 2016; Luan et al., 2016). Social influences on the water cycle are becoming increasingly apparent, with water shortages, water pollution and ecological degradation in many countries and regions, particularly in densely populated areas (Liu and Yang, 2012; Elías-Maxil et al., 2014; Gani and Scrimgeour, 2014; Miao et al., 2015). For example, the Belt and Road Initiative proposed by Chinese government has attracted much attention all over the world, which will induce very intensive and extensive human activities, and water resources will be one of the biggest concerns (Li et al., 2015; Howard and Howard, 2016). Understanding how to maintain healthy development of the water cycle has become an important proposition to maintain sustainable development of human society.

Zhang et al. (2006) proposed the concept of a healthy water cycle, that is, humans should fully respect the natural laws of water movement and make rational and scientific use of water resources; the social water cycle should not damage the natural circulation in order to maintain or restore the water environment of a city or watershed and achieve sustainable use of water resources. If

---

* Corresponding authors.
E-mail addresses: zhangsh928@126.com (S. Zhang), yiyujun@bun.edu.cn (Y. Yi).

http://dx.doi.org/10.1016/j.jhydrol.2017.06.013
0022-1694/© 2017 Elsevier B.V. All rights reserved.

humans use too much of the water resource, the social water cycle will interfere with natural circulation processes. Once the degree of interference exceeds the capacity of the natural water cycle, health of the regional water cycle may be damaged. The water cycle is a complex system involving water sources, uses, supply and consumptions. Any damage to a sub-process of the cycle will affect its health. Comprehensive evaluation of a healthy water cycle is related to the establishment of measures to control water resource use, and this topic has attracted the attention of researchers and government departments (Norris and Thomas, 1999; Zhao and Yang, 2009; Amores et al., 2013; Uche et al., 2015).

There are differences between objectives and methods in water cycle assessments. Evaluations have often examined either the natural or social attributes of the water cycle (Noble et al., 2007; Pont et al., 2007; Li et al., 2013; Zhang et al., 2015). The former includes assessment of wetland, lake or river health cycles. For example, Meng et al. (2009) evaluated the health status of a river, using water quality, aquatic organisms and physical habitats in the Liaohe Basin of China. The results showed that water quality and habitat quality indexes had the greatest impact on river ecological health. Pinto and Maheshwari (2011) used a multivariate data reduction technique, called factor analysis, to identify the key river health variables for a peri-urban river system, finding that anaerobic fermentation, microbial pollution and eutrophication were three major environmental problems of peri-urban rivers. Deng et al. (2015) put forward an improved, entropy-based fuzzy matter-element model to evaluate river health in the Taihu Basin of China. They verified the regional applicability and effectiveness of the evaluation model and suggested that it was necessary to improve flood control capacity over the entire river basin. However, these evaluations tended to ignore the health of the social water cycle.

Social water cycle assessments focus on the social properties of the water cycle, which are mainly related to water supply, drainage, consumption and reuse (Chen et al., 2012; Vilanova and Filho, 2015; Lu et al., 2016). Meneses et al. (2010) used life cycle assessment (LCA) to evaluate various disinfection treatments of urban wastewater reuse and their environmental benefits and drawbacks in non-potable applications, revealing that non-potable uses of reclaimed water have environmental and economic advantages. Godskesen et al. (2013) set out four alternative cases for water supply in Copenhagen, which were environmentally evaluated and compared using standard environmental impact categories from an LCA extended by a freshwater withdrawal category. Their results showed that rainwater harvesting and desalination programs had the least environmental impact, and groundwater extraction had a relatively strong impact. Coombes and Barry (2015) proposed a systems framework of big data for analysis of policy, strategy and design, which integrates water cycle, environmental and economic processes from “bottom-to-top,” using all available data and integrating spatial and temporal scales of behavior. As far as methods are concerned, construction of the system framework and the big-data analysis can clarify all aspects of the water cycle if detailed multifarious data are available (Daniell et al., 2014).

Owing to the duality of the water cycle, accurate water cycle health assessment involves several dimensions, including water-based ecological integrity, water quality, water resource abundance, and use level. Comprehensive understanding of how to analyze and evaluate weaknesses in the water cycle process is an urgent challenge. In addition, a healthy water cycle is a fuzzy concept, which depends on human needs and the characteristics of a particular water system, and many health evaluation factors are nonlinear and uncertain. Therefore, evaluation results cannot be answered simply with a “yes” or “no”. Most past assessment systems adopted specific methods for evaluating the water cycle process, such as LCA, material flow analysis, and environmental risk assessment (Montangero et al., 2007; Katz et al., 2009). However, these methods cannot capture the fuzzy boundary and dimensional hierarchy of healthy water cycles. It has become necessary to develop a method to accurately evaluate and describe water cycle health without a clear boundary.

In view of current problems in the assessment of healthy water cycles, the present study focused on the following aspects: (1) accounting for natural and social dualistic characteristics of the water cycle and proposing a composite-index evaluation system for regional healthy water cycle assessment; (2) defining weights and a threshold range of evaluation indices for a specific region; (3) exploring the advantages and drawbacks of assessment methods based on various theories; and (4) evaluating the water cycle status in Beijing, analyzing health levels and identifying reasons for varying index layer scores.

2. Study area

Beijing is in the northern part of the North China Plain (115.7°–117.4°E, 39.4°–41.6°N) and has a total area of 16,410 km^2. It has a semi-humid continental monsoon climate, with rain and heat in the same period. Average annual precipitation is 585 mm, of which 70%–75% falls during the monsoon season (June–August). The resident population in Beijing reached 21.516 million at the end of 2014, and the urban population is still growing (Beijing Municipal Bureau of Statistics, 2015). According to statistical data from 2014, the per-capita water resource in Beijing was only 94 m^3, which is 1/24 of the national per-capita resource (Beijing Water Authority, 2014). This severe shortage of water resources means that they do not meet the needs of that highly developed city, and the excess demand for water reached 1–1.5 billion m^3 annually in the evaluation period (Fig. 1). Moreover, surface water pollution has resulted in the deterioration of ecological water conditions, and the overexploitation of groundwater has led to ground subsidence (Liu et al., 2016). These environmental water conditions have restricted the long-term social development in Beijing.

To alleviate serious water shortages in northern China, trans-basin diversion may be an effective solution (Li et al., 2016). After 50 years of feasibility studies, the South-to-North Water Diversion Project (SNWDP) national development strategy was officially launched in 2002, and the midline project achieved water delivery to Hebei Province, Beijing, Tianjin and other areas by the end of 2014. According to the initial plans, future water supply from the midline project will reach 0.8–1.5 billion m^3 per year for Beijing (Fig. 2), which will greatly improve local water resources and water environment conditions (Zhang et al., 2014). The middle route of the SNWDP transfers water from the Han River, the largest tributary of the Yangtze River. According to initial engineering planning, water transfer reached 95 billion m^3 per year from Danjiangkou Reservoir, or 23% of its total inflow. To ensure normal water supply and water source protection, the crest elevation rose from 162 to 176.6 m, improving water supply and flood control capacities in the middle and lower reaches of the Hanjiang River. At the same time, the Xinglong water control project, water transfer from the Yangtze to Hanjiang Rivers, and waterway regulation works were planned and built to relieve the adverse effects of water transfer on the middle and lower reaches of the Hanjiang River.

3. Materials and methods

3.1. Meaning of a healthy water cycle

The traditional concept of a healthy water cycle emphasized that human activities should not affect the laws of the natural