Ecohydrology & Hydrobiology 14 (2014) 39–54

Contents lists available at ScienceDirect

Ecohydrology & Hydrobiology

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

Original Research Article

Systematic solutions and modeling on eco-water and its allocation applied to urban river restoration: case study in Beijing, China

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ARTICLE INFO

Article history:
Received 16 October 2013
Received in revised form 16 February 2014
Accepted 18 February 2014
Available online 3 March 2014

Keywords:
Urban river restoration
Eco-water volume
Water quality
DTVGM
Beijing
Yongding River

ABSTRACT

Water and related environmental problems have become a key barrier to the sustainable development of China, where multiple uses of water and urban water management are two significant means to sustain urban development and the ecological restoration of rivers. A new assessment approach and water system model were developed to estimate eco-water or the volume of water essential for maintaining healthy and sustainable urban river ecosystems under various natural landscapes and water quality objectives. Moreover, multiple scenario analysis was adopted to explore the influences of water quality on eco-water management. The Yongding River in Beijing was selected as a case study. The results showed that the eco-water volume was 0.079, 0.073 and 0.067 billion m^3/a under high, medium and low objectives without water quality requirements, and 0.112, 0.107 and 0.101 billion m^3/a further considering water quality. The water residence times anticipated under each development scenario were 34.8, 37.5 and 41.5 d, which were 13.0%, 14.5% and 13.6% longer than those when water quality was considered. Better water quality could be achieved by implementing water diversions. The comprehensive implementation of water diversion projects could increase the rate of water discharge by 45.1%, decrease the permanganate concentration by 16.1%, and reduce the water residence time by 28.9% on average. This study is expected to provide scientific bases for good water governance, prepare healthy water systems for sustainable communities, and provide a reference case to achieve multiple uses of water for human uses and ecological river restoration in water short areas in developing countries.

1. Introduction

Water problems are extraordinarily severe throughout the world due to natural and anthropogenic stresses (Vörösmarty et al., 2000). Such problems have become a serious threat to water security, especially in China (Varis and Vakkilainen, 2001; Liu and Xia, 2004; Liu and Diamond, 2005; Fu et al., 2007; Xia and Zhang, 2008; Jiang, 2009; Zhang et al., 2011, 2012) which is characterized by diverse regional climatic regimes, insufficient and unevenly distributed water resources, frequent floods and droughts, serious water contamination, relatively poor water governance, and rapid urbanization and economic development.

China's population is expected to increase by 23.1% between 2000 and 2030. The total water demand is

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http://dx.doi.org/10.1016/j.ecohyd.2014.02.003
1642-3593/

Table 1
Description of water quality grades in environmental quality standards for surface water in China (People's Republic of China, 2002).

Grade	Water function	Water quality concentration		
		COD_{Mn}	NH_4-N	DO
I	Source of water bodies and national nature reserves	≤2	≤0.15	≥7.5
II	Water source protection with primary class for centralized drinking water, rare aquatic habitats and spawning grounds for fish and shrimps	≤4	≤0.5	≥6
III	Water source protection with secondary class for centralized drinking water, wintering and spawning grounds for common fish species and swimming zones	≤6	≤1	≥5
IV	Industrial water supply and recreational waters without direct human contact	≤10	≤1.5	≥3
V	Agricultural water supply and landscape waters	≤15	≤2	≥2
Inferior to V	Essentially useless	>15	>2	<2

Note: COD_{Mn}, NH_4-N and DO are the common water quality indices for water quality assessment, and refer to permanganate index, ammonium nitrogen and dissolved oxygen, respectively. And the unit of water quality concentration is mg/l.

expected to increase by 26.1% during this period, while the usable water resources per capita are expected to decrease by 19.1%. Especially in the arid and semi-arid regions, a serious water scarcity is likely to be experienced due to the rising water demands and decreasing usable water resources. Furthermore, water vulnerability is anticipated to increase under the changing environmental conditions, especially in northern and northwestern China (Lu, 2004). Extreme hydrological events, such as the frequent floods in the southern China which have been observed since the 1980s and the serious droughts in the northern China which have been experienced since the 1950s, are forecast to be further aggravated by the changing global climate (Xia et al., 2011).

Additionally, the national wastewater emissions reported in 2006 were twice as those reported in 1980 (Zhang et al., 2008a), and the cumulative river length with water quality less than Grade III (Table 1; People's Republic of China, 2002) increased from 13.0% in 1980 to 35.8% in 2011. More than 70% of the rivers in the northern plain regions were seriously polluted (Jia et al., 2004). Thus, water and related environmental problems have become a key barrier and crucial restriction to the sustainable development of China.

Although the Ministry of Water Resources in China is implementing a new water strategy based on the 'Three Red Line' control (Chen, 2009), and the Chinese government has introduced environmentally sound construction, there still remains a challenge for the ecological restoration of rivers under the changing climate and intensification of human activities on the landscape.

China is amongst the countries with the fastest rates of urbanization in the world. The rate of increase in urbanizing population has been approaching 52.6% through the year 2012. In this regard, the population growth and economic development in Beijing are the most significant, with the urbanization rate increasing from 79.5% in 2004 to 86.0% in 2011. The gross domestic production (GDP) has risen to 1600 billion CNY in 2011.

Because urbanization and environment are mutually coupled, coordinated and constrained (Huang and Fang, 2003; Liu et al., 2005), excessive urbanization and economic growth will lead to increasingly serious environmental problems, such as climate change (Kalnay and Cai, 2003), resource depletion and ecological scarcity (Benfield et al., 1999; McKinney, 2002). Accompanying this economic prosperity, ecosystem degradation has increased in Beijing and has been manifested as water shortages and droughts. Since the 1970s, water resources have become increasingly scarce and water pollution has become extraordinarily severe in Beijing city. Specifically, water resources per capita are only 120 m^3, and about 50% of the rivers and 30% of the lakes have been polluted (Grade III of the national water quality standard; People's Republic of China, 2002). The Yongding River in Beijing has been dry for 30 years and its aquatic ecosystem has been severely damaged, which has seriously threatened ecological water security in Beijing. Therefore, in order to promote sustainable urban development, integrated water resources management (IWRM) and ecological protection, a systematic approach to urban water management and ecosystem restoration is urgently required (Postel, 2002; Ormerod, 2004). Key elements in this approach include low impact development (LID) and river ecosystem restoration (RER) in the mega city. To this end, a task force has been implemented by the Chinese government since 2010 to save the Yongding River, the Mother River of Beijing. This restoration program depends on restoring river morphology and topography, and recognizing eco-water volume by the river ecosystems. Eco-water volume refers to the amount of water which is essential to maintain a healthy river ecosystem and adequate water resources to support sustainable development (Tennant, 1976; Covich, 1993; Peter, 1998; Feng et al., 2003; Yang et al., 2005). Actions in this regard include the ecological restoration of the upstream mountainous regions to preserve their natural conditions and baseflows, and the ecological restoration of the middle- and down-stream river reaches, which have been intensively disturbed by anthropogenic activities.

Based on the characteristics and ecological functions of urban rivers and lakes as well as socio-economic development demands, this paper presents a new assessment approach to estimate eco-water volume related to RER under specific water quality objectives, and develops a new urban water system model to couple the hydrological