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Development and evaluation of a new index to assess hydrologic regulating service at sub-watershed scale

Ruonan Li[a,b], Hua Zheng[a,b,*], Sunyun Lv[c], Wenting Liao[a,b], Fei Lu[a,b]

[a] State Key Laboratory of Urban and Regional Ecology, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, 100085, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China
[c] Bureau of Hydrology, Changjiang Water Resources Commission, Wuhan, 430010, China

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ABSTRACT

Hydrologic regulation is an important ecosystem service, and is easily influenced by human disturbance. Many studies have been conducted on the impacts that human activities have on flow regime and regulating capacity by a single environmental factor. However, these studies have not clarified the comprehensive effects at sub-watershed scale; these effects are important for sub-watershed management. This research was conducted to reveal the spatial heterogeneity of hydrologic regulating service and identify the impact factors in China's Yangtze River Basin. This basin is the largest in China and frequently floods. We built a new index based on the coefficients of variation for precipitation and runoff. The proposed indicator reflected the relative strength of regulating service effectively, and distinguished the basin into two different groups (A and B) of sub-watersheds. The hydrologic regulating index was significantly and positively correlated to slope and coverage of bush and forest, and negatively correlated to hydraulic projects, farmland, and urban area. Land-use changes have the greatest contribution (more than 60%) to differences in sub-watershed hydrologic regulating service. Compared with the sub-watersheds of group A, the sub-watersheds of group B suffered more severe human activity, for which the relative contributions to hydrologic regulating service were 32.18% (hydraulic projects), 18.21% (farmland) and 6.21% (urban area). These results indicated that the ecological effects of human activities should be a concern, and that restoration of the natural environment should play an important role for hydrologic regulating capacity enhancement. Group A sub-watersheds should explore the existing massive potential of (cascade) reservoirs for improving hydrologic regulating ability. Our results not only present a useful tool for watershed hydrologic regulating assessment, but lay a foundation for exploring differentiated management strategies of flood mitigation at sub-watershed scale.

1. Introduction

Ecosystem services (ESs) are considered to be a linkage between the environment and human wellbeing (Cai et al., 2017; VanRiper and Kyle, 2014), and are defined as the benefits that people derive from ecosystems. These benefits are diverse (e.g., food, medicine, and raw materials of agriculture and industry). More importantly, ESs uphold and maintain the life-supporting system of the earth, including climate regulation; assuring a steady circulation of atmosphere, water and biogeochemistry; maintaining species and genetic diversity; drought and flood reduction; and supporting seed dispersal, soil formation, and environment self-purification (Daily, 1997; MA, 2005; Zheng et al., 2003). The regulating service is one of the three major categories of ESs; it is involved in the atmosphere, hydrosphere, and biosphere, and is susceptible to human activities, which in turn affect human wellbeing.

Regulating services are strongly connected to hydrologic processes in both positive and negative aspects (Ouyang et al., 2016). Hydrologic regulation is the significant component of watershed ESs, and exerts a dynamic force on water circulation and processes that form an ecosystem, leading to temporal and spatial changes in water distribution (Kong et al., 2016; LaNotte et al., 2017; Schmalz et al., 2016). Because water is the important linkage between nature and society, human activities could easily affect the hydrologic regulation via land-use change, hydropower construction and operation, and agricultural production. Numerous relevant studies have been conducted in recent years, most of which focused on the runoff response to human activities (Kong et al., 2016; Wang et al., 2015a,b; Yang et al., 2014; Zuo et al., 2016). With regard to the impacts on the hydrologic regime and regulation, most research has used mathematical models and statistical

* Corresponding author at: Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, 18 Shuangqing Road, Haidian District, Beijing, 100085, China
E-mail address: zhenghua@rcees.ac.cn (H. Zheng).

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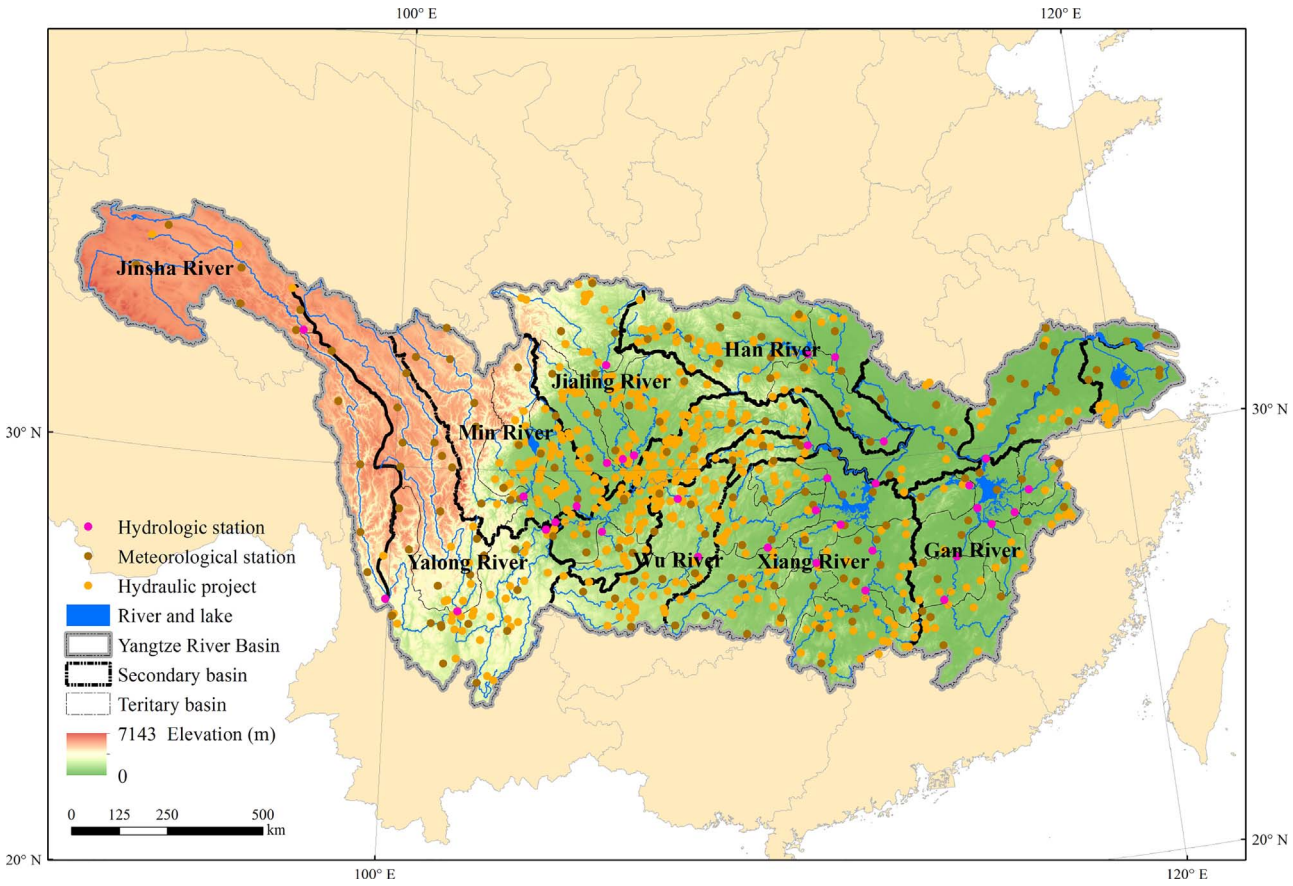

Fig. 1. The study area and locations of monitoring stations.

methods to focus on the hydrologic response to land use (Chen et al., 2017; Lørup et al., 1998; Sajikumar and Remya, 2015). From a spatial dimension, Algeetabarquero et al., 2015 and Niehoff et al., (2002) studied the implications of land-use on runoff regulation in small and meso-scale watersheds, respectively. Moreover, seldom considering monthly or seasonal variation, many studies have used annual time series data to reveal the effects on surface runoff variation caused by anthropogenic influences (Kong et al., 2016; Wang et al., 2015a,b; Yang et al., 2014; Zuo et al., 2016) and have attempted to identify the contributions of a single influence (Chang et al., 2015; Guo et al., 2016b; Jiang et al., 2015; Wang et al., 2015b). The dynamic relationships between land use and ESs have been investigated (Sonter et al., 2017). Additionally, the effects of urbanization on flow regime variation and ecosystem services have drawn attention (Bendor et al., 2017; Braud et al., 2013; Cai et al., 2017; Chen et al., 2017; Li et al., 2016; Liu et al., 2012; Trudeau and Richardson, 2015). Meanwhile, ample studies have revealed the impacts of reservoir construction and subsequent development on the magnitude, timing, and frequency variation of water flow (Kling et al., 2016; Magilligan and Nislow, 2005; Nilsson and Berggren, 2000; Räsänen et al., 2017; Rolls et al., 2013; Song et al., 2015; Vicente-Serrano et al., 2017; Yu et al., 2017).

From the essential principle of hydrologic regulation, the rainfall-runoff relationship is first to be considered for hydrological regulating service evaluation (Carvalho-Santos et al., 2014; Jiao et al., 2017; Kroll et al., 2015). By seasonal effect, the rainfall-runoff relationship should follow the rhythms of nature to maintain a well-balanced ecosystem function; hence the dynamic relation, which is reflected by natural and anthropogenic influences, should be concerned (Brauman et al., 2007). Furthermore, although many studies focus on the influence of human activities on hydrologic variation, these are usually single-factor based (e.g., Dagnew et al., 2017; Du et al., 2012; Mayerhofer et al., 2017; Silva, 2017), and rarely aim at identifying comprehensive effects of multiple factors; such effects can help illuminate sub-watershed hydrologic regulating service and explain differences among watersheds to provide targeted information for sub-watershed flood regulation.

The Yangtze River Basin (YRB) contains the most important economic areas in China and supports more than 400 million people, and always suffers from floods and droughts (Guo et al., 2016a; Ouyang et al., 2016; Wanders and Wada, 2015). Environmental degradation and runoff redistribution in time and space caused by human activities are the major factors that affect the hydrologic regulating capacity of the Yangtze River (Chen et al., 2014; Gu et al., 2011; Yang et al., 2014; Zhu et al., 2017). Therefore, quite a few projects, including hydraulic engineering works, natural forest conservation, the Grain for Green scheme and lake restoration, have been implemented to reduce natural disaster risk, improve the hydrologic regulating ability, and promote livelihoods and alleviate poverty (Ouyang et al., 2016; Yu et al., 2017).

Using the sub-watersheds of the Yangtze River as an example, the objectives of this research were to (i) develop a new indicator for hydrologic regulating service assessment, which measures the response of the rainfall-runoff relationship to different impact factors effectively; (ii) analyze the spatial heterogeneity of water regulation in the sub-watersheds and identify the corresponding driving force; and (iii) illustrate the response of comprehensive regulating effects to environmental factors, thereby providing guidance for hydrologic regulation improvement and management.

2. Study area

Ranked as the largest river in China and the third largest in the world, the Yangtze River has a long history of human disturbance, especially after reform and open policy implementation at the end of 1970s (Zhao et al., 2015). It is a typical rain fed river, and rainfall in the river basin is unevenly distributed through the year. More than 50,000