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Environmental flows and its satisfaction degree forecasting in the Yellow River

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ABSTRACT

Assessment of suitable environmental flows (EFs) and its satisfaction degree is significant for water resources management. We presented a forecasting framework for EFs, IFA and EF satisfaction degree to assess suitable EFs (minimum or threshold) and forecast EF satisfaction degree over the next 20 years. First, we investigated the temporal and spatial distribution characteristics of IFA using statistical analysis and Morlet wavelet analysis of the hydrologic series from 1919 to 2013. Second, forecasting models of IFA were established using hydrologic stochastic simulation based on wavelet analysis. Then, abrupt shifts of baseflow index (BI) were identified based on Mann-Kendall trend detection test. Subsequently, regressions models were developed between a normalized BI and the effect size (ES) of zoobenthos and fish species richness. Accordingly, EFs were calculated. Finally, the IFA and EF satisfaction degree for the forecasting years were calculated. Results show that thresholds of BI, with 0.8 and 0.4 as the lower limit, and 2.3 and 1.1 as the upper limit, were recommended as the limit percentage of the EFs standard during flood and non-flood seasons, respectively. An overall decreasing tendency of IFA was observed in all the seven stations from the 1910s to 2010s, which is especially particularly significant in the lower reaches in the past two or three decades. One major EFs deficit spell occurred throughout the river beginning in the 1990s. Forecasting results indicate that the IFA will satisfy the EFs for the stations located in the upper and middle reaches by 2020 and 2030, except for the stations in the lower reaches. Contradictions of EFs and IFA will be even graver in the future. The results will have important implications for the water management of the riverine ecosystem.

1. Introduction

Flow is demonstrably one of the most important variables and the flow regime is considered as the critical driver of river ecosystems (Hart and Finelli, 1999; Malard et al., 2006; Kennard et al., 2010). However, water resources management and river regulation have altered the natural flow regime of rivers globally in recent decades (Barnett et al., 2008; Mackay et al., 2014). Consequently, changes in flow regimes (e.g. magnitude, frequency, or duration) have seriously threatened the ecological sustainability of rivers and their associated floodplain wetlands (Poff et al., 1997; Bunn and Arthington, 2002; Arthington et al., 2006; Leigh et al., 2012; Belmar et al., 2013).

Environmental flows (EFs) are defined as the magnitude, frequency, timing, duration, spatial distribution, and water quality of the flows required to sustain freshwater and estuarine ecosystems that depend on these ecosystems (Botter et al., 2007; Poff et al., 2010; Liu et al., 2016). Therefore, determining suitable EFs to maintain a certain level of ecosystem health and prevent environmental degradation is of high theoretical and practical significance. With improvements in the people's awareness of environmental protection and theories and methods of EFs, a growing number of studies have paid more attention to EFs satisfaction while allocating water for instream usage (Perera et al., 2005; Marshall et al., 2010; Chen et al., 2013). The necessity of creating and implementing catchment water resources plans that include EFs has already been accepted in some developed countries, including parts of the United States (e.g. Florida), Australia, New Zealand, the countries of the European Union (e.g. France and England), and South Africa (Hirji and Richard, 2009; Overton et al., 2014). The science underpinning EFs has advanced considerably. Numerous methods for estimating EFs, such as applied ecology and model simulation methods now exist (Thoms and Sheldon, 2002; Cui et al., 2010; King et al., 2016). Meanwhile, more information is available on the ecological response to different flow regimes (Carlisle et al., 2011;

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Sims and Colloff, 2012). Experience in integrating the information from across a range of hydrological, geographical, ecological, and socioeconomic disciplines is also growing (Puckridge et al., 1998; Smakhtin, 2001; Tharme, 2003; Sivapalan et al., 2012; Acreman et al., 2014). Moreover, a wide variety of assessment methods for EFs have been developed to suit different levels of environmental conditions, access to data and skills (Cai and Rosegrant, 2002).

Regardless of the method selected, the ultimate goal of each EFs assessment practice is to recommend suitable EFs for a river, which is as close as possible to its natural regime (Ramsar Convention Secretariat, 2007). However, instream flow has shifted from a natural regime to a poor hydrologic condition resulting from natural and anthropogenic activities (Betts et al., 2015; Yin et al., 2015). How ecosystems, particularly the aquatic species, respond to the subsequent flow regime shifts may have important implications for the functioning of the river and riverine ecosystems (Kimmerer, 2002; Elmqvist et al., 2003; Reum et al., 2011). This question is one of the primary issues in ecology today.

Instream flow availability (IFA) is a critical component in the allocation and management of water resources. The water allocation of a river is aimed at keeping the natural regime of the river to maintain the instream ecosystem and its associated floodplain wetland in an ecologically viable state. In the early years, the IFA was directly or indirectly determined by ecological and environmental protection objectives guaranteed by laws and regulations established by governments (Johnson and DuMars, 1989). For example, the South African government developed a discharge schedule to regulate the IFA of rivers and wetlands (Arthington et al., 2003; Hirji and Panella, 2003). With improvements in theories and methods of IFA assessment, stochastic models are established and widely used to analyze the complicated characteristics of IFA that were influenced by climate changes and human activities (Efstratiadis et al., 2014). Traditional stochastic simulation models can describe the main statistical characteristics with a few simple parameters. However, the descriptions of the parameters obtained from mathematical and statistical methods lack specific information.

Current studies focus on addressing water allocation in the presence of an EFs and IFA imbalance, striving to achieve a balance between EFs and IFA, and maximizing profit with limited water resources (Thoms and Sheldon, 2002; King and Brown, 2006; Porse et al., 2015). Ecological and multi-objective optimization models help to analyze and solve the problems better, particularly that in dry years or unflooded seasons (Schlüter et al., 2005; Letcher et al., 2007; Johnston and Kummu, 2012). With the increased water demand and the improvements in people's awareness of the importance of freshwater ecosystem services, target EFs become more and more significant in the goal setting process, and the IFA has turned into a critical water user of water resources allocation. Otherwise, without considering target EFs and IFA, water used for freshwater ecosystem will be preoccupied by national economic water-use allocated by irrational exploitation and utilization plans of water, lead imbalances between them, and result in serious environmental degradation, such as river drying up, lake shrinking, vegetation degradation, and deterioration of water quality (Richardson et al., 2007; Du et al., 2011; Bond et al., 2014). In China, research on IFA to guarantee target EFs in the water resources allocation had undergone four periods, namely, (1) demand-driven period before the 1990s, during which only the demands of humans and economic production were considered but basic requirements of ecological environment were disregarded; (2) macroeconomic-based period in the 1990s, during which an optimal allocation of water resources was incorporated into the macroeconomic system to achieve a coordinated development of regional economies and water resource use; (3) sustainable development period during the late 1990s, during which a dynamic coordination among resources, economic and ecological environment to pursue water resources allocation for sustainable development; and (4) supply-driven and ecology-oriented period since the late 20th century, during which models were proposed based on the improvement of water resources management and water use efficiency.

Overall, in the past few decades, the approaches for the assessment of EFs and IFA in water allocation at home and abroad have been an utmost concern. Each country has formulated a variety of models to assess EFs and IFA, and has established optimal allocation models among different water users to guarantee the target EFs, according to their ecological goals of environmental protection or economic development demands. However, a lack of quantitative relationships between flow changes and ecological responses limits the usefulness of such studies for river managers who need to determine the minimum or threshold of EFs for specific rivers. The challenges are to quantify the desired ecosystem conditions or ecological goals and to evaluate the EFs correspondingly (Harris and Heathwaite, 2012; White et al., 2012). Meanwhile, to reveal the complicated characteristics of IFA, the detailed structure and more information on the IFA series should be analyzed. Therefore, we urgently need to analyze the characteristics of IFA in long-term temporal scales and large spatial scales, and develop optimal methods or models to assess the EFs and IFA.

Our aims are (1) to investigate the temporal and spatial distribution characteristics of IFA; (2) to develop linear or nonlinear regression models between aquatic species responses and the flow changes to determine suitable EFs (minimum or threshold); and (3) to analyze EF satisfaction degree over the next 20 years. Correspondingly, we develop a forecasting framework for EFs, IFA and EF satisfaction degree, and then apply the framework to a case study of the Yellow River in China, which has great inter-annual changes in flow regime in recent years.

2. Material and methods

2.1. Study area

The Yellow River originates in the Qinghai–Tibet plateau, flows through nine provinces, and is located approximately 5464 km east to the Bohai Sea near Dongying City in Shandong Province (Fig. 1). The Yellow River is the second longest river in China, following the Yangtze River. Spanning parts of the nine provinces of Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia Autonomous Region, Shanxi, Shaanxi, Henan, and Shandong, the Yellow River is one of the most critical sources of water in China. The average annual natural runoff of the Yellow River is 58 billion m^3, accounting for 2.1% of the total runoff of the seven largest rivers in China. The Yellow River and its tributaries provide water to more than 53 million people for municipal use, supply water used to irrigate approximately 80,000 km^2 of land, and are the lifeblood of at least nine important wetlands. However, the Yellow River often runs dry because of a severe water imbalance between the water supply and the demand in the river basin. A total of 21 events of drying up in the lower reach have been recorded from 1972 to 1998.

The Yellow River has 36 major hydrologic stations. After we considered the natural and human factors and data availability, seven of these hydrologic stations, namely, Tangnaihai (Tang), Lanzhou (Lan), Toudaoguai (Tou), Longmen (Long), Sanmenxia (San), Huayuankou (Hua), and Lijin (Li) are selected as the representative stations. These stations also are the main control hydrologic stations of the seven subregions, including above Longyangxia, Longyangxia–Lanzhou, Lanzhou–Hekouzhen, Hekouzhen–Longmen, Longmen–Sanmenxia, Sanmenxia–Huayuankou, and below Huayuankou (Table 1).