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Assessing water scarcity by simultaneously considering environmental flow requirements, water quantity, and water quality

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ABSTRACT

Water scarcity is a widespread problem in many parts of the world. Most previous methods of water scarcity assessment only considered water quantity, and ignored water quality. In addition, the environmental flow requirement (EFR) was commonly not explicitly considered in the assessment. In this study, we developed an approach to assess water scarcity by considering both water quantity and quality, while at the same time explicitly considering EFR. We applied this quantity–quality-EFR (QQE) approach for the Huangqihai River Basin in Inner Mongolia, China. We found that to keep the river ecosystem health at a "good" level (i.e., suitable for swimming, fishing, and aquaculture), 26% of the total blue water resources should be allocated to meet the EFR. When such a "good" level is maintained, the quantity- and quality-based water scarcity indicators were 1.3 and 14.2, respectively; both were above the threshold of 1.0. The QQE water scarcity indicator thus can be expressed as 1.3(26%)|14.2, indicating that the basin was suffering from scarcity problems related to both water quantity and water quality for a given rate of EFR. The current water consumption has resulted in degradation of the basin's river ecosystems, and the EFR cannot be met in 3 months of a year. To reverse this situation, future policies should aim to reduce water use and pollution discharge, meet the EFR for maintaining healthy river ecosystems, and substantially improve pollution treatment.

1. Introduction

Freshwater is a fundamental resource for human well-being and the natural environment; it is regarded as the most essential natural resource in the world (Gleick, 1993). Over the past few decades, climate change and human socioeconomic development have greatly changed global hydrological cycles, threatening human water security, the health of aquatic environments and river biodiversity (Vörösmarty et al., 2010; Jacobsen et al., 2012; van Vliet et al., 2013). Given this situation, increasing attention has been paid to assessing the environmental flow requirement (EFR) of rivers and water scarcity (Vörösmarty et al., 2010; Kirby et al., 2014).

EFR is defined as the quantity, timing, and quality of the water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend upon these ecosystems (Brisbane Declaration, 2007). More than 200 methods are being used worldwide to calculate EFR that is needed to maintain healthy rivers (Tharme, 2003). These methods can be grouped into four categories: hydrological approach, hydraulic rating, habitat simulation, and holistic methods. The selection of an appropriate method is primarily constrained by the availability of data for a region, as well as by local limitations in terms of time, funding, expertise, and logistical support.

The main approaches used to assess water scarcity include the Falkenmark water stress indicator (Falkenmark et al., 1989), the IWMI indicator (Seckler et al., 1998), the criticality ratio (Alcamo et al., 2000), and the water poverty index (Sullivan et al., 2003). These approaches all focused on water quantity, but did not account for water quality for water scarcity assessment. Zeng et al. (2013) developed a simple indicator that combines quantity with quality in an easily understood way. However, it did not include a realistic approach to quantifying EFR. It is worth noting that there is an increasing awareness of explicitly considering EFR in the assessment of water scarcity in the hydrology community. Hoekstra et al. (2012) assumed EFR to be 80% of the total water resources in the assessment of global water quantity scarcity. This assumption was too simplistic, as it did not consider the complexity of EFR in a river regime. Hence, there is a need for a water scarcity assessment

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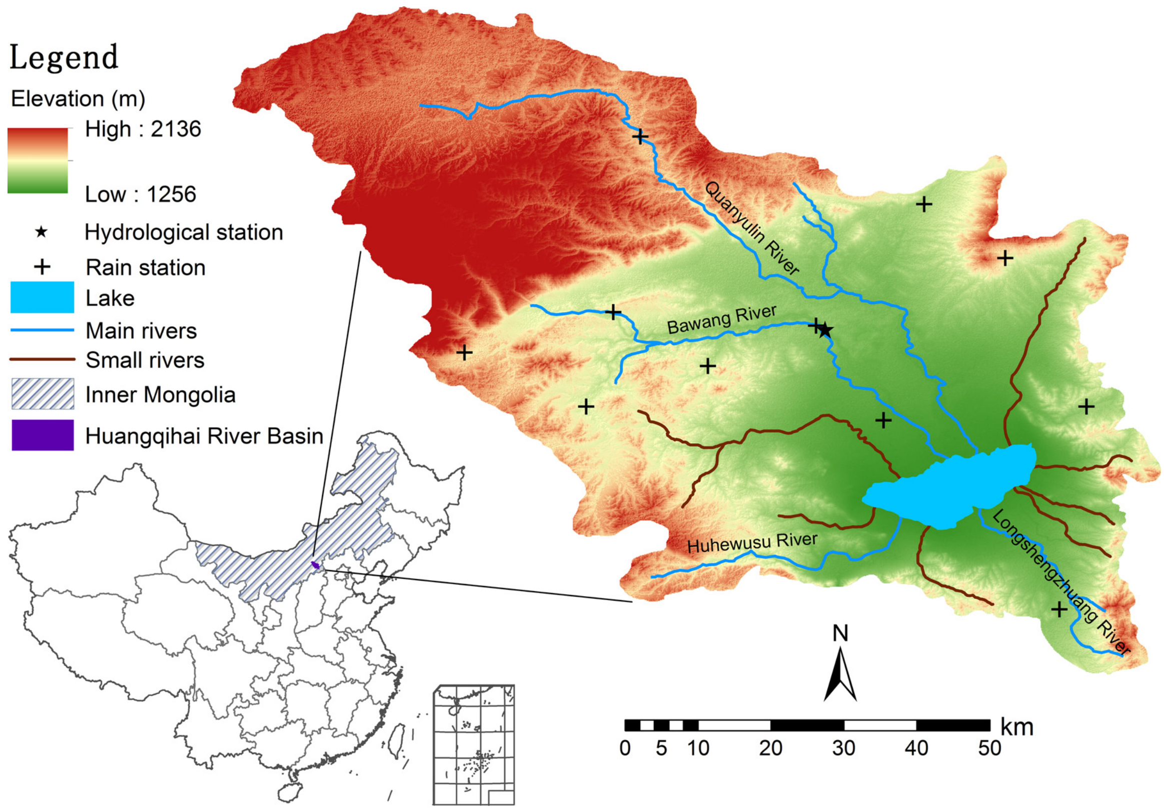

Fig. 1. Location of the Huangqihai River Basin in Inner Mongolia, China.

approach that can consider both water quantity and water quality, while also permitting a realistic consideration of EFR. Such a combined approach can provide more complete information on water scarcity.

The objective of this paper was to improve the water scarcity assessment approach by incorporating the water volume needed for EFR in the assessment. This new holistic water scarcity assessment approach provides an indicator that combines the status of quantity, quality and EFR (QQE indicator). The data used in this approach is easy to obtain, and can be quickly applied for a region. To demonstrate the application of the improved approach, we used it to assess the water scarcity in an arid and semi-arid region, the Huangqihai River Basin in Inner Mongolia, China.

2. Study area and methods

2.1. Case study area

The Huangqihai River Basin is located in the central part of Inner Mongolia Autonomous Region in China (Fig. 1). The average annual temperature of the basin is 4.6 °C, with mean monthly temperatures ranging from a minimum of −18 °C in January to a maximum of 26 °C in July and a freeze up period of more than 150 days. Annual precipitation ranges from an average of 270 mm in the southeast to 300 mm in the northwest. As an arid and semi-arid region, precipitation is unevenly distributed within a year, with 80% falling between June and September (Yu et al., 2013).

There are 11 primary rivers in the basin (Fig. 1). Only 4 of them have year-round recharge (the Bawang, Quanyulin, Huhewusu, and Longshengzhuang rivers); the others are seasonal rivers or have dried up completely (Li et al., 2013). The Bawang River and the Quanyulin River are the main water sources for the Huangqihai Lake, contributing more than 77% of the total annual river flows. In recent years, several reservoirs were constructed in upstream regions. They intercepted water flowing into the downstream reaches, thereby changing the natural runoff patterns. The downstream rivers often ran dry and underwent siltation, leading to a rapid shrinking of the Huangqihai Lake (Ma et al., 2002).

The basin is currently facing the problems of water shortage and poor water quality, as well as deterioration of ecosystem quality. The water availability per capita is only 985 m^3/year. With the increasing demand for water from the domestic and industrial sectors, conflicts for water use between agriculture and the other sectors have become more acute. Environmental water use has been deprived. The water quality in many river sections is below Grade III, the minimum quantity standard of water for direct usage. The poor quality of water further intensifies the water shortage problem because it reduces the usable water in the basin.

2.2. A quantity–quality-EFR (QQE) water scarcity indicator

The following equations are used to construct the QQE water scarcity indicator:

$$S_{qqe} = S_{\mathrm{quantity}}(\mathrm{P})|S_{\mathrm{quality}} \quad (1)$$

$$S_{\mathrm{quantity}} = \mathrm{BWF}/\mathrm{BWA} = W \times R/(\mathrm{BWR} - \mathrm{EFR}) \quad (2)$$

$$S_{\mathrm{quality}} = \frac{\mathrm{GWF}}{\mathrm{BWR}} \quad (3)$$

where S_{qqe} is the overall water scarcity index, which is a comprehensive indicator to reflect water scarcity by considering water quantity, water quality and EFR. S_{quantity} is the index of water quantity scarcity; S_{quality} is an index that quantifies the pollution-based water scarcity; P is the percentage of EFR in total blue water resources (BWR), and if not specifically mentioned, it is associated with the EFR for maintaining a level of "good" habitat quality. BWF (m^3) is the blue water footprint; BWA (m^3) is the blue water availability, which equals BWR (m^3) minus EFR (m^3); W (m^3) is the blue