

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



Junguo Liu<sup>a,\*</sup>, Qingying Liu<sup>a</sup>, Hong Yang<sup>b,c</sup>

<sup>a</sup> School of Nature Conservation, Beijing Forestry University, Qinghua East Road 35, Haidian District, 100083 Beijing, China

<sup>b</sup> Eawag, Swiss Federal Institute of Aquatic Science and Technology, Ueberlandstrasse 133, 8600 Duebendorf, Switzerland

<sup>c</sup> Department of Environmental Sciences, University of Basel, Petersgraben 35, 4001 Basel, Switzerland

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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.

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## 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).

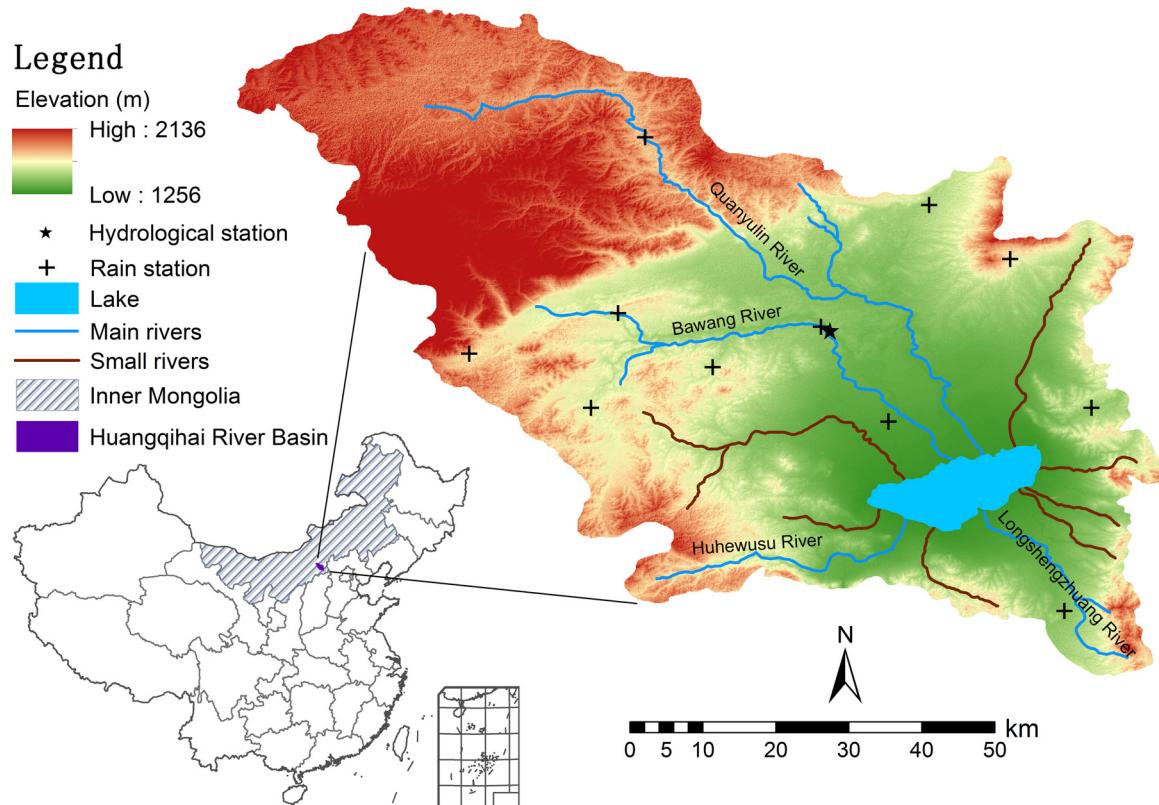
EFR is defined as the quantity, timing, and quality of the water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend upon these ecosystems (Brisbane Declaration, 2007). More than 200 methods are being used worldwide to calculate EFR that 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

\* Corresponding author. Tel.: +86 10 6233 6761; fax: +86 10 6233 6761.

E-mail address: [junguo.liu@gmail.com](mailto:junguo.liu@gmail.com) (J. Liu).



**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<sup>3</sup>/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:

$$S_{qqe} = S_{\text{quantity}}(P) \cdot S_{\text{quality}} \quad (1)$$

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

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

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.  $S_{\text{quantity}}$  is the index of water quantity scarcity;  $S_{\text{quality}}$  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<sup>3</sup>) is the blue water footprint; BWA (m<sup>3</sup>) is the blue water availability, which equals BWR (m<sup>3</sup>) minus EFR (m<sup>3</sup>);  $W$  (m<sup>3</sup>) is the blue

water withdrawal;  $R$  is the water consumption ratio; and GWF is the gray water footprint ( $\text{m}^3$ ). GWF is used to quantify the amount of water required to dilute pollutants in wastewater sufficiently to meet environmental water quality standards (Hoekstra et al., 2011). When  $S_{\text{quantity}} > 1.0$ , the available fresh water is not enough to meet the water consumption in the basin; at  $\leq 1.0$ , there is sufficient water to meet consumption needs. If  $S_{\text{quality}} > 1.0$ , the freshwater in this basin is insufficient to dilute the polluted water to the desired level specified in the water quality standard, and the region is experiencing water stress with respect to water quality; at  $\leq 1.0$ , there is enough water available for dilution (Hoekstra et al., 2011).

### 2.3. Simulation of hydrological processes and blue water resources

We used the Agricultural Policy/Environmental eXtender (APEX) model to simulate the basin's hydrological processes. The APEX model (Williams and Izaurralde, 2006) was developed by the Blackland Research and Extension Center (Temple, Texas, USA). It is a flexible, dynamic, and physically based distributed model that can be used to simulate the impacts of land use and management on watersheds. The applicability of the APEX model has been tested for the Huangqihai River Basin in previous studies (Liu et al., 2014; Wang et al., 2014). The results show that the APEX model is appropriate to simulate the hydrological processes throughout the Huangqihai River Basin.

The basin's BWR is the sum of the surface runoff, lateral subsurface flow, and percolation below the root zone. The APEX model simulates these flows for each sub-basin and for the entire basin on a daily basis. Surface runoff volume was simulated using a modified Soil Conservation Service (SCS) curve number technique described by Williams (1995), and the lateral subsurface flows and percolation were computed using the storage routing and pipe flow equations of Gassman et al. (2010). We used the average BWR within the simulated period (1982–2011) in this study.

The APEX model required a digital elevation model (DEM), soil data, land cover data, and climate data. The DEM data were obtained at a resolution of 90 m (<http://www.gscloud.cn>). Soil data were obtained at a resolution of 1 km from the Harmonized World Soil Database (<http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/index.html?sb=1>). The land cover data were based on the 1993 Landsat Thematic Mapper (TM) data at a resolution of 30 m (Chen and Liu, 2014). Daily maximum and minimum air temperatures, wind speed data, and relative humidity data from 1980 to 2011 were recorded at the Jining Weather Station (Fig. 1) (<http://cdc.cma.gov.cn/choiceStation.do>). Daily precipitation data during this period were obtained from 10 rainfall stations in the Huangqihai River Basin (Fig. 1). All of the data were rescaled to the 90-m DEM resolution.

### 2.4. Environmental flow requirement (EFR)

The EFR of the Huangqihai River Basin equals the sum of the in-stream flow requirements for all the rivers in the basin. Due to the lack of historical data on river flow, we used simulated flow data for the calculation. The APEX model simulated the long-term (1980–2011) natural flows in the absence of human disturbance for the basin's main and small rivers. The results of the first two years were used as the warm-up period for the model, and the river discharge for the rest of the study period (from 1982 to 2011) was used to calculate the EFR of the rivers based on the Tennant (1976) method. We used the following equations:

$$\text{EFR} = \sum_{i=1}^{12} e_{ij} \quad (4)$$

**Table 1**

Temporal variation in the range of proportions of the mean annual flow (MAF) that must be allocated to maintain various levels of habitat quality.

Flow category or habitat quality	Recommended flow (% of MAF)	
	October to March	April to September
Maximum	200	200
Optimum	60–100	60–100
Outstanding	40	60
Excellent	30	50
Good	20	40
Moderately degraded	10	30
Highly to severely degraded	≤10	≤10

Sources: Tennant (1976) and Arthington (2012).

$$e_{ij} = 3600 \times 24 \times n_i \times Q_i \times P_{ij} \quad (5)$$

where EFR<sub>j</sub> ( $\text{m}^3$ ) is the annual environmental flow requirement of a river at fish-habitat quality level  $j$  ( $j=\text{Maximum, Optimum, Outstanding, Excellent, Good, Moderately degraded, and Severely degraded}$ ). There is a temporal variation in the proportion of the mean annual flow (MAF) to maintain different levels of fish-habitat conditions (Table 1).  $e_{ij}$  ( $\text{m}^3$ ) is EFR in month  $i$  at habitat quality level  $j$ ,  $n_i$  is the number of days in month  $i$ ,  $Q_i$  ( $\text{m}^3/\text{s}$ ) is the mean daily flow in month  $i$  (calculated by the APEX model), and  $P_{ij}$  (%) is the percentage of the mean annual flow in month  $i$  at habitat quality level  $j$  (Table 1).

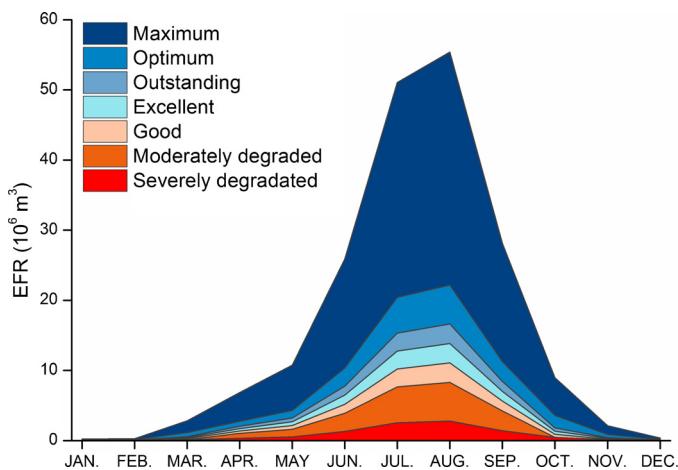
The Tennant (1976) method (also known as the "Montana" method) relies solely on the recorded or estimated river flow regimes to calculate EFR (Jowett, 1997; Arthington, 2012). The method is rapid, inexpensive, and easy to use. It is the most frequently used hydrological method to assess the habitat quality and the associated EFR in different areas of the world (Ubertini et al., 1996; Tharme, 2003; Smakhtin et al., 2006; Kumara and Srikantaswamy, 2011; Arthington, 2012; Pastor et al., 2014). In China, the Tennant method and the recommended EFRs for different levels of habitat qualities have been found also applicable in many regions, including in the arid and semi-arid regions (Xia et al., 2006; Jiang et al., 2006; Wang et al., 2013; Men et al., 2014). In this study, we quantified different levels of EFR to maintain the respective levels of habitat quality defined in the Tennant method. We paid particular attention to the proportion of BWR required to maintain a "good" level of habitat quality as the acceptable EFR. Below it, the habitat quality is in degraded status.

### 2.5. Blue water and gray water footprints

The BWF represents the consumptive use of surface and ground water (Hoekstra et al., 2011). To calculate BWF for the Huangqihai River Basin, we first calculated the BWF of each sector in this region by multiplying the water withdrawal by a water consumption ratio (i.e., the proportion of water consumption to total water withdrawal). This is because that part of the water withdrawal is return flow; it is not really "consumed" but returns to the river systems and can be reused by downstream users (Cai et al., 2003; Anisfeld, 2010; Hoekstra et al., 2012). No specific data were available for the water consumption ratios for the basin. We therefore used the overall water consumption ratios of three sectors for Inner Mongolia in the present study: 63% for agriculture, 62% for industry, and 69% for domestic sector. These ratios were obtained from the Inner Mongolia Water Resources Bulletin (<http://www.nmgslw.gov.cn/info/infoView.jsp?idcontent=18405>).

GWF can be calculated using a general approach proposed by Hoekstra et al. (2011):

$$\text{GWF} = L/(C_{\text{max}} - C_{\text{nat}}) \quad (6)$$



**Fig. 2.** Different levels of total environmental flow requirement (EFR) in the Huangqihai River Basin. Habitat quality levels correspond to the flows shown in Table 1.

where GWF ( $\text{m}^3$ ) is the gray water footprint,  $L$  ( $\text{kg}/\text{yr}$ ) is the pollutant load,  $C_{\max}$  ( $\text{mg}/\text{L}$ ) is the maximum acceptable concentration of the ambient water quality, and  $C_{\text{nat}}$  ( $\text{mg}/\text{L}$ ) is the natural pollutant concentration in the receiving water body. When natural concentrations are not known, one can assume  $C_{\text{nat}} = 0$  (Hoekstra et al., 2011). In this study, we assumed  $C_{\text{nat}} = 0$  due to data lacking. Using a value of 0 represents a conservative approach, since it increases the likelihood that sufficiently large environmental flows will be released to dilute the target pollutants to acceptable levels.

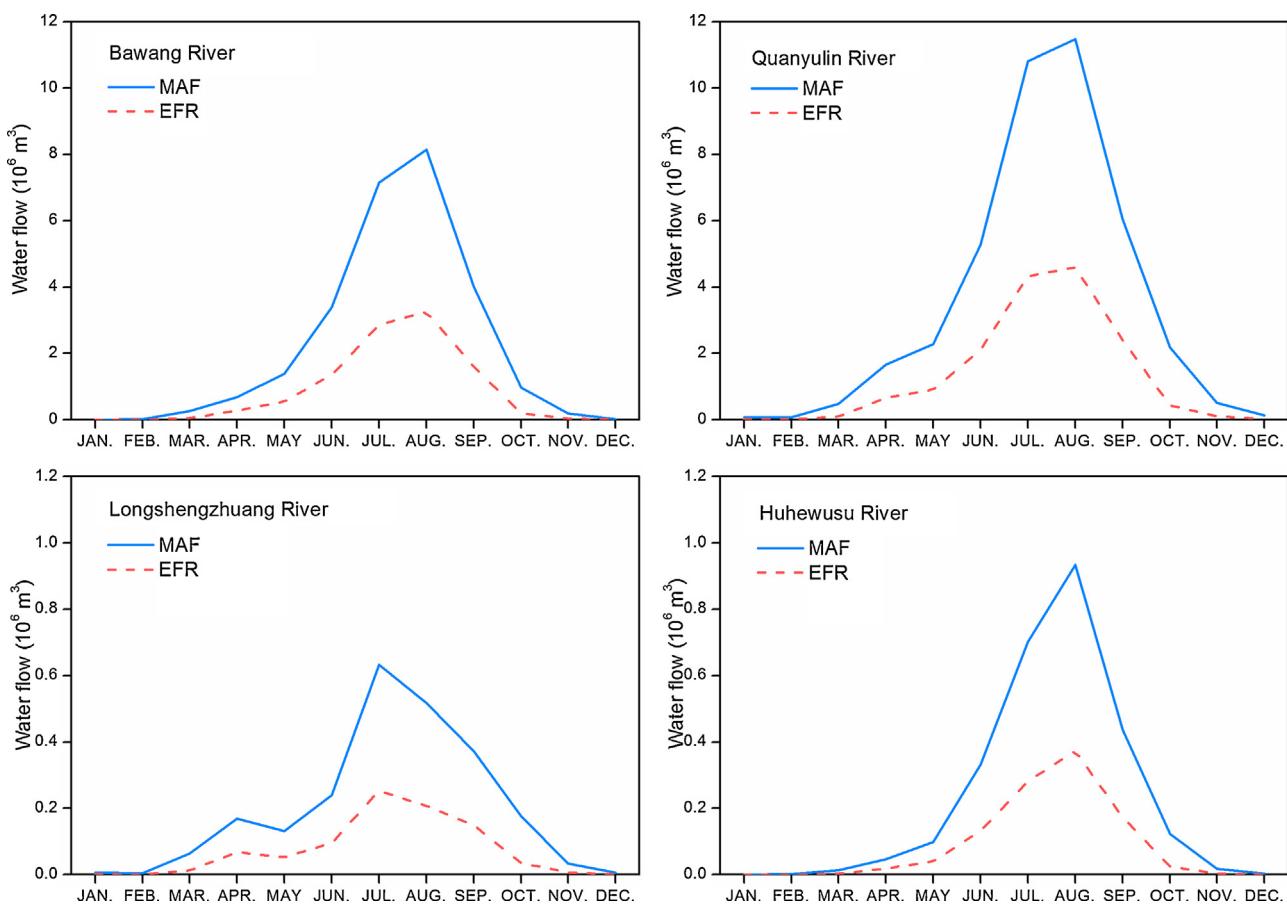
We calculated GWF for the farming, livestock, domestic rural consumption, domestic urban consumption, and industrial sectors. Chemical oxygen demand (COD) is the largest pollution factor in wastewater from the domestic and industrial sectors, and nitrogen is the major pollutant in the farming and livestock sectors (Zeng and Liu, 2013). To account for GWF, we selected COD as the main domestic and industrial pollutant, and total nitrogen as the main farming and livestock pollutant in the basin's water bodies. Based on the China's *Environmental Quality Standards for Surface Water* (MEPC, 2002), water quality is categorized into five grades, in which Grade III indicates that the water is suitable for fishing, aquaculture, and swimming; higher grades (IV and V) indicate poor water quality. Grade III was used to calculate GWF with a  $C_{\max}$  of 20 mg/L for COD and a  $C_{\max}$  of 1 mg/L for total nitrogen, following Zeng et al. (2013).

Data for water withdrawals and pollutant loads in 2010 for the five sectors considered were obtained from the planning report "Protection and Recovery Plan of Huangqihai Wetland" (Li et al., 2013), published by the Chinese Research Academy of Environmental Sciences.

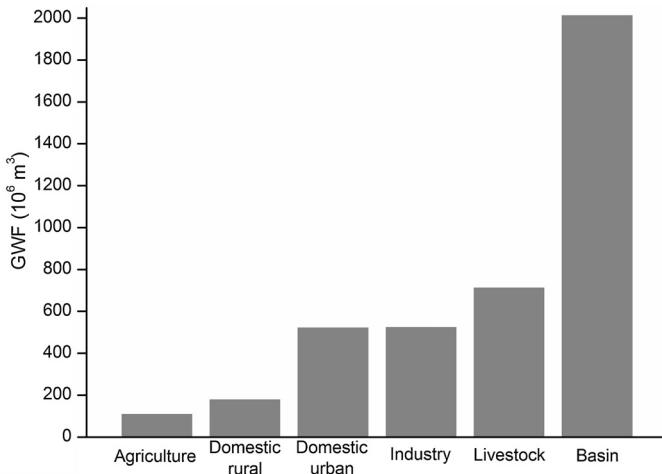
### 3. Results

#### 3.1. BWR and EFR

The annual BWR in the Huangqihai basin totaled  $144 \times 10^6 \text{ m}^3/\text{yr}$ . The river flows were concentrated between April and September, accounting for 92.6% of the total annual flow. From October to March, there were almost no flows in many rivers. The annual flow of the Bawang and Quanyulin rivers located in the



**Fig. 3.** Environmental flow requirement (EFR) and mean annual flow (MAF) for the four main rivers in the Huangqihai River Basin; EFR represents the recommended flow for the "good" level defined in Table 1.



**Fig. 4.** The gray water footprint (GWF) in the *Huangqihai River Basin*.

northern basin was more than 10 times the flow of the Huhewusu and Longshengzhuang rivers located in the southern basin (Fig. 1).

Our analysis showed that EFR in the basin ranged from  $170 \times 10^6 \text{ m}^3/\text{yr}$  to  $8 \times 10^6 \text{ m}^3/\text{yr}$  in association with the maximum to severely degraded habitat conditions defined in the Tennant method (Fig. 2). To keep the rivers' habitat health at a "good" level, at least  $37 \times 10^6 \text{ m}^3$  of water should be left in the rivers, which was equivalent to 26% of the total BWR. This means that, on average, over one quarter of BWR is required to sustain a healthy habitat of the rivers within the basin.

We also quantified the monthly mean flows and EFR at a "good" habitat health level for the four main rivers in the basin (Fig. 3). The total annual EFR at a "good" level was  $10 \times 10^6 \text{ m}^3/\text{yr}$  for the Bawang River,  $15 \times 10^6 \text{ m}^3/\text{yr}$  for the Quanyulin River,  $1 \times 10^6 \text{ m}^3/\text{yr}$  for the Huhewusu River, and  $0.9 \times 10^6 \text{ m}^3/\text{yr}$  for the Longshengzhuang River.

### 3.2. BWF and GWF

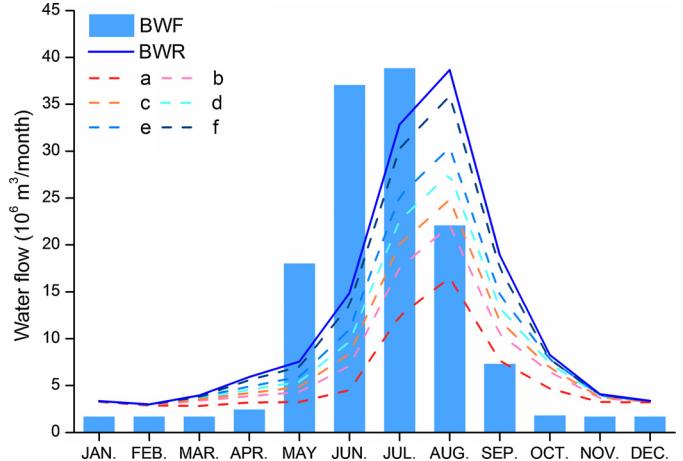
The BWF of the Huangqihai River Basin was  $135 \times 10^6 \text{ m}^3/\text{yr}$  in 2010, which was equivalent to about 94% of the BWR. Among the socioeconomic sectors, the BWF of the farming and livestock sectors accounted for 85% of the total ( $116 \times 10^6 \text{ m}^3/\text{yr}$ ). The BWF of the industry sector was  $9 \times 10^6 \text{ m}^3/\text{yr}$  (7% of the total), and rural and urban domestic sectors account for  $11 \times 10^6 \text{ m}^3/\text{yr}$  (8% of the total).

The total GWF in the basin was  $2.05 \times 10^9 \text{ m}^3/\text{yr}$  in 2010, which was 14.2 times the total BWR (Fig. 4). The highest GWF was from livestock,  $713 \times 10^6 \text{ m}^3/\text{yr}$ , followed by industry and domestic urban consumption,  $525 \times 10^6 \text{ m}^3/\text{yr}$  and  $523 \times 10^6 \text{ m}^3/\text{yr}$ , respectively. The GWF of the three sectors accounted for 86% of the total GWF.

### 3.3. Water scarcity assessment

The  $S_{\text{quantity}}$  and  $S_{\text{quality}}$  for the Huangqihai River Basin were estimated at 1.3 and 14.2, respectively. Both were above the threshold of 1.0, suggesting that the basin suffered from both water quantity scarcity and water quality scarcity. The overall water scarcity indicator,  $S_{\text{qqe}}$ , is thus  $1.3(26\%)|14.2$ .

We compared the BWF, BWR, and different levels of blue water availability on a monthly basis (Fig. 5) to identify quantity-induced water scarcity in each month. During a year, the basin suffers from quantity-induced water scarcity problem mainly in three months, i.e., May, June, and July (in all the three months BWF is even higher



**Fig. 5.** The blue water resource, blue water footprint and blue water available at different habitat level in the Huangqihai River Basin. The bar shows the blue water footprint, the solid line is the blue water resources, the dotted lines are blue water available for human use after accounting for EFR at different habitat level: (a) Optimum, (b) Outstanding, (c) Excellent, (d) Good, (e) Moderately degraded, (f) Severely degraded. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

than the BWR). Although precipitation and runoff are high in the growing season, water resources cannot meet water demand of the economic sectors, in particular the irrigation water demand. In other months,  $S_{\text{quantity}}$  is mostly below 1.0 when the EFR is met to maintain a "good" level of habitat quality. The basin does not have water quantity induced water scarcity in these months.

## 4. Discussion

### 4.1. Advantages and limitations of the QQE water scarcity indicator

The QQE water scarcity indicator developed in this study provides an easy to obtain and to understand measurement that contains the information of water quantity and quality status, as well as EFR. Although the case study is conducted in an arid and semi-arid area in China, the procedure can be adapted to any other areas in the world to provide a comprehensive assessment on water scarcity.

For the Huangqihai River Basin, the QQE water scarcity is  $1.3(26\%)|14.2$ . By default, the value in the bracket indicates that 26% of the total BWR of the basin is required, i.e., EFR, for maintaining the ecological habitat status at the 'good' level. By specification, one can also use the percentage of EFR to indicate any other levels of ecological habitat status.

Introducing the WF concept in the water scarcity assessment allows for accounting of the actual water consumption of local water resources as well as the ability to control water pollution. The  $S_{\text{quantity}}$  of 1.3 in the basin indicates that the water consumptive use in the economic sectors amounts to 1.3 times of blue water availability of the basin when the EFR is met for maintaining the good ecological habitat condition. The basin is therefore enduring severer quantity induced water scarcity. The  $S_{\text{quality}}$  of 14.2 indicates that 14.2 times of BWR would be needed to dilute the polluted water to meet the water quality standard for general use. With such a high value of  $S_{\text{quality}}$ , it can be expected that in many areas in the basin, the water is too polluted to be used for any purpose. A mere reduction of human water uses would not immediately mean a reduction of the water scarcity in the basin due to the remaining water pollution effects.

Despite the advantages specified above, the QQE indicator does have some limitations. It remains a rule of thumb indicator, as the other existing indicators, instead of a precise measurement. It is more suitable to be used for a quick and approximate assessment of water scarcity status on large scales and for obtaining general information on variations across regions. For detailed assessment, more specific local factors, such as technology, rainfall patterns and economic structure, have to be taken into consideration.

Unable to incorporate green water resources is a major limitation of the QQE indicator. This is also the problem in all the existing water scarcity indicators. Incorporating green water resources in water scarcity assessment is a challenge faced with the relevant scientific communities (Hoekstra et al., 2012). Another demerit of the QQE indicator is related to its hybrid nature, which contains three individual, through linked, components. The indicator is not as straight forward as the existing indicators, which use a single value to indicate the status of water scarcity. It requires some professional knowledge to understand the indicator and interpret the information contained. Furthermore, as the value of  $S_{\text{quantity}}$  is linked with the EFR, which is tied with the level of ecosystem habitat health, a comparison of QQE across regions would not be appropriate when the habitat health is set at different levels.

#### 4.2. Environmental flow requirement

Like all other models, uncertainties are inevitable in the results. In the simulation of the hydrological processes with the APEX model, the calibrated model differed from the observed flows by up to 11%. It would be reasonable to increase the estimate of 26% by 11% (i.e., to 29%) to provide a safety margin that would ensure the needs of the environment are met. This finding is similar to the results of Smakhtin et al. (2004), who calculated the EFR in northern China and obtained values of 25–30% of the total BWR. Both this study and Smakhtin et al. (2004) showed that the EFR is generally no more than 30% of the total BWR in northern China.

The EFR calculated in this study is much lower than the assumption of 80% proposed by Hoekstra et al. (2012) and adopted by Zeng et al. (2012). If we had used the percentage of Hoekstra et al. (2012) for EFR, the basin would have faced a much higher level of  $S_{\text{quantity}}$  with all months having serious water scarcity, especially in May ( $S_{\text{quantity}} = 11.9$ ) and June ( $S_{\text{quantity}} = 12.4$ ). It is likely that the assumption of 80% overestimates EFR, and will lead to an overestimate of the quantity-based water scarcity problem.

Setting different levels of habitat quality will influence the percentage of EFR in total BWR, as well as the value of water scarcity indicator. As shown in our study, when the ecosystem health is prioritized and river habitat is required to be maintained at an “optimum” level, 40% of BWR is required to meet EFR (Fig. 5). Consequently, the  $S_{\text{quantity}}$  will be over 2.0(40%). When the river habitat is at a “severely degraded” level, no more than 7% of BWR will be allocated to river ecosystems. The available water resources in the basin can almost meet human’s economic use ( $S_{\text{quantity}} = 1.0(7\%)$ ). Suppose the river ecosystem health is completely ignored, and the river runs dry, the  $S_{\text{quantity}}$  will be 0.94(0%). In this case, there will be no water scarcity for humans, but this will result in losing almost all of natural habitat and biological assemblages. The basic ecosystem functions will be destroyed (King et al., 2000). This will eventually make the region inhabitable for humans.

#### 4.3. Reducing the water scarcity in the Huangqihai River Basin

With the ongoing urbanization and economic development in the region, the domestic and industrial water supply has been

increasing continuously. The increased water demand has been met mainly with overexploitation of groundwater. It has resulted in a serious decline in the groundwater table, and some areas surrounding the Huangqihai Lake have developed cones of depression (Li and Wang, 2008). Such a trend cannot last for long because the overexploitation will eventually lead to exhaustion of available groundwater resources.

Given the fact that the irrigation accounts for 61% of the water use, while the contribution of the farming sector to the regional GDP is only 10%, a reduction of irrigation water use would be one of the options that the region should pursue. Based on this study, suppose a reduction of 20% of irrigation water use, 36 million m<sup>3</sup> of water would be released. The reduction would allow for the meet of the water uses for other economic sectors as well as the EFR. The reduction of GDP would be only about 2%.

Water pollution is another important cause of water scarcity. As the livestock and industrial sectors are major sources of water pollution in the basin, stringent control on the pollution discharge in these two sectors can significantly reduce the pollution load and consequently ease the water quality induced water scarcity. This is particularly so for the livestock sector whose pollution is typically diffused and hence difficult to be dealt with by centralized wastewater treatment plants. Limiting the expansion of livestock production in the basin is therefore important. Currently, the overgrazing and degradation of pastoral land are serious, which impose negative effects on the BWR availability in the basin (Li et al., 2013). Reducing the pressure on pastoral land is therefore also conducive for water conservation and making more BWR available for use.

#### 4.4. Shortcomings of this study

We would like to point out some shortcomings relating to the lack of data for the water scarcity assessment in the Huangqihai River Basin. The Tennant method was used to calculate the EFR mainly because it can be applied with only hydrological data. The Tennant method may have not been able to capture all the hydrological and ecological characteristic of the river system, leading to uncertainties in the estimation of the EFRs for the different levels of habitat qualities in this study.

When calculating BWF, we used the water consumption ratios of Inner Mongolia due to the lack of specific data in the studied area. This may lead to errors. But when local water managers were interviewed, they believed the ratios in the Huangqihai basin were not much different from the average in Inner Mongolia.

We only present results for one specific year mainly because water quality data were only available for one year (2010). This does not allow us to provide an analysis for multiple years and observe the changes. It is clear that the value of the QQE water scarcity indicator changes with the fluctuation of rainfall (and hence BWR each year). An average over a few years or for a year with normal rainfall would be more appropriate to represent a general status of water scarcity. For this reason, in calculating the QQE water scarcity indicator for the Huangqihai basin, we actually used the average BWR and EFR for the period 1982–2011. This caused a slight time inconstancy. We calculated the QQE with BWR and EFR for the year 2010 and found only minor differences with the QQE values reported in this study (because the BWR in 2010 was close to the average BWR during the period 1982–2011).

Local data on natural background concentration are not available. When calculating GWF, we assumed natural pollutant concentration to be zero. This may not be realistic because nitrogen exists in the natural water bodies. The assumption may overestimate the assimilation capacity for chemical substance, and underestimate GWF, but such an underestimation is believed to be marginal and will not largely influence the assessment results

(Hoekstra et al., 2011). For example, Franke et al. (2013) suggested using background concentration of Ammonium N-NH<sub>4</sub> of 0.015 mg/L following Chapman (1996). By using this background concentration in our study, the re-calculated GWF is only 1.5% higher than the current estimate. Hence, assuming a value of zero for natural background concentration will only lead to very small errors.

## 5. Conclusion

In this study, we proposed an approach to assessing water scarcity by considering both water quantity and water quality, while also explicitly accounting for the EFR. We used this method in the Huangqihai River Basin in China. We demonstrated that the QQE indicator can provide a more comprehensive picture of water scarcity status for a basin under the given levels of water uses in economic sectors, EFR and water pollution. For the Huangqihai River Basin, the results show that the basin is currently suffering from both quantity- and quality-induced water scarcity problems. The EFR for maintaining the good ecological status cannot be met in some months during a year. The very high value of quality related water scarcity index suggests that water pollution plays a big role in causing the water scarcity in the river basin. This implies that only focusing on reducing water use may not help significantly alleviate the water scarcity situation. Instead, a special attention has to be paid to reducing water pollution and encouraging water conservation. The QQE approach provides a general method to assess water scarcity, and it could be applied in other regions where both the hydrological and ecological data are scarce.

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