Using an improved interval technique for order preference by similarity to ideal solution to assess river ecosystem health

Wei Xu, Zengchuan Dong, Li Ren, Jie Ren, Xike Guan and Dunyu Zhong

ABSTRACT

A river ecosystem health (REH) assessment system, based on indicators for morphological form, hydrology features, aquatic life, and habitat provision was established to characterize REH. The standard interval Technique for Order Preference by Similarity to Ideal Solution method (TOPSIS) does not fully consider dynamic changes in REH, so interval numbers and the mean were introduced into an improved version of TOPSIS to achieve a more objective analysis. The improved interval TOPSIS method was tested in the Zhangweinan River and a river ecosystem health integrated index (*REHI*) was calculated. The *REHI* decreased from 0.376 to 0.346 over the past 25 years and the REH ranged from general to poor for 1991 to 1995 and from poor to very poor for 1996 to 2000, 2001 to 2005, 2006 to 2010, and 2011 to 2015. The ecosystem health is poor because of dams and reservoirs in the upper reaches that prevent water flowing to the lower reaches, over-abstraction of water, and severe pollution. This method gives objective and accurate assessments of REH and can be used to support decision-making and evaluation in a range of fields.

Key words | health assessment, interval number, mean number, river ecosystem, TOPSIS

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INTRODUCTION

A healthy river generally provides a range of functions including water supply, nutrient cycling, irrigation, transport, fisheries, hydro-electric power generation, recreation, biodiversity, and habitat (Deng *et al.* 2015; Speed *et al.* 2016). Humans have taken advantage of the provisioning functions of rivers by developing hydropower and exploiting the water resources, but have largely ignored their ecological functions (Ahn & Merwade 2014; Dong *et al.* 2014; Mittal *et al.* 2015). Water conservancy projects, such as dams, sluice gates, and water diversion schemes, have played a huge role in providing water, generating hydropower, and controlling floods (Speed *et al.* 2016). However, these schemes have also intensively altered the natural hydrological regime of rivers, causing discontinuity in stream flow and upsetting sediment flux regimes (Malveira *et al.* 2012; Yu *et al.* 2013). Other irrational human activities, such as wastewater discharges, development of river floodplains, and overexploitation of groundwater resources, have contributed either directly or indirectly to ecological problems in river systems such as contamination, shrinkages of natural wetlands, declining groundwater tables, stream betrunking, and the loss of endemic biodiversity. Various human activities have therefore transformed the natural state of rivers, and have caused serious degradation of river ecosystems (Xu *et al.* 2017).

Nowadays, river ecology receives more attention worldwide than at any time in history (Maddock 1999; Noble *et al.* 2007; Chen *et al.* 2016), and the restoration and maintenance of healthy river ecosystems has been adopted as a management objective for governments. The concepts of environmental flows (EF) (Brisbane Declaration 2007) and river ecosystem health (REH) (Oeding & Taffs 2015),

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introduced in recent decades, have formed the basis of river ecosystem assessments, carried out by environmental scientists and ecologists to determine the state of, and improve, river health. To provide good river habitat for aquatic organisms, the EF can be estimated using either a hydrological-, hydraulic-habitat-, or biological-based approach (Arthington 1998; Tharme 2003; Petts 2010; Linnansaari *et al.* 2012). Similarly, to evaluate river water quality, many mathematical approaches, typically based on physical, chemical, and biological indicators, have been proposed (Richter *et al.* 1996; Luo *et al.* 2018). At present, methods commonly used to assess river health include: (a) the Biotic Integrity Index (IBI) (Karr 1981), (b) the Range of Variability Approach (RVA) (Richter *et al.* 1996), (c) the Algae Abundance Index (AAI) (Munne & Prat 2004), (d) the River Invertebrate Prediction and Classification System (RIVPACS) (Daniel *et al.* 2006), (e) the Integrated Habitat Assessment System (IHAS) (Ollis *et al.* 2006), and (f) the River Health Integrated Index (RHI) (Xu *et al.* 2017). These methods are all based on indicators with values that are mean numbers. In reality however, REH is a dynamic concept and the indicators used to assess it fluctuate within a range. Because the maximum or minimum values and the variation of a given indicator also affect the health stability of river ecosystems, their values should be considered as intervals. In 2006, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) with interval data was first proposed by Jahanshahloo *et al.* (2006) and has been applied to numerous multi-criteria decision-making problems. The algorithm of this technique only considers the maximum and minimum values of the indicators. However, the standard interval TOPSIS method is not suitable for assessing river ecosystems, because it does not adequately consider the influence of dynamic changes in REH. River indicators in different REH states may have the same maximum and minimum values. This problem could be avoided by combining the mean and the interval (maximum and minimum), as the mean reflects different river ecosystem states. For the purposes of this study, the mean is the arithmetic mean of all the values of an indicator over the evaluation period, and is not the arithmetic average of the maximum and minimum values.

As a large nation with a rapidly growing economy, ecological problems in China are receiving increasing attention at the national level. The Zhangweinan River in China is one of five major river systems of the Haihe River and has an important role in the development of Northern China. In recent decades, with climate change and overexploitation of water resources, the runoff of the Zhangweinan River has decreased considerably. There is widespread concern about this river, as the water quality is very poor and many reaches of the river have lost ecosystem functionality, with implications for the ongoing growth in the region. China's Five-Year Plans provide important guidance for basic tasks and outline the principles for the nation's economic and social development; they include policies and plans for population growth, resources, environment, and major water engineering works that correspond with the different stages of the country's development (Zhang 2016; Zhang *et al.* 2018). As such, each river basin has its own five-year plan. In this study, the REH of the Zhangweinan River was evaluated for different time periods, namely, 1991–1995, 1996–2000, 2001–2005, 2006–2010, and 2011–2015, and the interval and mean of each indicator were included in the evaluation. It is quite difficult to access the actual REH status from the combination of the mean and the interval. To solve this problem, a river ecosystem health integrated index (*REHI*) that incorporated the proposed improved interval TOPSIS model was developed. The Zhangweinan River was selected as an example, and the *REHI* was calculated for the five periods mentioned above. Reasons for the variations in the index values for the Zhangweinan River were discussed and some measures were proposed to improve the river. The new improved interval TOPSIS method and the conventional standard interval TOPSIS were also compared. This improved method should be useful for monitoring changes in river ecological status to support sustainable management.

MATERIAL AND METHODS

Study area

The Zhangweinan River System, which consists of the Zhang River, Wei River, Wei Canal, and Zhangweixin River, is one of five major river systems within the Haihe River Basin. Approximately 932 km long, it flows northeastwards through Shanxi, Henan, Hebei, and Shandong Provinces and discharges into the Bohai Sea (Figure 1). The drainage area of the Zhangweinan Basin is 37,700 km^2, of which, 67.5% is mountainous terrain (25,436 km^2) and the remaining 32.5% is plains (12,264 km^2).

The Zhangweinan Basin has a temperate semi-humid monsoon climate. There is significant variation in the mean precipitation among the different seasons and, for example, precipitation during winter accounts for only 2% of the total annual precipitation, while that in summer, especially in July and August, accounts for around 75%. The water resources of this basin are therefore unevenly distributed, both spatially and temporally, and there are conflicts between economic development and water demand. To solve the water shortage problems, 281 reservoirs have been constructed in the upper reaches of the Zhang and Wei Rivers since the end of the 1950s. The largest of these reservoirs, the Yuecheng, with a usable capacity of 1.09×10^9 m^3, was built on the main stream of the Zhang River in 1961 (Figure 1). The average inflow of the Yuecheng Reservoir is 7.6×10^8 m^3, and the water in this reservoir meets the domestic, industrial, and agricultural demand in Anyang and Handan, in Henan and Hebei Provinces, respectively. To increase the crop yield, water for agricultural use in Anyang and Handan is delivered through the Zhangnan Channel and the Minyou Channel, respectively (Wang *et al.* 2016). The natural ecological processes of the river have been severely altered because no ecological protection measures were incorporated in the reservoir design and construction, and the ecological state was not investigated, monitored, or protected. For instance, the reservoir construction changed the hydrological condition of the basin and the spawning and migration paths of fishes were blocked by the dams. Most noticeable however, is the fact that, by establishing the reservoirs and inter-basin water diversion projects, the river flow has deteriorated such that it dries up, causing degradation of river ecological function and biodiversity loss. Because of the rapid economic development and population growth in the area, untreated polluted water is increasingly conveyed directly into Bohai Bay via the Zhangweixin River, and water conflicts in the sections that cross provincial boundaries have become a serious social problem. For example, there are water shortages at various levels in some 500 villages in Wuqiao

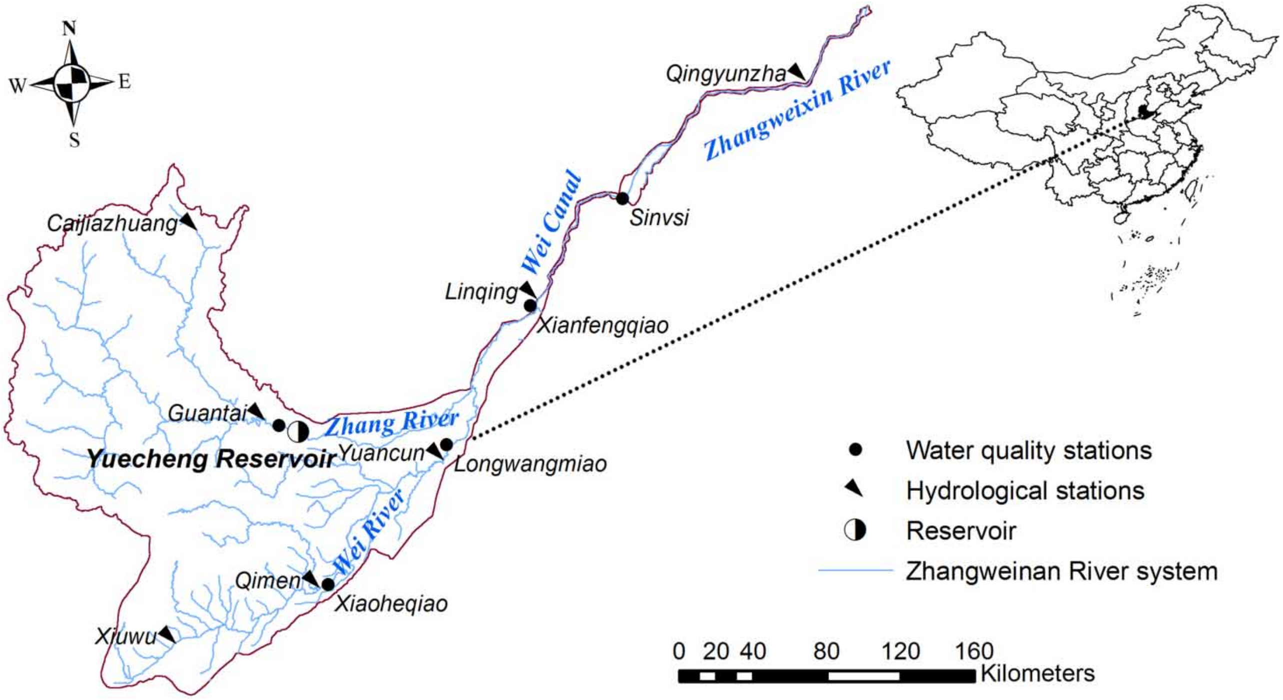

Figure 1 | Sketch of Zhangweinan River.

County, Hebei Province, such that about 1.9×10^5 people do not have adequate drinking water and agricultural production is well below its potential. Therefore, an important objective of basin management is to solve such trans-jurisdictional water conflicts (Wang *et al.* 2013). Since the 1980s, primarily because of the rapid urbanization across this region, the ecological and environmental problems have become worse, as reflected by the shrinking river, water pollution, flooding disasters, and biodiversity loss. Previously, the hydrology, environment, and human activities in the Zhangweinan River have been studied, but there have been few assessments of ecosystem health (Wang *et al.* 2013; Fu *et al.* 2015). To improve the environment in this basin, the river ecosystem condition assessment is particularly important and the factors that influence REH need to be identified.

Assessment indicator system

The mechanisms that drive the variation of river ecosystems are complex. A healthy river ecosystem has a variety of ecological functions, such as landform evolution, material transport, climate regulation, water purification, biodiversity conservation, and habitat provision, which should be considered when developing an indicator system to assess REH. In this study, the Indicators of Hydrologic Alteration (IHA) (Mathews & Richter 2010) were adopted and the indicators that were recommended in Shandong Provincial Evaluation Standard for Ecological River (DB 37/T 3081-2017) and the Guidelines for Rivers and Lake Health Assessment by China's Ministry of Water Resources were sought by the opinions' of experts and local stakeholders to ensure the indicator system was scientifically robust and fit for purpose, i.e., capable of adequately describing the river system.

In this study, the indicator system for the Zhangweinan River's ecosystem health comprised four items, namely, morphological form (B1), hydrological features (B2), aquatic life (B3), and habitat provision (B4). These four items are interdependent and interactive and describe the different ecological processes in the river (Table 1).

Table 1 | REH assessment indicator system

Items	Indicator layer
Morphological form (B1)	Lateral stability index (C1) Density of river-crossing structures (C2) Achievement rate of bank-protection works (C3) Rate of sediment transport changes (C4)
Hydrology features (B2)	Rate of monthly water condition changes (C5) Rate of magnitude and duration of annual extreme water condition changes (C6) Rate of timing of annual extreme water condition changes (C7) Rate of frequency and duration of high and low pulses changes (C8) Rate and frequency of water condition changes (C9) Rate of estuary runoff changes (C10) Wetland preservation rate (C11)
Aquatic life (B3)	Phytoplankton Shannon index (C12) Zooplankton Shannon index (C13) Fish species integrity index (C14) Benthic fauna integrity index (C15) Macrophytes integrity index (C16)
Habitat provision (B4)	Water quality compliance index (C17) Rate of water loss and soil erosion (C18) Vegetation index (C19)

Changes in river morphological form depend directly on rebuilding activities, such as erosion, transportation, and deposition. Therefore, the related river ecological processes are mainly manifested by exchanges between the water body and the riparian zone and may be represented by riverbank stability, connectivity with nearby waterbodies such as lakes and marshes, habitat integrity, fish pathways, and river-crossing structures that impede the migration of aquatic organisms (Zhao & Yang 2009). The (a) lateral stability index (C1), (b) density of river-crossing structures (C2), (c) achievement rate of bank-protection works (C3), and (d) rate of sediment transport changes (C4) can represent the morphological form.

From a hydrological point of view, many more hydrological alteration parameters need to be taken into account (e.g., frequency, duration, timing of events, alteration on flood occurrence and magnitude, etc.), which inherently reflect the distribution of precipitation across the drainage basin and the degree of disturbance by human activities. Thus, all the five IHA parameter groups that include (a) rate of monthly water conditions changes (C5), (b) rate of magnitude and duration of annual extreme water conditions changes (C6), (c) rate of timing of annual extreme water conditions changes (C7), (d) rate of frequency and duration of high and low pulses changes (C8), and (e) rate and frequency of water condition changes (C9) were adopted. Besides, estuary runoff and wetlands are also essential for aquatic organisms, control physical processes and biochemical reactions in the water body, and change frequently with variations in the runoff. Therefore, the hydrological features also include (f) rate of estuary runoff changes (C10) and (g) the wetland preservation rate (C11).

The aquatic life condition describes the overall condition of the river ecosystem, and reflects perturbations caused by human activities, such as dam construction and wastewater emissions. The aquatic life condition can be expressed with indicators such as the (a) Shannon phytoplankton index (C12), (b) Shannon zooplankton index (C13), (c) fish species integrity index (C14), (d) benthic fauna integrity index (C15), and the macrophytes integrity index (C16).

Water quality is the fundamental basis for biological life in aquatic systems. The water quality compliance index (C17) is an important indicator of habitat provision. The riparian zone also plays an important role in maintaining regional biodiversity, accelerating the exchange of material and energy, resisting flow erosion and infiltration, and filtering and absorbing nutrients. However, natural riparian zones have been disturbed by land use change, variations and disturbances in the hydraulic regime, and the destruction of landscape gradients. Habitat provision can therefore be expressed by the rate of water loss and soil erosion (C18) and the vegetation index (C19).

For the pressure–response relationship between the indicator and the REH state, the indicators can be classified into two types, namely, those with benefits (as the indicator value increases, the health of the river ecosystem also increases) and those with costs (as the indicator value decreases, the health of the river ecosystem increases). Of the 19 indicators described, C1, C2, C4, C5, C6, C7, C8, C9, C10, and C18 belong to cost type, and the other 9 belong to benefit type.

REH criteria

The criteria for REH have been studied for more than ten years. The criteria for this study were decided after considering previous studies, and checking the availability of long-term runoff data and environmental monitoring data for the Zhangweinan River Basin (Zhao & Yang 2009; Qin *et al.* 2014; Song *et al.* 2015; Xu *et al.* 2017). The standard values included the maximum, mean, and minimum value of each indicator in each grade. The REH was divided into five categories (Xia *et al.* 2014), shown in Table 2 and described below.

1. Excellent: Human activities have had a negligible impact on the river condition. Biological species are abundant and uniformly disturbed. The river ecosystem structure is stable, and its services are diverse.
2. Good: The river characteristics are normal, and the biodiversity and ecosystem structure are stable. The main ecosystem's services are functioning and the pressure from human activities is within the ecosystem's capacity.
3. General: The river characteristics are somewhat disturbed, and the biodiversity and ecosystem structure have been altered to some extent. The pressure of human activities on the river ecosystem exceeds the ecosystem's capacity but the ecosystem still demonstrates the ability to recover.
4. Poor: The natural characteristics of the river have been disturbed by human activities, and the species composition and ecosystem structure have been drastically altered. Ecosystem services are in decline. The stress of human activities has overwhelmed the ecosystem's capacity, resulting in instability.
5. Very poor: The natural characteristics of the river have been severely disturbed by human activities and the number of biological organisms is low. Key ecosystem functions have been lost, and the ecosystem is extremely unstable.

Improved interval TOPSIS assessment model

TOPSIS is a very practical technique for dealing with multi-objective decision-making problems (Ren *et al.* 2014). In a standard interval TOPSIS model, the concept that is relatively close to the measurements is adopted, and the processing method mainly focuses on the maximum and minimum numbers of the indicator (Jahanshahloo *et al.* 2006). In many practical problems, however, such as assessments of river health, the mean also has an important effect

Table 2 | Classification of the standard values of the assessment indicators

Indicator layer	Excellent	Good	General	Poor	Very poor
C1	[0,0.1,0.2]	[0.2,0.3,0.4]	[0.4,0.5,0.6]	[0.6,0.7,0.8]	[0.8,0.9,1]
C2	[0,0.1,0.2]	[0.2,0.3,0.4]	[0.4,0.5,0.6]	[0.6,0.7,0.8]	[0.8,0.9,1]
C3	[0.8,0.9,1]	[0.6,0.7,0.8]	[0.4,0.5,0.6]	[0.2,0.3,0.4]	[0,0.1,0.2]
C4	[0,0.025,0.05]	[0.05,0.125,0.2]	[0.2,0.3,0.4]	[0.4,0.5,0.6]	[0.6,0.8,1]
C5	[0,0.025,0.05]	[0.05,0.075,0.1]	[0.1,0.15,0.2]	[0.2,0.3,0.4]	[0.4,0.7,1]
C6	[0,0.025,0.05]	[0.05,0.075,0.1]	[0.1,0.15,0.2]	[0.2,0.3,0.4]	[0.4,0.7,1]
C7	[0,0.025,0.05]	[0.05,0.075,0.1]	[0.1,0.15,0.2]	[0.2,0.3,0.4]	[0.4,0.7,1]
C8	[0,0.025,0.05]	[0.05,0.075,0.1]	[0.1,0.15,0.2]	[0.2,0.3,0.4]	[0.4,0.7,1]
C9	[0,0.025,0.05]	[0.05,0.075,0.1]	[0.1,0.15,0.2]	[0.2,0.3,0.4]	[0.4,0.7,1]
C10	[0,0.025,0.05]	[0.05,0.125,0.2]	[0.2,0.3,0.4]	[0.4,0.5,0.6]	[0.6,0.8,1]
C11	[0.8,0.9,1]	[0.6,0.7,0.8]	[0.4,0.5,0.6]	[0.2,0.3,0.4]	[0,0.1,0.2]
C12	[3,3.5,4]	[2,2.5,3]	[1.5,1.75,2]	[0.5,1,1.5]	[0,0.25,0.5]
C13	[3,3.5,4]	[2,2.5,3]	[1.5,1.75,2]	[0.5,1,1.5]	[0,0.25,0.5]
C14	[0.8,0.9,1]	[0.6,0.7,0.8]	[0.4,0.5,0.6]	[0.2,0.3,0.4]	[0,0.1,0.2]
C15	[0.8,0.9,1]	[0.6,0.7,0.8]	[0.4,0.5,0.6]	[0.2,0.3,0.4]	[0,0.1,0.2]
C16	[0.8,0.9,1]	[0.6,0.7,0.8]	[0.4,0.5,0.6]	[0.2,0.3,0.4]	[0,0.1,0.2]
C17	[0.8,0.9,1]	[0.7,0.75,0.8]	[0.5,0.6,0.7]	[0.25,0.375,0.5]	[0,0.125,0.25]
C18	[0,0.075,0.15]	[0.15,0.2,0.25]	[0.25,0.325,0.4]	[0.4,0.5,0.6]	[0.6,0.8,1]
C19	[0.7,0.85,1]	[0.5,0.6,0.7]	[0.25,0.375,0.5]	[0.1,0.175,0.25]	[0,0.05,0.1]

on the river ecosystem state. Therefore, to expand the applications of this method, an improved interval TOPSIS method that considered both the interval number and the mean was introduced. The basic steps of this improved interval TOPSIS assessment model follow.

1. Suppose that there are m evaluation objects and n assessment indicators, and then the data matrix of the problem is:

$$X' = \begin{pmatrix} x'_{11} & x'_{12} & \cdots & x'_{1n} \\ x'_{21} & x'_{22} & \cdots & x'_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x'_{m1} & x'_{m2} & \cdots & x'_{mn} \end{pmatrix} \tag{1}$$

   In the data matrix, the indicator value is an improved interval number, and the value of the jth assessment indicator of the ith evaluation objects can be expressed as $x'_{ij} = [x^{L'}_{ij}, \bar{x}'_{ij}, x^{U'}_{ij}]$.

2. Of the indicators in Table 1, C1, C2, C4, C5, C6, C7, C8, C9, C10, and C18 belong to cost type, and others belong to benefit type. Before normalizing, the cost indicators were inverted into benefit indicators ($x_{ij} = [x^{L}_{ij}, \bar{x}_{ij}, x^{U}_{ij}]$):

$$x^{L}_{ij} = 1 - x^{U'}_{ij} \tag{2}$$

$$\bar{x}_{ij} = 1 - x'_{ij} \tag{3}$$

$$x^{U}_{ij} = 1 - x^{L'}_{ij} \tag{4}$$

   A new data matrix resulted:

$$X = \begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix} \tag{5}$$

3. The normalization was carried out based on the new matrix. In the standard interval TOPSIS, the processing focuses on the interval number. However, the mean number is also important for the river ecosystem state. Thus, in this study, the normalization considered both

the mean and the interval number, as follows:

$$r_{ij}^{L} = \frac{x_{ij}^{L}}{\sqrt{\sum_{i=1}^{m} x_{ij}^{U2}}} \tag{6}$$

$$\bar{r}_{ij} = \frac{\bar{x}_{ij}}{\sqrt{\sum_{i=1}^{m} \bar{x}_{ij}^{2}}} \tag{7}$$

$$r_{ij}^{U} = \frac{x_{ij}^{U}}{\sqrt{\sum_{i=1}^{m} \bar{x}_{ij}^{L2}}} \tag{8}$$

The normalized matrix was obtained: ($r_{ij} = [r_{ij}^{L}, \bar{r}_{ij}, r_{ij}^{U}]$):

$$R = \begin{pmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{pmatrix} \tag{9}$$

4. In order to analyze the health status of river ecosystem objectively, the weights of all indicators are equal ($w_i = (1/n)$), and the vector weight was calculated as follows:

$$W = (w_1, w_2, \cdots w_n) \tag{10}$$

5. The weight was multiplied by the normalized matrix to obtain the weighted decision matrix $z_{ij} = [z_{ij}^{L}, \bar{z}_{ij}, z_{ij}^{U}]$.

$$z_{ij} = w_j \bullet r_{ij} \tag{11}$$

6. The ideal solution A^* and the negative ideal solution A^- of the problem were calculated:

$$A^* = [\max z_{ij}^{L},\ \max \bar{z}_{ij},\ \max z_{ij}^{U}] \tag{12}$$

$$A^- = [\min z_{ij}^{L},\ \min \bar{z}_{ij},\ \min z_{ij}^{U}] \tag{13}$$

7. The Euclidean distances from all the objects to the ideal solution and the negative ideal solution were calculated:

$$d_i^* = \sqrt{\sum_{j=1}^{n} d_{ij}^{*2}} \tag{14}$$

$$d_i^- = \sqrt{\sum_{j=1}^{n} d_{ij}^{-2}} \tag{15}$$

where

$$d_{ij}^* = \sqrt{(z_{ij}^{L} - a_j^{L*})^2 + (\bar{z}_{ij} - \bar{a}_j^{*})^2 + (z_{ij}^{U} - a_j^{U*})^2} \\ [a_j^{L*}, \bar{a}_j^{*}, a_j^{U*}] \in A^* \tag{16}$$

$$d_{ij}^- = \sqrt{(z_{ij}^{L} - a_j^{L-})^2 + (\bar{z}_{ij} - \bar{a}_j^{-})^2 + (z_{ij}^{U} - a_j^{U-})^2} \\ [a_j^{L-}, \bar{a}_j^{-}, a_j^{U-}] \in A^- \tag{17}$$

8. The *REHI* was calculated:

$$REHI = \frac{d_i^-}{d_i^- + d_{i*}} \tag{18}$$

According to the derivation process, the *REHI* can also be classified as a benefit, i.e., as the *REHI* increases, the health of the river ecosystem increases.

Data sources

Various data were used in this study, as follows.

Flow data

Daily time series flow discharge (m^3/s) data from 1955 to 2015 at Caijiazhuang, Guantai, Yuecheng Reservoir, Xiuwu, Qimen, Yuancun, Linqing, and Qingyunzha (Figure 1) were obtained from the Haihe River Water Resources Commission (HWRC), China. The homogeneity and reliability of the hydrological data were checked by the HWRC and no data were missing.

Quantity of water entering the sea

The annual estuary runoff ($\times 10^8$ m^3) data from 1955 to 2015 were obtained from the Zhangweinan River Administration (ZA).

Sediment data

The annual suspended sediment concentration (kg/m^3) data from 1955 to 2015 at Caijiazhuang, Guantai, Qimen, Yuancun, and Linqing (Figure 1) were obtained from the

HWRC. The homogeneity and reliability of the sediment data were checked by HWRC and there were no missing data.

Water quality data

Daily water quality monitoring data from 1991 to 2015 and corresponding water quality objectives were obtained for five monitoring stations (Yuecheng Reservoir, Xiaoheqiao, Longwangmiao, Xianfengqiao, and Sinvsi) (Figure 1). The locations and water quality objectives of these monitoring stations were preapproved by the HWRC. Data for six variables were collected, including dissolved oxygen (DO), chemical oxygen demand (COD), ammonia nitrogen (NH_3-N), total phosphorus (TP), arsenic (As), and volatile phenol (VLPH).

Soil and water loss data and vegetation data

Information about vegetation was interpreted from clear TM remote sensing images obtained from the International Scientific Data Service Platform (ISDSP) and data for soil and water losses from 1990 to 2015 were collected from the Haihe Basin Soil and Water Conservation Monitoring Center (HSWCMC).

Aquatic biological data

Information about phytoplankton, zooplankton, fish, benthic fauna, and macrophytes from 1991 to 2015 were collected from the HWRC and Huazhong Agricultural University (HZAU).

In line with the national five-year planning system for economic and social development, the evaluation periods of the index were (a) 1991–1995, (b) 1996–2000, (c) 2001–2005, (d) 2006–2010, and (e) 2011–2015. The values for each period are provided in Table 3.

RESULTS

The results of the evaluated standards and the five periods, calculated as outlined earlier, are shown in Tables 4 and 5, respectively, and the curve of the health of the Zhangweinan River ecosystem from 1991 to 2015 is shown in Figure 2. As shown in Figure 2, the Zhangweinan River's *REHI* dropped from 0.384 to 0.346 over the past 25 years and the ecosystem became more unstable and less healthy. As shown in Table 3, the decrease mainly results from decreases in all the indicators annually, including the density of river-crossing structures, rate of sediment transport changes, rate of monthly water conditions changes, rate and frequency of water condition changes, wetland preservation rate, zooplankton Shannon index, fish species integrity index, and benthic fauna integrity index.

The REH state for the five periods was also obtained by comparing the calculation and evaluation standards, as shown in Table 5 and Figure 2. We found that the river health ranged from general to poor for 1991–1995, and from poor to very poor for 1996–2000, 2001–2005, 2006–2010, and 2011–2015. These results indicate that the river's natural characteristics were disturbed by human activities, which drastically altered the species composition and ecosystem structure. The river ecosystem's capacity was overwhelmed by human activities, the key functions were lost, and the ecosystem was extremely unstable. As shown in Table 3, the indicators including density of river-crossing structures, rate of estuary runoff changes, rate of sediment transport changes, rate of monthly water condition changes, rate of magnitude and duration of annual extreme water condition changes, rate of timing of annual extreme water condition changes, rate of frequency and duration of high and low pulses changes, rate and frequency of water condition changes, wetland preservation rate, fish species integrity index, benthic fauna integrity index, macrophytes integrity index, and the water quality compliance index were poor.

DISCUSSION

Comparison of the improved interval TOPSIS and the standard interval TOPSIS

The REH states for the five periods were also obtained using the standard interval TOPSIS method and are presented as *REHI-c* in Figure 2. This standard method only considers the maximum and minimum. As shown in Figure 2, the

Table 3 | Indicator values for each period

Indicator layer	**Monitoring values**				
	1991–1995	**1996–2000**	**2001–2005**	**2006–2010**	**2011–2015**
C1	[0.3,0.38,0.65]	[0.32,0.50,0.92]	[0.23,0.50,0.7]	[0.31,0.45,0.57]	[0.37,0.42,0.48]
C2	[0.48,0.74,0.99]	[0.25,0.72,0.93]	[0.70,0.89,0.97]	[0.73,0.82,0.89]	[0.83,0.87,0.94]
C3	[0.54,0.55,0.56]	[0.54,0.55,0.56]	[0.56,0.57,0.58]	[0.59,0.61,0.64]	[0.64,0.65,0.68]
C4	[0.24,0.53,0.61]	[0.20,0.45,0.71]	[0.7,0.85,0.89]	[0.71,0.87,0.96]	[0.75,0.79,0.87]
C5	[0.64,0.71,0.92]	[0.17,0.55,0.91]	[0.71,0.83,0.93]	[0.59,0.67,0.87]	[0.47,0.82,0.89]
C6	[0.56,0.76,1]	[0.75,0.89,1]	[0.35,0.52,1]	[0.22,0.34,0.61]	[0.32,0.47,0.83]
C7	[0.47,0.67,0.88]	[0.74,0.83,1]	[0.45,0.63,0.88]	[0.31,0.45,0.67]	[0.35,0.56,0.83]
C8	[0.43,0.65,1]	[0.55,0.76,1]	[0.25,0.54,0.87]	[0.19,0.36,0.55]	[0.33,0.48,0.61]
C9	[0.54,0.67,0.89]	[0.15,0.58,0.89]	[0.68,0.88,0.98]	[0.63,0.75,0.88]	[0.77,0.81,0.85]
C10	[0.86,0.96,1]	[0.55,0.9,1]	[0.25,0.62,1]	[0.12,0.45,0.71]	[0.36,0.61,0.93]
C11	[0.35,0.36,0.37]	[0.29,0.32,0.36]	[0.33,0.34,0.36]	[0.32,0.32,0.33]	[0.32,0.33,0.34]
C12	[3.04,3.14,3.22]	[3.04,3.05,3.06]	[3.07,3.11,3.22]	[3.14,3.30,3.46]	[3.2,3.33,3.47]
C13	[2.34,2.88,3.21]	[0.64,1.89,2.77]	[1.08,2.01,3.03]	[0.88,2.02,3.11]	[0.71,1.97,3]
C14	[0.27,0.35,0.39]	[0.15,0.24,0.27]	[0.17,0.20,0.21]	[0.15,0.17,0.19]	[0.13,0.16,0.19]
C15	[0.37,0.40,0.43]	[0.23,0.36,0.41]	[0.29,0.35,0.39]	[0.18,0.25,0.33]	[0.21,0.25,0.29]
C16	[0.25,0.31,0.34]	[0.11,0.18,0.37]	[0.17,0.23,0.39]	[0.25,0.31,0.40]	[0.23,0.32,0.39]
C17	[0.07,0.19,0.51]	[0.04,0.08,0.1]	[0.15,0.21,0.29]	[0.11,0.15,0.19]	[0.10,0.15,0.18]
C18	[0.4,0.41,0.41]	[0.4,0.41,0.41]	[0.4,0.4,0.41]	[0.39,0.39,0.4]	[0.37,0.38,0.4]
C19	[0.38,0.4,0.41]	[0.39,0.4,0.41]	[0.38,0.39,0.39]	[0.37,0.38,0.39]	[0.38,0.39,0.4]

Table 4 | The standards calculated by the improved interval TOPSIS method

Evaluation grade	**Excellent**	**Good**	**General**	**Poor**	**Very poor**
d^*	0.001	0.044	0.086	0.130	0.185
d^-	0.198	0.159	0.121	0.080	0.032
REHI	0.994	0.784	0.584	0.382	0.147

Table 5 | Health evaluations of the Zhangweinan River ecosystem calculated by the improved interval TOPSIS method

Evaluation period	**1991–1995**	**1996–2000**	**2001–2005**	**2006–2010**	**2011–2015**
d^*	0.137	0.145	0.146	0.140	0.146
d^-	0.085	0.080	0.076	0.083	0.077
REHI	0.384	0.355	0.343	0.373	0.346
Evaluation result	General–poor	Poor–very poor	Poor–very poor	Poor–very poor	Poor–very poor

trends in both curves were roughly the same, and the curve for the standard method was a little higher than that for the improved method. The standard interval TOPSIS method indicated that the river health ranged from general to poor for 1991–1995, and ranged from poor to very poor for 1996–2000, 2001–2005, 2006–2010, and 2011–2015. The distribution of the values of each indicator is not linear, and the mean of a given indicator is the arithmetic mean of all the data values over the evaluation period and not the arithmetic mean of the maximum and minimum numbers. In the Zhangweinan River, the actual mean values of most indicators were smaller than the arithmetic averages of the maximum and minimum, so the REHI curve of the standard method was higher than that of the improved method. The maximum and minimum values of different indicators may be the same, but their actual health status may be different. Therefore, the standard interval TOPSIS method is not suitable for assessing REH because it cannot fully consider the influence of dynamic changes in

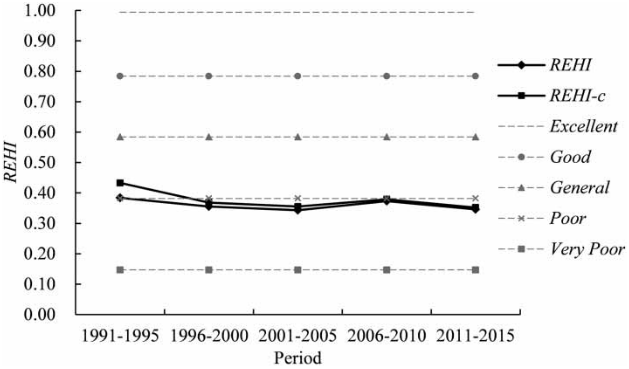

Figure 2 | Health curve of the Zhangweinan River ecosystem from 1991 to 2015.

REH. The different mean numbers can reflect different river ecosystem states, so, by combining the mean number and the interval number, dynamics in the REH can be considered and the shortcoming of the standard interval TOPSIS can be avoided. The improved interval TOPSIS method is more rigorous and gives a better picture of REH than the standard interval TOPSIS.

Causes for the variation in the Zhangweinan River REHI

The low values for the integrated index of the Zhangweinan River's ecosystem health reflect the values of the river-crossing structures' density, estuary runoff, annual runoff, sediment transport, wetland preservation, fish species integrity index, benthic fauna integrity index, macrophytes integrity index, and water quality compliance, which are a consequence of the construction and operation of the reservoirs and agricultural irrigation system, inadequate wastewater management, and lack of awareness of the need for ecological protection.

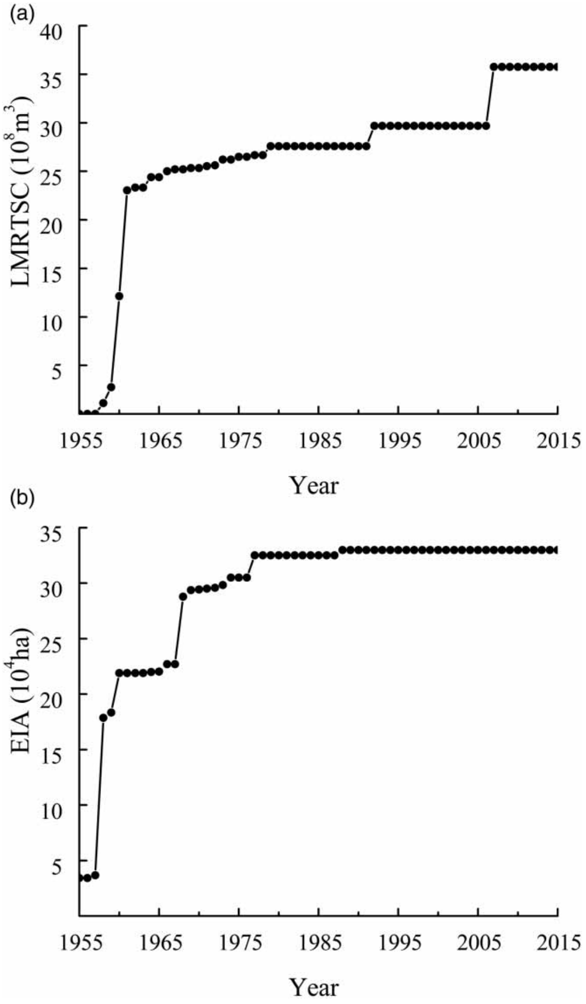

Figure 3 | Variation in (a) the total storage capacity of large and medium-sized reservoirs and (b) the effective irrigation area in the Zhangweinan.

Figure 3(a) and 3(b) show the total storage capacity of the large and medium-sized reservoirs (LMRTSC) and the effective irrigation area (EIA) in the Zhangweinan Basin from 1955 to 2015, respectively. The Zhangweinan River's major reservoirs, including the Yuecheng Reservoir, and the irrigated areas, including the Zhangnan, Minyou, and Hongqi Channels, were both constructed between the end of the 1950s and the 1970s. The EIA reached 3.299×10^5 ha in 2015, which was ten times the area covered in the early 1950s. Wheat, maize, cotton, and vegetables are the main crops in these areas that consume most of the water from the reservoirs. The agriculture in this area is dominated by wheat–maize double cropping. The maize is sown in early June, immediately after the wheat harvest, and is harvested in the middle of September; winter wheat is then sown in early October and harvested the following June (Wang *et al.* 2016). Therefore, the reservoirs have a flood control function in the flood season from July to September, but supply water to the irrigated areas in the other seasons. To protect against flooding, water is generally discharged from the reservoir in mid- and late-June. The river flow is stopped after the flood season, the water is stored in the reservoirs, and there is no flow in the lower reaches of the river. This situation is particularly pronounced in the spring irrigation period and mainly arises because of a lack of awareness of the need for ecological protection. For instance, the discharge from the reservoir is not regulated to ensure it meets the EF required to sustain the ecosystem. The reservoir construction has improved irrigation, promoted the development of agriculture, extended the irrigated areas, and supported increases in the water consumed by crops, such as wheat and maize. The urban water supply has also improved, and the economies have grown. The reservoir construction has resulted in the growth of water-consuming industries and over-allocation and overconsumption of urban water resources. The runoff that is generated in the hilly area in the upper reaches of the Zhang and Wei Rivers is trapped and stored in the reservoirs, causing the flow in the rivers to dry up during the low-flow season. Data collected at the Yuancun Station on the Wei River show that the river has dried up during more than 20 low-flow seasons from 1991 to 2015; simulations with the Soil and Water Assessment Tool (SWAT) based on long term precipitation-runoff data showed similar results (Fu *et al.* 2015). The domestic water consumption, and evaporation and seepage from the reservoir are the main controls on the runoff, and account for more than 80% of the reduction in the total river runoff caused by human activities (Fu *et al.* 2015); these factors explain the 'poor' state of the rate of monthly water condition changes, rate of magnitude and duration of annual extreme water conditions changes, rate of timing of annual extreme water condition changes, rate of frequency and duration of high and low pulses changes, rate and frequency of water condition changes, rate of sediment transport changes, rate of estuary runoff changes, wetland preservation rate, fish species integrity index, and benthic fauna integrity index. The reservoirs and the irrigated areas have contributed to the degradation of the Zhangweinan River ecosystem. Water-saving agriculture needs to be established, in which the crop planting structure is adjusted, the surface irrigation methods are improved, and advanced irrigation technology is developed to reduce inefficient use of water. The reservoir regulation regime should also be changed so that EF are restored to the downstream ecosystem.

The deterioration in the river health is also partly attributable to wastewater discharges. The annual wastewater discharge from the basin's industries, households, and agricultural activities has reached 8.3×10^8 tons, which is twice the discharge for 1980 and 1.3 times the discharge in 1991. Together, the huge volumes of sewage and the continuous reduction in the flow mean that the lower reaches of the Zhangweinan River are seriously polluted and degraded, with adverse effects on marine aquaculture and severe loss of fisheries. At present, the Zhangweinan River can be divided into two parts based on the water quality, the Zhang River where the water quality is relatively good, and the Wei River, Wei Canal, and Zhangweixin River, which are seriously polluted (Xu *et al.* 2012). Previous researchers reported lower biodiversity in the polluted and nutrient-rich conditions in the Wei River, Wei Canal, and Zhangweixin River (Yu & Wang 2009), and that, because of the serious pollution and intermittent stream betrunking, only zooplankton and phytoplankton could survive, and fish were almost extinct in some regions. These conditions help to explain why water quality compliance index, fish species integrity index, benthic fauna integrity index, and macrophytes integrity were poor. The unhealthy river ecosystem mainly reflects the lack of ecological protection over past decades.

CONCLUSIONS

Assessments of REH are essential, but can also be difficult, for integrated river restoration and management. In this study, an REH assessment indicator system that included morphological form, hydrological features, aquatic life, and habitat provision was established using indicators from IHA system and other relevant results. The standard interval TOPSIS method does not fully consider the influence of dynamic changes in REH. The indicators of rivers with different REH states may have the same maximum and minimum values but different mean values. For the purposes of this study, we therefore incorporated the mean and interval numbers into an improved version of the interval TOPSIS to obtain a more objective view of REH status. We then successfully used the improved interval TOPSIS model to examine the ecosystem health of the Zhangweinan River over the past 25 years.

The Zhangweinan River's *REHI* has decreased over the past 25 years and the river ecosystem state ranged from general to poor for the periods from 1991–1995, and from poor to very poor for 1996–2000, 2001–2005, 2006–2010, and 2011–2015. We examined why the ecosystem health of the Zhangweinan River was poor and found that the construction and operation of the reservoirs and agricultural irrigation areas, wastewater emissions, and poor ecological protection consciousness were the main contributors. We have made various suggestions to improve ecosystem health of the Zhangweinan River:

1. Land managers should encourage water saving in agriculture, and should adjust the crop planting structure, implement improved surface irrigation management, and develop advanced irrigation technology to conserve water and reduce the use of runoff in Zhangweinan Basin.
2. The dams and sluice regulation should be based on ecological rather than economic outcomes, and the water quantity, quality, and ecology should be considered together. The operation of the Yuecheng Reservoir should be optimized to restore the original flow and provide the aquatic ecosystem ecological water requirements for the Zhang River, Wei Canal, and Zhangweixin River, and so reduce the negative effects of the construction of the reservoirs.
3. The sources of the pollutant discharges in the Zhangweinan Basin should be investigated. Pesticides and chemical fertilizers should be applied in line with crop requirements to reduce non-point source pollution. More sewage treatment plants should be planned and built to improve the wastewater treatment, especially in the catchments of the Wei River, Wei Canal, and Zhangweixin River.
4. Riparian vegetation and wetland communities should be reconstructed after the water quality and flow are restored in the Zhangweinan River.
5. Education programs should be introduced to raise the awareness of the need for ecological and environmental protection.

Overall, the improved interval TOPSIS method can be used to quantify the integrated health of river ecosystems, especially where the indicator value is composed of an interval number and the mean. This type of index is easy for stakeholders and policy-makers to understand a river's health status. This method can also be applied to many other decision-making and evaluation fields.

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