Integrated impact assessment method for the water transfer project on regional development

Zhangling Xiao, Zhongmin Liang, Binquan Li, Yiming Hu and Jun Wang

ABSTRACT

Water transfer projects in China have become a popular research topic in recent years. This study develops a method for evaluating the comprehensive impacts of water transfer projects on regional development. In the qualitative assessment, the comprehensive index method is employed, and an evaluation index system is established from economic, social and environmental perspectives. In this approach, the weights are determined by the analytic hierarchy process (AHP) and the entropy combined method. In the quantitative assessment, the sharing coefficient method is used.
The procedure is applied to the water transfer project from the Yangtze River to the Taihu Lake. The qualitative results indicate that the conclusion of the water transfer project had a 'large positive impact' in 2016. In the quantitative assessment, the comprehensive benefit of increasing water supply via the project was 1.87 billion CNY in 2016. In addition, the integrated impact assessment method can be implemented at the seasonal scale to produce refined results. These results show that the proposed method can provide technical support for project operation and policy formulation.

Key words | AHP–entropy, integrated impact assessment, regional development, sharing coefficient method, water transfer project from the Yangtze River to the Taihu Lake

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INTRODUCTION

Heterogeneous temporal and spatial distributions of water resources are common in many countries, and population growth and socio-economic development lead to increased water demands and water shortage risks (Zhou *et al.* 2017; Li *et al.* 2019). The implementation of water transfer projects can be regarded as an effective engineering measure to alleviate such problems and extensively affect regional socio-economic development.

The economic, social and environmental impacts of water transfer projects in benefitting areas are the focus of many researchers. Many studies have analyzed the economic, social and environmental implications of water transfer projects (Berrittella *et al.* 2006; Fang 2006; Zhai *et al.* 2010; Li *et al.* 2015; Wilson *et al.* 2017). Lu *et al.* (2006) analyzed the economic benefits of the South-to-North Water Transfer Project for agricultural, forest, wetland and city greenbelt ecosystems based on the market value and shadow engineering methods. Feng *et al.* (2007) used a decision support system to assess the socio-economic impact of the South-to-North Water Transfer Project and performed a qualitative analysis of regional water resource vulnerability with a mathematical model. Hu *et al.* (2008) employed an ecological model (EcoTaihu) to investigate the environmental effects of two experimental water transfers from the Yangtze River to the Taihu Lake. Diao *et al.* (2009) developed an analytical framework to evaluate the economic benefits of supplying water to Huzhou city via a water transfer project from the Yangtze River to the Taihu Lake. Davies *et al.* (2010) assessed the ecological impacts of inter-basin water transfers and noted the importance of

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benefit evaluation for water transfer projects. Chen *et al.* (2013) developed a generalized model of the lower Yangtze River to assess the effect of water transfers to Shanghai. Wilson *et al.* (2017) evaluated the economic, social and environmental impacts of the South-to-North Water Transfer Project. Gao & Yu (2018) investigated the macroeconomic impact of the South-to-North Water Transfer Project on industrial sectors in Beijing using input–output analysis.

There are several methods of impact assessment for water transfer projects, and the selected method always depends on the background and objective of the assessment. Researchers have conducted studies on this issue from different perspectives, such as economic, social and environmental perspectives. Water transfer projects can meet the needs of industrial, agricultural and environmental water, and promote the economic growth to the water-receiving region. The economic impact assessment for the water transfer project can be evaluated by input–output analysis (Gao & Yu 2018), the market value and shadow engineering methods (Yang *et al.* 2005; Lu *et al.* 2006), the sharing coefficient method (Diao *et al.* 2009) and computable general equilibrium analysis (Berrittella *et al.* 2006). Moreover, literatures (Wang *et al.* 2009; Wilson *et al.* 2017) suggested that the social impact of water transfer projects focus on three aspects: disease (specifically schistosomiasis) transmission, water management and the impact on governance at a variety of spatial scales and organizational levels. The social impact assessment for water transfer projects is challenging, and many papers are rarely quantitative and rely heavily on the author's interpretation of documents and ongoing events (Wilson *et al.* 2017). The projects transfer water with high enough quality, ensuring regional water security. The potential environmental impacts in the water-receiving region can be evaluated by the game theoretic and virtual water approach (Manshadi *et al.* 2015), the hydraulic and water quality model (Karamouz *et al.* 2010; Wang & Wang 2014) and the eco-hydrological model (Wang *et al.* 2013). However, systematic and comprehensive impact evaluation methods have rarely been reported. In view of this limitation, a quantitative and qualitative integrated framework is developed to evaluate the impacts of water transfer project on regional development in economic, social and environmental contexts.

The integrated impact assessment method comprises two parts: quantitative and qualitative assessments. The sharing coefficient method is applied to estimate the quantitative impact of water transfer projects in the form of currency. The comprehensive index method is employed in the qualitative assessment, and the index weights are determined by the analytic hierarchy process (AHP) and the entropy combined method. Additionally, an evaluation index system is required to reflect the comprehensive influence of a water transfer project on the water-receiving area, and reliability analysis is needed to assess the proposed system. It is worth noting that as long as water transfers occur, the impact of the water transfer process can be evaluated. The method described in this paper can be used to evaluate the water transfer impact throughout the year and in each period of the water transfer process.

The remainder of the paper is organized as follows. The section 'Methods' describes the quantitative and qualitative impact assessment method. The section 'Study area' briefly introduces the study area, and the section 'Results and discussion' provides a case study of the water transfer project from the Yangtze River to the Taihu Lake in 2016. The conclusions are drawn in the section 'Conclusion'.

METHODS

Quantitative assessment of a water transfer project

During the operational period of a water transfer project, the impact of an increased water supply in the water-receiving area must be quantitatively analyzed. The impacts of the water transfer project can be divided into visible economic impacts and intangible impacts, such as social and environmental impacts. However, the use of monetary units to evaluate invisible impacts is still relatively new. Therefore, the social and environmental impacts of water transfer projects are estimated based on the visible economic impacts in this study.

The economic impacts refer to the contributions of water transfer projects to the local economic development in water-receiving areas. These contributions can be directly reflected in the added GDP due to the increased water supply. The commonly used quantitative evaluation methods include the sharing coefficient method, the productivity change method, and the shadow engineering method. Water transfer impacts are quantitatively determined with the sharing coefficient method in this study (MWR 2013).

The sharing coefficient method assumes that the added GDP is the result of joint investments, and that the increased water supply is a type of investment. Therefore, increased water supply from a water transfer project partially contributes to the GDP. The benefits of an increased water supply for primary industry, secondary industry and tertiary industry can be calculated according to the following equation:

$$M_j = V_j \cdot q_j \cdot k = \left(\frac{I_j}{W_j}\right) \cdot f_j \cdot q_j \cdot k \quad (j = 1, 2, 3) \tag{1}$$

In the formula, M_j represents the benefits of an increased water supply for the jth industry; V_j represents the value of each cubic meter of water in the jth industry; q_j represents the increased water supply for the jth industry; and k is a utilization coefficient related to water transfer, that is, the proportion of actual utilized water to the total quantity of transferred water. This coefficient is mainly determined by the capacity of water resource utilization. I_j represents the GDP of the jth industry, W_j represents the water consumed by the jth industry, and f_j is the water supply benefit sharing coefficient of the jth industry.

The key step in this method is the determination of the sharing coefficient. If the involved coefficient is appropriately chosen, the estimated benefits of an increased water supply should match those observed in practice (Diao *et al.* 2009). The coefficient reflects various factors that influence the water supply benefits and the corresponding relationships. This value is also related to the industrial structure, the quantity of water savings and the actual water supply. Because there are no uniform criteria or methods for calculating the assessment coefficient, the existing empirical estimators are often used.

Qualitative assessment of a water transfer project

The comprehensive impacts of water transfer projects on regional development involve several factors. In this paper, the qualitative impact assessment is based on the comprehensive index method, in which the weights of indicators in the qualitative assessment are determined by an AHP and the entropy combined method. In addition, an evaluation index system is required and is constructed based on economic, social and environmental factors to reflect the comprehensive impacts of water transfer projects on water-receiving areas. In addition, reliability analysis is required for the proposed system.

Establishing an evaluation index system

An evaluation index system plays a crucial role in qualitative assessment. The impact evaluation index system of a water transfer project can be divided into three layers in the AHP: a target layer, a criterion layer and an index layer. The target layer reflects the purpose of the assessment. The criterion layer comprises the economic, social and environmental impacts, and is an expansion of the target layer. Moreover, the index layer includes concrete indicators that directly and indirectly contribute to the assessment. These indicators are selected and combined with the actual information from the study area. The general hierarchy diagram is shown in Figure 1.

To test the reliability of the evaluation index system, it is necessary to analyze the reliability of the internal consistency of the constructed index system. The internal consistency of the index system is measured with Cronbach's alpha coefficient α, which is the most frequently used reliability coefficient in many studies.

$$\alpha = \frac{k\bar{r}}{1 + (k-1)\bar{r}} \quad \alpha \in (0,\ 1) \tag{2}$$

where k denotes the number of indicators and $\bar{r}$ denotes the mean of the correlation coefficient of k indicators.

The larger α is, the better the correlation between evaluation indicators and the higher the internal consistency. Related studies have shown that the internal consistency of an index system is excellent if $\alpha > 0.8$; therefore, α should be greater than 0.7 in practical applications (Carlbring *et al.* 2007).

Comprehensive index method

There are many methods of a multi-index comprehensive evaluation, such as principal component analysis, gray

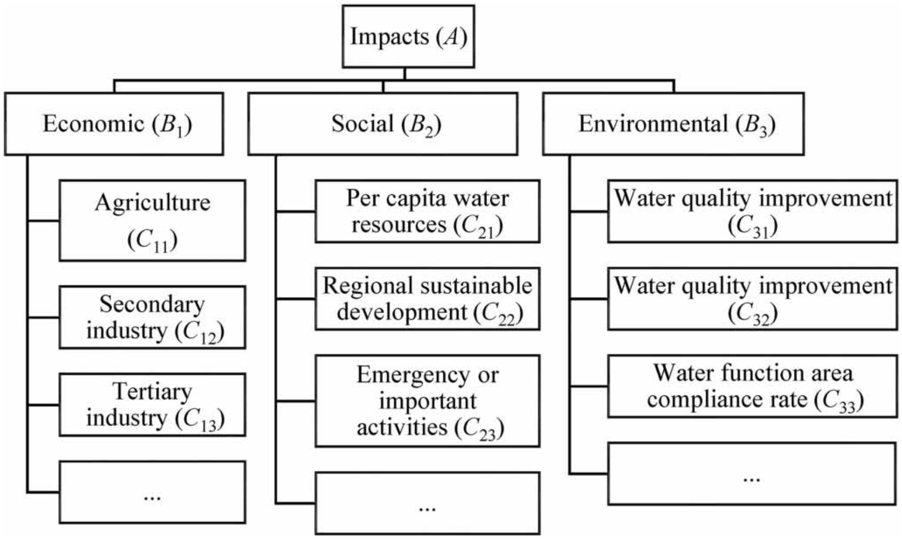

Figure 1 | Hierarchical structure chart of the water transfer impact evaluation system.

relational analysis and artificial neural network evaluation methods. The comprehensive index method is employed in this study, and the weights of the index are determined by the AHP and the entropy combined method.

Suppose $P = (P_1, P_2, \ldots, P_k)$ are the scores of indicators and $Z_1, Z_2, \ldots, Z_k$ are the weights assigned to the indicators. First, calculate the score of each indicator according to the grading standard. Then, the comprehensive index can be computed by the following formula:

$$P = \sum_{j=1}^{k} Z_j P_j, \quad \sum_{j=1}^{k} Z_j = 1 \tag{3}$$

where P denotes the comprehensive impact, P_j represents the score of the jth indicator and Z_j is the weight of the jth indicator. The scores can be obtained in accordance with the values of indicators and corresponding scoring criteria. The weights are determined through the AHP and the entropy combined method (hereafter referred to as the 'AHP–entropy method'). First, two sets of weights are separately calculated by the AHP and entropy methods. Then, the final weights can be obtained from the average of these two methods for simplicity, as shown in Equation (13).

The AHP is a type of subjective weighting method that reflects research objectives but is often limited by the knowledge and experience of researchers, and the entropy method is a type of objective weighting methods that calculates the weights through observed data (Bai *et al.* 2018). The AHP–entropy combined weighting method considers data and the subjective references of decision makers to achieve unity between subjective and objective perspectives and obtain more realistic and reliable results (Xie *et al.* 2012).

1. AHP method

The AHP method is a multi-objective and multi-criteria decision-making approach developed by Saaty in 1970. In the AHP, complex problems are first stratified and organized in a hierarchical order. Second, the indicators in the same layer are compared to construct a set of pairwise comparison matrices A based on Saaty's scale (Saaty 1980). The pairwise comparison matrices are determined based on the knowledge and experience of the stakeholders according to a nine-point verbal scale (Saaty 1977), as shown in Supplementary Table A1 (see Appendix A, available with the online version of this paper). To make comparisons, a scale of numbers is needed that indicates how many times more important or dominant one indicator is over another indicator.

First, the maximum characteristic root $\lambda_{\max}$ of matrix A and its corresponding eigenvector X are calculated. The obtained eigenvector is the ranking of the importance of each indicator, that is, the weight of each indicator. In addition, to ensure that the obtained weights are reasonable, it is necessary to check the consistency of A (Saaty

& Vargas 2017). Otherwise, the comparison matrices must be modified until the consistency requirement is met.

$$AX = \lambda_{\max} X \tag{4}$$

$$w = \left\{ \frac{X_1}{\sum_{j=1}^{k} X_j}, \frac{X_2}{\sum_{j=1}^{k} X_j}, \ldots, \frac{X_k}{\sum_{j=1}^{k} X_j} \right\} = \{w_1, w_2, \ldots, w_k\} \tag{5}$$

2. Entropy method

In information theory, the concept of 'entropy' is employed to evaluate uncertainty and indicates the degree of disorder in accordance with the objective data. If an indicator has high information entropy and a low variation in its value, such an indicator should be assigned a low weight. Conversely, if an indicator has low information entropy and high variation in its value, it should be given a high weight (Delgado & Romero 2016; Li & Zhao 2017). The procedure for assigning weights in the entropy method is illustrated as follows.

Step 1: Suppose an evaluation system consists of n evaluation objects (samples) and k indicators. Thus, an evaluation matrix H can be obtained ($h_{ij} \in V$, $i = 1, 2, \ldots, n$; $j = 1, 2, \ldots, k$). In this study, n and k are the number of years and indicators, respectively.

$$H = (h_{ij})_{nk} = \begin{bmatrix} h_{11} h_{12} \cdots h_{1k} \\ h_{21} h_{22} \cdots h_{2k} \\ \cdots\cdots\cdots\cdots \\ h_{n1} h_{n2} \cdots h_{nk} \end{bmatrix} (i = 1, 2, \cdots, n;\ j = 1, 2, \cdots, k) \tag{6}$$

Step 2: Next, the evaluation matrix H is standardized. The standardization can be divided into two cases according to different indicators: (i) 'larger is better' indicators (positive indicators) and (ii) 'smaller is better' indicators (negative indicators). The standardization formulas for positive indicators and negative indicators are given in Equations (7) and (8), respectively.

$$l_{ij} = \frac{h_{ij} - \min\{h_{ij}\}}{\max\{h_{ij}\} - \min\{h_{ij}\}} \text{for positive indicators} \tag{7}$$

$$l_{ij} = \frac{\max\{h_{ij}\} - h_{ij}}{\max\{h_{ij}\} - \min\{h_{ij}\}} \text{for negative indicators} \tag{8}$$

Then, the standardized matrix L can be computed as follows:

$$L = (l_{ij})_{nk} = \begin{bmatrix} l_{11} & l_{12} & \ldots & l_{1k} \\ l_{21} & l_{22} & \ldots & l_{2k} \\ \ldots & \ldots & \ldots & \ldots \\ l_{n1} & l_{n2} & \ldots & l_{nk} \end{bmatrix} \\ (i = 1, 2, \cdots, n;\ j = 1, 2, \cdots, k) \tag{9}$$

Step 3: In this step, the entropy values of indicators are calculated.

Take p_{ij} as the proportion of the ith evaluation object for the jth indicator.

$$p_{ij} = \frac{l_{ij}}{\sum_{i=1}^{n} l_{ij}} \quad (i = 1, 2, \cdots, n;\ j = 1, 2, \cdots, k) \tag{10}$$

The entropy value en_j of the jth indicator can be calculated based on the following formula:

$$\mathrm{en}_j = -\frac{1}{\ln(n)} \left(\sum_{i=1}^{n} p_{ij} \ln p_{ij} \right) \quad (j = 1, 2, \cdots, k) \tag{11}$$

In particular, when $p_{ij} = 0$, $p_{ij} \ln p_{ij} = 0$.

The weights of indicators can be calculated according to the following formula:

$$z_j = \frac{1 - \mathrm{en}_j}{\sum_{j=1}^{k} (1 - \mathrm{en}_j)} \tag{12}$$

where $j = 1, 2, \ldots, k$, $0 \le z_j \le 1$, and $\sum_{j=1}^{k} z_j = 1$.

$$Z_j = \frac{w_j + z_j}{2} \tag{13}$$

STUDY AREA

The Taihu Lake Basin, located in the lower part of the Yangtze River Delta, is one of the most important economic centers in China. Faced with pollution and eutrophication problems, the Taihu Basin Authority of the Water Resources Ministry launched a water transfer project from the Yangtze River to the Taihu Lake (WTPYT) beginning in 2002 to aid this serious situation. The course of water transfer is from the Yangtze River to the Taihu Lake through the Wangyu River, and the project provides freshwater to its surrounding areas (such as Wuxi, Suzhou and Huzhou). Additionally, water is discharged for the downstream area (like Jiaxing and Shanghai) via the Taipu River, as shown in Figure 2. The WTPYT has enhanced the water exchange in the Taihu Lake Basin and increased the water supply in the surrounding areas, achieving remarkable economic, social and environmental benefits. Therefore, it is of great practical significance to evaluate the impacts of water transfer for developing sustainable management strategies and maintaining the successful operation of the project. The proposed assessment method was applied to evaluate the impact of the WTPYT in 2016.

According to the water transfer data from 2002 to 2016, a total of approximately 27.3 billion m^3 of water was introduced from the Yangtze River, of which 12.6 billion m^3 was introduced into the Taihu Lake; in addition, 14.6 billion m^3 of water was supplied downstream via the Taipu River. In 2016, the Taihu Lake Basin received an unusually high rainfall total of 1,792.4 mm, the largest annual total since 1951. The precipitation in February, March and August was 58–64% lower than usual, and the precipitation in other months was greater than usual. In 2016, the Taihu Lake Bureau implemented two water transfers: from March 5 to April 1 and from August 30 to September 12. The WTPYT transferred a total amount of 4.8 billion m^3 water, of which 1.44 billion m^3 of water entered the Taihu Lake during the periods of the transfer. At the same time, 4.58 billion m^3 of water was supplied to downstream areas through the Taipu River, thereby improving the water environment and providing crucial support for the G20 summit.

RESULTS AND DISCUSSION

Quantitative assessment

The operation of the water transfer project from the Yangtze River to the Taihu Lake greatly improved the water environment in the surrounding cities and contributed to regional development. The impacts of water supply can be divided into visible and invisible impact. The visible impacts refer

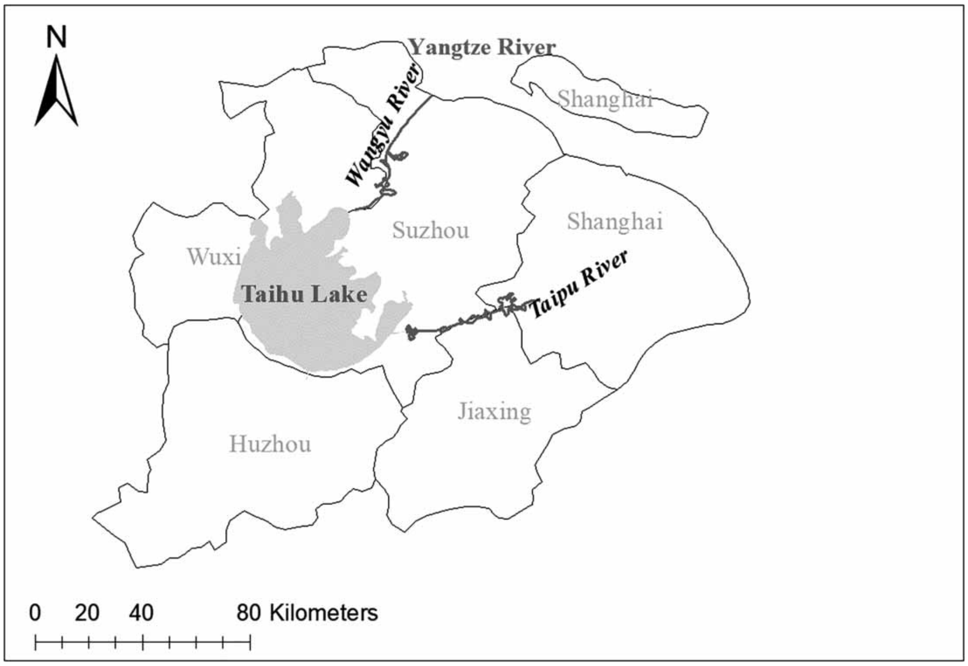

Figure 2 | Map of the water transfer project from the Yangtze River to the Taihu Lake.

to the economic impacts due to the added water supply, and the invisible impacts are mainly social and environmental impacts. A quantitative evaluation is performed to assess the impacts of the project using a monetization method. The economic impact can be calculated by the sharing coefficient method. However, at present, there is no reliable method available to quantify the social and environmental impacts of water transfer projects. Therefore, the social and environmental impacts (also regarded as invisible impacts) are qualitatively estimated by a proportional coefficient of the economic impacts (visible impacts).

According to the sub-industry impact results from 2002 to 2004 (as shown in Table 1) reported in the book published by the Taihu Basin Authority of Water Resources Ministry ('Water Transfer Test from the Yangtze River to the Taihu Lake'), the total invisible impact was determined to be 28% of the visible impact of the WTPYT.

The water transfer project promoted the economic growth and increased the water supply in the surrounding cities, including Suzhou, Shanghai, Huzhou, Jiaxing and Wuxi. According to the basic industrial structure of the Taihu Lake Basin, the economic benefits of increasing water supply to primary industry, secondary industry and tertiary industry were estimated by the sharing coefficient method.

Visible economic impact evaluation

The water transfer to Suzhou is mainly used for ecological purposes; therefore, at 0.2, the coefficient of water transfer k in Suzhou is smaller than those in other administrative regions (0.25). According to the increased water supply and the water transfer coefficients for different sources, the water supplied for production in various industries in each administrative region can be obtained, as shown in Supplementary Table A2 (see Appendix A, available with the online version of this paper).

Table 1 | Sub-industry impact of the water transfer project from 2002 to 2004

Category	Sub-industry	2002	2003	2004
Visible impact	Agriculture	3,789	17,596	3,716
	Industry	16,896	87,169	50,460
Invisible impact	Waterworks	585	1,898	711
	Tourism	1,273	4,958	2,272
	Family consumption	670	2,462	838
	Human health	5,131	19,449	6,438

The Taihu Lake Basin is located in the transitional zone between the northern subtropics and middle subtropics. The landforms in the basin are mainly plains, with dense river networks and natural conditions that provide a good foundation for the development of agriculture, forestry, fisheries, etc. In this study, the impact of the increased water supply on the primary industry mainly focuses on irrigation. There are many large and medium-sized cities in the Taihu Basin that cover wide ranges of industrial categories, production levels and scales. The iron and steel, petrochemical, machinery, light textile and other industries in the basin are of national importance and have maintained relatively rapid growth for many years. Due to the large proportion of industrial production in the total output of the secondary industry and the lack of detailed statistical information regarding the secondary industry, the contribution of water to the gross output value of the second industry is approximated by the contribution of water to the gross industrial output value.

Based on the literature (Zang *et al.* 1997; Diao *et al.* 2009; Bo *et al.* 2017) and the specific situation in the Taihu Lake Basin, the sharing coefficients of the water supply benefits associated with primary industry, secondary industry and tertiary industry were determined to be 0.3, 0.03 and 0.03, respectively. Water consumption data were extracted from the official websites of the statistical offices of the studied cites. The calculation results for the water supply benefits in primary industry, secondary industry and tertiary industry in 2016 are shown in Supplementary Tables A3–A5 (see Appendix A, available online).

Invisible social and environmental impact evaluation

In addition to the visible economic benefits of increasing the water supply in the study region, the transfer project also produces obvious invisible benefits in the region, including environmental and social benefits. Considering the visible and invisible impacts of WTPYT in 2016, the comprehensive quantitative evaluation results for each administrative district in the Taihu Basin are provided in Table 2.

Table 2 | Comprehensive benefits of Taihu Basin in 2016 (unit: hundred million CNY)

	Visible impact					
City	M_1	M_2	M_3	**Total**	**Invisible impact**	**Comprehensive benefits**
Wuxi	/	0.171	0.186	0.357	0.100	0.457
Suzhou	0.454	1.788	1.960	4.202	1.177	5.379
Shanghai	0.141	1.590	3.852	5.584	1.563	7.147
Jiaxing	0.884	1.890	1.685	4.459	1.248	5.707
Huzhou	0.017	0.014	0.014	0.046	0.013	0.058

Table 2 shows that the comprehensive benefit of increased water supply via the water transfer project in 2016 was 1.87 billion CNY, of which the visible benefit was 1.46 billion CNY. According to Table 2, Shanghai received the largest benefit of 0.71 billion CNY among all involved cities, followed by Jiaxing and Suzhou at 0.57 and 0.54 billion CNY, respectively. The water supply benefits for the secondary and tertiary industries were larger than those for the primary industry, mainly because the water consumption per unit GDP of the secondary and tertiary industries was large.

Qualitative assessment

Building the evaluation index system

In this study, an impact evaluation index framework is developed that considers expert opinions and the principles of comprehensiveness, representativeness and maneuverability based on the actual situation in the Taihu Lake Basin and the availability of data. Evaluation indicators were selected for economic, social and environmental factors, as discussed below.

1. Agriculture C_{11}

   This indicator refers to the ratio of the agricultural value added by the water transfer project $\mathrm{GDP}_{\mathrm{p,w}}$ to the GDP of the primary industry $\mathrm{GDP}_{\mathrm{p}}$ in the water-receiving area. Thus, this value reflects the impact of the water transfer on agriculture. $\mathrm{GDP}_{\mathrm{p,w}}$ is calculated as part of the quantitative assessment method.

$$C_{11} = \frac{\mathrm{GDP}_{\mathrm{p,w}}}{\mathrm{GDP}_{\mathrm{p}}} \tag{14}$$

2. Secondary industry C_{12}

   This indicator refers to the ratio of the secondary industry value added by the water transfer project $\mathrm{GDP}_{\mathrm{s,w}}$ to the GDP of the secondary industry $\mathrm{GDP}_{\mathrm{s}}$ in the water-receiving area. This value reflects the impact of the water transfer on the secondary industry. $\mathrm{GDP}_{\mathrm{s,w}}$ is calculated as part of the quantitative assessment method.

$$C_{12} = \frac{\mathrm{GDP}_{\mathrm{s,w}}}{\mathrm{GDP}_{\mathrm{s}}} \tag{15}$$

3. Tertiary industry C_{13}

   This indicator refers to the ratio of the tertiary industry value added by the water transfer project $\mathrm{GDP}_{\mathrm{t,w}}$ to the GDP of the tertiary industry $\mathrm{GDP}_{\mathrm{t}}$ in the water-receiving area. This value reflects the impact of the water transfer on the tertiary industry. $\mathrm{GDP}_{\mathrm{t,w}}$ is calculated as part of the quantitative assessment method.

$$C_{13} = \frac{\mathrm{GDP}_{\mathrm{t,w}}}{\mathrm{GDP}_{\mathrm{t}}} \tag{16}$$

4. Per capita water resources C_{21}

   This indicator refers to the contribution of the water transfer project in term of per capita water resources, evaluated by the proportion of transferred water T_{w} to regional water consumed water C_{w}.

$$C_{21} = \frac{T_{\mathrm{w}}}{C_{\mathrm{w}}} \tag{17}$$

5. Regional sustainable development C_{22}

   This indicator reflects the impact of the water transfer project on regional sustainable development and is evaluated by experts.

6. Emergency or important activities C_{23}

   The indicator reflects the impact of the water transfer project on emergencies or important activities and is evaluated by experts.

7. Public acceptance C_{24}

   The indicator reflects whether the water transfer project is accepted by the public and it is evaluated by experts.

8. Residents' living environment C_{25}

   The indicator refers to the improvements in water quality, the landscape and the living environment of residents and is evaluated by experts.

9. Water quality improvement in the water-providing area C_{31}

   The indicator reflects the difference in water quality improvement with or without the operation of the water transfer project, thereby reflecting the influence of water transfer on the water quality of Taihu Lake. The average values of four water quality indicators are calculated. These indicators include permanganate index, ammonia nitrogen, total phosphorus and total nitrogen in the Gonghu water source area (Xidong water plant and Gonghu water plant) and the Jinshugang water source area. The above results are compared with the average concentrations prior to the water transfer, and the improvement in each indicator is expressed based on the rate of change relative to the target concentration in 2016. The average improvements in the above four water quality indicators are considered as the water quality improvement of the water source area.

10. Water quality improvement in the water-receiving area C_{32}

    The indicator reflects the difference in water quality improvement of the water-receiving area with or without the operation of the water transfer project. It is calculated in the same manner as the water quality improvement in the water source area.

11. Water function area compliance rate C_{33}

    The water function area compliance rate refers to the percentage of the qualified water function area based on all water function areas. In this paper, the monthly water function area compliance rates are recorded in the report published by the Taihu Lake Bureau Authority, and the average value is used for evaluation.

12. Water use outside river channel C_{34}

    The ecological water in this study includes water associated with water and soil conservation, forestry and ecological engineering, urban ecological water, groundwater recharge water, etc. This indicator is used to reflect the influence of the water transfer project on the water use outside the river channel and is evaluated by experts.

13. River network ecosystems C_{35}

    The indicator refers to the influence of water transfer on the hydrological and water environmental factors such as flow, flow velocity and water quality of the river network. It is evaluated by experts.

14. Cyanobacteria population C_{36}

    The indicator represents the change of cyanobacteria population due to the water transfer project and reflects the influence of the project on eutrophication.

The reliability of the established index system is evaluated using Cronbach's coefficient α. The internal consistency test for α is shown in Table 3.

It can be concluded from Table 3 that the overall α coefficient was 0.974, and the α coefficients of economic, social and environmental criteria were 0.995, 0.974 and 0.974, respectively. The degree of internal consistency of the index system was satisfactory, which indicates that the proposed evaluation index system is reliable.

Table 3 | Reliability analysis of the proposed evaluation index system

Secondary layer	Coefficient of Cronbach	Number of indicators
Economic impact B_1	0.995	3
Social impact B_2	0.974	5
Environmental impact B_3	0.974	6
Overall	0.974	14

Weight determination

To reasonably evaluate the comprehensive impact of the WTPYT, a survey was conducted in Shanghai in December 2013. The participants included experts from the Water Resources Ministry of China and responsible persons from the relevant departments. The results of this survey were used to analyze the weights in the evaluation.

1. AHP method

   According to the evaluation indicator system, nine-point verbal scale and survey results, pairwise comparison matrices are constructed as shown in Supplementary Tables A6–A9 (see Appendix A, available online). Supplementary Table A6 exhibited an example in which the scale was used to compare the relative importance of economic (B_1), social (B_2) and environmental (B_3) impacts of water transfer projects on regional development. For example, the stakeholders reckoned that social impact was more important than economic impact, so 5/3 was assigned in the (B_2, B_1) position, and 3/5 was assigned in the (B_1, B_2) position. One always entered the whole number in its appropriate position and automatically entered its reciprocal in the transpose position. Then, a square root method was used to calculate the weights of indicators in these matrices, and the consistency test was carried out.

   Based on the results of the pairwise comparison matrices, the final weights of all indicators in the qualitative evaluation index system determined by the AHP method are shown in Table 4. The weight of social impact and environmental impact is large, indicating that the experts attached more importance to social and environmental factors in the evaluation.

2. Entropy method

   The entropy values and weights determined by the entropy method are shown in Table 5. It indicates that the weights determined by the entropy method are similar, because the entropy method reduces the influence of subjective factors on weight determination. The final weights were determined by the AHP–entropy combined method.

Table 4 | Weights of indicators calculated by the AHP

Objective *A*	**Criterion *B***	**Relative weight in the index layer**	**Weights**
Impacts *A*	B_1(0.222)	C_{11}(0.643)	0.143
		C_{12}(0.205)	0.045
		C_{13}(0.152)	0.034
	B_2(0.511)	C_{21}(0.402)	0.205
		C_{22}(0.199)	0.102
		C_{23}(0.209)	0.107
		C_{24}(0.078)	0.040
		C_{25}(0.113)	0.058
	B_3(0.267)	C_{31}(0.203)	0.054
		C_{32}(0.203)	0.054
		C_{33}(0.063)	0.017
		C_{34}(0.043)	0.011
		C_{35}(0.131)	0.035
		C_{36}(0.357)	0.095

Table 5 | Entropy values and weights of each indicators in the evaluation system based on the entropy theory

Target layer	**Criterion layer**	**Indicator layer**	**Entropy value**	**Weight**
Impact (A)	Economic (B_1)	Agriculture (C_{11})	0.970	0.067
		Secondary industry (C_{12})	0.970	0.069
		Tertiary industry (C_{13})	0.970	0.068
	Social (B_2)	Per capita water resources (C_{21})	0.969	0.071
		Regional sustainable development (C_{22})	0.971	0.066
		Emergency or important activities (C_{23})	0.969	0.070
		Public acceptance (C_{24})	0.957	0.098
		Residents' living environment (C_{25})	0.965	0.079
	Environmental (B_3)	Water quality improvement in water-providing area (C_{31})	0.970	0.069
		Water quality improvement in water-receiving area (C_{32})	0.968	0.073
		Water function area compliance rate (C_{33})	0.975	0.057
		Water use outside river channel (C_{34})	0.965	0.079
		River network ecosystems (C_{35})	0.972	0.064
		Cyanobacteria population (C_{36})	0.969	0.071

Table 6 | Classification criteria for the impact assessment (comprehensive indicator)

Rank	I	II	III	IV	V	VI	VII
Centesimal system	100–85	85–70	70–55	55–45	45–30	30–15	15–0
[−1,1]	1–0.7	0.7–0.4	0.4–0.1	0.1 to −0.1	−0.1 to −0.4	−0.4 to −0.7	−0.7 to −1
Comprehensive impact	Significant positive	Large positive	Small positive	None	Small negative	Large negative	Significant negative

Comprehensive qualitative evaluation

Since the indicator values are not variate in the same range, a classification criterion is required to convert the indicator values to percentiles and range of [−1, 1]. According to the existing national and international standards, opinions from related experts and the actual project scenario, classification criteria for comprehensive impacts assessment are determined as percentiles and [−1, 1] interval. The classification consists of seven levels and these levels have numerical ranges of 100–85, 85–70, 70–55, 55–45, 45–30, 30–15 and 15–0, which represent significant positive, large positive, small positive impacts, none, small negative, large negative and significant negative impacts, respectively (see Supplementary Table A10 in Appendix A, available online). The classification criteria associated with the comprehensive impacts are displayed in Table 6.

According to the relevant data and expert opinions, the score of each indicator was determined based on the classification criteria, and scores are presented in Figure 3. The figure indicates that social impacts had the highest average score, and environmental impacts had the lowest average score. This finding suggests that more attention and efforts are needed to increase the environmental benefits of WTPYT. In addition, there were eight indicator scores below the average score for total indicators, which showed that the positive impacts of the WTPYT could be considerably improved in future operation. The results of these indicators are shown in Supplementary Table A11 (see Appendix A, available online), and the results of the final evaluation with the AHP–entropy weighting method are displayed in Table 7.

Supplementary Table A11 shows that the comprehensive score of the qualitative impact assessment for WTPYT

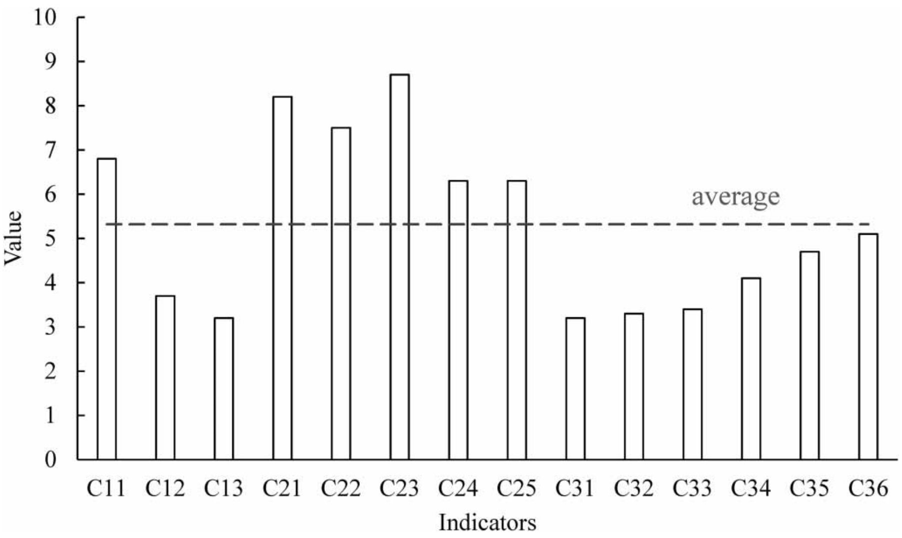

Figure 3 | Value of indicators in the evaluation index system for WTPYT in 2016.

Table 7 | Weights and final impact assessment results of WTPYT

			Weights						
Target layer	**Criterion layer**	**Index layer**	**AHP**	**Entropy**	**Average**	**Centesimal system**	**[−1, 1]**	**Centesimal system**	**[−1, 1]**
A	B_1	C_{11}	0.143	0.067	0.105	6.8	0.031	13.7	0.06
		C_{12}	0.045	0.069	0.057	3.7	0.017		
		C_{13}	0.034	0.068	0.051	3.2	0.012		
	B_2	C_{21}	0.205	0.071	0.138	8.2	0.027	37.0	0.29
		C_{22}	0.102	0.066	0.084	7.5	0.067		
		C_{23}	0.107	0.070	0.088	8.7	0.085		
		C_{24}	0.040	0.098	0.069	6.3	0.058		
		C_{25}	0.058	0.079	0.068	6.3	0.057		
	B_3	C_{31}	0.054	0.069	0.061	3.2	0.003	23.7	0.14
		C_{32}	0.054	0.073	0.064	3.3	0.002		
		C_{33}	0.017	0.057	0.037	3.4	0.031		
		C_{34}	0.011	0.079	0.045	4.1	0.036		
		C_{35}	0.035	0.064	0.049	4.7	0.045		
		C_{36}	0.095	0.071	0.083	5.1	0.019		
Total						74.4	0.49	74.4	0.49

was 74.4 based on the percentage system and 0.49 based on the interval system. The impact evaluation conclusion for this project in 2016 was 'large positive impact' according to the classification criteria in Table 7. The scores for the economic, social and environmental impacts were 13.7, 37.0 and 23.7, respectively, in the percentage system, while 0.06, 0.29 and 0.14, respectively, in the interval system. These results indicate that the social and environmental impacts were high in 2016. In the actual, water transfer from the Yangtze River to the Taihu Lake, the incoming water in 2016 was abundant; therefore, the quantity of transferred water was relatively less than that in previous years. However, the ability of the water transfer project to ensure regional water security and improve the water environment are the most important societal concerns. The results of the qualitative evaluation reflect the present project situation, which is largely consistent with the goals of the project.

There are still some problems that need to be improved. First, the sharing coefficient is crucial in quantitative impact analysis and is related to many factors such as the level of industrial development, the internal industrial structure, and the level of water management. This value was estimated on the basis of previous research in this study; therefore, the determination of this coefficient requires further research. Second, the quantitative impact assessment of social and environmental aspects was relatively weak, and these impacts were estimated according to the proportion of visible economic impacts. Thus, future research will focus on quantitatively assessing the social and environmental impacts of water transfer projects. Finally, to further assess the impacts of the water transfer projects in the flood season and the dry season, the proposed integrated impact assessment method should be implemented at the seasonal scale. These results would provide a scientific basis for project operations and policy formulation.

CONCLUSION

The implementation of a water transfer project can effectively improve the living environment, alleviate water stress issues and sustain regional development in the water-receiving areas. An impact evaluation of a water transfer project can provide technical support for decision makers to choose scientific and reasonable dispatch schemes and achieve successful long-term operations.

In this paper, an integrated method of assessing the impacts of water transfer projects on regional development is put forward. The method was applied to the water transfer project from the Yangtze River to the Taihu Lake. The main conclusions of the study are as follows:

1. An integrated method was developed to assess the impacts of water transfer projects on regional development. The proposed method includes quantitative assessment and qualitative assessment techniques. The former is to analyze the economic, social and environmental impacts of the project from a macro-level perspective, and the latter is to furtherly evaluate benefits of the project by the monetization method from the micro-level perspective. In the quantitative evaluation of the impacts of water transfer impact, the sharing coefficient method was adopted. In the qualitative assessment, a comprehensive index method was employed. The qualitative evaluation index system was established from economic, social and environmental perspectives, and the weights of indicators were determined by the AHP–entropy combined method.
2. The method was applied to the water transfer project from the Yangtze River to the Taihu Lake. The qualitative assessment results indicated that the impact of the project on regional development was regarded as a 'large positive impact' in 2016. In the quantitative assessment, the comprehensive benefit of increasing water supply via the water transfer project was 1.87 billion CNY, of which the visible benefit was 1.46 billion CNY in 2016. Among all involved cities, Shanghai had the highest benefit of 0.71 billion CNY from supplied water, followed by Jiaxing and Suzhou, with 0.57 and 0.54 billion CNY, respectively.
3. This paper proposed an integrated framework for assessing the impacts of water transfer projects on regional development; however, there are still some problems that need to be addressed. First, the sharing coefficient in this study was determined on the basis of previous research, and the coefficient needs specific research in the future. Second, the method of determining the quantitative benefit on social and environmental impacts was insufficient; therefore, future research will focus on quantitative assessments of the social and environmental impacts of water transfer projects. Finally, to further assess the impacts of the water transfer project in the flood season and the dry season, it is suggested that the integrated impact assessment needs implementation at seasonal scales. The results will provide a scientific basis for project operation and policy formulation.

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