

Research papers

Assessing environmental, economic, and social impacts of inter-basin water transfer in China

Yuan Liu^a, Zhuohang Xin^{a,*}, Siao Sun^{b,d}, Chi Zhang^a, Guangtao Fu^c^a Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian, Liaoning 116024, China^b Key Laboratory of Regional Sustainable Development Modeling, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China^c Centre for Water Systems, University of Exeter, Exeter EX4 4QF, UK^d University of Chinese Academy of Sciences, Beijing, China

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ABSTRACT

Inter-basin water transfer (IBWT) has been widely implemented to address water deficit problems in many parts of the world. IBWT projects can pose various environmental, economic, and social impacts on both water recipient and source basins. This study presents an analysis of multi-dimensional impacts of China's IBWT at the sub-basin scale, using three newly developed indicators. The analysis is based on China's operating IBWT projects in 2016, which had a collective capacity of transferring ~ 48 billion m^3/yr water across sub-basins. Results indicate that IBWT helped improve environmental flow conditions in 20 out of 26 recipient sub-basins, with 6 out of 17 source sub-basins experiencing critical environmental flow conditions. IBWT generated net economic benefits of approximately 4.2 billion US dollars and net social benefits of providing domestic water use for 170 million people. IBWT posed overall positive environmental, economic, and social impacts, with the most benefits delivered to the North China Plain (i.e., the Huai and Hai River Basins). However, a few water source basins with relatively low local water availability were faced with a high risk of low environmental flows and high socio-economic costs, especially under low water resources conditions. Large spatial variations of IBWT impacts were found across sub-basins, which cannot be known by assessment at the major basin level. This highlights the need to assess IBWT impacts at finer spatial scales, considering regional differences in local water resources and social-economic development conditions. This study for the first time reveals multi-dimensional impacts of IBWT in China at the sub-basin scale. The results can be used by policymakers to inform water transfer and water management policies.

1. Introduction

Spatial and temporal mismatch between water resource availability and demand has been a critical challenge in many countries across the world (Gupta and van der Zaag, 2008; Zhou et al., 2017). To address this, inter-basin water transfer (IBWT) projects have been considered a practical approach and received worldwide implementation (Chung and Helweg, 1985; Davies et al., 1992; Wei et al., 2010). IBWT projects are conveyance schemes that transport water from basins with abundant water resources to those subject to water shortages via reservoirs, channels, and pump stations (Xiong et al., 2018). With economic and infrastructure development, the number of IBWT projects and global cumulative transfer capacities have increased rapidly in recent periods

(Shumilova et al., 2018; J. Wang et al., 2021; Yevjevich, 2001). While a large volume of water is relocated through these projects to balance water supply and demand at various temporal and spatial scales, environmental, economic, and social impacts of IBWT associated with water relocation on involved basins have received great research interest recently (L. Zhang et al., 2015; Zhuang, 2016).

IBWT has impacts on both water recipient and source basins (Kundell, 1988). The recipient basins can benefit from increased water supply while the source basins may encounter potential costs due to loss of water availability (J. Liu and Yang, 2012; Zeng et al., 2015). Benefits of IBWT include water stress reduction (Sinha et al., 2020), streamflow recharge (Ding et al., 2020), water quality improvement (Nong et al., 2019), and groundwater level rise (Long et al., 2020). Studies also

* Corresponding author.

E-mail address: xinzh@dlut.edu.cn (Z. Xin).<https://doi.org/10.1016/j.jhydrol.2023.130008>

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showed that water supply from IBWT can facilitate economic development and satisfy living water demand in the recipient basins (Wang et al., 2019; Xiao et al., 2019; Zhou et al., 2017). On the other hand, source basins can face negative impacts such as increasing water scarcity (Sun et al., 2021), streamflow alternation (Tien Bui et al., 2020), aggravated water pollution (F. Sun et al., 2014), and ecosystem degradation (Micklin, 1988). In addition, negative socio-economic impacts include losing development opportunities and large-scale resettlement (Sneddon, 1999; Wilson et al., 2017). Overall, the impacts of IBWT are broad and may cover multiple dimensions (Shumilova et al., 2018). However, most previous studies focused on a single impact of IBWT (Gao et al., 2021; Rollason et al., 2022; N. Zhao et al., 2021). While a few recent studies have explored the multi-dimensional impacts of IBWT projects (Wilson et al., 2017; Kattel et al., 2019; Rogers et al., 2020; Jiao et al., 2021), their focus has primarily been on individual projects or single basins. Multi-dimensional impact of many IBWTs at the national scale is not well understood, despite its importance to water resources management.

China is one of the countries with a large number of constructed and planned IBWT projects in the world (Ding et al., 2020; Sun et al., 2021). It has a long history of constructing IBWT projects to address the mismatch between water availability and demand across the country. The capacity of IBWT projects has been increasing since the 1950s and has grown rapidly in recent years due to the development of the South-North Water Transfer Project (SNWTP; Rollason et al., 2022; Sun et al., 2021; Cheng et al., 2009). It is estimated that there exist about 60 projects (including those under planning and construction) with a design capacity greater than 0.1 billion m³/year or a channel length longer than 50 km (Yu et al., 2018). The SNWTP, being the largest IBWT project in the world, is expected to deliver about 45 billion m³ of water per year from the Yangtze River to the North China Plain by 2050 (Berkoff, 2003; Long et al., 2020). Such a large collection of IBWT projects with high transfer volume calls for a multi-dimensional assessment to evaluate their impacts on water delivering and receiving basins. A recent study by Yu et al. (2018) assessed the sustainability impacts of 59 planning and operating IBWT projects on China's major river basins (e.g., the Yangtze River Basin). These major basins were defined based on the first-level basin classification scheme, which divides the country into 10 major geographical regions with an average area of 950,000 km². However, such a large-scale assessment makes it difficult to consider spatial differences in water resources, socio-economic development, and IBWT projects within each major basin. A finer scale assessment (i.e., based on sub-regions inside major basins) is needed to better characterize the local impacts of IBWT on water recipient and source areas.

To address the abovementioned knowledge gaps, this study presents a framework to assess the multi-dimensional impacts of IBWT at a finer spatial scale (i.e., at the sub-basin level with an average area of 120,000 km²). Compared to the previous basin-level assessment, the sub-basin scale can reveal spatial heterogeneity of IBWT impacts within a major basin. In this framework, the environmental, economic, and social impacts are measured by three corresponding indicators, i.e., Environmental Flow Indicator (EFI), Economic Impact Indicator (EII), and Social Impact Indicator (SII). Specifically, EFI measures how IBWT influences a basin's water availability to meet its environmental flow requirements, i.e., the water quantity required to sustain ecological health in the basin. EII measures the economic value created by using transferred water in agricultural and industrial production. SII represents the number of people whose domestic water use can be influenced by IBWT. The framework is applied to assess the impacts of IBWT projects in China based on the 2016 scenario when the SNWTP just started its preliminary operation and led to a significant increase in transfer capacity. The remaining paper is organized as follows: Section 2 describes the IBWT projects in China, indicators for impact assessment, and data sources. Impact results are shown and discussed in Section 3. Concluding remarks are drawn in Section 4.

2. Methodology

2.1. Overview of IBWT projects in China

The mainland China is comprised of 10 major river basins, which can be further divided into 76 sub-basins (Sun et al., 2021). This study focuses on the 45 IBWT projects that were in operation in 2016, which influenced 43 sub-basins across all the major river basins. Among the involved sub-basins, 26 of them were net recipients, and the remaining 17 sub-basins were net water providers. The total design capacity of all the IBWT projects amounted to approximately 48 billion m³/year by 2016. Sixteen of these projects, each with a design capacity greater than 1 billion m³/year, collectively accounted for 73% of the national IBWT capacity. The Yangtze River Basin provided the largest volume of water supply (31 billion m³/year, about 66% of the national IBWT capacity, Fig. 1b). The Huai and Hai River Basins were primary recipient basins, receiving 14 billion m³ (29%) and 13 billion m³ (27%) of water each year. The IBWT was designed to transfer a total of 29 billion m³/year of water across major basins, and 19 billion m³/year of water between sub-basins within the boundary of a major basin.

2.2. Multi-dimensional impact analysis

2.2.1. Environmental impact assessment

Environmental flow requirement (EFR), i.e., the water quantity required to sustain ecological system health in the sub-basin, is used to assess the environmental impacts of IBWT projects (Aceman and Dunbar, 2004; Arthington et al., 2018). An IBWT project is considered to pose positive environmental impacts if it provides water to meet the sub-basin's EFR and vice versa. This impact is measured by the Environmental Flow Indicator (EFI), defined as the mean of the ratio of monthly water availability for environment to EFR in the sub-basin:

$$EFI_i = \frac{1}{12} \sum_{j=1}^{12} f\left(\frac{R_{ij}}{EFR_{ij}}\right) \quad (1)$$

$$f\left(\frac{R_{ij}}{EFR_{ij}}\right) = \begin{cases} \frac{R_{ij}}{EFR_{ij}} & R_{ij} < EFR_{ij} \\ 1 & R_{ij} \geq EFR_{ij} \end{cases} \quad (2)$$

where $EFI_i \in [0, 1]$ is the Environmental Flow Indicator in sub-basin i , R_{ij} is the water availability for environment in month j (i.e., natural water availability subtracted by water consumption and transfer, unit: m³), and EFR_{ij} is the environmental water requirement in month j (unit: m³).

$\frac{R_{ij}}{EFR_{ij}}$ represents the ratio of water availability for environment to EFR in month j . If R_{ij} is higher than or equal to EFR_{ij} , $f\left(\frac{R_{ij}}{EFR_{ij}}\right)$ is assigned to 1, indicating that the EFR is met in month j , otherwise $f\left(\frac{R_{ij}}{EFR_{ij}}\right)$ returns the ratio $\frac{R_{ij}}{EFR_{ij}}$, indicating only a proportion of the EFR is met. The water availability for environment R_{ij} is calculated as follows:

$$R_{ij} = \begin{cases} 0 & W_{ij} - P_i \sum_{k=1}^4 U_{ijk} + T_{ij} < 0 \\ W_{ij} - P_i \sum_{k=1}^4 U_{ijk} + T_{ij} & W_{ij} - P_i \sum_{k=1}^4 U_{ijk} + T_{ij} \geq 0 \end{cases} \quad (3)$$

where W_{ij} is the monthly water resources (unit: m³). P_i is the consumption ratio (unit: %), i.e., the percentage of water that does not return to the surface or groundwater after use. U_{ijk} ($k = 1, 2, 3, 4$) is the water use in agricultural, industrial, domestic, and ecological sectors (unit: m³). T_{ij} represents the net volume of water transfer in the sub-basin (unit: m³, received volume minus diverted volume). R_{ij} is assigned to zero if monthly water resources are less than water demand (i.e., water consumption and transfer), indicating that there is no water available for environmental flows. Following Sun et al. (2021), upstream

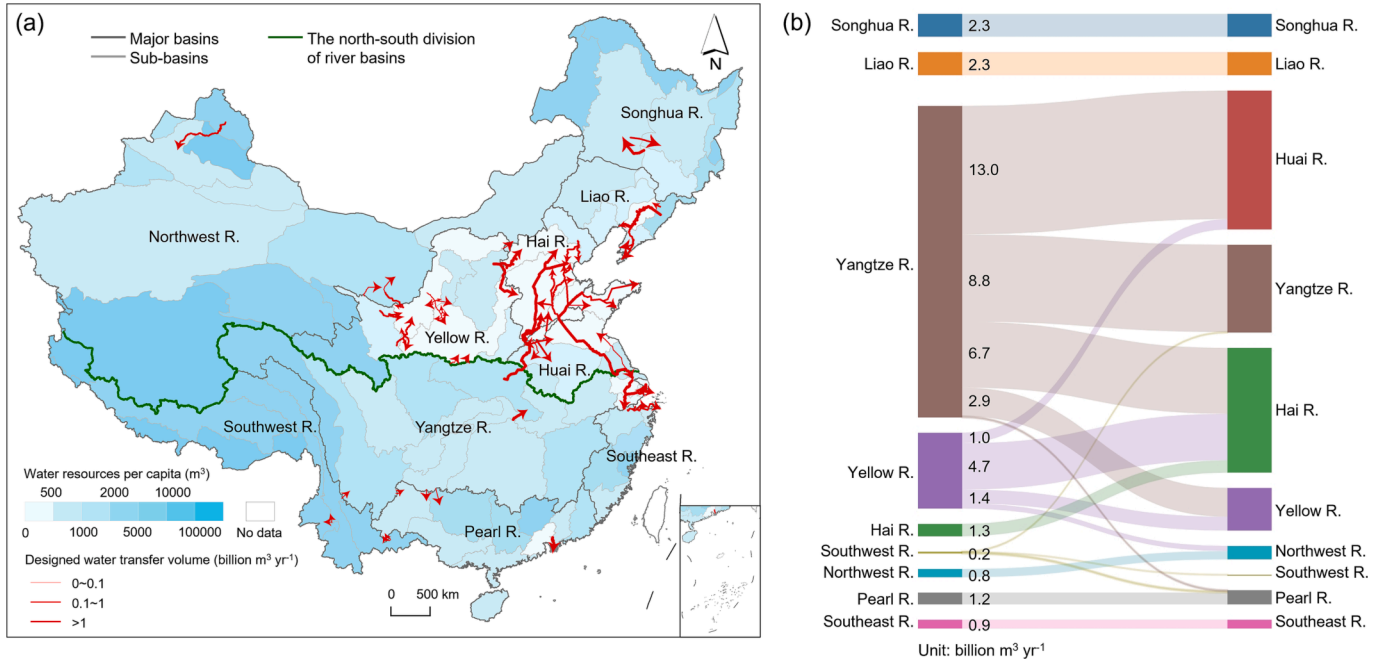


Fig. 1. a) Inter-basin water transfer projects in China by 2016 (modified from Sun et al., 2021). Each red arrow represents one IBWT project, starting from the source sub-basin and pointing to the recipient sub-basin. The arrow stem width denotes the magnitude of designed transfer volume. The background color represents water resources per capita in each sub-basin. b) Designed transfer volume between major basins. The left column shows the volume diverted from each major basin while the right column shows the volume received by each major basin. The numbers indicate the transfer volumes. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

water resources are considered available for downstream sub-basins in the Yangtze and Yellow River Basins to avoid overestimating downstream water shortage. The EFR in Eq. 1 is calculated using the Tennant Method, which defines EFR as 40% of the monthly mean water resources (i.e., long-term average from 1956 to 2016) from April to September and 20% of the monthly mean water resources from October to March. The 40% (20%) thresholds represent water resources needed to sustain a “good” level of environmental quality of a basin (Tennant, 1976). The sensitivity of choosing different levels of EFR will be discussed in Section 3.1.2.

We assess the environmental impacts of IBWT by computing the percent change of EFI before and after including the water transfer volume:

$$\Delta EFI_i = \frac{EFI_{i-div} - EFI_{i-0}}{EFI_{i-0}} \times 100\% \quad (4)$$

where EFI_{i-div} represents the EFI with water transfer in basin i . It was computed with the water transfer volume T_{ij} included in Eqs. (1)–(3). EFI_{i-0} is the EFI computed without considering IBWT. A positive ΔEFI_i indicates an improved environmental flow condition due to IBWT.

2.2.2. Economic impact assessment

The economic impact is measured as the economic value created by IBWT in agricultural and industrial production. We focus on computing the “extra value” of transferred water to quantify its economic benefits over local water resources. Specifically, in the agricultural sector, we calculate the increased economic value of crops irrigated by transferred water compared to rain-fed conditions. In the industrial sector, we calculate water costs saved by using transferred water to replace local alternative sources (i.e., reuse water). The Economic Impact Indicator (EII) is defined as:

$$EII_i = \sum_{j=1}^{12} [T_{Aij}(V_{Ai} - C) + T_{Iij}(V_{Ii} - C)] \quad (4)$$

where EII_i is the Economic Impact Indicator in sub-basin i (unit: \$), T_{Aij} is the water received (lost) for agricultural use in the recipient (source) sub-basin in month j (unit: m³), V_{Ai} is the economic value of irrigation water, i.e., the increased benefit of crops irrigated by transferred water compared to those fed by rainfall (unit: \$/m³, described further in Section 2.3), T_{Iij} is the water received (lost) for industrial use in the recipient (source) sub-basin (unit: m³), V_{Ii} is the saved cost of using transferred water instead of local reuse water in industrial production, measured as the production cost of reuse water (unit: \$/m³), C is the cost of transferred water (set as 0.03 \$/m³), which is calculated based on average electricity consumption for IBWT (0.6 kWh/m³, Yu et al., 2018) and national average electricity price (National Energy Administration, 2016).

We allocate transferred water to agricultural and industrial sectors (i.e., T_A and T_I) based on the IBWT project’s design goal and its destination subbasin’s sectoral water use. For example, if an IBWT project is designed for agricultural and industrial water supply, the transferred water is allocated to these two sectors based on the share of sectoral water uses in the recipient sub-basin. In contrast, the economic cost of a source sub-basin indicates that the source sub-basin may lose opportunities to generate such economic values with the diverted water. The water loss is subtracted from each sector proportional to corresponding sectoral water use in the source sub-basin. We assume no economic cost in a source sub-basin if the EFR can be met after water diversion. That is, the economic cost in the source basin only occurs when the water availability for environment is lower than EFR after water transfer. For each sub-basin, the economic impact is measured as the net economic value, i.e., economic benefits from received water subtracted by economic costs from diverted water.

2.2.3. Social impact assessment

The social impact of IBWT is defined as the number of people influenced by changes in domestic water supply due to water transfer:

$$SII_i = \frac{1}{12} \sum_{j=1}^{12} \frac{T_{Dij}}{w_{ij}} \quad (5)$$

where SII_i is the Social Impact Indicator in sub-basin i (unit: people), T_{Dij} is the water obtained (lost) for domestic use in the recipient (source) sub-basin in month j due to water transfer (unit: m^3), w_{ij} is the domestic water use per capita in month j in the sub-basin (unit: m^3/person , details see Section 2.3). T_{Dij} is allocated based on the proportion of domestic water use in the sub-basin and the design goal of the IBWT project. A positive SII value represents social benefit, i.e., the number of people whose domestic water use can be supported by received IBWT in the recipient basin. A negative SII value represents social cost, indicating that the source sub-basin lost opportunities to provide domestic water supply for a number of people. The cost only occurs if the EFR is not met after considering water transfer. The social impact is measured as the net social benefit that sums up the impacts from all the IBWT in this sub-basin. For example, if a sub-basin receives water and also provides water for other IBWT projects, the social impact is the social benefits of received water minus the social costs of diverted water.

2.3. Data sources and processing

The 2016 IBWT project records are collected from multiple sources, including literature, official reports, planning documents, news, and other online materials, based on previous studies (Sun et al., 2021; Sun et al., 2023). Due to the lack of operation data in IBWT, we assume that most projects (except the SNWTP) operate with a transfer volume that follows a Gaussian distribution with a mean of 80% design capacity and a relative standard deviation of 0.1. The 95% confidence interval (CI) of the transfer volume covers 64–96% of the design capacity. Since the SNWTP was under testing in 2016, its mean transfer volume is assumed to be 50% of its design capacity. These proportions are our best estimates of the actual transfer volume based on project documents, reports, and online news (Sun et al., 2021).

Inter-annual fluctuations of natural water resources directly impact the water availability after IBWT. For example, source sub-basins have less environmental flows in a dry year than a wet year. Previous studies considered this source of uncertainty by using multiple years of water resources based on observations and model simulations (Hu et al., 2013; Long et al., 2020; Sun et al., 2023). There were also applications that used multi-year averages (Y. Zhao et al., 2017) or records in specific years (Zeng et al., 2015; Nong et al., 2020; J. Liu et al., 2020), depending on the experiment design and data availability. Here we consider inter-annual water resource uncertainty by computing the impact indicators based on annual water availability from 1956 to 2016. These annual water resource data are collected at the major basin level from the literature and China Water Resource Bulletins (Li et al., 2014; Ministry of Water Resource of China, 2016). The collected data are downscaled to a monthly, 0.25-degree grid scale proportional to the monthly runoff simulations from a calibrated Variable Infiltration Capacity (VIC) model (Zhang et al., 2014b). The downscaled water resources data are then aggregated by sub-basins to compute each impact indicator. The water resources data has a good representation of the mean annual water resources (2.76 trillion m^3 from 1956 to 2016, Fig. A1a), close to the long-term average of 2.77 trillion m^3 according to China Water Resources Bulletins (Ministry of Water Resource of China, 2016).

Monthly water use in 2016 in each sub-basin is obtained by downscaling the province-scale annual water use data collected from China Water Resource Bulletins, categorized by agricultural, industrial, domestic, and ecological sectors (Ministry of Water Resource of China, 2016). The provincial water use data are first downscaled to a monthly, 0.25-degree grid scale based on multi-source data, including meteorological data, land use, gross domestic product, nightlight brightness, and population, by a previous study (Ma et al., 2020). The grid-scale water use data are then aggregated by sub-basins (Fig. A1b). Province-scale

water consumption ratios are also collected from China Water Resource Bulletins (Ministry of Water Resource of China, 2016). The consumption ratio for each sub-basin (Fig. A1c) is computed by averaging the consumption ratios from overlapped provinces, weighted by corresponding water use.

The economic value of irrigation water represents the increased profit of agricultural production using irrigation water (i.e., transferred water in this study) in comparison to rain-fed conditions. They are calculated by a mechanistic biophysical method on 10-km grids at the global scale, based on the distributions, yields, and prices of crops in 2000, according to D'Odorico et al. (2020). We derive the value of irrigation water for each sub-basin by averaging the non-zero grids within the sub-basin boundary (Fig. A1d). The value is then converted to the 2016 price based on inflation rates. The computed value of irrigation water for sub-basins ranges from 0.1 $\$/\text{m}^3$ to 0.4 $\$/\text{m}^3$, and the national average is 0.25 $\$/\text{m}^3$. To compute the economic impacts in the industrial sector, the production costs are collected for two common approaches of water reuse production, i.e., seawater desalination and wastewater reclamation. The seawater desalination costs were computed at the provincial level by Jia et al. (2019) based on Annual Report for China Desalination in 2016 (State Oceanic Administration, 2017). The wastewater reclamation costs are retrieved from a survey of 54 wastewater treatment plants conducted by Zhang et al. (2014a), which covered almost all the running centralized reclaimed wastewater treatment plants in China by 2014. We compute the production cost for each province by averaging the costs of wastewater treatment plants, weighted by their production capacities. If no treatment plant data is available in one province, the national average cost is assigned. We then obtain the cost for each sub-basin by averaging the costs of overlapping provinces, weighted by corresponding industrial water uses (Fig. A1e). The population data in 2016 are collected from China Statistical Yearbooks on the provincial scale (National Bureau of Statistics of China, 2016). They are downscaled to grid cells based on rural residential areas, urban areas, and nighttime light by a previous study (Ma et al., 2020) and then aggregated at the sub-basin level (Fig. A1f). Monthly domestic water use per capita is calculated as the ratio of monthly domestic water use to total population.

The process for assessing the IBWT impacts is summarized here. The three impact indicators are computed taking into account uncertainties in both annual water resources and water transfer volume. We use annual water resources from 1956 to 2016 (61 years), where each year is associated with 1,000 random realizations of water transfer volume sampled from Gaussian distributions (as described earlier in this section). This results in 61,000 hypothetical cases with combinations between different water resources and IBWT volumes. We then compute and analyze the average and extreme values of the three indicators based on these combinations.

3. Results and discussion

3.1. Environmental impacts

3.1.1. Impact estimates

The IBWT improved the environmental flow conditions of most recipient sub-basins in North and Northeast China. However, some source sub-basins with relatively low water resources were likely to experience aggravated environmental flow conditions. Based on the average EFI scenario from different water resources and transfer volumes (Fig. 2a), a total of 20 sub-basins had increased EFIs after IBWT (i.e., experienced improved environmental flow conditions). The Huai River Basin had a median of 4 EFI-improved sub-basins, with an average increase in EFI ranging from 8% to 54%. This was followed by the Hai, Liao, and Northwest River Basins, each having 3 sub-basins with EFI increments varying between 90%–360%, 5%–122%, and 0.15%–25%. The remaining sub-basins with improved environmental flow conditions were mainly distributed in the Songhua River and Pearl River Basins,

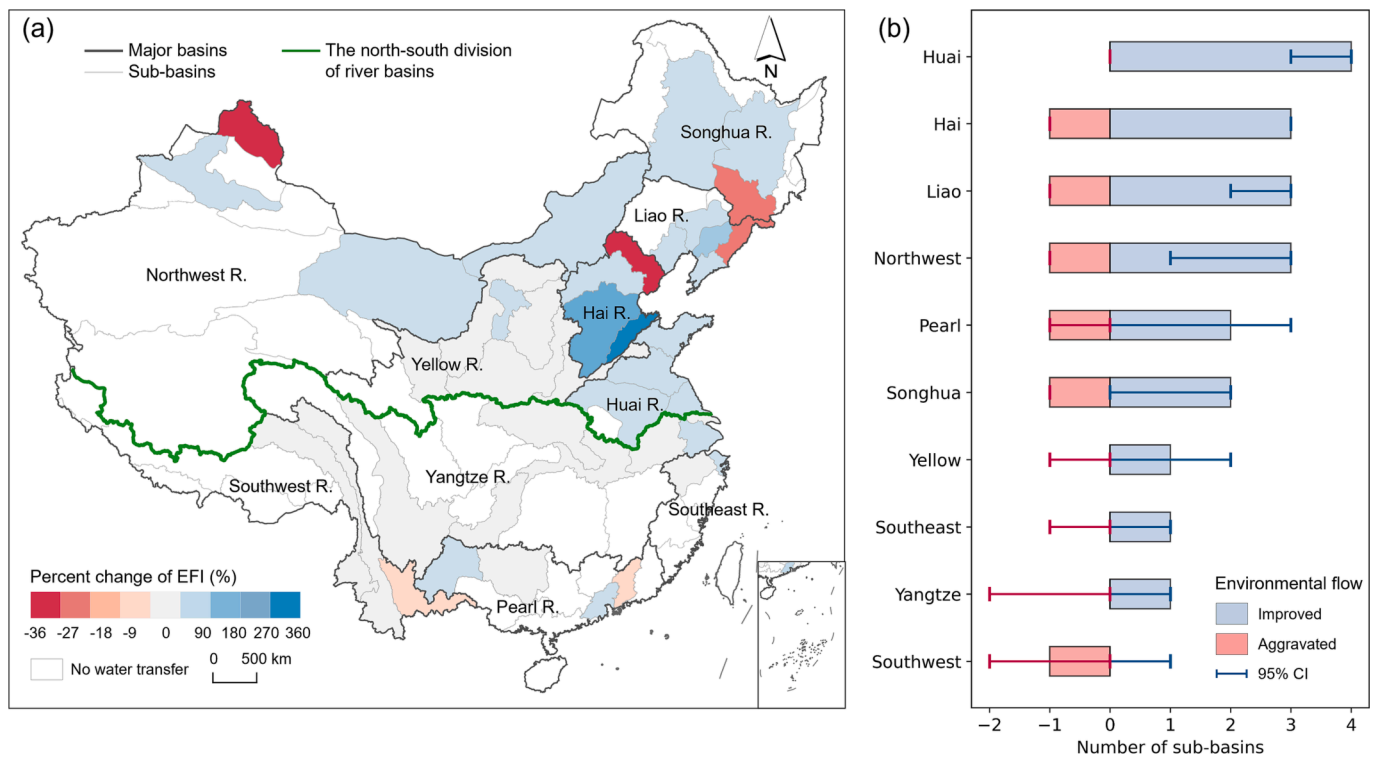


Fig. 2. (a) Average percent change of EFI after IBWT, taking into account uncertainties in water resources and transfer volume. (b) The number of sub-basins with improved and aggravated environmental flow conditions in each major basin. The bar shows the median of EFI-improved/aggravated sub-basin numbers, and the whisker shows the 95% confidence interval, based on annual water resources between 1956 and 2016 and transfer volume uncertainties.

with an average of 7% increase in EFI. On the other hand, 6 sub-basins faced decreased EFIs (i.e., aggravated environmental flow conditions) that ranged from -38% to -4%. Most of them were located in the north and northwest of China. The average EFIs in the other 17 involved sub-basins remained unchanged (consistently at 1). A majority of them (11 sub-basins) were source regions and were mostly located in the Yangtze and Yellow River Basins. This suggests that they had abundant water availability to meet the EFR after water transfer.

Variations in annual water resources and water transfer volume can influence the environmental flow status. By analyzing the EFI estimates from all hypothetical cases, we find that changes in annual water resources have a greater influence on EFI estimates than changes in IBWT volume. Here we show four extreme cases where the highest/lowest number of sub-basins with improved/aggravated environmental flow conditions (Fig. 3). These cases are computed using water resources from a historical year paired with the average IBWT volume in 2016. The highest number of EFI-improved sub-basins was 22 based on water resources in 1984, which was a dry year ranking in the 39th percentile of 1956–2016 annual water resources (Fig. 3a). The two additional EFI-improved sub-basins, compared to the average condition, also had relatively low water resources (on average, at the 30th percentile of their long-term water resources). Conversely, the lowest number of EFI-improved sub-basins was 14 based on the 2013 water resources (Fig. 3b). In this case, the 6 sub-basins that shifted from “improved” to “unchanged” environmental flow conditions, as compared to the average scenario, had higher water resources (ranking at an average of the 75th percentile of long-term records). This suggests that IBWT plays a more important role in improving the environmental flow conditions of recipient sub-basins in a drier year, when sub-basins struggle to maintain the EFRs.

The largest number of sub-basins with worsened environmental flow conditions occurred in 1966 with 10 sub-basins showing decreased EFIs, which was another dry year in the 26th percentile of long-term records (Fig. 3c). The 4 additional EFI-aggravated sub-basins were also under

dry conditions, ranking at an average of 30th percentile in their respective long-term water resources. In contrast, in the year 1975 (with the 87th percentile of water resources), only 4 sub-basins showed a decreased EFI (Fig. 3d). These sub-basins remained in aggravated environmental flow conditions regardless of changing annual water resources, indicating that they are the most vulnerable source regions of worsening environmental flow due to IBWT. The number of EFI-aggravated sub-basins tends to increase when the water resources in source sub-basins decrease.

Overall, the IBWT generally improved the environmental flow conditions in an average of 20 recipient sub-basins, predominantly located in North and Northeast China. Conversely, aggravation in environmental flows occurred in an average of 6 sub-basins that were mainly located in North and Northeast China. Variations in annual water resources and IBWT volume can change the number of EFI-improved sub-basins from 14 to 22 and the number of EFI-aggravated sub-basins from 4 to 10. The number of EFI-improved/aggravated sub-basins tends to increase as the annual water resources decrease, while other factors such as the monthly distribution of water resources can also influence the estimates. This indicates that both positive and negative IBWT impacts on environmental flows are expected to be more pronounced during dry years. Evaluating under both average and extreme climatic conditions (e.g., the driest and wettest years) are needed in understanding the impact of IBWT.

3.1.2. Influence of environmental flow requirement (EFR)

This study uses a uniform EFR level (i.e., the same seasonal proportion of long-term annual water resources) to estimate the EFI. However, sub-basins in different geographic and climatic regions may require different EFRs, i.e., the minimum amount of water resources, to sustain the local environment. Using a uniform EFR level neglects this regional heterogeneity and may cause under or over-estimation of IBWT impacts on environmental flows. To evaluate the influence of EFR, we perform a sensitivity analysis by computing the EFIs based on EFR levels

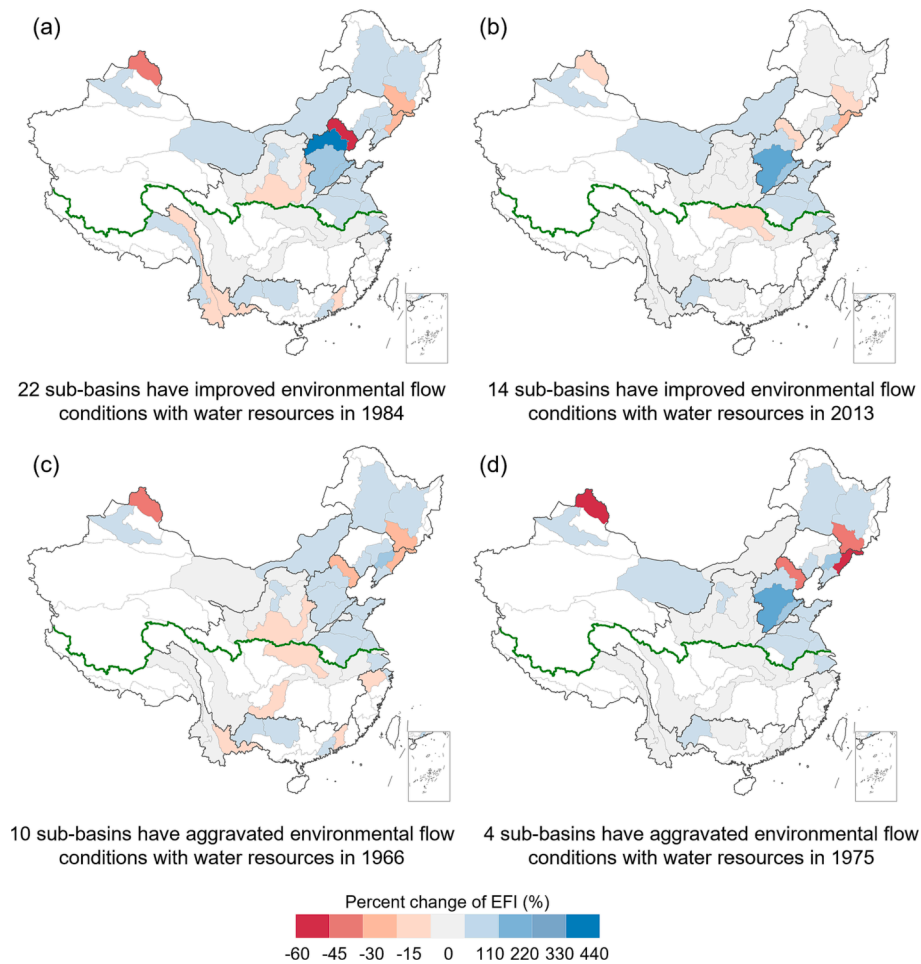


Fig. 3. Extreme EFI scenarios based on water resources in a historical year. (a) The largest number of EFI-improved sub-basins. (b) The least number of EFI-improved sub-basins. (c) The largest number of EFI-aggravated sub-basins. (d) The least number of EFI-aggravated sub-basins.

from “moderately degraded” to “excellent,” according to the Tennant method (Table 1; Tennant, 1976). The other variables are fixed in the computation, i.e., using the average IBWT volume and long-term average of annual water resources. The analysis shows that as the EFR level increased from “moderately degraded” to “excellent,” the number of EFI-improved sub-basins increased from 15 to 20 (Figs. A2 and A3). This is because at a higher EFR level, more recipient sub-basins failed to meet the EFR before IBWT, and those gaps were filled by additional water supplied through IBWT projects.

Source sub-basins appear to be rather insensitive to EFR changes, as there were consistently 4 sub-basins that showed decreased EFI using different levels of EFRs. This suggests that most of the source basins had sufficient remaining water resources to meet even the “excellent” level of EFR. However, the inability to meet the lowest EFR level in the 4 source sub-basins indicates severe threats to environmental flows in these areas. In short, while using the “good” level of EFR for all the sub-basins can have a certain influence on estimating EFIs, most of the sub-

basins were generally not sensitive to changes in EFR levels. For a more accurate assessment, it is recommended to use regional-specific EFR for each sub-basin. More comprehensive EFR-estimating methods, such as the Range of Variability Approach (RVA; Richter et al., 1997) and the Building Block Method (BBM; Acreman and Dunbar, 2004), can be utilized to determine EFR values that better represent the regional characteristics of the sub-basins.

3.1.3. Limitations of the EFI

The EFI is developed to reveal the direct impact of IBWT on environmental flow conditions in both recipient and source sub-basins. It primarily measures the monthly gaps between remaining water resources and EFR in the involved sub-basins, which also allows it to incorporate seasonal variations in water resources and usage. The changes in EFIs represent how these gaps were narrowed or widened due to water gain or loss after IBWT, serving as a convenient indicator to evaluate IBWT impacts on environmental flow conditions. However, this indicator is based on several assumptions that could limit its applications. First, it assumes that increasing a sub-basin’s water availability to meet the EFR can improve local environments and vice versa. The indicator does not represent IBWT influences on other environmental aspects such as groundwater level, water quality, carbon emission, or habitat quality, which require additional representative variables from observations or models. Second, the indicator assumes uniform seasonal EFRs for all the evaluated sub-basins, which can neglect regional EFR differences and result in under or over-estimated EFIs (discussed in detail in Section 3.1.2). Third, the indicator depends on the quality of

Table 1

Recommended EFR (% of mean water resources) to maintain various levels of environmental quality, according to Tennant (1976).

EFR category	Proportion of mean water resources (%)	
	October to March	April to September
Outstanding	40	60
Excellent	30	50
Good (this study)	20	40
Moderately degraded	10	30

water resources and water use data at the sub-basin level, which are obtained through data downscaling (see Section 2.3). Although we are using the best available estimates at the sub-basin scales, biases in runoff models and other observation-based data sources can introduce uncertainty to the final impact results. Expanding the current framework with multi-indicators that incorporate extra variables, such as water quality indices, can provide more comprehensive estimates of the environmental impacts of IBWT projects.

3.2. Economic impacts

3.2.1. Impact estimates

The estimated average annual net economic benefit of IBWT was 4.3 billion US dollars, with a 95% CI ranging from \$3.9 billion to \$4.6 billion. The Huai, Hai, and Yangtze River Basins benefited the most from IBWT and, on average, gained about \$1.7, \$0.9, and \$0.8 billion, respectively (Fig. 4a). The Huai River Basin obtained the largest agricultural benefit of \$1.5 billion, while the Hai River Basin gained the largest industrial benefit of \$0.26 billion. The other major basins had economic benefits ranging from \$0.01 to \$0.2 billion. The agricultural benefits were larger than industrial benefits in most major basins, constituting an average of 66% of the total benefits. On the contrary, the industrial benefit was the primary component in the Northwest (53%), Liao (71%), and Southeast (73%) River Basins.

A total of 24 sub-basins experienced positive average economic impact due to IBWT, while 9 sub-basins faced negative average economic impacts (Fig. 4b). All the involved sub-basins in the Huai River Basin obtained economic benefits ranging from \$0.07 to \$1 billion, one of which achieved the highest agricultural benefit (\$0.9 billion) among all the sub-basins. There were 3 sub-basins in the Hai River Basin and 2 sub-basins in the Yangtze River Basin that achieved economic benefits between \$0.1 billion to \$0.6 billion. The Northwest River Basin also had 2 sub-basins with benefits of \$0.13 and \$0.24 billion; the latter obtained the largest industrial benefits of \$0.2 billion of all the sub-basins. The economic benefits of other sub-basins ranged from \$0.002 to \$0.2 billion. Among the 9 sub-basins with negative economic benefits, 5 of them experienced relatively higher net economic costs ranging from \$0.02 to \$0.06 billion. These sub-basins are located in the Liao, Songhua, Northwest, Pearl, and Hai River Basins. The remaining 4 sub-basins incurred comparatively minor costs, with an average of \$0.002 billion each. There were 10 sub-basins that exhibited zero economic benefit and cost. Half of these sub-basins had abundant water availability to meet EFR so that no economic cost would occur (Section 2.2.2). The remaining of them received water for domestic use and did not generate agricultural and industrial benefits.

The economic benefits were primarily influenced by uncertainties in

IBWT volumes, as greater water transfers typically yielded higher benefits in the recipient sub-basins. The Huai River Basin (\$1.5–1.9 billion within the 95% CI) and Yangtze River Basin (\$0.6–1 billion within the 95% CI) exhibited higher variability in economic benefits. This can be attributed to the significant transfer volume uncertainties associated with the SNWTP. Additionally, the Pearl River and Southwest River Basins could experience negative economic impacts between -0.03 and -0.005 billion dollars within the 95% CI. The economic impacts can also be influenced by changes in economic costs in the source sub-basins. When local water resources are low, economic costs tend to increase. For example, IBWT projects in the Yangtze River Basin generated a maximum cost of \$0.4 billion in their source sub-basins, based on water resources in 1978—an extremely dry year (2nd percentile among 61 years of records). Overall, while IBWT generally yielded economic benefits for the recipient sub-basins, it can impose significant costs on source sub-basins during dry years, which might be overlooked under average water year conditions.

3.2.2. Comparison with previous results and limitations of the EII

The economic benefits estimated in this study are significantly lower than those reported in the previous study (Yu et al., 2018). This is because our indicator focuses on the “extra value” of transferred water (i.e., the extra benefits compared to using local water resources) as an alternative resource. We also incorporate a more detailed water allocation process in which the benefits for agricultural and industrial production are computed separately. This allocation process represents a more realistic scenario for IBWT, where a large portion of transferred water is allocated to the agricultural sector with relatively low-value returns. It highlights the inter-sectoral variability of economic impacts in the involved sub-basins, which depends on their sectoral water use structure. This approach contrasts with the direct calculation of the “absolute value” of water (e.g., using GDP per cubic meter of water), which may lead to overestimation. Also, the transferred volume used in this study is based on the operating IBWT projects in 2016, which is lower than the water volume of all the projects including planned and running ones in Yu et al. (2018).

It is important to note that the EII has several limitations that can introduce uncertainties and affect its interpretation. First, the EII assumes that the diverted water is allocated and consumed according to the design goals of the IBWT projects. In practice, however, water use may deviate from the original IBWT objectives, increasing uncertainties in the estimated results. Second, the indicator only incorporates the energy cost (measured as electricity consumption) of operational IBWT projects. While energy consumption for pumping water is one major cost during IBWT operation (Chen et al., 2019; Y. Liu et al., 2023), other expenses related to maintenance and water treatment can reduce

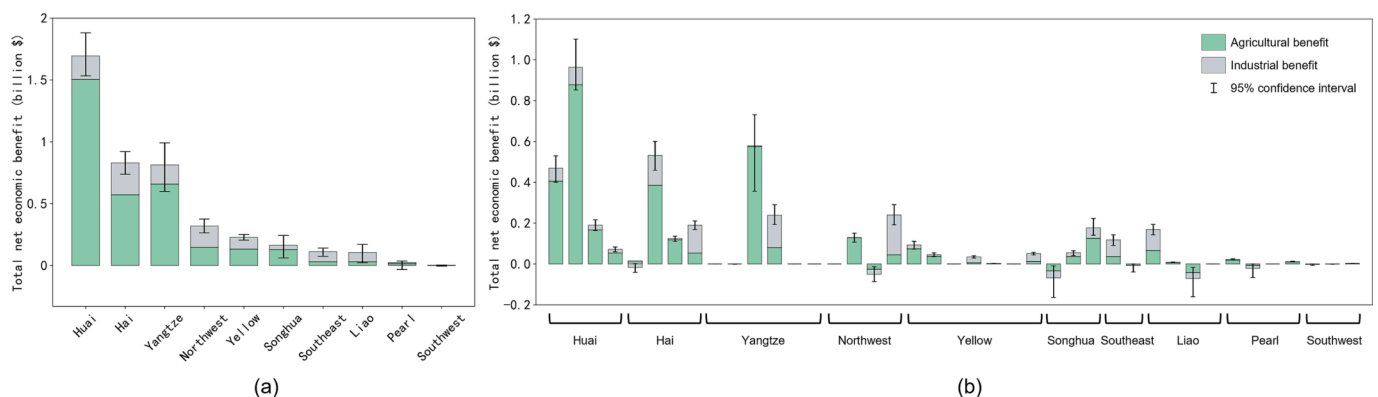


Fig. 4. Average annual net economic benefits of agricultural (green) and industrial (grey) production based on the 2016 IBWT scenario at the (a) major basin scale; (b) sub-basin scale (only IBWT involved sub-basins are shown). The whisker represents the 95% confidence interval of total net economic benefit considering uncertainties in water resources and transfer volume. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

economic benefits. Third, the indicator is influenced by the quality of the economic variables, i.e., the values of irrigation water and costs of reuse water production. The value of irrigation water, as computed by D'Odorico et al. (2020), is based on global crop prices and distributions in 2000. Changes in crop values and distributions from 2000 to 2016 can alter the value of irrigation water, thereby influencing the agricultural benefit estimates. The cost of reuse water production is referred from a government report (Jia et al., 2019) and a comprehensive survey conducted by Zhang et al. (2014a). These sources covered most information on seawater desalination and wastewater reclamation in China up to 2016. However, these economic variables are rescaled from the provincial level to the sub-basin level based on local water use, which can introduce additional bias through rescaling. To address the above-mentioned limitations, more data specific to each IBWT project or sub-basin are needed to compute the EII. This would involve collecting actual allocation and consumption records of transferred water, detailed operating costs of IBWT projects, and values of transferred water for agricultural and industrial production at the sub-basin level.

3.3. Social impacts

3.3.1. Impact estimates

The IBWT provided domestic water supplies that could potentially support an average of 170 million people in the recipient sub-basins, with a range between 158 million and 180 million within the 95% CI. The Hai River Basin benefited the most among all the major basins, receiving domestic water supply for 62 million people (Fig. 5a). The Yangtze River Basin, despite being the primary source basin, received domestic water for 41 million people. This was followed by the Huai and Yellow River Basins; each obtained water supply for 19 million people. The social benefits of the Liao River, Pearl River, Songhua River, and Southeast River Basins ranged from 3 to 12 million people. The social benefit in the Southwest River Basin was close to zero, while a negative social impact of 1 million people was found in the Northwest River Basin. At the sub-basin level, there were 25 sub-basins that received positive social impacts (Fig. 5b). The largest social benefit of individual sub-basins occurred in the Hai River Basin, with IBWT providing domestic water supply for 32 million people, followed by one sub-basin from the Yangtze River Basin, with the social benefit of 30 million people. A total of 9 sub-basins had average negative social impacts; 4 of them encountered more significant domestic water loss, affecting 2–4 million people. The other 5 sub-basins experienced a reduced domestic water supply during periods of low annual water resources, resulting in a negative impact that affected 0.13 million people. The other 9 sub-basins experienced zero social benefit/cost. In these sub-basins, no social cost was accounted for since the available water resources met the EFR (described in Section 2.2.3), or no social benefit was generated because the transferred water was not targeted for domestic use.

Overall, IBWT provided a positive social impact in terms of domestic water supply to recipient sub-basins. Nevertheless, the social costs are sensitive to changes in inter-annual water resources. Domestic water loss in the source sub-basins can affect up to 19 million people under extremely low water resource conditions. Major basins such as the Songhua and Liao River Basins faced a higher risk of losing domestic water supply, potentially threatening up to 8 million people during dry water years. Similar to the economic aspect, assessing social impacts under extreme water resource conditions is necessary to reveal the vulnerability of source sub-basins in IBWT.

3.3.2. Comparison with previous results and limitations of the SII

A similar social impact index was used by Yu et al. (2018), with an estimation of 32–43 million people benefiting from IBWT supply in the Hai, Huai, and Yellow River Basins. On the contrary, our estimates have a larger inter-basin variability, with the largest social benefit occurring in the Hai River Basin (62 million people). The differences are partly attributed to the design goals of IBWT projects being considered in our study, which affected transferred water allocation to domestic use. Spatial variations in population and domestic water use among sub-basins can also contribute to the regional differences. In our study, the Yangtze River Basin received positive social impacts of domestic water supply for 41 million people, compared to the negative impacts of 70 million people estimated by Yu et al. (2018). The difference is because our study assesses social impacts among sub-basins, whose social benefits can be neglected or averaged out in the analysis at the major basin scale. Also, the source sub-basins in the Yangtze River Basin had abundant water availability, so no social cost was accounted for when the EFR was met after water diversion.

A major limitation of the SII is that it only covers the social impact in terms of domestic water supply. Readers should be aware that other social influences, such as large-scale resettlement, public health, and cultural heritage damages, can also pose significant socio-economic losses in the source sub-basins (Rogers et al., 2020; Shumilova et al., 2018). These impact factors, which require additional variables based on more records and surveys of IBWT, are still not well understood and can be a future study direction. Additionally, our indicator is affected by the deviation in transferred water allocation from the original IBWT design goals. The results are influenced by domestic water use per capita in each sub-basin, which was computed by downscaling official report data at the major basin or provincial level and can introduce uncertainties.

3.4. Impact comparison across the major basins

The environmental, economic, and social impacts of IBWT are compared across the major basins (Fig. 6). The environmental impacts are represented by the ratio of the “net” number of EFI-increased sub-

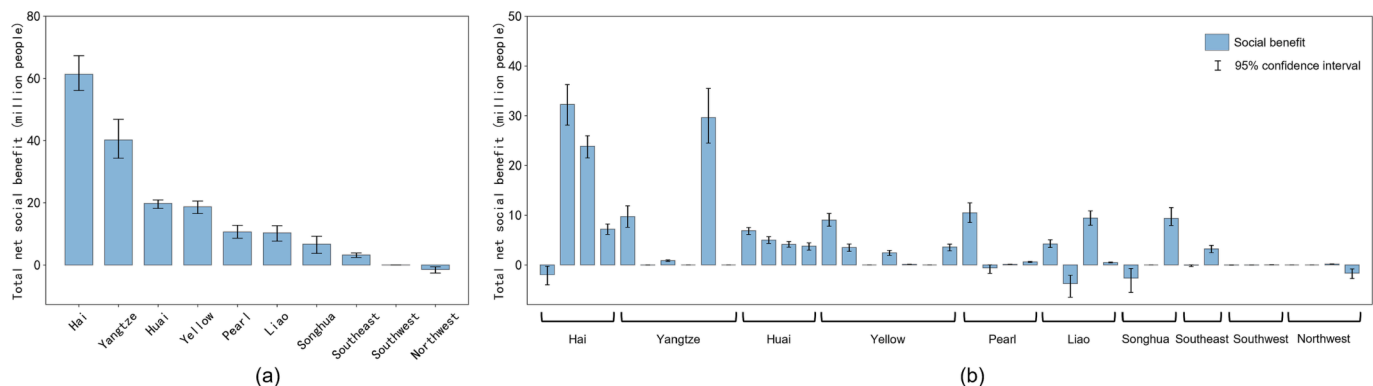


Fig. 5. Average annual net social benefits based on the 2016 IBWT scenario at the (a) major basin scale; (b) sub-basin scale (only IBWT sub-basins are shown). The whisker represents the 95% confidence interval of total net social benefit considering uncertainties in water resources and transfer volume.

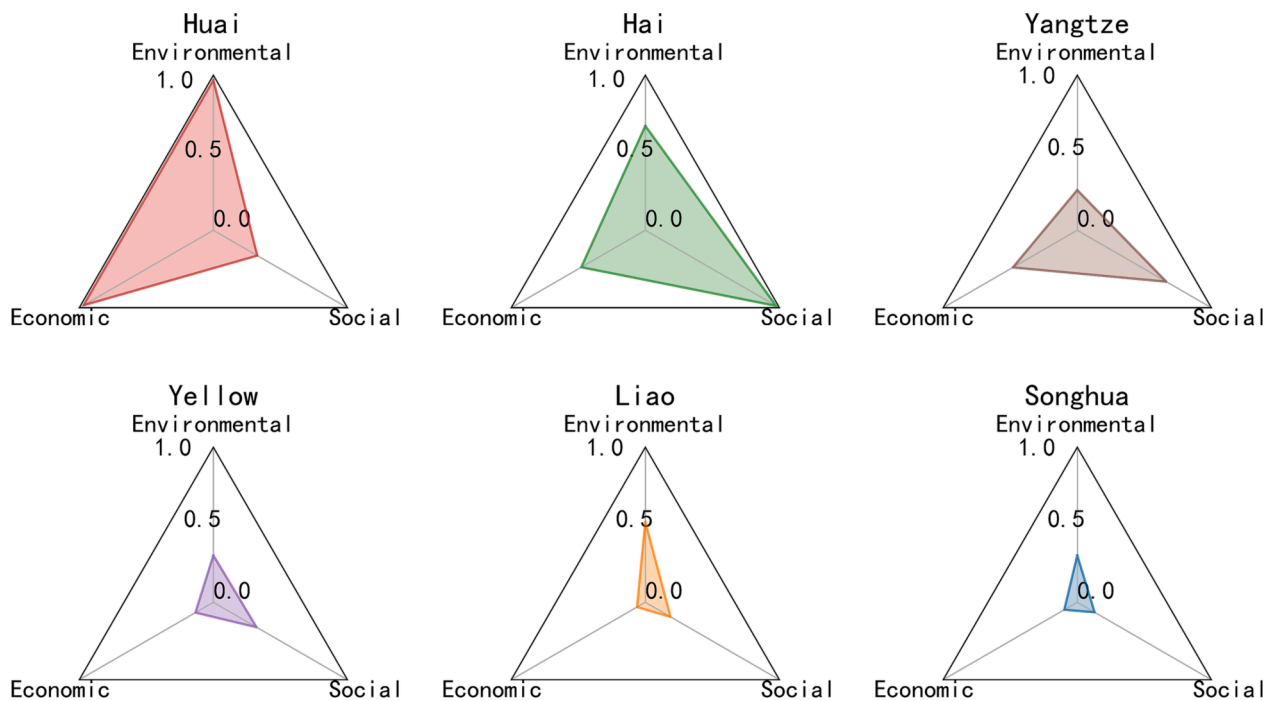


Fig. 6. Radar map of the environmental, economic, and social impacts of IBWT at the major basin level. The “environmental” axis represents the ratio of the “net” number of EFI-increased sub-basins (i.e., the number of sub-basins with improved environmental flow conditions subtracted by the number of those with aggravated environmental flow conditions) to the total number of sub-basins, the “economic” axis represents the annual net economic benefit, and the “social” axis represents the annual net social benefit. The values for the three axes are rescaled between 0 and 1 by min–max normalization.

basins (i.e., the number of sub-basins with increased EFI minus the number of those with decreased EFI) to the total number of sub-basins. The economic and social impacts are represented by annual net economic benefit and annual net social benefit for each major basin. The impact estimates used here are average values, taking into account variations in annual water resources and water transfer volume.

The Huai and Hai River Basins achieved the highest economic and social benefits, with 4 out of 5 sub-basins and 3 out of 4 sub-basins showing positive impacts, respectively. The two major basins also received improvements in environmental flow conditions. However, one sub-basin in the Hai River Basin encountered aggravated EFI due to IBWT. In the Yellow River Basin, 5 out of 7 sub-basins obtained positive economic and social benefits, with one of them experiencing improved environmental flow conditions. The Liao and Songhua River Basins also benefited from IBWT, particularly in the environmental aspect. Specifically, 3 out of 6 sub-basins in the Liao River Basin and 2 out of 8 sub-basins in the Songhua River Basin experienced improved environmental flow conditions. The impacts on other major basins were relatively minor, with the exception of the Yangtze River Basin, which will be discussed separately.

Although the Yangtze River Basin served as the largest water supplier in IBWT, it achieved the third largest economic benefits and second largest social benefits, with 3 of the 12 sub-basins receiving positive economic and social impacts. The environmental benefit in the Yangtze River was relatively minor, with only one sub-basin seeing an increase in EFI. The overall positive benefits were a result of water relocation between its sub-basins, generating more socio-economic benefits in the recipient sub-basins than costs in the source regions. However, it is important to note that during a dry water year, 2 of its source sub-basins may face aggravated environmental flow conditions (see Figs. 2b and 3c). The associated IBWT projects could lead to a maximum economic cost of \$0.4 billion and impact domestic water supply for 2 million people under extremely low water resource conditions. It should be mentioned that the social impact estimated in this study only covers domestic water supply. Other social impacts, such as compensation costs

for resettlement and loss of job opportunities, would further increase the socio-economic losses in the Yangtze River Basin.

Overall, IBWT primarily brought positive impacts to the North China Plain (i.e., the Huai and Hai River Basins). The relative magnitude of the impacts across the major basins is generally consistent with the received water volume from IBWT (Fig. 1b). The proportions of environmental, economic, and social impacts in each major basin depend on the allocation of transferred water, which is influenced by project goals and local sectoral water use. Significant differences in IBWT impacts can be observed both within and between major basins, underscoring the importance of conducting fine scale assessment (e.g., at the sub-basin level) of operating IBWT projects.

4. Conclusions

In this study, the environmental, economic, and social impacts of IBWT on the recipient and source sub-basins in China are assessed using three newly developed indicators, i.e., EFI, EII, and SII. EFI evaluates the ratio of water availability for the environment to the environmental flow requirement (EFR) in the basin. The change in EFI before and after IBWT reflects the influence of changing water quantities on the sub-basin's ability to meet the EFR, i.e., to maintain certain water resources to sustain ecological health. EII measures the value of using transferred water over local sources for agricultural and industrial production. A positive (negative) EII indicates that the sub-basin gained (lost) opportunities to use transferred water to generate economic benefits. SII measures the maximum number of people whose domestic water use could be affected by IBWT. A positive (negative) SII suggests that the sub-basin gained (lost) opportunities to support domestic water supply for a certain number of people due to IBWT. The three indicators are calculated for the 43 involved sub-basins based on the 45 IBWT projects in 2016 when the SNWTP began its test operation. Annual water resources from 1956 to 2016 are used to determine the possible range of impacts under climatic variations. Additionally, the uncertainties of water transfer volume are taken into account by sampling transfer

amounts based on assumed Gaussian distributions.

IBWT improved environmental flow conditions (i.e., EFI increased after water transfer) in an average of 20 recipient sub-basins, considering variations in annual water resources and transfer volume. These sub-basins were primarily located in North and Northeast China. However, decreased EFIs were observed in an average of 6 source sub-basins. Both positive and negative IBWT impacts on environmental flows are likely to intensify under low water resource conditions, with the number of EFI-improved and EFI-aggravated sub-basins reaching 22 and 10 in certain dry water year scenarios. IBWT generated an average net economic benefit of 4.2 billion US dollars based on 2016 water transfer scenarios. The economic benefit can range between \$3.9 billion and \$4.6 billion, primarily due to uncertainties in IBWT volume. The top three economic beneficiaries were the Huai, Hai, and Yangtze River Basins, yielding average economic benefits of \$1.7, \$0.9, and \$0.8 billion, respectively. A total of 24 sub-basins obtained economic benefits with an average of \$0.2 billion per sub-basin, while 9 sub-basins experienced negative impacts of -\$0.03 billion on average. IBWT also provided social benefits by supporting domestic water use for an average of 170 million people (158–180 million within the 95% CI). The largest social impact beneficiary was the Hai River Basin, receiving domestic water supply capable of supporting 62 million people. There were 25 sub-basins receiving water that could support an average of 7 million people per sub-basin, with large spatial variations among sub-basins. Additionally, 9 sub-basins faced negative social impacts, affecting an average of 1 million people. The economic and social costs of IBWT tend to increase when water resources are low in the source sub-basins, which can potentially lead to an economic loss of \$0.7 billion and impact domestic water use of 19 million people in extremely dry years.

The environmental-economic-social impacts show that IBWT generally had positive effects on the sub-basins, with the most benefits occurring in the North China Plain (i.e., the Huai and Hai River Basins). However, some source sub-basins with low local water availability faced a high risk of insufficient environmental flow and socio-economic costs. These losses tend to be intensified when local water resources are low during dry years, highlighting the importance of considering inter-annual water resource variability in impact assessments. In contrast to previous studies focusing on either one project or one basin, our fine scale assessment uncovers large spatial variations in IBWT impacts across sub-basins. The findings of this study can inform future IBWT planning and management to promote equitable development in both water recipient and source basins.

One limitation of the study is that the assessment does not cover a full range of IBWT impacts, but instead focuses on several key aspects. Other important impacts, such as resettlement compensation and cultural heritage influences, are not evaluated in this study. Therefore, the results should be interpreted carefully under the scope represented by the three indicators. It should also be noted that the impacts are evaluated for IBWT scenarios in 2016; for IBWT in other time periods, the impacts should be recalculated using corresponding water transfer data. Another limitation is that we assume the transferred water was allocated based on the design goal of the IBWT project. This assumption can introduce uncertainties to the impact estimates when practical water allocation deviates from the original IBWT objectives. Furthermore, our indicators require sub-basin level environmental or socio-economic variables (e.g., EFR, values of irrigation water, and water use per capita). The choice of EFR, downscaling of large-scale socio-economic variables, and data quality can all influence the final estimates.

Future research should include more impact-measuring variables under each of the environmental, economic, and social aspects. This may involve evaluating changes in water quality and groundwater levels, as well as the resettled population and associated compensation costs. Another important area is to investigate future projections of IBWT impacts under the influences of a non-stationary climate and human activities. Changing climate will alter regional distributions of precipitation and may intensify the unevenness of water resources between

humid and dry regions. Meanwhile, the number and total capacity of IBWT projects may plateau or even recede in the future, depending on the country's socio-economic developments. The environmental and socio-economic costs of IBWT are also expected to decrease with improvements in water management techniques and strategies. It is anticipated that IBWT will help alleviate water stress caused by climate change. Scenario studies will be needed to understand IBWT impacts in the future, with the help of climate projection information from global climate models.

CRedit authorship contribution statement

Yuan Liu: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization, Writing – review & editing. **Zhuohang Xin:** Conceptualization, Methodology, Visualization, Writing – review & editing. **Siao Sun:** Conceptualization, Methodology, Visualization, Writing – review & editing. **Chi Zhang:** Project administration, Supervision, Funding acquisition. **Guangtao Fu:** Conceptualization, Methodology, Writing – review & editing, Project administration, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jhydrol.2023.130008>.

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