Journal of Hydrology 657 (2025) 133090

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

Quantitative assessment and analysis of the impact of inter-basin water transfer on regional water resource stress

Lichuan Wang [a,b], Fan He [b,*], Yong Zhao [b], Jianhua Wang [b], Meng Hao [c], Peiyi Lu [b], Yage Jia [b], Kuan Liu [b], Haodong Deng [b]

[a] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China

[b] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China

[c] ChinaCollege of Geoscience and Surveying Engineering, China University of Mining and Technology (Beijing), Beijing 100083, China

ARTICLE INFO

This manuscript was handled by A. Bardossy, Editor-in-Chief, with the assistance of Gerald Augusto Corzo, Associate Editor

Keywords:
Water stress
Inter-Basin water transfer
Impact
Spatial-temporal differentiation
Huang-Huai-Hai-Yangtze River Basin

ABSTRACT

With the increasingly serious water shortage and other problems, Inter-basin water transfer (IBWT) has become an important measure to alleviate regional water stress. In this study, based on the improved water stress index (WSI), we comprehensively assessed the multi-scale (urban, tertiary basin zones) spatio-temporal status of WSI in the four major basins of the Huang, Huai, Hai and Yangtze River Basins (HHHYRB) from 1965 to 2020, and analysed the contribution of Inter-basin water transfer to alleviate regional water stress. The Dagum Gini coefficient method was used to determine the differences and sources of WSI distribution. Finally, the impact of each water transfer project was quantitatively analysed through bottom-up scenario derivation. The results show that 35.8% of the cities in the HHHYRB, and 40.4% of the tertiary basins are at medium or higher risk of water stress. The impacts of external inter-basin water transfers in the HHHYRB are all less than 0.002. The IBWT effectively mitigated the WSI in the Hai River Basin (75%) and the Huaihe River Basin (15.6%), negatively affected the WSI in the Yellow River Basin (−6.4%), and had only a 2% impact on the Yangtze River Basin. There is obvious spatial heterogeneity in the WSI of the HHHYRB, and the coefficients between groups (48.3%–66%) are higher than the coefficients within groups (17.3%–23.7%) and hypervariable density coefficients (10.8%–31%). IBWT projects effectively moderate the degree of inequality in water resources, with intra-basin impacts ranging from 1.77% to 33.69% and inter-basin impacts reaching 2.29%–7.28%. Most of the IBWT projects tend to transfer water from areas with low WSI to areas with high WSI with positive impacts, but there are still 10 water transfer projects with negative impacts. Therefore, the impacts of IBWT should be considered comprehensively when formulating water resources management policies in order to achieve long-term sustainable use of water resources.

1. Introduction

Water resources are essential for sustaining human existence, promoting socio-economic development and safeguarding the balance of ecosystems. Over the past few decades, global demand for water has dramatically increased due to socio-economic development and rapid population growth, with consumption rising by approximately 1 percent per year. This trend is expected to continue at a similar rate until 2050 (Amarasinghe and Smakhtin, 2014; He et al., 2021; Hejazi et al., 2013). According to World Bank projections, global freshwater resources will decline by 40 per cent by 2030 (Boretti and Rosa, 2019; Wada and Bierkens, 2014). In many regions, human demand for water resources is approaching or exceeding the total amount of locally available water resources (He et al., 2021; Scanlon et al., 2023), leading to water scarcity as one of the major obstacles threatening sustainable development. In order to alleviate the pressure caused by the uneven natural distribution of water resources and increasing demand, water resources have been redistributed through the construction of Inter-Basin Water Transfer (IBWT) projects (Purvis and Dinar, 2020; Rollason et al., 2021). IBWT projects have been constructed in most countries around the world, and it is estimated that the amount of water to be transferred will increase by a factor of ninefold in the future (Khadem et al., 2021; Nyingi et al., 2024; Rollason, et al., 2021; Roozbahani et al., 2020). This trend not only demonstrates the effectiveness of IBWT in addressing the

* Corresponding author.
E-mail address: hefan@iwhr.com (F. He).

https://doi.org/10.1016/j.jhydrol.2025.133090
Received 20 March 2024; Received in revised form 12 January 2025; Accepted 12 March 2025
Available online 17 March 2025

uneven distribution of water resources, but also highlights the challenges and needs of global water management (Fig. 1).

However, the operation of IBWTs may cause significant impacts on water intake sources and receiving areas. Most of the existing studies have focused on large-scale water transfer projects either individually or producing direct linkages. For example, Wu, et al. (2023) assessed the impacts of climate change runoff and hydrological droughts on inter-basin water transfers using the Hanjiang-Wei project as an example; Sheng and Qiu (2023)investigated the impacts of inter-basin water transfer policies on water use technical efficiencies using China's South-to-North Water Transfer (SNWT) as an example; Matete and Hassan (2006)analysed the ecological impacts of inter-basin water transfers and their economic and environmental effects of Lesotho and South Africa using the Lesotho Highlands Water Project (LHWP) as an example to analyse the impacts of inter-basin water transfer on the ecological environment and its economic costs and benefits. With the construction of IBWT projects, the impacts of IBWT projects are gradually upscaled to the basin or national scale. Duan et al. (2023) quantified the efficiency of 50 inter-basin transfer projects in the United States in relieving regional water stress; Sun et al. (2021) analysed the impacts of inter-basin transfers on water scarcity and its inequality in China's secondary river basins; and Liu et al. (2023) evaluated the impacts of inter-basin transfers in China on the environment, the economy, and the society. However, their studies focused more with large-scale water transfer projects and neglected the regional impacts of intra-basin water transfer projects.

China is alleviating regional water scarcity through the construction of 128 inter-tertiary basin transfer projects, such as the South-North-North Water Diversion Centre-East Line. The Yellow, Huai, Hai and Yangtze River Basins (HHHYRB) are China's main development areas and major water transfer areas (Wang et al., 2023). The HHHYRB is located in the north of China, while the Yangtze River Basin straddles the north and south of the country. The HHHYRB is home to about 78 per cent of the country's population and 75 per cent of China's GDP (Ma et al., 2020; Yang et al., 2022). However, the distribution of water resources in the HHHYRB is extremely uneven, and the Yellow, Huai and Hai River Basins in particular face serious water scarcity problems. For example, the water resources of the Huanghuaihai basin in the North China Plain account for only 7.2 per cent of the country's water resources, but carry 31.6 per cent of the country's population, 28.8 per cent of its GDP and 42 per cent of its arable land's water demand, which is far from being able to meet the high density of the local population and economic development (Sun et al., 2024; Xiangmei et al., 2021). In contrast, the Yangtze River Basin is richer in water resources and has become the main source of water transfer for these northern basins (Xiong et al., 2022). Therefore, when considering the management and deployment of water resources in the four major basins of the Yellow, Huaihai and Yangtze River Basins, it is necessary to take into account the inter-basin allocation and balance of water resources in an integrated manner.

The Water Stress Index (WSI), defined as the ratio of the amount of water withdrawn to the amount of water available, is widely used to measure global and regional water scarcity (Huang et al., 2021; Kummu et al., 2016). A large number of studies have assessed the spatial and temporal patterns of water scarcity in different regions; Gosling and Arnell (2016) assessed the impact of climate change on water scarcity at the global scale using the Water Crowding Index (WCI; a measure of the annual water resources per capita in a watershed) and WSI, with 1.6 to 2.4 billion people currently living in water-scarce areas, and the number is expected to increase due to climate change; Huang et al. (2021) applied the WSI to assess the global water scarcity evolution from 1971 to 2010 on a half-degree resolution and a monthly time scale to assess the evolution of global water scarcity from 1971 to 2010; Li et al. (2017) assessed the multi-scale WSI index for watersheds and cities in northern

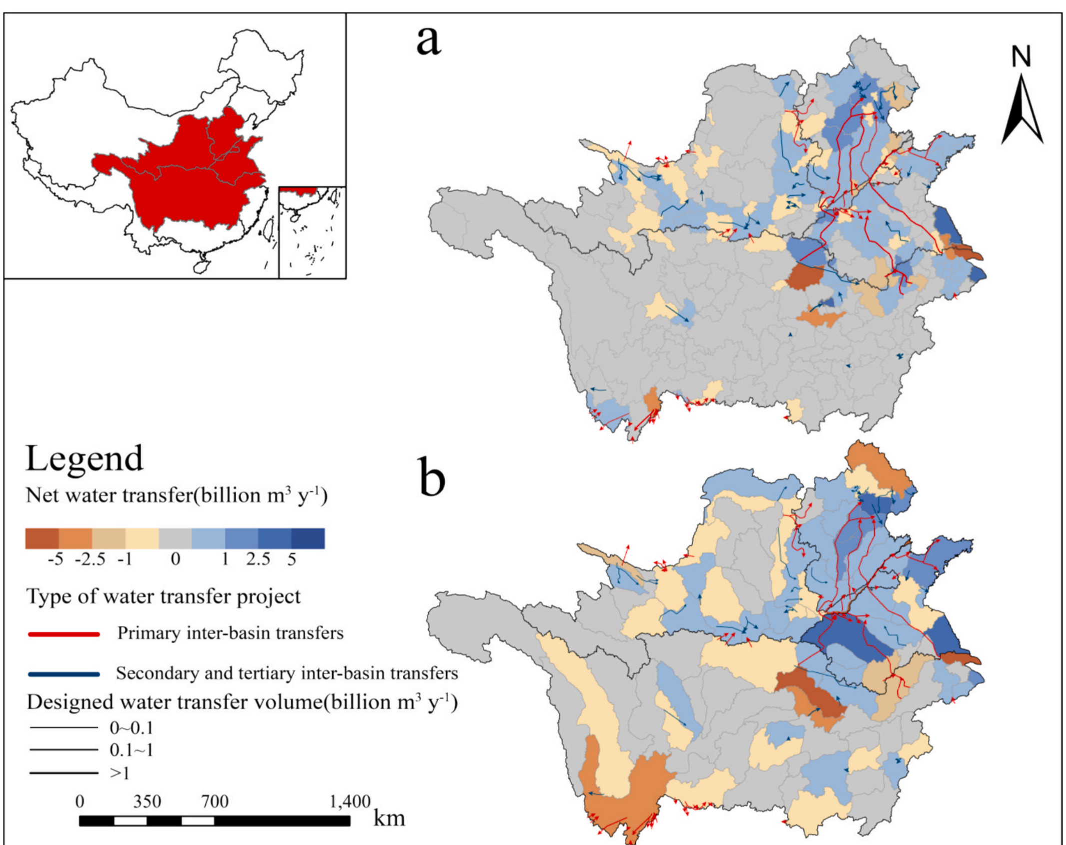

Fig. 1. Study area. (a) Urban-scale water transfers, (b) Tertiary scale water transfer.

China; Zhou et al. (2016) developed a spatial cell non-overlapping WSI model. They applied the model to the Yarlung Tsangpo River and demonstrated its effectiveness in assessing regional water scarcity; Zhang et al. (2023) analysed the changes in WSI pressure in China before and after the most stringent water resources management policy, identifying the key role of the policy.

The aim of this study is to remedy the shortcomings of existing studies by investigating the impacts of inter-basin water transfers on China's water use and WSI. For this reason, we chose the four major basins of HHHYRB, where water transfers are most concentrated, mainly the South-to-North Water Diversion Project, as the study area, and constructed a database of the inter-basin water transfer project by combining data on water use and available water resources in the cities and the three tiers of basins in the study area. We aim to answer the question How did WSI evolve? To what extent can WSI be mitigated by the contribution of water transfer projects to regional WSI before and after the implementation of inter-basin water transfers? How does inter-basin water transfer affect the spatial heterogeneity of WSI between and within basins? What is the impact of each water transfer project separately? The innovation and contribution of this study is twofold. For the first time, the impacts of inter-basin water transfers on WSI were analysed at multiple scales (prefecture level and tertiary level basins), thus providing a comprehensive assessment of the contribution of inter-basin water transfer projects to WSI.

2. Overview of four major inter-basin water transfer projects

China's water resources are unevenly distributed in time and space, and the contradiction between supply and demand is prominent, with more than 300 cities experiencing water shortages of varying degrees (Li et al., 2017; Zhai et al., 2022). To address the water shortage problem, China has been constructing inter-basin water transfer projects (IBWT projects) since 1949. In this paper, a database of 125 completed IBWT projects in China is constructed, including 56 water transfer projects across primary basins (L1-IBWT) projects, 42 water transfer projects across secondary basins (L2-IBWT) projects, and 27 water transfer projects across tertiary basins (L3-IBWT) projects. Among the 125 water transfer projects, 88 projects are located in the four major basins of HHHYRB, accounting for 70.40 % of all projects, and the amount of water diverted and transferred accounts for 89.5 % of the total amount of water transferred in the country. The largest south-to-north water transfer project is also in the four major basins. Therefore, this paper selects HHHYRB as the study area.

The HHHYRB has 29 L2-basins and 105 L3-basins, involving 212 cities in 25 provinces. Before 1980, there were 13 water transfer projects in the HHHYRB, with a diversion volume of 8.643 km^3, mainly within the first level basin, and IBWT was mainly concentrated in the Yellow River to Huai River project in Henan Province and Shandong Province. By 2012, the initial development of IBWT projects, mainly short-distance intra-provincial water transfer projects, the number increased by 29, the amount of water transferred increased by 12.275 km^3. After that, the construction of water transfer projects increased significantly, the construction of the South-to-North Water Diversion in the middle and east, the diversion of the River to Huai, the diversion of the Yellow River to Hebei to replenish the precipitation of the long-distance water transfer projects, the amount of water transferred increased by 21.850 km^3.

3. Methodologies and data

3.1. Consider the water stress index of IBWT

3.1.1. Improved water stress index

Water scarcity is a complex and often demand-driven phenomenon. To quantify regional water stress, we typically use the Water Stress Index (WSI), which compares available water resources and total demand (de O. Vieira and Sandoval-Solis, 2018; Nilsalab et al., 2017). Traditionally, the WSI is calculated by comparing the ratio of local abstractions to the amount of water available to the region (Nilsalab et al., 2018). However, the implementation of inter-basin transfer projects has challenged this traditional approach by changing the geographical distribution and availability of water resources. In light of this, we propose an improved WSI model that integrates the impacts of inter-basin transfer projects on water availability, thereby providing a more comprehensive and accurate tool for measuring water stress.

$$WSI = \frac{WU - \sum_i WTI_i}{WA + \sum_i WTO_i} \tag{1}$$

Where, WU is the regional local water consumption; WA is the amount of regional available water resources; WTI_i is the amount of water transferred into the i IBWT project; WTO_i is the amount of water transferred from the i IBWT project.

Following the commonly used classifications of water stress levels (Duan et al., 2023; Vörösmarty et al., 2000), WSI can be divided into four levels: low (WSI<=0.2), moderate (0.2–0.4), severe (0.4–1.0), and extreme (>1).

3.1.2. Influence of inter-basin water transfer project on WSI

The impacts of the water transfer project on water stress in the basin are manifested in three main ways. First, there is the direct impact of the project itself on the receiving and supplying zones, both in terms of increased water resources in the supplying zones and possible reductions in water resources in the receiving zones. These impacts are usually closely related to the design of the project, its mode of operation and regional water management policies. Second, there are the indirect impacts of the project on the allocation of water resources between upstream and downstream areas. Specifically, upstream water transfer projects may reduce the amount of water flowing downstream, thereby increasing water stress in downstream areas, which may lead to redistribution of water use rights, ecosystem changes and even regional conflicts. A comprehensive understanding and assessment of these three types of impacts is essential for the development of sustainable water resources management strategies:

$$IWSI = \Delta WSIIN + \Delta WSIO + \Delta WSIIM \tag{2}$$

Where, $IWSI$ is IBWT project water stress index; $\Delta WSIIN$ is influence value of water resources pressure in receiving zones; $\Delta WSIO$ is influence value of water resources pressure in supplying zones; $\Delta WSIIM$ is influence value of IBWT project on downstream water resources stress.

3.2. Water uses and water transfer in tertiary basins and cities of HHHYRB

Given that the water transfer project draws water by zones within the basin and supplies it within administrative areas, we chose to define the study area by superimposing municipal administrative areas on three-level basins. To ensure the accuracy of the water use data and water transfer data, we employed downscaling techniques to refine them according to different water use demands and spatial distribution characteristics. Agricultural water use is downscaled based on arable land area, industrial water use is downscaled according to regional GDP, domestic water use is downscaled based on population distribution, and ecological water use is downscaled according to urban area. At the same time, the downscaling of water transfers is based on the main water supply types of each transfer project. This approach allows us to more accurately delineate and assess water stress within each region and consider the specific impacts of the transfer projects on it.

$$WU = Da + Di + Dd + De \tag{3}$$

Where, Da is agricultural water consumption; Di is industrial water consumption; *Dd* is domestic water consumption; *De* is ecological water consumption.

To accurately assess the distribution and demand for agricultural water, the agricultural water demand of each study unit was determined by analysing the relationship between the ratio of cultivated land area to urban cultivated land area within the study area, and the amount of water used for agriculture. This approach not only takes into account the overall cultivated area, but also refines the characteristics of agricultural water use within the city, thus allowing us to more accurately depict and understand the spatial distribution patterns of agricultural water use:

$$da_j = \frac{AR_j}{\sum_{k=1}^{N} AR_k} Da \tag{4}$$

Where, da_j is agricultural water use in the study unit j; AR_j is cultivated land area of the research unit j, and N is the number of study units in this basin.

In order to accurately assess the demand and distribution of industrial water, we estimated the relationship between the GDP within each study unit and the total GDP of the city, and the corresponding industrial water use by comparing:

$$di_j = \frac{GDP_j}{\sum_{k=1}^{N} GDP_k} Di \tag{5}$$

Where, di_j is industrial water use in the study unit j; GDP_j is the total GDP in the study unit j.

Domestic water use was determined by comparing domestic water use from population data to the study unit population and the urban population:

$$dd_j = \frac{Pop_j}{\sum_{k=1}^{N} Pop_k} Dd \tag{6}$$

Where, dd_j is domestic water use in the study unit j; Pop_j is the total population in the study unit j including rural and urban.

Ecological water use was determined by comparing ecological water use from land use data to the study unit urban area and urban area:

$$de_j = \frac{AU_j}{\sum_{k=1}^{N} AU_k} De \tag{7}$$

Where, de_j is ecological water use in the study unit j; AU_j is the total urban area in the study unit j.

The amount of water transferred to each city and each tertiary zone is allocated according to the type of water transfer project. For inter-basin water transfer (IBWT), which primarily serves urban domestic needs, we allocate water based on the urban land-use area and population distribution of the supplied city. For production water, allocation is based on GDP, and for ecological recharge (lake recharge), it is based on the area being recharged (lake area). The formula for downscaling is similar to that used for water use, so it is not detailed in the text. The amount of water transferred in each year is 50 % of the designed water transfer in the first year of completion, 75 % in the second year, 90 % in the third year, and then calculated according to the designed water transfer. South-to-North Water Diversion Centre and East Route Project water transfer according to the "South-to-North Water Diversion Statistical Yearbook" statistics of the actual amount of water transferred to the exhibition. The amount of water to be transferred each year is based on the minimum value of the incoming water from the water intake source and the designed amount of water to be transferred.

$$IBWT_j = \min(IBWT, WA - WU) \tag{8}$$

3.3. Water available resources of HHHYRB

In this study, a modified SMAR model was used to simulate the amount of available water resources (Fazal et al., 2005; Tan and O'Connor, 1996). In the surface flow production process, the model distinguishes between two types of flow production: impervious and permeable surfaces. For impervious surfaces, the water volume after deducting evapotranspiration losses will directly produce flow, while for permeable surfaces, a combination of storage-full flow production and hyperinfiltration flow production is used. Full impoundment flow occurs when the soil is saturated with water, whereas hyperinfiltration flow occurs when the intensity of rainfall exceeds the infiltration capacity of the soil. The model also considers the effect of mid-loam flow, which reflects the recharge process of rainfall on soil moisture changes and contributes to surface runoff, shallow groundwater recharge, and soil water evaporation, respectively. Two reservoirs, shallow and deep, are provided in the model to simulate the subsurface runoff process through a linear reservoir approach. The shallow reservoir receives soil water, infiltration from rivers and reservoirs as recharge, and some of its water volume forms rapid runoff, some infiltrates to recharge deep groundwater, and the remaining is consumed through evaporation. Deep reservoirs are mainly recharged by shallow water infiltration. Evaporation in the natural water cycle includes vegetation retention, soil evaporation and shallow water evaporation, of which soil evaporation and shallow water evaporation are calculated using the SIMHYD model (Young et al., 2007).

In this paper, data from 41 hydrological stations were used to rate and validate the model, with 1960–2000 selected as the calibration period and 2001–2020 as the validation period. The station distribution and simulation results are shown in Fig. 2 and Table 1, respectively, and the simulation results are good enough to meet the research needs.

3.4. Water availability in downstream sub-basins

In the WSI modelling of the HHHYRB, the WSI of the downstream sub-basins will be significantly overestimated if the availability of water resources from upstream inflows is ignored. Therefore, for each downstream sub-basin in the HHHYRB, the availability of water resources includes not only the local naturally occurring water resources, but also the contribution of water resources from the upstream sub-basin should be considered. In addition, since the transfer project has changed the natural spatial distribution of water resources, the formula for calculating the amount of water resources flowing from upstream to downstream has been improved to accurately reflect the impacts of the transfer. This approach ensures an accurate assessment of water scarcity in the lower sub-basin, taking into account the impact of the transfer on the spatial distribution of water resources:

$$WA_{up} = r\sum_i (WA_i - WU_i - IBWTI_i + IBWTO_i) \tag{9}$$

where WA_{up} is upstream water flowing into a downstream sub-basin, WA_i and WU_i are water availability and water use in upstream sub-basin i, respectively, and r is a coefficient that accounts for water losses when water flows downstream. In this study, we consider $r = 0.9$.

3.5. Dagum Gini coefficient decomposition

In order to quantitatively analyze the WSI imbalance of HHHYRB, the Gini coefficient decomposition method proposed by Dagum was used to decompose the spatial variation into intra-regional variation (Chameni, 2006; Rey and Smith, 2013), analyze the WSI difference of HHHYRB, and then decompose into intra-group coefficient by comparing the specific differences of each basin. The definition formula is:

$$G = \sum_{j=1}^{k}\sum_{h=1}^{k}\sum_{i=1}^{n_j}\sum_{r=1}^{n_h} \left| y_{ji} - y_{hr} \right| / 2n^2\overline{y} \tag{10}$$

Where, G is the Gini coefficient of the population difference; K is the number of basins; $n_j(n_h)$ is the number of tertiary basins within the $j(h)$ basin, $y_{ji}(y_{hr})$It is the WSI of any tertiary watershed in the $j(h)$ region; $\overline{y}$ is

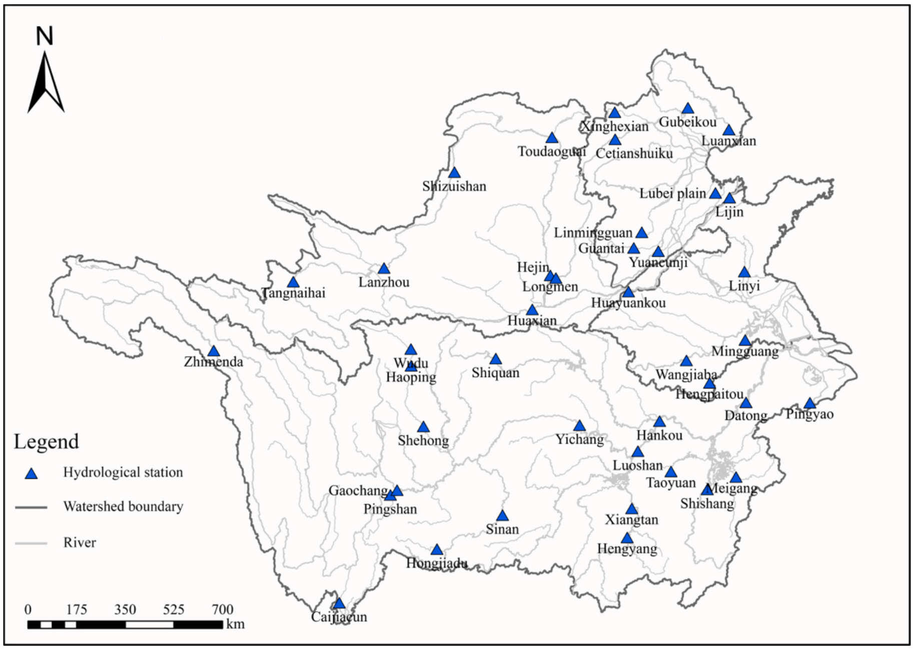

Fig. 2. Location of hydrological stations.

Table 1
Runoff process rate determination results.

Name	R^2	Nash	Name	R^2	Nash	Name	R^2	Nash
Tangnaihai	0.86	0.74	Guantai	0.85	0.71	Hengyang	0.89	0.77
Lanzhou	0.87	0.76	Yuancunji	0.86	0.73	Xiangtan	0.88	0.77
Shizuishan	0.86	0.72	Lubei plain	0.80	0.64	Shiquan	0.87	0.75
Toudaoguai	0.83	0.62	Chimenda	0.89	0.80	Shishang	0.89	0.78
Longmen	0.84	0.66	Caijiacun	0.89	0.80	Meigang	0.93	0.87
Huayuankou	0.84	0.69	Pingshan	0.88	0.78	Luoshan	0.87	0.72
Lijin	0.82	0.67	Gaochang	0.93	0.82	Hankou	0.86	0.68
Hejin	0.79	0.63	Haoping	0.88	0.70	Datong	0.82	0.63
Huaxian	0.83	0.69	Wudu	0.83	0.64	Pingyao	0.81	0.65
Luanxian	0.84	0.69	Shehong	0.88	0.76	Wangjiaba	0.82	0.66
Gubeikou	0.79	0.61	Hongjiadu	0.89	0.78	Hengpaitou	0.85	0.66
Chetian reservoir	0.78	0.61	Sinan	0.89	0.79	Mingguang	0.83	0.68
Xinghexian	0.79	0.62	Yichang	0.92	0.83	Linyi	0.89	0.80
Linmingguan	0.95	0.91	Taoyuan	0.91	0.80			

the average WSI of each basin.

Before decomposition of WSI, it is also necessary to calculate the mean value of WSI in each basin and sort it. The formula is as follows:

$$\overline{Y}_l \leq \cdots \leq \overline{Y}_h \leq \overline{Y}_k \tag{11}$$

The WSI Gini coefficient G, which represents the total difference, can be further decomposed into part G_w contributed by intra-basin difference, part G_{nb} contributed by inter-regional net difference, and super-variable density G_t. Relationship satisfaction:

$$G = G_w + G_{nb} + G_t \tag{12}$$

G_w, G_{nb}, G_t are represented by:

$$G_{jj} = \frac{\sum_{i=1}^{n_j}\sum_{r=1}^{n_j}\left|y_{ji} - y_{jr}\right|}{2n_j^2\overline{Y}_j} \tag{13}$$

$$G_w = \sum_{j=1}^{k} G_{jj} p_j s_j \tag{14}$$

$$G_{jh} = \frac{\sum_{i=1}^{n_j}\sum_{r=1}^{n_j}\left|y_{ji} - y_{hr}\right|}{n_j n_h(\overline{Y}_j + \overline{Y}_h)} \tag{15}$$

$$G_{nb} = \sum_{j=2}^{k}\sum_{h=1}^{j-1} G_{jh}(p_j s_h + p_h s_j) D_{jh} \tag{16}$$

$$G_t = \sum_{j=2}^{k}\sum_{h=1}^{j-1} G_{jh}(p_j s_h + p_h s_j)(1 - D_{jh}) \tag{17}$$

Where, $p_j = n_j\overline{Y}$, $s_j = n_j\overline{Y}/n\overline{Y}, j = 1, 2, 3, \cdots, k$; $n_j(n_h)$ is the number of tertiary catchments within the $j(h)$ catchment;

$$D_{jh} = \frac{d_{jh} - p_{jh}}{d_{jh} - p_{jh}} \tag{18}$$

$$d_{jh} = \int_0^\infty dF_j(y)\int_0^y (y - x) dF_h(x) \tag{19}$$

$$p_{jh} = \int_0^\infty dF_h(y)\int_0^y (y - x) dF_j(x) \tag{20}$$

Where D_{jh} is the interaction between indicators of j basin and h basin; d_{jh} is the WSI difference between two tertiary basins; $F_j(F_h)$ is the cumulative distribution function of $j(h)$ basin.

4. Results

4.1. Trend analysis of water use and water availability

Since 1965, annual water utilization across the four major basins has exhibited a rising trend. As can be seen in Fig. 3 the Yangtze River Basin has experienced the most pronounced increase, with an annual growth rate of 1.37 %, a slope of 2.09 km^3/a in water use growth, and the highest volatility in annual water use, evidenced by a standard deviation of 34.51 km^3. The Yangtze River basin shows the greatest volatility in water use, with a median water use of 2.51 km^3, and its interquartile range of 3.63 km^3. Such variability likely mirrors the disparities in economic development levels, population densities, and industrial activities across different regions within the basin. The Yellow River Basin followed with an annual growth rate of 1.39 % and a growth trend slope of 0.35 km^3/a, with relatively low volatility. The median water use in the Yellow River Basin is 0.94 km^3, and the interquartile range is 1.18 km^3. Although the overall water use is lower than that in the Yangtze River Basin, the volatility of water use within it is still significant. The annual growth rate of the Huai River Basin is 1.33 %, and the slope of the growth trend is 0.48 km^3/a, with the volatility between the Yangtze River and the Yellow River. The median water consumption in the Huai River basin is 2.81 km^3, and the interquartile range is 2.88 km^3, indicating a relatively balanced distribution of water consumption. The Hai River Basin has the lowest growth rate of 1.22 %, and the slope of the growth trend is 0.16 km^3/a, with the least volatility. The median water use in the Hai River Basin was 1.97 km^3 with an interquartile range of 1.53 km^3, showing the least volatility in water use. This characteristic of the Hai River Basin may be related to its small geographic extent and relatively stable water demand.

As can be seen in Fig. 4 the amount of available water resources varies greatly among the four major basins, with the Yangtze River basin showing the most significant increasing trend (0.918 km^3/a) and the greatest volatility (standard deviation of 79.37 km^3) from 1965 to 2020. The median of the tertiary basin was 14.07 km^3 and the interquartile range was 11.88 km^3, reflecting significant differences in water availability between regions within it. Such may be related to the wide area of the basin, climate variability and uneven distribution of economic activities. The Yellow River Basin has a relatively slower growth trend in the amount of available water resources (0.070 km^3/a) and relatively less volatility (standard deviation of 4.68 km^3), which may reflect the relative stability of the Yellow River Basin in terms of water resource management and utilisation, as well as the relative balance between water supply and demand in the region. The annual growth slope of available water resources in the Huai River Basin is 0.090 km^3, indicating that the amount of available water resources in the basin is also growing steadily. Unlike the other three basins, the Hai River Basin shows a negative growth trend in the amount of available water resources, with an annual growth slope of -0.059 km^3.

4.2. Analysis of temporal variations in WSI

In this study, the change in WSI of HHHYRB is divided into four phases: 1965–1980, 1981–2000, 2001–2012, and 2013–2020 in order to provide an insight into the change in water stress during each period (Fig. 5).

In HHHYRB, the WSI showed a significant increasing trend (0.0076 km^3/a) during the first phase (1965–1980), reflecting the intensification of water stress during that period. This may be related to the rapid acceleration of regional population growth and industrial development. The growth rates in the second (0.0032 km^3/a) and third phases (0.0033 km^3/a) have slowed down, indicating that water management measures are beginning to take effect. However, the WSI in Stage IV (2013–2020) shows a decreasing trend (-0.0062 km^3/a), which may be attributed to effective water management strategies and technological advances implemented in recent years. The situation in the Yangtze River Basin is different from the HHHYRB. The basin was in a low water stress phase until 1986. However, it then entered a medium stress phase, showing similar growth and decline trends as the HHHYRB. Water availability (WA) in the Yangtze River Basin has an important impact on the water resources status of the country as a whole, especially as the main source of water for South-North Water Diversion. WSI fluctuates significantly in the Yellow River, Huai River and Hai River basins, showing changes in water stress from severe to extreme. In the Yellow River Basin, the growth rates of WSI in the first and second stages (0.0183 km^3/a and 0.0227 km^3/a, respectively) indicate a significant increase in water stress. The WSI fluctuations in the Huai River and Hai River basins were even greater, especially in the Hai River basin, where the growth rate in the first stage was as high as 0.0993 km^3/a, followed by a significant decreasing trend in the next three stages.

By simulating the no transfer scenario, we analysed in detail the impacts of inter-basin transfers on the WSI of the major basins. The

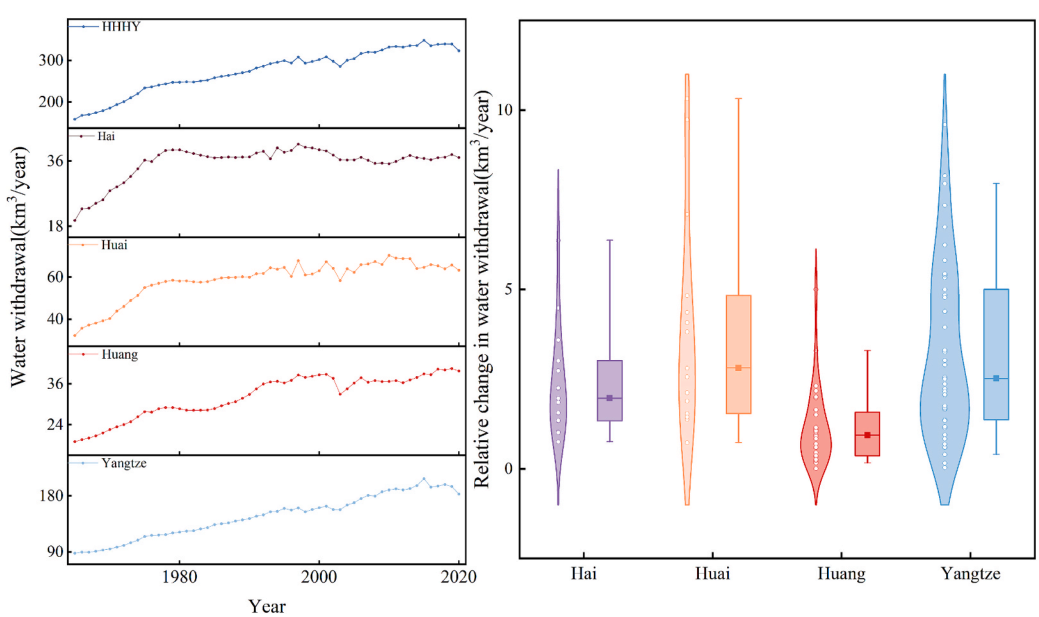

Fig. 3. Line chart and box chart of water consumption in each basin.

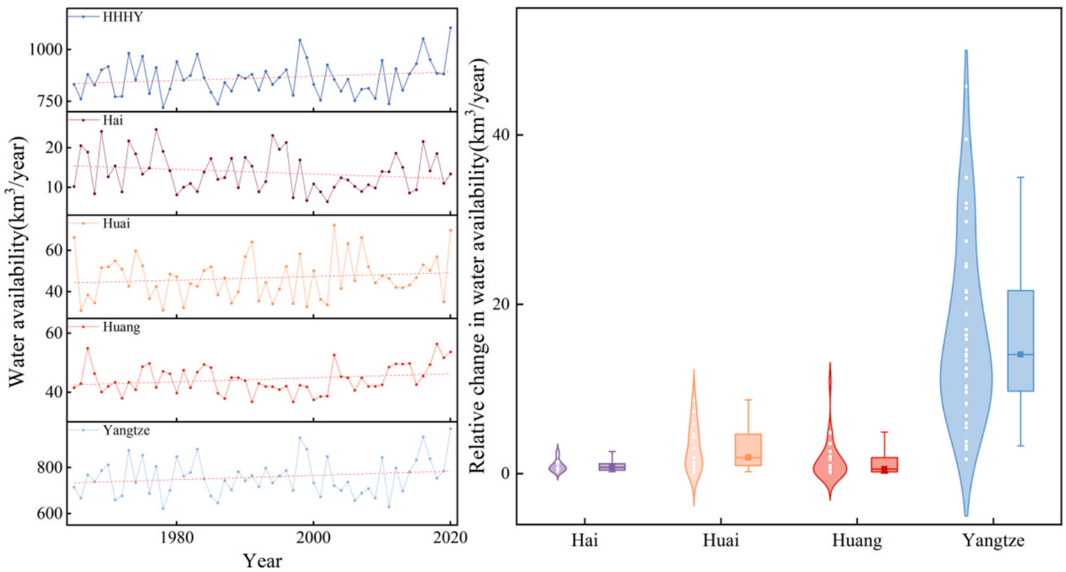

Fig. 4. Line chart and box chart of available water resources in each basin.

impacts of external inter-basin transfers of HHHYRB are all less than 0.002. The Yangtze River Basin is less affected by the inter-basin transfer project, and due to the construction of the South-to-North Water Transfer (SNDT), the WSI no-transfer scenario grows by 2 % in Stage IV. This is due to the fact that the Yangtze River Basin is much larger in terms of WA relative to the other basins, and it is the most important basin for the other basins as a source of water intake. WSI in the Yellow, Huai and Hai river basins is more affected by inter-basin water transfers. In the Yellow River basin, the trend of water transfer on WSI will increase from 2.8 % to 6.4 %, reflecting that water transfer is increasing WSI in the region. water transfer in the Huai River basin reduces the basin WSI from 1.0 % in Stage 1 to 15.6 % in Stage 4, showing the criticality of water transfer in maintaining water resource stability in the region. The Hai River basin has the most significant dependence on water transfers. In Stage 4, without inter-basin water transfers, the WSI would have increased dramatically, from 1.7 per cent to 75.0 per cent. This means that the water stress in the Hai River Basin would be extremely high under the no water transfer scenario, and the inter-basin water transfer project plays a crucial role in ensuring water security in the region.

4.3. Analysis of spatial variations in WSI

This study provides insights into the characteristics of the spatial distribution of WSI in cities and tertiary watersheds over the period 1965–2020 (Fig. 6), and explores the specific contribution of inter-basin transfers to WSI in these regions by simulating a scenario without water transfers. The quantitative results show that WSI exhibits significant spatial heterogeneity in a sample of 212 cities with a mean value of 1.12, indicating that most cities face extreme water security challenges. The average contribution of water transfer projects to WSI was −0.142, indicating that they generally had a favourable positive impact on regional water security, but this impact showed significant differences between cities.

In particular, at the urban scale of the Yangtze River Basin, although the overall WSI is in a low state, the lower reaches of the Yangtze River, such as Shanghai, Jiaxing, Wuxi, and Xiantao, are experiencing severe or even extreme WSI. The high WSI in these cities may be related to rapid urban development, increased water use, and the mismatch between water use (WU) and water availability (WA). Extreme WSI in the Yellow River Basin is mainly concentrated in the middle and lower reaches, such as the cities of Ordos, Bayannur, Baotou, and Yulin. The Huai River Basin as a whole is at extremes, but the central regions have better WSI, thanks to the implementation of the Yellow River Diversion Project, which effectively reduced WSI in these regions. In contrast, the Hai River Basin, although benefiting from the mitigating effects of inter-basin water transfers, is still at extremes as a whole due to the basic conditions of water availability (WA), with only cities such as Qinhuangdao and Chengde having moderate WSI.

At the basin scale, the WSI in the western and lake areas of the Yangtze River Basin is at a moderate level, while the extreme WSI conditions in the Huangpu River area and the Wuyang area highlight the significant water stress in specific areas of the basin. The Yellow River several bends area of the Yellow River Basin exhibits extremely high WSI values, suggesting that the region faces severe water security challenges. The north bank of the Benghong interval in the Huai River Basin and parts of the Hai River Basin also show high WSI values, e.g., 1.76 in the mountainous areas of the North Three Rivers, which point to severe water stress in these regions. Even though the inter-basin water transfer project has played a role in alleviating water stress in some areas, the Hai River Basin is still facing an extreme state of water stress even with the help of water transfers. These findings emphasise the need for more integrated and diversified water management strategies in regions facing extreme water stress.

4.4. Analysis of the degree of spatial–temporal differentiation of WSI and the impact of IBWT

In order to identify more clearly the sources of WSI differences in the HHHYRB and to identify the effects of water transfers on them, this paper analyses the watershed differences between the four major watersheds in the HHHYRB from 1965 to 2020 using the Dagum Gini coefficient method.

As can be seen from the sources of variation and contributions in Fig. 7, the within-group coefficient (Gw) of the 1965–2020 WSI averaged about 20.6 per cent over the study period, with a range of fluctuations from 17.3 per cent to 23.7 per cent, reflecting the relative consistency and slight degree of inequality in water allocation within individual regions or groups. In contrast, the coefficient of between-groups (Gb) has a mean value of 59.1 per cent, with a much larger range of fluctuations from 48.3 to 66 per cent, which shows significant differences in the degree of inequality in the allocation of water resources between different regions or groups. Noteworthy is the coefficient of hypervariable density (Gt) with a mean value of about 20.3 per

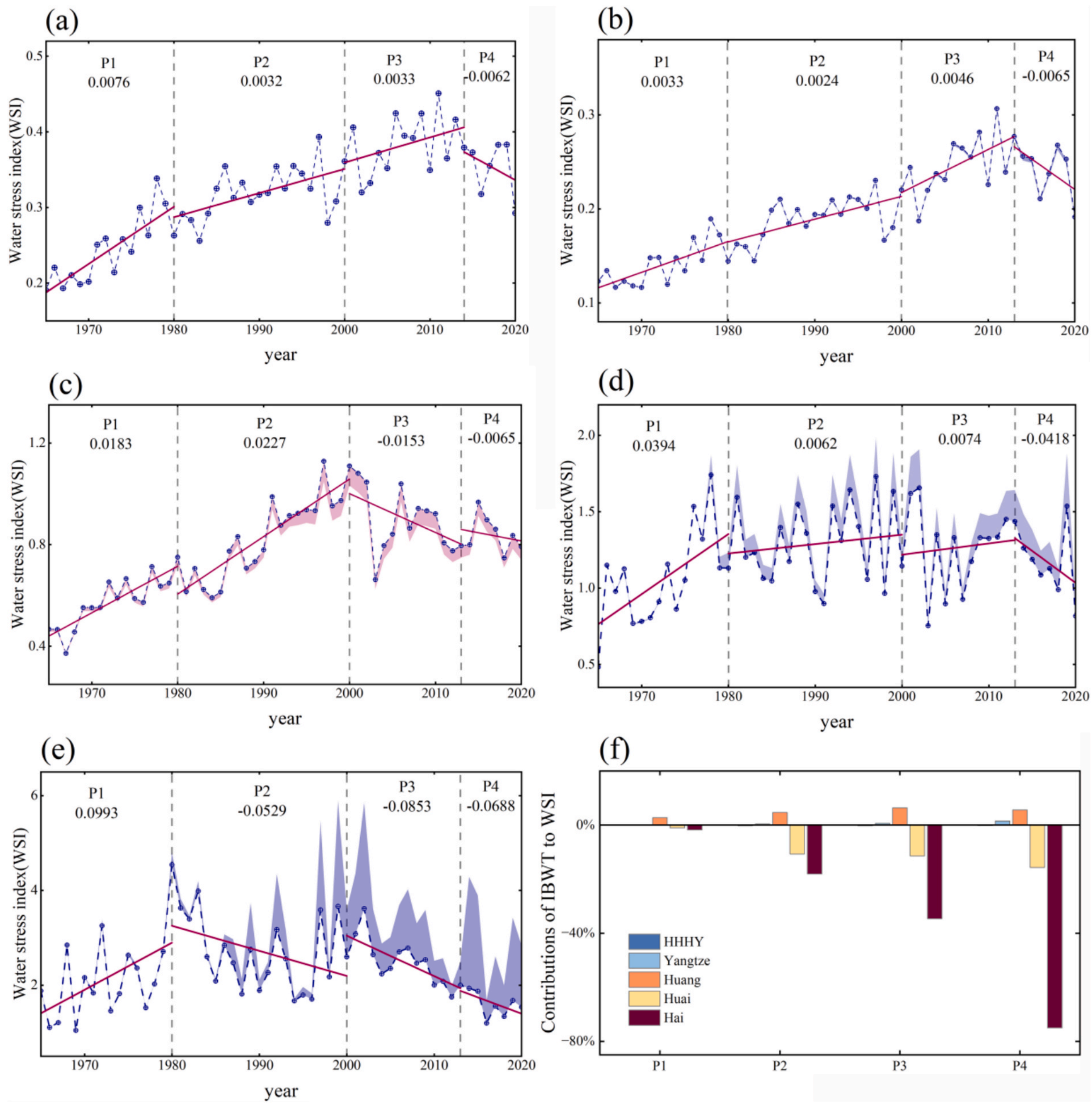

Fig. 5. Water stress index of each basin. (a) Huang-Huai-Hai-Yangtze river basin, (b) Yangtze river basin, (c) Huang river basin, (d) Huai river basin, (e) Hai river basin, (f) Contribution of IBWT to WSI. The shaded areas in (a–e) indicate the contribution of IBWT to WSI.

cent and the largest range of fluctuation from 10.8 per cent to 31 per cent, implying that extreme inequality varies significantly between years. The coefficients of within-group (Gw) and between-group (Gb) inequality decreased slightly over time, while the coefficient of hypervariance density (Gt) showed a slight upward trend. These trends indicate that while there was a slight decrease in inequality within and between groups, there was an increase in extreme inequality.

In the Dagum Gini coefficient analysis of WSI of HHHYRB from 1965 to 2020, by comparing the change in Gini coefficient with and without considering the water transfer project (Fig. 8), we found that the water transfer project has a significant positive impact on improving the regional WSI differences. From the overall trend, the Gini coefficient shows a decreasing trend in all the basins with the consideration of water transfer projects, which means that the inequality of WSI has been reduced. In HHHYRB basin, the water transfer project reduced the Gini coefficient by about 6.94 per cent, showing a positive impact on the equity of water allocation in the basin. The most significant change was observed in Huai basin, which showed a yearly average decrease in the Gini coefficient of −0.0029 when the water transfer project was considered, and a slight upward trend (0.0004) when the water transfer project was not considered. The positive impact of the water transfer project was also shown in Hai basin, which had an annual average decrease of −0.0029 when the water transfer project was considered, and a slight upward trend (0.0004) when the water transfer project was not considered. The Hai basin also shows the positive impact of the water transfer project with an average annual decrease in the Gini coefficient of −0.0037 when the water transfer project is considered, which is much higher than that of −0.0009 when the water transfer project is not considered. The Hai basin and the Huai basin show a decrease in the Gini coefficient of about 31.98 % and 33.69 %, respectively, highlighting the significant role of water transfer projects in reducing inequality in water allocation. These findings are consistent with the high water stress indexes observed in these basins, as noted in the previous section, suggesting that the projects may have been strategically designed to address regions facing severe water scarcity. This interpretation implies that the water transfer initiatives might have

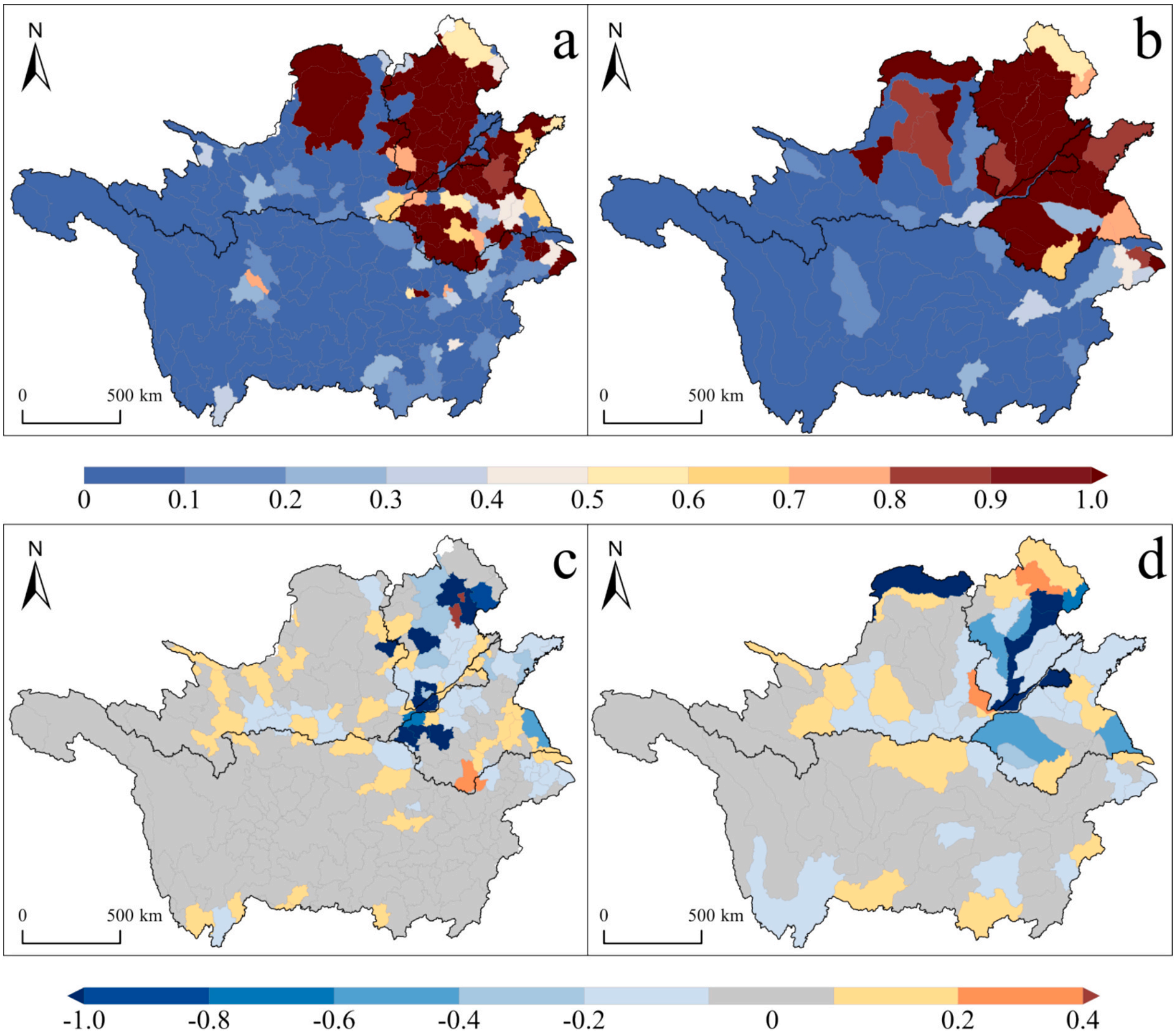

Fig. 6. WSI spatial distribution. (a) Spatial distribution of WSI in the city, (b) Spatial distribution of WSI in tertiary watersheds, (c) The contribution of IBWT to the WSI of the city, (d) Contribution of IBWT to WSI in a tertiary watershed.

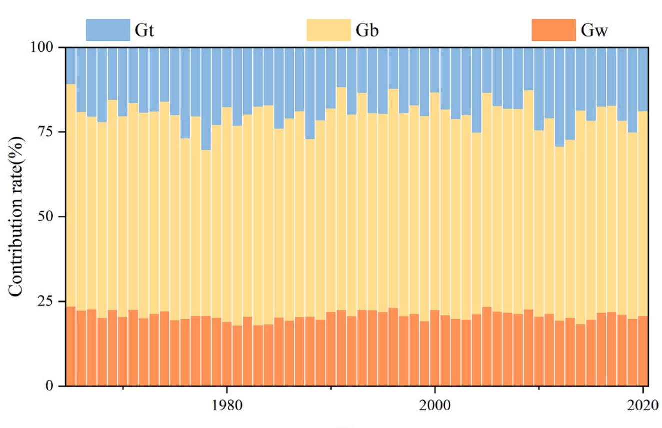

Fig. 7. Contribution rate of Gt, Gb and Gw to WSI.

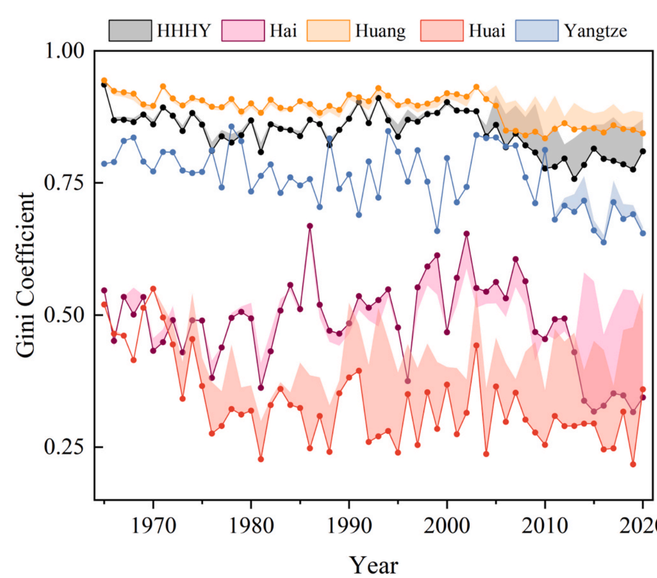

Fig. 8. The total Gini coefficient of WSI. The shaded areas indicate the contribution of IBWT to Gini coefficient.

prioritized subbasins with extreme water stress to alleviate distributional disparities and ensure regional water security. For Huang basin, the Gini coefficient was reduced by about 4.46 per cent, and although the Gini coefficient declined at a faster rate when the water transfer project was considered, the difference was relatively small. For Yangtze basin, the impact of the water transfer project is relatively small, with the Gini coefficient reduced by only about 1.77 per cent. This may be related to the abundance of water resources in the Yangtze River basin itself, making the impact of the water transfer project more limited in these basins.

Fig. 9 illustrates the variation of Dagum's Gini coefficient among different basins, and the results of the analyses among the six basins, Hai-Huang, Hai-Huai, Hai-Yangtze, Huang-Huai, Huang-Yangtze, and Huai-Yangtze, reveal significant differences in the average annual trend and average difference of Gini coefficients as a result of the transfer project's Impact. This effect is most significant in the Hai-Huai pair, where the increase in the mean annual trend reaches 158.12 % and the effect on the Gini coefficient is –33.61 %, indicating that the water transfer project plays a key balancing role between the two basins and greatly contributes to the fairness of water resources allocation. The results of the analyses among the six basins, namely, Huang-Yangtze, Huai-Yangtze, Huang-Huai and Huang-Yangtze, show that the water transfer project plays a key balancing role between the two basins and greatly promotes equity in water resources allocation. Huang-Yangtze and Huai-Yangtze, the reduced Gini coefficients are 6.51 per cent, 6.58 per cent, 7.02 per cent, 2.29 per cent and 7.28 per cent, respectively, suggesting that the water transfer project has effectively moderated the degree of inequality in WSI among these basins.

4.5. Impact of water transfer projects on WSI

This study analyses in detail the impact of the water transfer project on the regional Water Stress Index (WSI) through a layer-by-layer extrapolation from downstream to upstream. This analysis takes into account all levels from the source of water abstraction to the receiving area and their overall impacts. We classified the water transfer projects into three categories: water transfer projects across primary basins (L1-IBWTP), water transfer projects across secondary basins (L2-IBWTP), and water transfer projects across tertiary basins (L3-IBWTP), with the numbers of 46, 16, and 19 projects, respectively. The results, as shown in Fig. 10, show that at the water intake sources, the increase in WSI of 73 IBWTPs is less than 0.2, indicating that these projects have less impact on the water stress in the water intake source area. In particular, the impact of L1-IBWTP projects on the WSI of water intake sources is generally less than 0.2. In L2-IBWTP, only Luan River to Tianjin Water Diversion Project (LRTJWDP) presents a medium level of impact, Tianjin North-South Water Diversion Project (TNSWDP) presents an extreme level of impact, and there are one of the six projects with medium and higher impacts in L3-IBWTP. These higher impact level projects, such as the Luan River to Tangshan Water Diversion Project (LRTSWDP), Jingmi Diversion Canal Project (JWDCP) and Yongding River Diversion Canal Project (YRDCP), affect more than 90 % of the water sources. This may be due to the fact that the L1-IBWTP mainly draws water from the water-rich Yangtze and Yellow River Basins, while the L2-IBWTP and L3-IBWTP are located in the Hai and Huai River Basins, where water resources are relatively scarce, leading to greater impacts on water source areas.

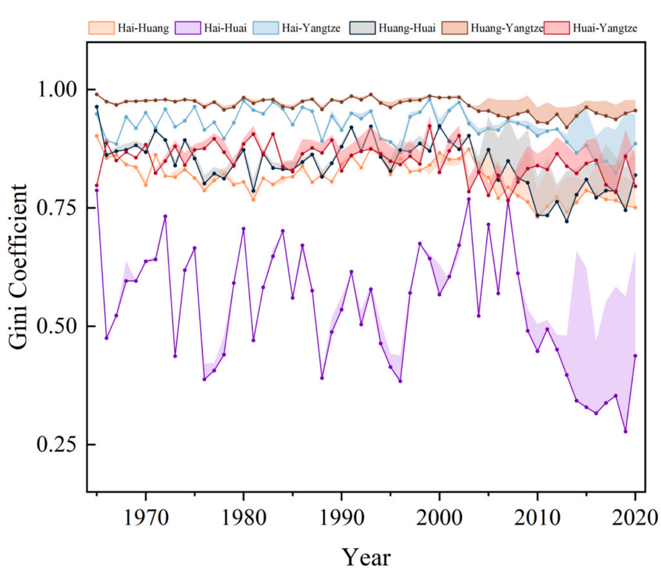

Fig. 9. Gini coefficient of WSI between watersheds. The shaded areas indicate the contribution of IBWT to Gini coefficient.

IBWTP plays a crucial role in mitigating WSI in a specific area. L1-IBWTP shows a significant advantage over the other types in reducing WSI, with an average WSI change of −0.542, which is significantly higher than the average change values of −0.353 and −0.342 for L2-IBWTP and L3-IBWTP. This difference may be indicative of the L1-IBWTP is advanced in terms of technology, design, or management strategy. The impacts of the projects on the receiving waters show significant distributional variability, with five projects having moderate impacts, four having severe impacts, and ten having extreme impacts. This variability may be related to a variety of factors such as the size of the project, geographical location, design features and implementation strategies. The South-North Water Diversion Central Route 1 (SNWDP-CR1) produced the largest impacts among all the projects, followed closely by the People's Victory Canal Project (PVCP) and the LRTSWDP, which are particularly concentrated in water-stressed regions such as the Hai and Huai River Basins.

For total impacts, most of the IBWTPs have positive impacts, the WSI of receiving water is greater than the WSI of withdrawing water. This suggests that the IBWTPs tend to transfer from areas with more WA to areas with less WA and more WU. These projects mitigate the regional water imbalance. Only 10 projects have negative impacts, and they are all located in the Huai and Hai river basins, among which YRDCP, JWDCP and TNSWDP have large negative impacts, with WSIs greater than 1, contributing more than 20 %.

We find that most IBWTPs tend to have positive impacts, i.e., transferring water from water-rich regions to water-scarce and high-demand regions. This strategy has been effective in mitigating the problem of unequal distribution of water resources in the region. However, it is of concern that there are still 10 projects that show negative impacts. The existence of these projects suggests that although inter-basin water transfers can help balance water resources to a large extent, the geographic, environmental, and socio-economic conditions of each project need to be carefully considered to to ensure long-term sustainability and benefits. Future research and policy development should take these factors into account in order to optimise water resources management and reduce adverse impacts, while enhancing regional and national water security.

5. Discussion

5.1. Inter-basin water transfers effectively alleviate stress on water resources

There is an incongruous relationship between supply and demand of water resources in China, and inter-basin water transfers are gradually gaining attention as an important initiative to alleviate the pressure on water resources. Our study provides valuable insights into the growing inter-basin water transfers and demonstrates the effectiveness of inter-basin water transfers in alleviating WSI. Most previous studies have focused on the Yellow, Huai, and Hai River basin or separate basins, ignoring the water resources status of the Yangtze River Basin (YRB). In this paper, we chose the HHHYRB as the study area, which is a unique hydrological linkage brought about by inter-basin water transfers. We analysed the urban-scale and tertiary basin-scale water stress indices of the HHHY, which is in line with several studies, such as White et al. (2015), that the Hai River Basin suffers from very serious water scarcity,

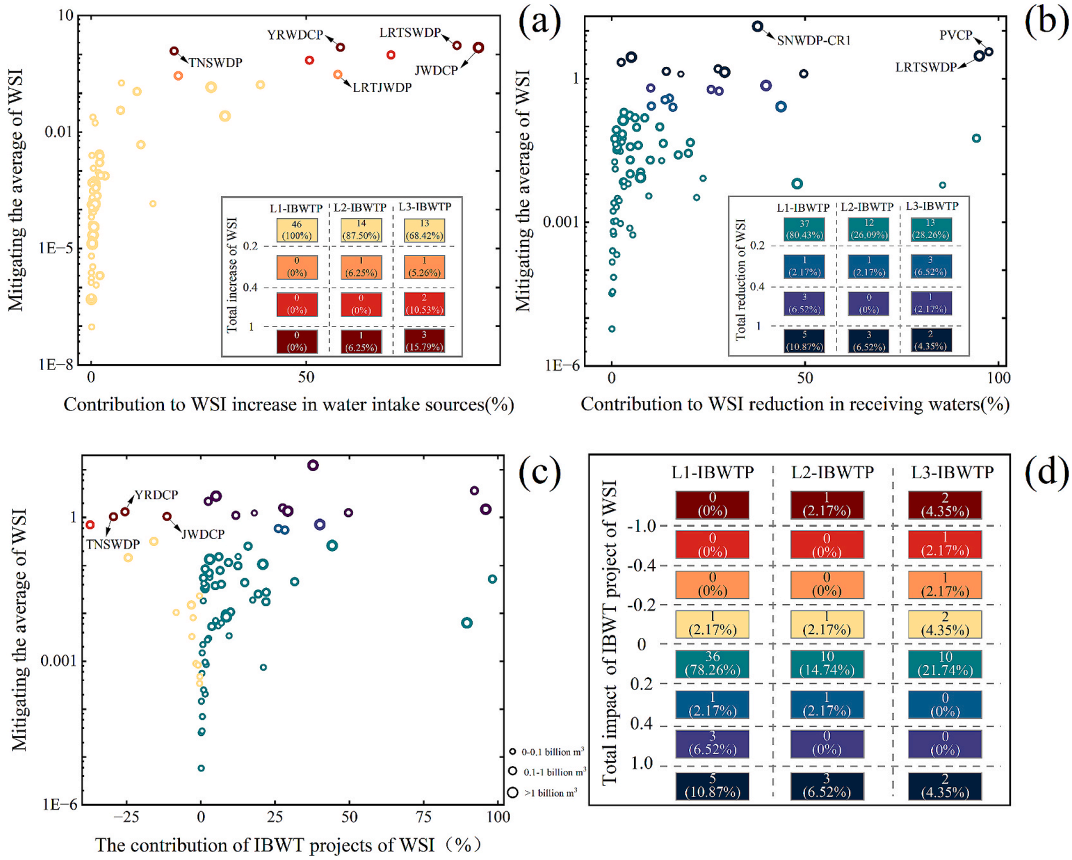

Fig. 10. Impact of water transfer projects. (a) Contribution to WSI increase in receiving waters, (b) Contribution to WSI reduction in receiving waters, (c) The contribution of IBWT projects of WSI, (d) The contribution of IBWT projects of WSI quantity and proportion.

which may be directly related to the implementation and management of inter-basin water transfer projects in the region. Based on this, we analysed the impact of inter-basin water transfer on WSI through a counterfactual scenario, and the impact of water transfer on WSI in each basin was Hai (75 %) > Huai (15.6 %) > Yellow (−6.4 %) > Yangtze (2 %).

There is significant spatial heterogeneity in the 1965–2020 WSI in the HHHY region, and we find that the between-group coefficients (48.3 %–66 %) are significantly higher than the within-group coefficients (17.3 %–23.7 %) and the hypervariable density coefficients (10.8 %–31 %), which suggests that spatial differentiation of the WSI stems mainly from inter-regional differences. This finding contrasts with the results of similar studies in other regions, thus emphasising the uniqueness of water distribution and management patterns specific to the HHHY region. Detailed statistical analyses were used to calculate these coefficients to ensure the accuracy and reliability of the results. Particularly noteworthy is the decisive role played by the water transfer project in reducing the spatial heterogeneity of the WSI, effectively mitigating the inequality of water resources distribution. Within the basin, the impact of the water transfer project ranges from 1.77 % to 33.69 %, and between the basins, this impact is even higher, ranging from 2.29 % to 7.28 %. This result not only reveals the important role of water transfer projects in water resources management, but also provides an important reference for future water resources policy formulation. However, there are limitations in this study, such as the limitation of time scale and spatial resolution, which can be expanded in future studies to further deepen our understanding of the spatial distribution of water resources and their management. In addition, this study has important practical implications for the formulation of effective water resources management strategies and policies, especially in the context of global climate change and population growth, which are essential to ensure the sustainable use and equitable distribution of water resources.

In addition, we adopt a layer-by-layer extrapolation approach from downstream to upstream to analyse in depth the impact of inter-basin water transfer projects (IBWTP) on the water stress index (WSI) in different regions of China. Our analyses reveal the different roles and impacts of IBWTPs in water resources management. In particular, inter-level basin transfer projects (L1-IBWTP) show significant advantages in reducing WSI, with significantly higher average WSI changes than the other types, reflecting the advancement of L1-IBWTP in terms of technology, design, or management strategies. However, we also found some concerns, especially the negative impacts of some inter-secondary and tertiary basin transfer projects (L2-IBWTP and L3-IBWTP) in the Huai and Hai river basins, which suggests that we need to consider geographic, environmental, and socio-economic factors more carefully when implementing inter-basin transfer projects.

In summary, we believe that inter-basin water transfer projects have a significant effect in relieving the pressure on water resources in a given area, but their impacts on different basins are not equal, and that the importance of the water allocation scheme and the possible long-term environmental and social impacts of inter-basin water transfers should be fully taken into account when planning and implementing the projects. These factors should therefore be taken into account in the formulation of water resources management policies to achieve the long-term sustainable use of water resources.

5.2. Uncertainty and limitations

This study faced multiple uncertainties and limitations in assessing the impacts of inter-basin water transfers on WSI, which may have an impact on the accuracy and reliability of the results.

The methodology used in downscaling water use data relies on proxy variables such as area of arable land, regional GDP, population distribution, and urban area, which can lead to uncertainty. The use of cropland area as a proxy in the estimation of agricultural water demand may not capture the impact of climatic conditions and agricultural management practices on water use (Govoni et al., 2003). Domestic water demand is usually closely related to population density, but the accuracy and availability of population data may affect the reliability of the downside results (Koutiva and Makropoulos, 2016). In the case of industrial water use, the downward estimation of water use through regional GDP may ignore differences in water efficiency across industries, leading to inaccurate water demand forecasts (Liu et al., 2024). In terms of ecological water use, urban area is used as a basis for downward mobility, but this may underestimate the actual relationship between the demand for ecosystem services and ecosystems such as urban green spaces and wetlands (Zhao et al., 2024).

Uncertainty due to climate change is also an important factor affecting this study. The current study uses discrete time periods and does not adequately consider the impacts of climatic extreme events (e.g., droughts and floods) on water resource availability and basin water stress. Extreme weather events due to climate change have increased in frequency and intensity in China (Tofiq and Güven, 2015; Zhang et al., 2024), which may have significant impacts on the spatial and temporal distribution of water resources. Particularly in watershed management, extreme climate events can exacerbate seasonal fluctuations in water resources, leading to imbalances in water resource allocation and thus increasing WSI.

The sources and uncertainties of the input data are also not negligible when using the Dagum Gini coefficient to assess inequalities in water stress. The accuracy of hydrometeorological and socio-economic data has a direct impact on the calculation of the Gini coefficient. Uncertainty of data in hydrological models and socio-economic databases may lead to biased results in the calculation of the Gini coefficient. Population or income disparities can lead to incorrect assessments of water demand and use, incorrectly overstating or minimizing the Gini coefficient. To address these uncertainties, it is critical to incorporate reliable data validation techniques, such as cross-referencing multiple data sources and applying statistical adjustments to account for known inaccuracies. In addition, sensitivity analyses can be conducted to assess how changes in these data sets affect the Gini coefficient, providing a clearer picture of potential biases in the results.

In summary, hydrometeorological and social data are critical to understanding the impacts of interbasin water transfers on WSI. These uncertainties and limitations must be fully considered when interpreting the results. Future research should focus on integrating high-quality water use data, adopting dynamic modeling to address climate change impacts, and enhancing transparency in the calculation of the Gini coefficient for more effective water resource management and policymaking.

6. Conclusion

Inter-basin water transfers have alleviated the growing water scarcity problem in the four major basins of the HHHYRB. In this study, we analysed the impact of inter-basin water transfers on the Water Stress Index (WSI) of the HHHYRB by using improved WSI indexes using newly compiled data on inter-tertiary river basin transfer projects and high-resolution water use and available water resources data from 1965 to 2020. The spatio-temporal contribution of inter-basin water transfers to WSI was explored through counterfactual analysis, the degree of spatio-temporal differentiation of WSI and the impact of its transfer on inter- and intra-basin water transfers were explored by using Dagum's Gini coefficient, and finally the impacts of different types of water transfer projects on the WSI of the abstraction sources and the receiving zones were analysed quantitatively by means of scenario extrapolation:

1) The total water consumption of the four major basins increased significantly at a rate of 3.08 km^3/a, with the Yangtze River basin showing the most significant increase in water consumption and the rest of the basins showing lower growth rates; the amount of available water resources showed that the Yangtze River, the Huai River and the Yellow River were on an increasing trend, while the Hai River basin showed a decreasing trend at a rate of -0.059 km^3/a, and the Haihe River basin will face a more severe pressure on water resources.
2) The WSI of the Huanghuaihai Basin are all in the severe and above stage, mainly concentrated in the Huanghuaihai Plain. 7.5 % of the cities and 5.8 % of the tertiary basins are at the risk of moderate water stress; 28.3 % of the cities and 34.6 % of the tertiary basins are at the risk of severe and extreme water stress. The impacts of external inter-basin water transfers of the HHHY are all less than 0.002, and the impacts of the water transfers on WSI of all the basins are from high to low are Hai River (75 %), Huai River (15.6 %), Yellow River (−6.4 %), and Yangtze River (2 %).
3) The Dagum Gini coefficient analysis further indicates that there is significant spatial heterogeneity in the WSI of the HHHY, with intergroup coefficients (48.3 %–66 %) being higher than intragroup coefficients (17.3 %–23.7 %) and hypervariable density coefficients (10.8 %–31 %) in the 1965–2020 period, which is the main source of spatial differentiation. The water transfer project played a key role in reducing spatial heterogeneity within and between WSI basins, effectively moderating the degree of water inequality, with intra-basin impacts ranging from 1.77 %–33.69 % and inter-basin impacts reaching 2.29 %–7.28 %.
4) Most of the water transfer projects tend to transfer water from areas with low WSI to areas with high WSI, resulting in positive impacts. The impacts of the L1-IBWTP projects on the WSI of the water intake sources are generally less than 0.2, and for the average change in WSI in the receiving areas reaches −0.542. The L2-IBWTP and L3-IBWTP are mostly located in the Hai River and Huai River Basin, where the water resources are relatively scarce, resulting in larger impacts on the water source areas. zone's greater impact. There are still 10 water transfer projects with negative impacts, all of which are located in the Huai and Hai river basins, with WSI greater than 1, contributing more than 20 %.

CRediT authorship contribution statement

Lichuan Wang: Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Fan He:** Writing – review & editing, Conceptualization. **Yong Zhao:** Investigation, Conceptualization. **Jianhua Wang:** Investigation, Conceptualization. **Meng Hao:** Validation, Data curation. **Peiyi Lu:** Validation, Data curation. **Yage Jia:** Validation. **Kuan Liu:** Visualization, Data curation. **Haodong Deng:** Visualization.

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.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (52394231, 52061125101), the National key research and development program of China (2021YFC3200204).

Data availability

Data will be made available on request.

References

Amarasinghe, U.A., Smakhtin, V., 2014. Global water demand projections: Past, present and future. IWMI Res. Rep. 156, 1–24. https://doi.org/10.5337/2014.212.

Boretti, A., Rosa, L., 2019. Reassessing the projections of the World Water Development Report. Npj Clean Water 2 (1), 15. https://doi.org/10.1038/s41545-019-0039-9.

Chameni, C., 2006. A note on the decomposition of the coefficient of variation squared: Comparing entropy and Dagum's methods. Econ. Bull. 4, 1–8.

de O. Vieira, E., Sandoval-Solis, S., 2018. Water resources sustainability index for a water-stressed basin in Brazil. J. Hydrol. Reg. Stud. 19, 97–109. https://doi.org/10.1016/j.ejrh.2018.08.003.

Duan, K., et al., 2023. Evolving efficiency of inter-basin water transfers in regional water stress alleviation. Resour. Conserv. Recycl. 191, 106878. https://doi.org/10.1016/j.resconrec.2023.106878.

Fazal, M.A., Imaizumi, M., Ishida, S., Kawachi, T., Tsuchihara, T., 2005. Estimating groundwater recharge using the SMAR conceptual model calibrated by genetic algorithm. J. Hydrol. 303 (1), 56–78. https://doi.org/10.1016/j.jhydrol.2004.08.017.

Gosling, S.N., Arnell, N.W., 2016. A global assessment of the impact of climate change on water scarcity. Clim. Change 134 (3), 371–385. https://doi.org/10.1007/s10584-013-0853-x.

Govoni, C., D'Odorico, P., Pinotti, L., et al., 2003. Preserving global land and water resources through the replacement of livestock feed crops with agricultural by-products. Nat Food 4, 1047–1057. https://doi.org/10.1038/s43016-023-00884-w.

He, C., et al., 2021. Future global urban water scarcity and potential solutions. Nat. Commun. 12 (1), 4667. https://doi.org/10.1038/s41467-021-25026-3.

Hejazi, M., Edmonds, J., Chaturvedi, V., Davies, E., Eom, J., 2013. Scenarios of global municipal water-use demand projections over the 21st century. Hydrol. Sci. J. 58 (3), 519–538. https://doi.org/10.1080/02626667.2013.772301.

Huang, Z., Yuan, X., Liu, X., 2021. The key drivers for the changes in global water scarcity: Water withdrawal versus water availability. J. Hydrol. 601, 126658. https://doi.org/10.1016/j.jhydrol.2021.126658.

Khadem, M., Dawson, R.J., Walsh, C.L., 2021. The feasibility of inter-basin water transfers to manage climate risk in England. Clim. Risk Manage. 33, 100322. https://doi.org/10.1016/j.crm.2021.100322.

Koutiva, I., Makropoulos, C., 2016. Modelling domestic water demand: An agent based approach. Environ Modell Softw 79, 35–54. https://doi.org/10.1016/j.envsoft.2016.01.005.

Kummu, M., et al., 2016. The world's road to water scarcity: shortage and stress in the 20th century and pathways towards sustainability. Sci. Rep. 6 (1), 38495. https://doi.org/10.1038/srep38495.

Li, J., Liu, Z., He, C., Yue, H., Gou, S., 2017. Water shortages raised a legitimate concern over the sustainable development of the drylands of northern China: Evidence from the water stress index. Sci. Total Environ. 590–591, 739–750. https://doi.org/10.1016/j.scitotenv.2017.03.037.

Liu, B., Zhang, L., Wang, W., Sun, C., Dong, S., Wang, Z., 2024. Development of a conceptual regional industrial water use efficiency model driven by economic development level. J. Hydrol: Reg Stud 55, 101926. https://doi.org/10.1016/j.ejrh.2024.101926.

Liu, Y., Xin, Z., Sun, S., Zhang, C., Fu, G., 2023. Assessing environmental, economic, and social impacts of inter-basin water transfer in China. J. Hydrol. 625, 130008. https://doi.org/10.1016/j.jhydrol.2023.130008.

Ma, T., et al., 2020. Pollution exacerbates China's water scarcity and its regional inequality. Nat. Commun. 11 (1), 650. https://doi.org/10.1038/s41467-020-14532-5.

Matete, M., Hassan, R., 2006. Integrated ecological economics accounting approach to evaluation of inter-basin water transfers: An application to the Lesotho Highlands Water Project. Ecol. Econ. 60 (1), 246–259. https://doi.org/10.1016/j.ecolecon.2005.12.010.

Nilsalab, P., Gheewala, S.H., Pfister, S., 2018. Method Development for Including Environmental Water Requirement in the Water Stress Index. Water Resour. Manage. 32 (5), 1585–1598. https://doi.org/10.1007/s11269-017-1892-2.

Nilsalab, P., Gheewala, S.H., Silalertruksa, T., 2017. Methodology development for including environmental water requirement in the water stress index considering the case of Thailand. J. Cleaner Prod. 167, 1002–1008. https://doi.org/10.1016/j.jclepro.2016.11.130.

Nyingi, R.W., Mwangi, J.K., Karimi, P., Kiptala, J.K., 2024. Reliability of stream flow in inter-basin water transfer under different climatic conditions using remote sensing in the Upper Tana basin. Phys. Chem. Earth, Parts a/b/c 134, 103527. https://doi.org/10.1016/j.pce.2023.103527.

Purvis, L., Dinar, A., 2020. Are intra- and inter-basin water transfers a sustainable policy intervention for addressing water scarcity? Water Secur. 9, 100058. https://doi.org/10.1016/j.wasec.2019.100058.

Rey, S.J., Smith, R.J., 2013. A spatial decomposition of the Gini coefficient. Lett. Spat. Resour. Sci. 6 (2), 55–70. https://doi.org/10.1007/s12076-012-0086-z.

Rollason, E., Sinha, P., Bracken, L.J., 2021. Interbasin water transfer in a changing world: A new conceptual model. Prog. Phys. Geogr.: Earth Environ. 46 (3), 371–397. https://doi.org/10.1177/03091333211065004.

Roozbahani, A., Ghased, H., Hashemy Shahedany, M., 2020. Inter-basin water transfer planning with grey COPRAS and fuzzy COPRAS techniques: A case study in Iranian Central Plateau. Sci. Total Environ. 726, 138499. https://doi.org/10.1016/j.scitotenv.2020.138499.

Scanlon, B.R., et al., 2023. Global water resources and the role of groundwater in a resilient water future. Nat. Rev. Earth & Environ. 4 (2), 87–101. https://doi.org/10.1038/s43017-022-00378-6.

Sheng, J., Qiu, W., 2023. Inter-basin water transfer policies and water-use technical efficiency: China's South-North Water Transfer Project. Socio-Econ. Plan. Sci. 85, 101432. https://doi.org/10.1016/j.seps.2022.101432.

Sun, J., et al., 2024. Decoupling trend and drivers between grain water-carbon footprint and economy-ecology development in China. Agric. Syst. 217, 103904. https://doi.org/10.1016/j.agsy.2024.103904.

Sun, S., et al., 2021. Unraveling the effect of inter-basin water transfer on reducing water scarcity and its inequality in China. Water Res. 194, 116931. https://doi.org/10.1016/j.watres.2021.116931.

Tan, B.Q., O'Connor, K.M., 1996. Application of an empirical infiltration equation in the SMAR conceptual model. J. Hydrol. 185 (1), 275–295. https://doi.org/10.1016/0022-1694(95)02993-1.

Tofiq, F.A., Güven, A., 2015. Potential changes in inflow design flood under future climate projections for Darbandikhan Dam. J. Hydrol. 528, 45–51. https://doi.org/10.1016/j.jhydrol.2015.06.023.

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth. Science 289 (5477), 284–288.

Wada, Y., Bierkens, M.F.P., 2014. Sustainability of global water use: past reconstruction and future projections. Environ. Res. Lett. 9 (10), 104003. https://doi.org/10.1088/1748-9326/9/10/104003.

Wang, L., et al., 2023. Complex network-based analysis of inter-basin water transfer networks. Ecol. Indic. 156, 111197. https://doi.org/10.1016/j.ecolind.2023.111197.

White, D.J., Feng, K., Sun, L., Hubacek, K., 2015. A hydro-economic MRIO analysis of the Haihe River Basin's water footprint and water stress. Ecol. Model. 318, 157–167. https://doi.org/10.1016/j.ecolmodel.2015.01.017.

Wu, L., Su, X., Zhang, T., 2023. Challenges of typical inter-basin water transfer projects in China: Anticipated impacts of climate change on streamflow and hydrological drought under CMIP6. J. Hydrol. 627, 130437. https://doi.org/10.1016/j.jhydrol.2023.130437.

Xiangmei, M., Leping, T., Chen, Y., Lifeng, W., 2021. Forecast of annual water consumption in 31 regions of China considering GDP and population. Sustain. Prod. Consum. 27, 713–736. https://doi.org/10.1016/j.spc.2021.01.036.

Xiong, J., et al., 2022. Projected changes in terrestrial water storage and associated flood potential across the Yangtze River basin. Sci. Total Environ. 817, 152998. https://doi.org/10.1016/j.scitotenv.2022.152998.

Yang, C., Liu, Y., Yang, J., Li, Y., Chen, S., 2022. Reconstructing the Historical Terrestrial Water Storage Variations in the Huang–Huai–Hai River Basin With Consideration of Water Withdrawals. Front. Environ. Sci. 10. https://doi.org/10.3389/fenvs.2022.840540.

Young, C., et al., 2007. Modeling shallow water table evaporation in irrigated regions. Irrig. Drain. Syst. 21 (2), 119–132. https://doi.org/10.1007/s10795-007-9024-4.

Zhai, R., et al., 2022. Future water security in the major basins of China under the 1.5 °C and 2.0 °C global warming scenarios. Sci. Total Environ. 849, 157928. https://doi.org/10.1016/j.scitotenv.2022.157928.

Zhang, F., et al., 2024. Study on adaptive regulation based on water supply-demand system structure and water use desirability under extreme drought. Int. J. Disast. Risk. Re 110, 104602. https://doi.org/10.1016/j.ijdrr.2024.104602.

Zhang, L., et al., 2023. China's strictest water policy: Reversing water use trends and alleviating water stress. J. Environ. Manage. 345, 118867. https://doi.org/10.1016/j.jenvman.2023.118867.

Zhao, X., et al., 2024. Whether the ecological benefits will continue to increase as usual and improve under the background of continuous ecological water delivery?—Taking the Lower Tarim River in China as an example. Ecol. Indic 159, 111733. https://doi.org/10.1016/j.ecolind.2024.111733.

Zhou, Q., et al., 2016. Development and implementation of a spatial unit non-overlapping water stress index for water scarcity evaluation with a moderate spatial resolution. Ecol. Indic. 69, 422–433. https://doi.org/10.1016/j.ecolind.2016.05.006.