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Do Water Transfer Projects Promote Water Use Efficiency? Case Study of South-to-North Water Transfer Project in Yellow River Basin of China

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Abstract: With a huge capital and labor input influx, inter-basin water transfer (IBWT) projects have been shown to effectively mitigate water stress and ensure the water demand for social and economic development in the receiving area. Whether they have promoted the improvement of regional water use efficiency (WUE) is crucial for sustainable management of regional water resources. Targeting the South-to-North Water Transfer Project (SNWTP), the largest and most ambitious inter-basin water transfer project in China, this study establishes quantitatively econometric models to analyze the impact of different water diversion projects, specifically the eastern route of the SNWTP (ER-SNWTP), middle route of the SNWTP (MR-SNWTP), and diversion from the main stream of the Yellow River (DYR), on the regional water consumption per unit of GDP; regional water stress, water use structure, economic structure, and urbanization level are used as control variables in different types of cities in the Yellow River Basin, and some intriguing results are found. While the overall water transfer project demonstrates a positive impact on water use efficiency, the effects of the three water transfer measures vary significantly. The ER-SNWTP does not exhibit a notable positive effect on regional water use efficiency, whereas the MR-SNWTP demonstrates a significant positive impact. Interestingly, the DYR has a notable negative influence on water use efficiency in developed cities. The water use structure, shaped by the pricing, scale, and policies of different projects, emerges as a pivotal factor in explaining these differences. Finally, this paper suggests that the impact of water transfer projects on the improvement of regional water use efficiency be viewed from a more comprehensive and developmental perspective.

Keywords: inter-basin water transfer project; South-to-North Water Transfer Project; diversion from main stream of Yellow River; water use efficiency; Yellow River Basin of China

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1. Introduction

Ensuring adequate water supply for human life and development is a crucial aspect of sustainable development goals. Nevertheless, water scarcity has become a global concern due to the escalating demand for water and its mismatch with water availability in terms of spatial and temporal distribution [1,2]. To address this problem, various types of measures and water infrastructure had been implemented and constructed, including sea water desalinating, water reclaiming, Inter-Basin Water Transferring, and water diverting from major river streams [3]. Inter-basin water transfer (IBWT) projects refer to the water conservancy infrastructure to transfer water from one basin to another, from one river to another, and from freshwater bodies (such as rivers, lakes, and underground water sources) to places where water is urgently needed [4].

It has been shown that IBWT projects have significantly enhanced the allocation and supply capacity of water resources in the receiving area, effectively mitigated water stress, and ensured the water demand for social and economic development [4–7]. However, do IBWT projects promote water use efficiency (WUE) in the receiving area? This aspect has received limited attention in existing studies because the majority of studies have primarily focused on its effectiveness in alleviating regional water scarcity [8] and associated ecological and environment impacts [9,10]. Some scholars argued that while IBWT projects have effectively alleviated water resource shortage, they do not guarantee the fundamental sustainable utilization of water resources and may even potentially reduce WUE as the scarcity of water resource is no longer a constraint [7]. To achieve sustainable water resource utilization, comprehensive measures must be implemented to manage the transferred areas. A fundamental approach was to establish a comprehensive water-saving society. For instance, Sheng et al. examined the impact of IBWT policies on water-use technical efficiency (WUTE) and discovered that IBWT can enhance WUTE in water-receiving cities accompanied by water-saving policies and environmental regulations [11]. Duan et al. addressed the relative contribution of various driving forces to the efficiency of IBWT in mitigating water stress, considering complex hydrological and socioeconomic changes, water use patterns, population dynamics, and transfer magnitude, and found the changes in water use sectors, such as the shift from thermal power generation to other uses and the decrease in irrigation water use, can significantly impact on the efficiency of IBWT [6]. On the other hand, some scholars have suggested that IBWT may also stimulate population and economic growth in the water-receiving area [12]. However, the high cost of water and stringent regulations pertaining to water management can serve as catalysts for industrial structural transformation and advancements in water technology, ultimately leading to the enhancement of water-use technical efficiency [11]. Nevertheless, some scholars observed that factors such as the escalating water consumption in the residential sector, unregulated water usage, and water leakage contributed to the inefficiency of water utilization [13]. When water scarcity is alleviated through water transfers, individuals' awareness of water saving may diminish, leading to a decrease in water use efficiency [12]. Therefore, IBWT and WUE may not operate as standalone solutions to water scarcity, indicating that neglecting their interdependence could jeopardize the ultimate resolution. Therefore, a comprehensive approach that accounts for the intricate interplay between IBWT and WUE is crucial for achieving sustainable water management.

Since the 1950s, China has been constructing IBWT infrastructure to redistribute water resources across diverse river basins to address the escalating demand for water in cities and irrigation areas. Among these projects, the South-to-North Water Transfer Project (SNWTP) stands out as one of the largest and most ambitious inter-basin water transfer projects globally, transporting water from the Yangtze River Basin to the northern and northwestern regions of the country via three distinct routes: eastern, middle, and western [13–15]. The eastern route of the SNWTP (ER-SNWTP) channels water from the lower reaches of Yangtze River to the provinces of Jiangsu, Anhui, Shandong, and Hebei, as well as the municipality of Tianjin through a sophisticated network of pumps, rivers, lakes, reservoirs, and canals. The first phase of this route became operational in 2013, with a planned annual water transfer capacity of 8.8 billion cubic meters [8,16]. The middle route (MR-SNWTP) transfers water from the Danjiangkou Reservoir, situated in the middle and upper reaches of the Han River (a tributary of the middle Yangtze River) to Henan, Hebei, Beijing, and Tianjin through a newly constructed canal. In 2014, the first phase of this route was commissioned, with an annual average water transfer capacity of 9.5 billion cubic meters. The west route (WR-SNWTP), which aims to deliver water from upper Yangtze River to Northwest China, is in the planning stages [14,17,18]. Despite the construction, a significant proportion of studies have focused primarily on the social, economic, and ecological impact of the water transfer project itself. There has been a notable lack of attention paid to the socio-economic impact of the project on the affected areas post-implementation [4,18,19]. Official statements have often highlighted the SNWTP's substantial contributions in enhancing the water supply capacity and ensuring the water needs for social and economic development [8]. It was reported that the first stage of this particular IBWT project had improved water availability for 120 million people in 41 cities in China, which equates to 8.5% and 12.4% of the whole country, respectively, by the end of 2020 [16]. However, does the change in water supply create or limit the opportunities and space for an increase in water use efficiency? There have not been enough analyses performed. Lin et al. conducted life cycle impact assessment modeling and estimated that the SNWTP could lead to a 5.74% net reduction in the environmental impact of water consumption embodied in the final demand from both southern and northern China [20]. However, Shen et al. adopted a difference-in-differences approach to scrutinize the effect of the SNWTP on the water-use technical efficiency, and found that the increase in WUTE in water-receiving cities not related to the improvement in water endowment resulting from IBWT, but rather with the water-saving capacity and regulation [11]. Therefore, it is necessary to explore in depth the relationship between the SNWTP and water use efficiency, and what factors affect the changes in this relationship.

The Yellow River Basin is a region with serious shortage of water resources in north of China, with an average annual precipitation of merely 476 mm, exacerbated by the uneven spatiotemporal distribution and challenges in utilization. Therefore, IBWT projects play an important role in supplementing water resources and mitigating water scarcity pressure. However, challenges such as low efficiency in water resource utilization persisted [21]. This study aims to investigate the impact of transferring water resources on regional water use structure, water use efficiency, and industrial structure adjustment in cities within the Yellow River Basin compared to water diversion project from main stream of the Yellow River (DYR), and quantitatively identify the contribution of water transfer projects towards fostering a water-saving society.

The contributions of this study lie in addressing three key questions. Firstly, it evaluates the contribution of IBWT to local water consumption taking into account various water transfer measures. Secondly, it quantitatively explores the impact of water transfer on water use efficiency, comparing with other water diversion project. Thirdly, it delves into the internal factors that constrain the effect of water transfer on water use efficiency, encompassing water pricing, water use structure, economic structure, as well as local economic and urbanization levels. The aim is to provide scientific backing for enhancing the economic viability of water transfer projects and more sustainable and efficient water resource management.

2. Materials and Methods

2.1. Model

Water-use efficiency, defined as the quantity of water consumed per unit of gross domestic product (GDP), serves as a metric that effectively gauges magnitude and efficacy of water utilization in economic growth [22,23]. Typically, water-use efficiency emerges as a composite outcome of water supply and demand dynamics (Figure 1). In scenarios where water supply significantly exceeds demand, water-use efficiency tends to be lower, as achieving higher efficiency necessitates greater capital and technological investments. On the supply side, local water availability is influenced by endogenous water resource and external water transfers. On the demand side, the structure and efficiency of water utilization primarily determine the scale of water consumption.

Existing studies have probed into the various factors that influence water efficiency, including water resource per capita, economic level, industrial structure, foreign investment, urbanization level, and even environmental regulation [21,23–25]. Additionally, scholars have paid attention to the effect of water price on water-use efficiency [26]. Given the disparities in engineering complexity and investment scales, the cost and scale of various water infrastructure are different, resulting in differentiated effects on water use efficiency. Typically, a lower water price coupled with ample water supply fails to effectively constrain local water utilization, leading to a reliance on existing water consumption patterns and efficiencies. Conversely, higher water prices and constrained supply tend to restrict water usage by elevating its cost. This prompts local consumers to reconfigure their water use patterns, prioritizing high-value-added industrial production, ultimately stimulating the adoption of water-saving technologies and enhancing water use efficiency.

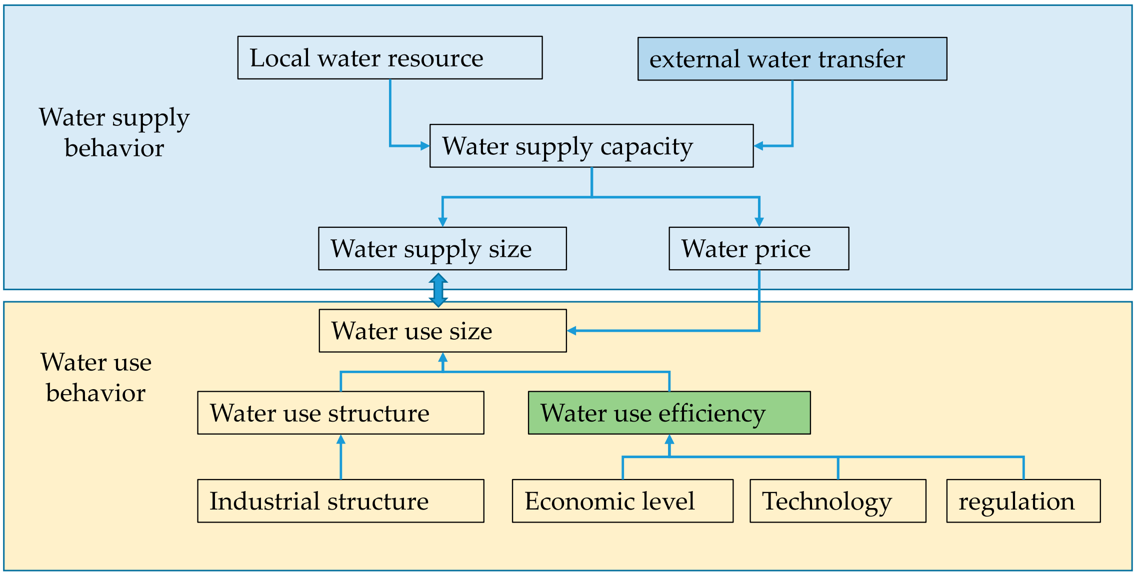

Figure 1. Framework for the influencing factors of water use efficiency.

There are several types of water supply infrastructure in China, including lifting water from rivers, lakes, and reservoirs on the surface, extracting groundwater, and transferring water from external basins. Normally, the first four types of water intake infrastructure are all located within the region, with comparatively low costs for construction, operation, and maintenance, resulting in lower water prices. Cross-basin water transfer projects involve the construction, operation, and maintenance (by multiple engineers) of pumping stations, canal, dams, water conservancy, and shipping, which lead to a relatively higher water price and smaller quantities of water compared to local water infrastructure. Therefore, based on the intricate relationship between water efficiency, quantity, and price, we derived the following hypothesis: cross-basin water transfer projects contribute to enhancing regional water use efficiency.

To analyze the impact of IBWT projects on local water use efficiency compared with other water diversion projects, we established a panel model incorporating water supply capacity from IBWT and local water diversion projects, local water stress, water use structure, industrial structure, economic level, and urbanization level based on existing research, such as [21,23–25], and data availability:

$$\begin{aligned} wateruseeff_{it} = f(&waterpress_{it}, watertransfer_{it}, wateragri_{it}, \\ &agri_{it}, cornp_{it}, GDPP_{it}, urban_{it}) \end{aligned} \quad (1)$$

The functional relationship of Equation (1) can be expressed as:

$$\begin{aligned} wateruseeff_{it} = \; & \beta_1 waterpress_{it} + \beta_2 watertransfer_{it} + \beta_3 wateragri_{it} + \beta_4 agri_{it} \\ & + \beta_5 cornp_{it} + \beta_6 GDPP_{it} + \beta_7 urban_{it} \end{aligned} \quad (2)$$

The later model for the individual fixed effects regression model just added fixed effects on the basis of Equation (2), which has been expressed in Equation (3):

$$\begin{aligned} wateruseeff_{it} = \; & \lambda_i + \beta_1 waterpress_{it} + \beta_2 watertransfer_{it} + \beta_3 wateragri_{it} \\ & + \beta_4 agri_{it} + \beta_5 cornp_{it} + \beta_6 GDPP_{it} + \beta_7 urban_{it} + u_{it} \end{aligned} \quad (3)$$

where $wateruseeff_{it}$ refers to the water use efficiency indicated by the water consumption per unit of GDP of prefectural unit i at time t. $\lambda_i, \beta_1, \beta_2, \beta_3, \beta_4, \beta_5, \beta_6,$ andβ_7 are the unknown parameters to be estimated. $waterpress_{it}$ is the local water stress, which is the ratio of regional water consumption to local water endowment. $watertransfer_{it}$ is the proportion of water received from water transfer in local water consumption. In this study, we first took the total water transfer (*watertransfer*) in the model and analyzed the impact of water transfer projects on water use efficiency. Then, we divided it into SNWTP (*watersnwtp*) and DYR (*waterdyr*), and analyzed the impact of two different projects separately. $wateragri_{it}, agri_{it}, GDPP_{it}, cornp_{it},$ and$urban_{it}$ refer to the proportion of water consumption of agriculture sector, the proportion of primary sector in total regional GDP, GDP per capita level, corn production per capita, and urbanization level, respectively, and the u_{it} is the error term. Table 1 summarizes all variables.

Table 1. Description and data source of variables.

Variables	Description	Unit	Min	Max	Mean	Std. Dev.
wateruseeff	water use efficiency as the water consumption per unit of GDP	m^3/10,000 CNY	7.820	877.910	99.888	119.975
urban	urbanization rate	%	24.120	95.370	54.869	14.989
GDPP	gross domestic product per capita	10,000 CNY	0.841	18.596	5.145	3.028
agri	proportion of agriculture in GDP	%	0.800	62.000	11.378	8.036
wateragri	proportion of agriculture water use in total water consumption	%	0.167	1.298	0.619	0.195
waterpress	ratio of water consumption to local water resource	/	0.001	37.905	2.083	4.307
cornp	corn production per Capita	tons	2.768	1795.022	489.484	284.273
watertransfer	proportion of water received from water transfer project in total water consumption	%	0.000	1.553	0.225	0.277
watersnwtp	proportion of water received from SNWTP in total water consumption	%	0.000	1.170	0.021	0.086
waterdyr	proportion of water received from DYR project in total water consumption	%	0.000	1.183	0.199	0.249

2.2. Study Area and Data Source

In this study, we take the Yellow River Basin as the study area, which is located in northern China and involves Qinghai, Gansu, the Ningxia Hui Autonomous Region, the Inner Mongolia Autonomous Region, Shaanxi, Shanxi, Henan, and Shandong province (Figure 2). According to the scope of the natural geographical boundary of the Yellow River Basin, a total of 78 prefecture level cities are involved.

The Yellow River Basin is an area with severe water scarcity in China, characterized by insufficient local water resources as well as higher water consumption due to rapid industrialization and urbanization [27]. Apart from utilizing local surface water in branch of Yellow River, lake, reservoir, and groundwater to meet the water demand for regional socio-economic development, cities along the Yellow river actively divert water from the main stream to develop irrigation agriculture and fulfill the needs of industrial and urban economies. Furthermore, selected cities in Shandong and Henan provinces receive water transfers from the ER-SNWTP and the MR-SNWTP, respectively (Figure 2).

The sample period is from 2013 to 2020 with ER-SNWTP and MR-SNWTP put into use continuously. The original data are collected from several sources, namely, the Water Resources Bulletin of each province (multiple issues on https://www.cnki.net), statistical yearbooks of each province (multiple issues on http://www.stats.gov.cn/), Yearbook of

China's South-to-North Water Diversion Project [16], and Yellow River Water Distribution Plan of each province based on related literature [28–30].

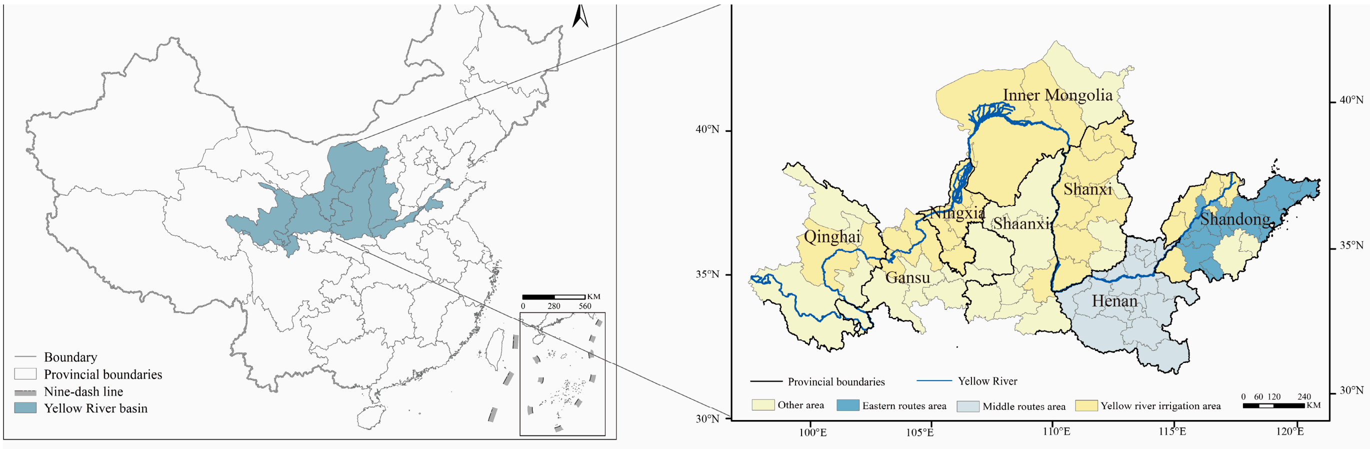

Figure 2. Location of the research area in China and types of water received from water transfer projects.

3. Results

3.1. Spatial Pattern of Water Use Efficiency and Water Supply Infrastructure in Yellow River Basin

3.1.1. Spatial Pattern of Water Use Efficiency

Based on water consumption per unit of GDP, we analyzed the spatial patterns and changes in water use efficiency during the period from 2013 to 2020 (Figure 3). It can be found that cities situated downstream exhibited superior water use efficiency compared to those in the middle and upstream regions. Qingdao in Shandong Province was the city with the highest water use efficiency with its water consumption per unit of GDP less than 10 m^3/10,000 CNY in 2020. Following closely behind were several provincial capital cities, including Taiyuan of Shanxi Province, Xi'an of Shaanxi Province, Jinan of Shandong Province, Zhengzhou of Henan Province, and some economic developed cities in east of Shandong Province, such as Weihai and Yantai, also demonstrated impressive water use efficiency with water consumption per unit GDP below 20 m^3/10,000 CNY. On the other side, cities in upstream regions, particularly those along the main stream of the Yellow River, such as Yinchuan, Shizhuishan, Zhongwei in Ningxia, and Bayannur in Inner Mongolia, lagged behind with water consumption per unit GDP surpassing 100 m^3/10,000 CNY [31]. A comparative analysis of water use efficiency among cities supplied by the DYR, MR-SNWTP, and ER-SNWTP revealed intriguing patterns. Cities serviced by the ER-SNWTP exhibited significantly lower water consumption per unit GDP than those relying on the other two water transfer projects. Cities receiving water from MR-SNWTP ranked second in terms of water use efficiency improvements. However, cities utilizing water from the DYR fell below the basin's average level.

Also, with the increase in economic development, the water use efficiency of cities within the Yellow River Basin showed an increasing trend. However, the rates of increase varied among different cities. The cities with a higher water use efficiency, located in the middle and lower reaches of the Yellow River Basin, still experienced significant improvement, while the cities in the upper reaches had a slower growth of water use efficiency, especially those situated in major irrigation areas.

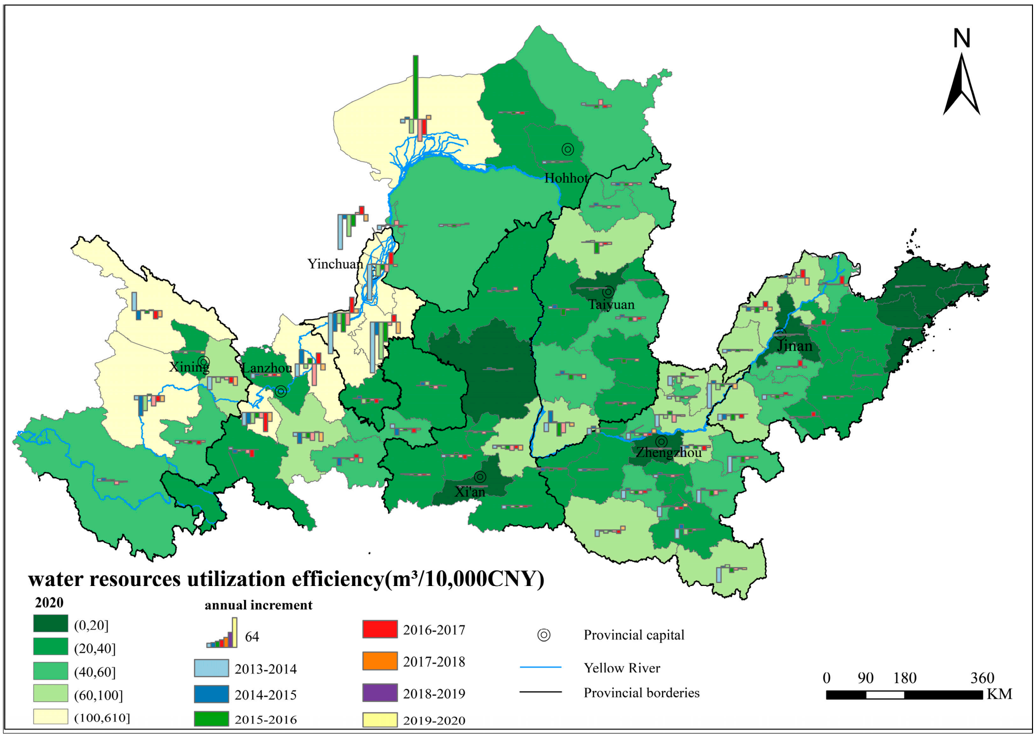

Figure 3. Spatial pattern of water use efficiency in Yellow River Basin.

3.1.2. Spatial Pattern of Water Received from DYR and SNWTP

All provinces along the Yellow River withdraws water from its mainstream based on quotas assigned by the central government to meet the requirement of agricultural irrigation, and industrial and urban development [32]. In 2020, there were 50 prefectural cities involved. According to the absolute scale and the proportion of the DYR in the overall regional water consumption, it can be found that the city with the largest water diversion scale was Bayannur City, located in the northwest corner of the Yellow River's inverted U-shaped bend, with the absolute scale of 4.812 billion cubic meters and the proportion of 74.6% in 2020 (Figure 4). However, the city with the largest proportion of the DYR in water consumption was Binzhou located at the Yellow River's terminus, where it empties into the sea, with the proportion of 80.6% and 1.34 billion cubic meters of DYR water used. Further, four cities in upper stream of basin in Ningxia, including Yinchuan, Wuzhong, Zhongwei, and Shizuishan, and two cities in Inner Mongolia as Baotou and Wuhai, and Dongying in Shandong where the Yellow River meets the sea, all exhibited a total water consumption proportion exceeding 60% (as a percentage of its water received from the DYR).

Within the Yellow River Basin, the ER-SNWTP specifically serves Shandong Province, including Jining, Liaocheng, Dezhou, and Jinan City. Further, in order to address the serious water shortage in the eastern cities of Shandong Province, a dedicated water transmission line has been established as a branch of the ER-SNWTP, which extends eastward and serves Yantai, Weihai, and Qingdao, collectively known as the "Jiaodong Water Transmission Line". Shandong has been receiving water from the ER-SNWTP since 2014, and a cumulative total of 5.3 billion cubic meters water had been received up to July 2021. With the proportion of the ER-SNWTP in regional water consumption in 2020, it becomes evident that Qingdao, the most developed city in the eastern part of Shandong, topped the list with a proportion of 18.9%. Yantai, another economically and urbanization advanced city in the same region, followed closely. However, it is worth noting that the absolute annual volume of water received from the ER-SNWTP is less than that sourced from the DYR. In 2020, Shandong Province received only 500 million cubic meters water from the ER-SNWTP, accounting for less than 10% of the water received from the DYR (Figure 5).

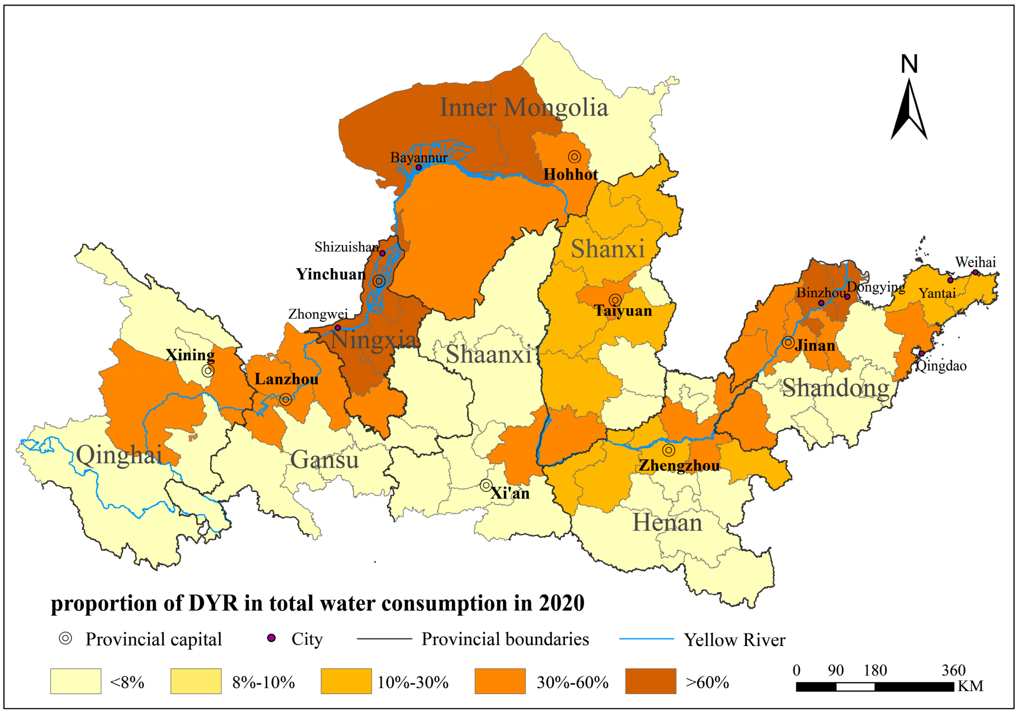

Figure 4. Spatial pattern of cities diversion water from main stream of Yellow River.

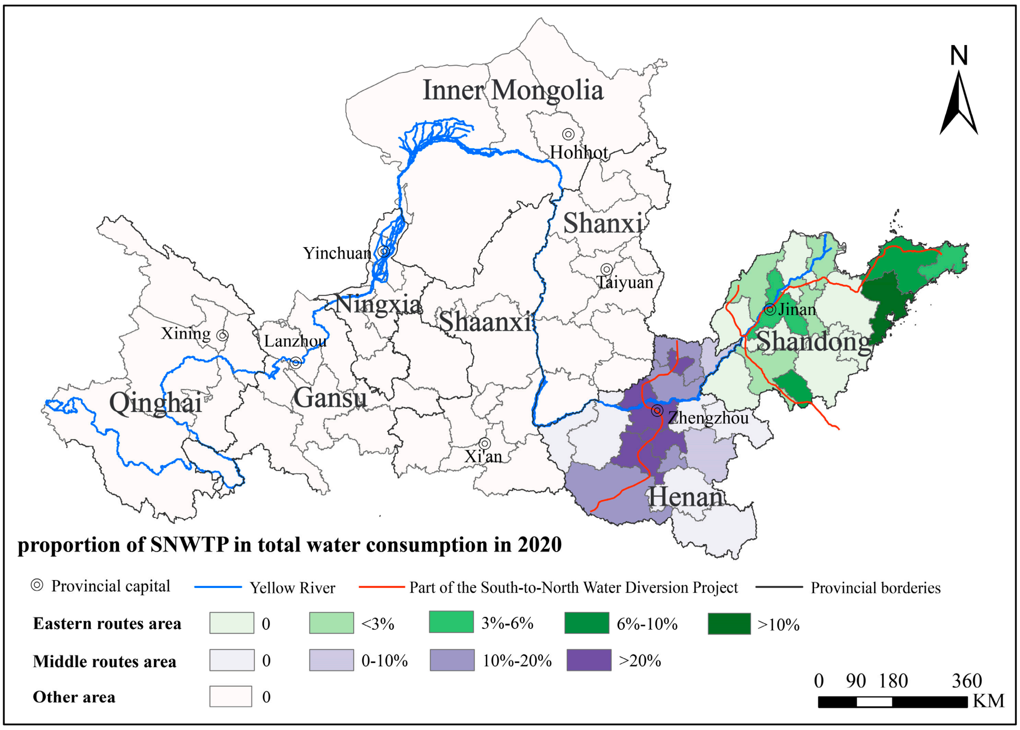

Figure 5. Spatial pattern of cities receiving water from SNWTP.

The MR-SNWTP primarily benefits Henan Province within the Yellow River Basin. Significantly, following its inception in 2015, the project delivered 2.64 billion cubic meters water to Henan Province in 2020 alone, accounting for a remarkable 69.23% of the water sourced from the DYR. In particular, cities situated along the MR-SNWTP route exhibit a particularly high proportion of SNWTP water in their overall water consumption, exceeding 20% in each case (Figure 5).

3.2. Main Factors Influencing Water Use Efficiency

Representing costly infrastructure that has a profound impact on natural water systems, cross-basin water transfer projects are bound to address water scarcity issues. However, do these infrastructures optimize or enhance regional water efficiency? While it is observed that cities receiving water through the SNWTP exhibited significantly higher water use efficiency than non-beneficiary areas, this trend closely mirrors the distribution of regional economic development. This prompts further inquiry: to what extent does the improvement in water use efficiency in these cities stem from their economic development, water utilization patterns, or the cross-basin water transfer projects themselves? Therefore, this study employs Equations (1)–(3) to quantitatively assess the influence of various factors, including water transfer scale, water use structure, economic structure, and economic level, on water use efficiency, specifically focusing on cities within the Yellow River Basin that utilize water transfer facilities.

3.2.1. Cointegration Test

Variance Inflation Factors (VIFs) were used to evaluate the severity of multi-collinearity in regression analysis. Given that the three water transfer projects in focus in this study are not all simultaneously underway in any one city, we put the variables of *watertransfer*, *watersnwtp*, and *waterdyr* separately with other variables to test according to combination situation of water transfer projects utilized in various cities in Yellow River Basin, and we found that all the VIFs for the independent variables are below 5, suggesting that the estimations are free from severe multi-collinearity (Table 2).

Table 2. VIFs test of independent variables.

Variables	VIF	1/VIF	VIF	1/VIF	VIF	1/VIF	VIF	1/VIF
urban	4.1	0.2439	4.1	0.244	4.12	0.2427	4.12	0.2425
GDPP	2.55	0.3926	2.54	0.393	2.55	0.3922	2.55	0.3922
agri	2.34	0.4276	2.24	0.4457	2.29	0.4359	2.3	0.434
wateragri	1.72	0.5813	1.61	0.6225	1.79	0.5575	1.81	0.5533
waterpress	1.41	0.7094	1.37	0.7315	1.43	0.7006	1.43	0.6996
cornp	1.23	0.8132	1.24	0.8097	1.38	0.7231	1.26	0.7944
watertransfer	1.29	0.7728						
watersnwtp			1.04	0.9571			1.05	0.9566
waterdyr					1.23	0.8159	1.38	0.7227
Mean VIF	2.09		2.02		2.11		1.99	

Also, as a Unit Root Test found some variables were non-stationary, a cointegration test is needed to examine the long-run relationships among the variables. Therefore, panel cointegration tests developed by Kao were applied. We still put variables *watertransfer*, *watersnwtp*, and *waterdyr* into testing with other interdependent variables, respectively. Table 3 presents the results of cointegration tests. All of the results confirm a long-run relationship between *wateruseeff* and the variables *watertransfer*, *watersnwtp*, *waterdyr*, *waterpress*, *wateragri*, *agri*, *urban*, *GDPP*, and *cornp*, respectively; spurious regression is avoided.

Table 3. Results of cointegration test using Kao method.

	***Watertransfer* with Other Variables**		***Watersnwtp* with Other Variables**	
	Statistic	***p*-Value**	**Statistic**	***p*-Value**
Modified Dickey–Fuller t	6.099	0	6.6656	0
Dickey–Fuller t	1.8689	0.0308	3.0815	0.001
Augmented Dickey–Fuller t	2.7996	0.0026	3.9716	0
Unadjusted modified Dickey–Fuller t	−2.1671	0.0151	−2.1832	0.0145
Unadjusted Dickey–Fuller t	−7.4499	0	−7.4507	0

Table 3. *Cont.*

	***Waterdyr*with Other Variables**		***Watersnwtp*and *Waterdyr* with Other Variables**	
	Statistic	***p*-Value**	**Statistic**	***p*-Value**
Modified Dickey–Fuller t	5.8503	0	5.6826	0
Dickey–Fuller t	1.4041	0.0801	0.942	0.1731
Augmented Dickey–Fuller t	2.3853	0.0085	1.773	0.0381
Unadjusted modified Dickey–Fuller t	−2.1866	0.0144	−2.674	0.0037
Unadjusted Dickey–Fuller t	−7.4355	0	−8.0237	0

3.2.2. Results of Regression Models

Given the multiple water transfer projects operating within the Yellow River Basin, this study categorized cities based on the actual water transfer measures employed in each. We hypothesized that changes in water use efficiency are primarily influenced by the previous year's water supply and consumption patterns. To this end, we introduced a one-year lag in the core explanatory variable, *wateruseeff*, and strived to incorporate various control variables, using the significance of the core dependent variable as a criterion for selecting appropriate control variables, ultimately enabling us to derive regression coefficients for each factor. Table 4 shows the regression outcomes for different city group according to Equation (3). Model 1 encompasses all cities involved in water transfer, while Model 2 specifically focuses on cities without such measures. Model 3 centers on cities receiving water from the ER-SNWTP, and Model 4 concerns cities benefiting from the MR-SNWTP. Finally, Model 5 examines cities supplied by the DYR.

Table 4. Results of regression models.

	(1) All Cities	**(2) Cities without IBWT**	**(3) ER-SNWTP**	**(4) MR-SNWTP**	**(5) DYR**
watertransfer	−0.077 ***	−2.343 ***	0.006	−0.085 ***	−0.082 **
	(−3.24)	(−14.23)	(0.53)	(−3.28)	(−2.57)
waterpress	0.080 ***	0.053	0.047	0.009	0.121 **
	(3.23)	(0.79)	(1.19)	(0.20)	(2.67)
agri	0.108 *	0.060 ***	0.180 **	0.210 ***	0.174
	(1.88)	(5.96)	(3.19)	(5.73)	(1.00)
wateragri	0.070 *	0.094 *	0.052 **	0.023	0.129
	(1.83)	(1.85)	(2.52)	(0.94)	(1.40)
Constant	0.062 ***	0.077 ***	−0.017 *	0.024 **	0.060
	(3.60)	(3.19)	(−2.16)	(2.53)	(1.14)
Observations	623	231	63	126	203
Number of Cities	89	33	9	18	29
Company FE	0.061	0.600	YES	YES	YES
Year FE	YES	YES	YES	YES	YES

Notes: Clustered standard error is used in estimation to correct the effect of heteroscedasticity. Statistical significance at the 1%, 5%, and 10% levels is indicated by ***, **, and *, respectively.

It can be seen that, except for Model 3, the coefficient values of *watertransfer* in other models are all negative and statistically significant, which means an increase in the proportion of water transfer in total water consumption results in a decrease in the water consumption per unit of GDP, indicating an enhancement in water use efficiency. A higher proportion of water transfer reflects a greater reliance on external water resource and consequently higher costs associated with water supply. Furthermore, the absolute values of variable *watertransfer* coefficient in the models of the MR-SNWTP group, DYR group, and other cities group are all higher than that of ER-SNWTP group, which implies that water transfer in these cities exerts a more pronounced influence on water use efficiency. This finding corroborates existing related literature [11].

For the control variables, the positive coefficient values of variables *waterpress*, *agri*, and *wateragri* indicate that cities experiencing a higher water resource pressure, higher proportion of agricultural output in GDP, and higher proportion of agricultural water use within total water consumption tend to exhibit a higher water consumption per unit of GDP and consequently a lower water use efficiency. Notably, in Model 5, which focuses on cities supplied by the DYR, the pressure of water resources exhibits a particularly significant inhibitory effect on water use efficiency. This could be attributed to the relatively inexpensive and abundant water supply from the main stream of the Yellow River, leading to a predominantly agricultural allocation of water resources and potential water wastage. Furthermore, the coefficients of *agri* in the Model 3 and Model 5 are higher than that of total cities group in Model 1. Also, *wateragri* mainly has a significant coefficient in Models 2 and 3, indicating that regions with a higher proportion of agricultural production and irrigation tend to have relatively lower water use efficiency, which underscores the influence of both economic structure and water use structure on water use efficiency.

Given the significant proportion of water allocated to agriculture irrigation, it can be inferred that water transfer can enhance water use efficiency by modulating the proportion of agricultural water use. Drawing on the casual stepwise regression method, we established the mediation effect model for this study. To ensure the validity of the results, we also used the Bootstrap method to set up the model. The results obtained from both methods are consistent. The control variables of *waterpress*, *agri*, and *urban* indicate the existence of indirect effects with a significant coefficient of −0.0101, and the proportion of intermediary effects is 11.7%. This means that the water transfer effectively contributed to the reduced proportion of agricultural water use, leading to a decline in water consumption per unit of GDP (Table 5).

Table 5. Results of intermediary effect.

	Wateragri	***Wateruseeff***
watertransfer	−0.1456 *** (−4.72)	−0.0867 *** (−4.10)
wateragri		0.07 * (1.83)
Bootstrap indirect effect		−0.0101 * (−1.93)
Bootstrap95% confidence interval (indirect effect)		[−0.0236, −0.0033]
Fixed effect	YES	YES
N	623	623

Note: Statistical significance at the 1% and 10% levels is indicated by *** and *, respectively.

Water use efficiency is differentially influenced by various water transfer measures. As for the cities in the ER-SNWTP and MR-SNWTP groups, they receive water from both SNWTP and DYR simultaneously. To comprehensively assess the individual impacts of these water transfer projects, we separately incorporated the proportions of water originating from the SNWTP and the DYR into the model, and explored their impact on water consumption per unit of GDP (Table 6). The significant positive coefficient of variable *waterdyr* indicates that cities that rely more heavily on water from the main stream of the Yellow River tend to exhibit a lower water use efficiency, while variable *watersnwtp* has a negative, but not significant, effect on the water consumption per unit of GDP. Collectively, these observations suggest that the water use efficiency of the ER-SNWTP and MR-SNWTP groups is primarily influenced by the DYR. Although the direct influence of the SNWTP itself (variable *watersnwtp*) is not statistically significant, an increase in its water transfer scale is anticipated to enhance regional water use efficiency. Additionally, the urbanization rate (*urban*) and per capita grain production (*cornp*) have a significant negative impact on the water consumption per unit of GDP. A higher urbanization rate indicates a more developed non-agriculture economy, leading to an increased product output and reduced water consumption per unit of economic activity.

Table 6. Regression model of SNWTP and DYR on water use efficiency.

Variables	Coefficient
watersnwtp	−0.018
	(−1.01)
waterdyr	0.022 ***
	(3.32)
urban	−0.106 ***
	(−6.29)
waterpress	−0.011
	(−0.40)
cornp	−0.084 ***
	(−3.23)
wateragri	0.015
	(0.95)
Constant	0.111 ***
	(9.12)
Observations	189
Number of CITY	27
Company FE	0.615
Year FE	YES

Note: Statistical significance at the 1% level is indicated by ***.

3.2.3. Robust Test

To ascertain the robustness of our model, we employed various techniques, including the substitution of explanatory variables, sample reduction, and the utilization of instrumental variables for robustness testing (Table 7). Columns (2) and (3) show the regression results after replacing the core explanatory variable with *watertransfer* lagged by two periods and all independent variables lagged by one period as instrumental variables to solve the potential endogeneity issues. Column (4) is the result obtained after winsorizing the data. Based on these comprehensive test results, it can be concluded that *watertransfer* still has a significant inhibitory effect on *wateruseeff*, which can verify the strong robustness of the benchmark regression model, ensuring the reliability and validity of our findings.

Table 7. Results of robustness test.

	(1)	(2)	(3)	(4)
Variables	**y**	**Lagged by Two Periods**	**All Variables Lagged by One Period**	**Data Winsorized**
watertransfer	−0.077 ***	−0.073 ***	−0.040 *	−0.075 ***
	(−3.24)	(−3.14)	(−1.97)	(−2.86)
waterstress	0.080 ***	0.099 ***	−0.085 **	0.105 ***
	(3.23)	(4.62)	(−2.48)	(2.88)
agri	0.108 *	0.087	0.148 **	0.112
	(1.88)	(1.65)	(2.08)	(1.49)
wateragri	0.070 *	0.084 **	0.137 **	0.091 **
	(1.83)	(1.99)	(2.11)	(2.23)

Note: Statistical significance at the 1%, 5%, and 10% levels is indicated by ***, **, and *, respectively.

4. Discussion

4.1. Higher Price of SNWTP Water Facilitated Water Use Structure and Efficiency

The variance in the impact on water use efficiency between the SNWTP and DYR is primarily ascribed to disparities in pricing mechanisms. The pricing of water supplied through the SNWTP is determined by the central government of China. To guarantee the sustained operation of the project and distribute the risks associated with water supply and consumption equitably, the ER-SNWTP and MR-SNWTP employ a two-tier pricing scheme, encompassing both basic and measured water prices [33,34]. The basic water price is established on the basis of reimbursing reasonable construction loans, operational management expenses, and maintenance costs of the project. Conversely, the measured water price aims to cover additional costs beyond the basic price and incorporate a profit margin. The calculation of the basic water fee involves multiplying the basic water price by the planned net volume of water transferred, regardless of whether the host province accepts it. The metered water fee, on the other hand, is determined by multiplying the metered water price by the actual water consumption at the outlet. Consequently, local authorities not only face higher prices for SNWTP water but also must invest in constructing the necessary infrastructure, including pipelines, pumping stations, and treatment facilities, to deliver water to end-users. These dual expenses for water and its associated infrastructure have evidently contributed to the SNWTP's higher water prices compared to the original water price.

Furthermore, cities in eastern Shandong Province concurrently receive water from both the ER-SNWTP and the DYR. Compared to water supply by the ER-SNWTP, the DYR offers a more reliable and cost-effective alternative. The varying water price associated with different water supply sources has promoted authorities to carefully consider which sources to prioritize and who should bear the costs. The elevated price of water from the ER-SNWTP has led some jurisdictions to initially refrain from utilizing the water upon the commencement of the project. Instead of being consumed by residents or used for industrial production, the water was merely stored in reservoirs [18,35]. In 2016, the Shandong Provincial Government held a press conference on the operation, management, and benefits of the SNWTP. It was reported that from 2013 to 2016, Shandong received 1.1 billion cubic meters of water from the Yangtze River, of which only 30% was directly delivered to consumers, including power plants, industrial enterprises, and urban residences. The remaining water was utilized for ecological water compensation or stored in lakes and reservoirs [36]. Also, water scarcity and higher water prices have contributed to a decrease in the proportion of agriculture water use within total water consumption, ultimately leading to improved water use efficiency [19]. From 2013 to 2020, the proportion of agriculture water use in the total water consumption of the nine cities receiving water from the ER-SNWTP in Shandong Province has consistently fallen below the average level of the basin.

The pricing of the MR-SNWTP is primarily determined by the distance of water transfer. As the source province for water exports, Henan Province enjoys a relatively lower water price for the MR-SNWTP, albeit still higher than that of DYR and local groundwater. However, fortunately, the price difference is not substantial. In 2014, China's National Development and Reform Commission issued a directive regarding the water supply pricing policy for the initial phase of the MR-SNWTP, which specified that the comprehensive water price for cities north of the Yellow River in Henan Province stood at 0.34 CNY/m^3, whereas for the southern section, it was 0.18 CNY/m^3. In contrast, the price for non-agricultural water supplied by DYR was 0.14 CNY/m^3 [37,38]. By the end of 2023, a cumulative total of 20.8 billion cubic meters of water had been received by 11 cities in Henan Province from the MR-SNWTP since December 2014, representing 34.3% of the project's total water capacity. In 2022, the MR-SNWTP supplied 3.076 billion cubic meters of water to Henan Province (including 606 million cubic meters for ecological replenishment), surpassing the volume supplied by the DYR that year (2.625 billion cubic meters) and accounting for 13.49% of the province's annual water supply. This water primarily serves urban and rural residents, significantly enhancing the urban and rural water security rate and water quality. Additionally, it ensures that Henan Province has an adequate supply of water resources for economic development and urbanization, thereby facilitating the improvement of water use efficiency [39].

4.2. Lower Price and Large Scale of DYR Water Used to Agriculture Irrigating

A significant proportion of DYR water is allocated to agricultural irrigation in the Yellow River Basin. This region, renowned for its rich agricultural history and currently serving as a vital national grain production hub in China, relies on DYR water for several key national irrigation areas. The total area of these irrigation area is 1.96 million hectares and accounts for 6% of the basin's total cultivated land. However, these irrigation areas are also the largest consumers of water resources. In 2020, agriculture accounted for 64% of water consumption in the Yellow River Basin. Alarmingly, only 39.1% of the entire areas employ high-efficiency and water-saving irrigation techniques. Henan Province, a crucial agricultural hub within the basin, manage only 30.3% of its irrigated arable land with efficient water-saving methods [40]. Specifically, the Hetao Irrigation Area and the downstream Yellow River Diversion Irrigation Area, occupying only 42.5% of the total irrigation area, consume 67.5% of the river's irrigation, relying on inefficient water use methods such as flood irrigation.

On the other side, the DYR water price is relatively lower and therefore favors the agriculture sector. The pricing of DYR comprises two main components: the canal head water price and the engineering water price. The canal head water price is determined by the National Development and Reform Commission, specifying that agricultural water costs 0.012 CNY/m^3 from April to June each year and 0.01 CNY/m^3 during remaining months. In contrast, non-agricultural water is priced at 0.14 CNY/m^3 from April to June and 0.12 CNY/m^3 for the rest months. The engineering water price, inclusive of raw water fees, is jointly approved by the local Development and Reform Commission (pricing) and the Water Administrative Bureau. Finally, the water price for grain crops does not exceed 0.10 CNY/m^3. It is evident that this pricing is significantly lower than that of urban and industrial water use and other water sources as the urban water price is 0.28 CNY/m^3 and the industrial water price is 0.35 CNY/m^3. Alarmingly, it is even below the cost of water supply [41]. This lower pricing of DYR water for agricultural use leads to reduced water use efficiency and often results in wasteful utilization of this precious resource.

4.3. Technopolitics Characteristic of IBWT Infrastructure

Although there is no significant promotional relationship between the scale of the SNWTP and the subsequent year's water use efficiency in the models (Table 7), the negative efficiency value indicates that an increase in the scale of water received from the SNWTP is associated with a decrease in water consumption per unit of GDP, thereby enhancing water use efficiency. This can be attributed primarily to the significant spatial coupling between the SNWTP and water use efficiency.

In the Yellow River Basin, the SNWTP solely serves Henan and Shandong provinces, both of which possess prime locations for economic development, resulting in robust economic foundations, advanced technology, and higher levels of industrialization and urbanization. Consequently, their water use structures are relatively focused on non-agricultural industries that generate higher economic output per unit of water consumed, thereby leading to increased water use efficiency. In essence, the superior water efficiency observed in these two SNWTP served provinces is mostly attributed to their geographical advantages and economic development, rather than the outcomes of inter-basin water transfer projects.

Moreover, Henan and Shandong are not the sole beneficiaries of the ER-SNWTP and MR-SNWTP. The ER-SNWTP ultimately serves Tianjin, a municipality directly under the central government in Northern China, while the MR-SNWTP targets Beijing, the capital of China. By the end of 2020, Shandong and Henan accounted for merely 9.54% and 33.06% of the total water received through the SNWTP, respectively. The prolonged water scarcity in these provinces has prompted them to adjust their industrial structure and upgrade production techniques to enhance water use efficiency [35]. Additionally, their robust economic foundation and high income levels enable them to bear the substantial construction and maintenance costs of the projects, as well as the higher water prices. In essence, the current inter-basin water transfer projects in China primarily aim to fulfill the water needs for further economic development in relatively developed areas, rather than adjusting the water use structure or promoting water use efficiency [30]. Consequently, water scarcity remains severe in the upstream cities along the Yellow River. Therefore, some scholars argue that the SNWTP reflects a powerful, technocratic, and controlling central government [42], as it relies primarily on increasing the water supply through costly engineering solutions without addressing the demand side through efficient water use practices [18]. Unfortunately, due to limitations in data acquisition, this study was unable to quantitatively characterize factors such as water prices and water use structures of different water transfer projects through specific variables. We hope that with the gradual openness and transparency of data on water consumption and management in China, future research can more scientifically analyze the impact of economic, technological, and other factors on the water use efficiency of the SNWTP.

5. Conclusions

The South-to-North Water Transfer Project (SNWTP), as China's largest water diversion project in China, exemplifies the Chinese government's aspirations to address regional human–water relations through engineering solutions. The immense cost, extensive distance, and vast scale of water transfer associated with this project have given rise to concerns over high water prices, potential risks to water environmental quality, and conflicts among government entities in managing water resources. Consequently, the SNWTP's impact on water use efficiency is multifaceted and varies across regions and timeframes. In this study, we focused on the Yellow River Basin in China and employed econometric analysis models to quantitatively assess the influence of various water diversion projects, including the ER-SNWTP, MR-SNWTP, and DYR, on regional water use efficiency. Additionally, we explored the interactive effects between water use structure and industrial structure. Our findings reveal that although the overall water transfer project has a positive impact on water use efficiency, the effects of the three water transfer measures differ. Specifically, the ER-SNWTP does not significantly promote regional water use efficiency, whereas the MR-SNWTP does. Conversely, the DYR has a notable negative impact on water use efficiency in developed cities. Furthermore, our analysis identifies water use structure as the primary mediating factor influencing water use efficiency in the context of the SNWTP and DYR. This structure is shaped by the interplay of water prices, project scales, and policies implemented by various stakeholders involved in managing the SNWTP and DYR projects. Our study contributes to a deeper understanding of the complex relationships between water diversion projects, water use structures, and water use efficiency in China, providing insights for policymakers in water resource management.

As a giant, centralized decision-making project, the construction and operation of the SNWTP inevitably necessitates negotiations between the central and local governments on diverse issues encompassing water volume, pricing, and cost. This negotiation process is further complicated by China's fragmented authoritarianism, which manifests horizontally across segmented administrative boundaries and vertically within poorly coordinated conglomerations of regions and departments that do not align well with the natural hydrological cycle [43]. Consequently, this structural arrangement gives rise to significant changes in water resource allocation, consumption patterns, and payment mechanisms. Ghassemi and White argued that several jurisdictions, such as Australia, Canada, and the United States, have refrained from pursuing inter-basin water transfer projects due to their prohibitive costs and adverse social and environmental impacts. Instead, these nations have favored demand management measures [19]. Therefore, it is imperative not to oversimplify the SNWTP as a rigid, pre-determined, and authoritative intervention infrastructure that clashes with the dynamic nature of water demand and local political landscapes [35]. Instead, the project has undergone continuous evolution and adjustment through various technological advancements and institutional rearrangements. For instance, the ER-SNWTP has been integrated with the DYR, enabling the water supply to the eastern regions of Shandong Province. This integration has facilitated the efficient allocation of water resources within the ER-SNWTP and enhanced the water use efficiency of the DYR. Given the complexity and contested nature of the SNWTP, which has undergone numerous negotiations, mediations, and reconciliations with local water supply systems, it is advisable to afford China more time to optimize its water network construction and management, and investigate the impact of the SNWTP on water use efficiency later. Just as Lin stated, the SNWTP in China serves as a rare and invaluable laboratory for critically examining the interplay between water infrastructure, technology, society, and environment so that a comprehensive understanding of the project's far-reaching implications can be unveiled [44].

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