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Structural optimization of sectoral exports from the perspective of water footprint: A study from Henan Province, China

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ABSTRACT

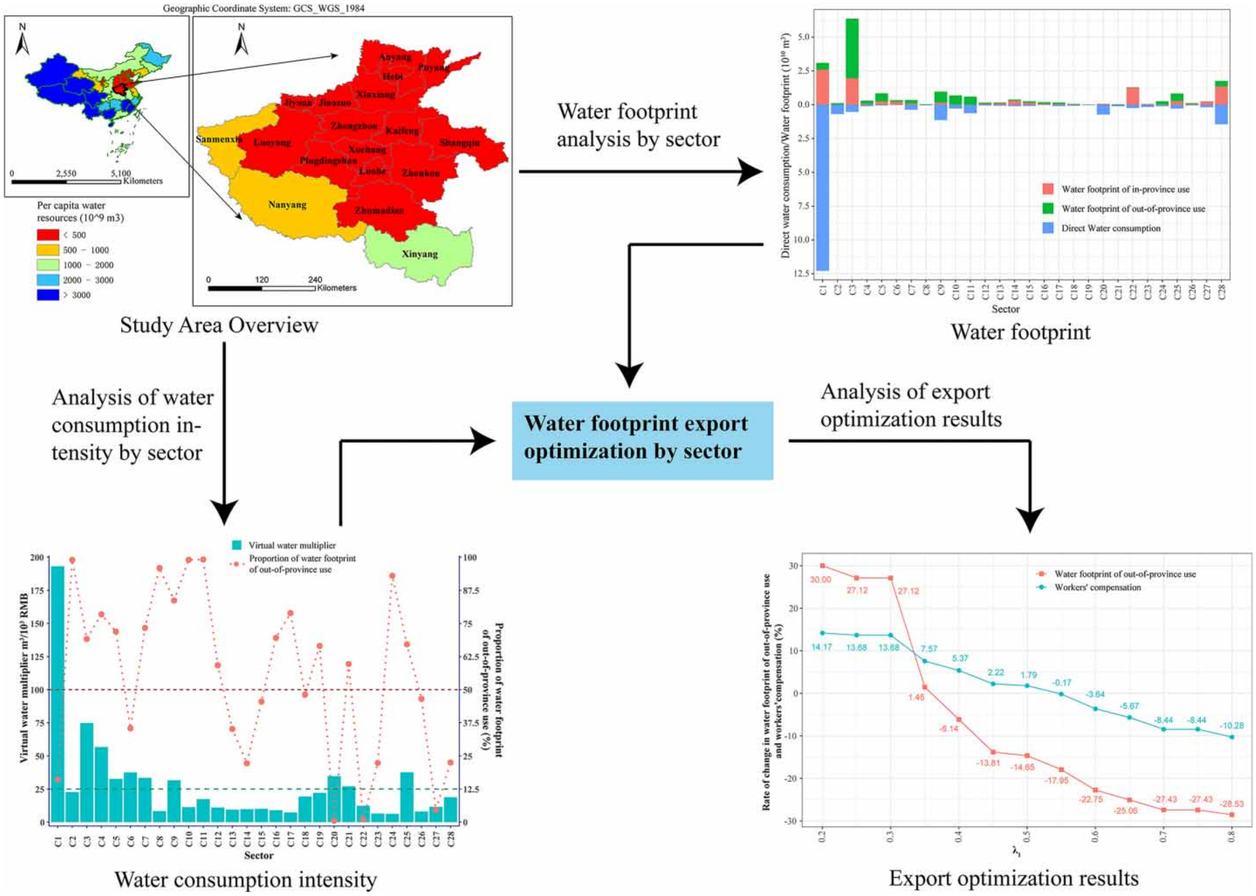
Water used for production is the primary consumer of regional water. Water footprint reflects the actual water consumption of each product, which can reflect the intensity of water consumption of each production sector and the flow of water resources implied in the product trade. In this paper, the water footprint of each sector in Henan Province in 2017 was calculated using non-competitive input-output techniques. Furthermore, a dual-objective planning model that minimizes water resource export and maximizes labor compensation was established, based on which the export structure of the sector in the province was optimized. Research findings show that agriculture is the primary consuming sector of water resources from the direct water use perspective. In comparison, the food processing industry is the major consuming sector of water resources from the water footprint perspective. The difference in water resources consumed by sectors from the perspective of water footprint is smaller than that from the perspective of direct water use. Second, most water-intensive sectors have a relatively large water footprint of out-of-province use, which results in 52.75% of Henan Province's produced water being consumed outside the province. Third, the current export structure adjustment of sectors in Henan Province can achieve a Pareto improvement of water conservation and economic development. It is expected to save 14.65% of the province's export water resources and increase Henan Province's total exports by 170.61 billion (170.61×10^9) yuan and increase labor compensation by 39.76 billion yuan. This study can be used to optimize water allocation and improve sustainable water use in water-scarce regions.

Key words: multi-objective planning, non-competitive inputs and outputs, water footprint, water saving program

HIGHLIGHTS

- Proposes a method to save water resources and enhance the economy by adjusting sectoral exports from a water footprint perspective.
- Most water-intensive sectors in Henan Province have a relatively large water footprint of out-of-province use.
- Export structure adjustment of sectors in Henan Province can achieve a Pareto improvement of water conservation and economic development.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water resources as a basic natural resource are necessary for social development and economic growth (Li & Qian 2018). Water conflicts between humans and ecosystems are occurring in many locations throughout the world as the global economy expands, posing significant challenges to the sustainability of water resources (Li *et al.* 2018). Therefore, the development of effective water conservation policies has become an important task for managers in water-scarce regions. Generally speaking, production water is the main consumer of regional water resources (Wang *et al.* 2018). With the intensification of economic trade among regions, the water resources hidden in production activities are also redistributed among regions and sectors (Liu *et al.* 2019). Deng *et al.* (2021) revealed that consumption in one area can significantly influence the demand for water in distant places, and virtual water trade can increase water stress in areas that have already faced water scarcity. Thus, for water-scarce regions, reasonable adjustment of the export structure of sectors and effective control of the export of water-consuming products are expected to save a lot of water resources while maintaining economic operation (Delpasand *et al.* 2020). Water footprint quantifies the demand for and use of water resources by humans in terms of production and consumption (Hou *et al.* 2018). It provides a new method to determine the transregional transfer of water resources in trade (Zhao *et al.* 2017). So, optimizing the sectoral export structure from the water footprint perspective is significant for regional water resources management.

Currently, in China, based on regional or multi-regional input-output tables, estimating a product's implied virtual water volume by tracking its production process has become an important method for measuring the water footprint of a commodity (Zhang *et al.* 2019b). Zhang *et al.* (2019a) measured the water footprint of Chinese provinces based on multi-regional input-output tables in China and analyzed the pattern of water resource flow in China. Feng *et al.* (2012) examined the virtual water flow relationships within the Yellow River basin based on a multi-regional input model, and studied the water use of sub-sectors. Liu *et al.* (2017a) conducted in-depth analyses of water footprints in the Hebei province. They found that water embodied in Hebei's final demand is much lower than the direct water withdrawal uncovered. Since the input-output tables provided by domestic provinces are all competitive, most of the studies for single domestic provinces are based on competitive input-output tables for provincial water use. However, competitive input-output tables cannot distinguish whether the upstream products in the production process come from within or outside a province (Liu *et al.* 2017b). Therefore, it is impossible to distinguish whether the water resources implied in the production of raw materials come from the region or other regions (Shao *et al.* 2017). In virtual water trade, understanding the sources of virtual water resources consumed by a region's productive sectors is an important guide to regional water management (Zhao *et al.* 2020). Therefore, it is necessary to use non-competitive input-output techniques to differentiate the sources of raw materials for production.

Bae & Dall'erba (2018) analyzed the impact of export changes on regional water resources and the economy using water footprints, stating that intra-regional water resources can be conserved by adjusting industry exports. However, their findings come at the expense of the economy, and they do not give a method for enacting specific export adjustments. Zhu *et al.* (2016) established a multi-objective planning model with blue water footprint, gray water footprint, and domestic value added as objectives to optimize in China's export trade sector structure. Although they considered water resources and economic development, they only targeted domestic added value when portraying economic development. They did not consider the impact of adjusting exports on workers' compensation. Export adjustment causes sectors to readjust their products' output, which affects workers' compensation. As the primary source of income for people, labor compensation is crucial for improving the human capital of workers, accelerating the regional economy, and improving the quality of life of the people (Wyganowska 2018). It should be considered in the export's optimization structure.

As a predominantly agricultural province and an emerging industrial province in China (Guo *et al.* 2020), Henan Province plays a vital role in supporting national food security and driving regional economic development (Jia *et al.* 2018). In recent years, scholars have studied the utilization of water resources in Henan Province. Zhu *et al.* (2015) used the cluster analysis method to study the water footprint structure of Henan Province. They found that the water footprint of Henan Province showed an increasing trend and there were significant differences in water resource utilization among cities. Jiao *et al.* (2021) measured the water footprint of different departments in Henan Province. They found significant differences in the water footprints of different sectors, with the agricultural sector having a much higher water footprint than other sectors. Wu *et al.* (2020) assessed the extent of regional water scarcity in Henan Province from a water footprint perspective, and found that the region has been suffering from and is likely to continue to face water scarcity in the near future. However, to the best of our knowledge, few studies use non-competitive input-output techniques to measure the water footprint of different sectors in Henan Province. Meanwhile, few scholars have studied how to optimize the export structure of various sectors in Henan Province to achieve water-saving goals from the water footprint perspective.

Given the research gaps mentioned above, this work studies the water footprint of Henan Province and the adjustment of the structure of the export sectors in the following aspects: (1) the water footprint of Henan Province is measured in the framework of non-competitive input-output techniques by transforming the competitive input table into a non-competitive input-output table and measuring the water footprint of each sector in Henan Province under this framework. This can provide a more accurate reference for the current sectoral water footprint in Henan Province; (2) based on the water footprint of each sector in Henan Province, the export structure of sectors is optimized for both water resources protection and economic development. With the rapid development of Henan Province and the lack of water resources, this study attempts to provide a reference for the protection and efficient utilization of water resources in Henan Province.

2. METHODOLOGY

2.1. Water footprint calculation method by sector

In this paper, we transform a competitive input-output table into a non-competitive one based on the transformation method of input-output association (Ma *et al.* 2019). The core idea is to assume that the proportion of imports included in the sectoral intermediate and final use is the same as the proportion of total imports in total output. Then, that ratio is used to further split the intermediate and final use module into intra-regional and imported products (Guan *et al.* 2020; Pu *et al.* 2020). The transformed table is shown in Table 1, and we assume that there are n sectors in the region.

In Table 1, the superscripts d and m are used to distinguish whether the products come from within or outside the province, with d indicating production within the province and m indicating production outside the province. x_{ij} represents the

Table 1 | Simplified table of non-competitive inputs and outputs

		Intermediate use Sector 1 Sector 2 … Sector n	End Use Consumption	Capital	Export	Import	Total output
Provincial	Sector 1	x_{ij}^d	c_i^d	in_i^d	ex_i^d		x_i
Products	Sector 2						
Intermediate	…						
Inputs	Sector n						
Imported	Sector 1	x_{ij}^m	c_i^m	in_i^m	ex_i^m	im_i	
Products	Sector 2						
Intermediate	…						
Inputs	Sector n						
Workers' Compensation		s_j					
Other value added		v_j^{2-4}					
Value added		v_j					
Total input		x_j					

intermediate input of sector i to sector j. c_i, in_i, ex_i, and im_i denote the consumption, capital stock, exports, and total imports of products in sector i, respectively. x_j and s_j represent total inputs (or total output), and labor compensation in sector j, respectively.

According to the input-output theory, Equation (1) can be obtained according to Chen *et al.* (2018):

$$x_i = \sum_{j=1}^{n} x_{ij}^d + c_i^d + in_i^d + ex_i^d \quad i = 1, \ldots, n \tag{1}$$

Equation (1) can be rewritten in matrix form as shown in Equation (2):

$$X = (I - A^d)^{-1}(C^d + IN^d + EX^d) \tag{2}$$

where $A^d = (a_{ij}^d)_{i,j=1,\ldots,n}$ is the direct consumption coefficient matrix, and $a_{ij}^d = x_{ij}^d / x_j$ is the direct consumption coefficient of sector j for sector i products. $L^d = (I - A^d)^{-1}$ is called the Leontief inverse matrix (Wang *et al.* 2016), and its element l_{ij}^d indicates the amount of input required by a province's i sector for each unit of end use of the j sector. $y_i = w_i / x_i$ denotes the direct water consumption coefficient of sector i, where w_i denotes the direct water consumption of sector i. Then $\sum_{i=1}^{n} y_i l_{ij}^d$ denotes the total amount of water consumed in a province per unit of end use in sector j. It is also referred to as the virtual water multiplier. Multiplying the virtual water multiplier with the end use of each sector can give the water footprint of the corresponding sector. That is, $(\sum_{i=1}^{n} y_i l_{ij}^d) * (c_j^d + in_j^d)$ indicates the number of water footprints consumed in the province of the j sector, and $(\sum_{i=1}^{n} y_i l_{ij}^d) * (ex_j^d)$ indicates the amount of water footprints in the j sector for out-of-province consumption.

2.2. The impact of sectoral export adjustment on imported products and labor compensation

When the volume of product exports changes, the output of products in each sector in the region will change, which will bring about changes in the compensation of labor and intermediate use of imported products. Note that s_i is the amount of labor compensation in sector i. Then the input coefficients of labor compensation and intermediate input coefficients of imported products for sector i are $\omega_i = s_i / x_i$ and $im_{ij}^m = x_{ij}^m / x_j$, respectively. In turn, after the volume of product exports in the j sector is changed by Δex_j^d, it causes the total change of labor compensation and imported product intermediate inputs to be $(\sum_{i=1}^{n} \omega_i l_{ij}^d) \cdot \Delta ex_j^d$, $\sum_{j'=1}^{n} \sum_{i=1}^{n} im_{j'i}^m l_{ij}^d \Delta ex_j^d$, respectively.

2.3. Export optimization modeling

Assume that the amount of product export adjustment in each sector in the region is $\Delta EX^d = (\Delta ex_1^d, \ldots, \Delta ex_n^d)^T$. From the previous section, we know that after the export change ΔEX^d, the export water footprint and labor compensation change are $\sum_{j=1}^n \sum_{i=1}^n (y_i l_{ij}^d) \cdot \Delta ex_j^d$, $\sum_{j=1}^n \sum_{i=1}^n (\omega_i l_{ij}^d) \cdot \Delta ex_j^d$. In optimizing intra-regional sectoral exports to minimize the amount of water footprint exports and maximize the amount of labor compensation, a dual-objective planning model is developed as shown in Equation (3):

$$obj. \begin{cases} \min \sum_{j=1}^{n} (\sum_{i=1}^{n} y_i l_{ij}^d) * (\Delta ex_j^d) \\ \max \sum_{j=1}^{n} (\sum_{i=1}^{n} \omega_i l_{ij}^d) * (\Delta ex_j^d) \end{cases}$$
$$s.t. \begin{cases} -p_j ex_j^d \leq \Delta ex_j^d \leq p_j ex_j^d, \quad j = 1, \ldots, n \\ 0 \leq \sum_{j=1}^{n} \omega_i l_{ij}^d \cdot \Delta ex_j^d \leq s_i, \quad i = 1, \ldots, n \\ 0 \leq \sum_{j=1}^{n} im_{j'i}^m l_{ij}^d \Delta ex_j^d \leq x_{j'i}^m, \quad i = 1, \ldots, n, \ j' = 1, \ldots, n \end{cases} \tag{3}$$

The p_i in model (3) denotes the maximum rate of change in the exports of sector i, controlling for the maximum adjustment in the exports of sector i. Objective 1 denotes minimizing water footprint exports; objective 2 denotes maximizing labor compensation. Condition 1 is a constraint on the amount of change in exports by sector. Condition 2 requires that the reduction in each sector's labor compensation is positive and cannot exceed its current total labor compensation. Condition 3 requires that the amount of intermediate use change from sector j' outside the province to sector i is positive and does not exceed its current amount.

We used the evaluation function method to solve model (3). The objectives in Equation (3) are normalized using total water resources and total labor compensation, and weight coefficients λ_1, λ_2 are introduced to integrate the objective function of Equation (3) to obtain the final optimization model according to Equation (4):

$$obj. \ \min \ \lambda_1 \frac{\sum_{j=1}^{n} (\sum_{i=1}^{n} y_i l_{ij}^d) \cdot (\Delta ex_j^d)}{\sum_{i=1}^{n} y_i} - \lambda_2 \frac{\sum_{j=1}^{n} (\sum_{i=1}^{n} \omega_i l_{ij}^d) \cdot (\Delta ex_j^d)}{\sum_{i=1}^{n} s_i}$$
$$s.t. \begin{cases} -p_j ex_j^d \leq \Delta ex_j^d \leq p_j ex_j^d, \quad j = 1, \ldots, n \\ 0 \leq \sum_{j=1}^{n} \omega_i l_{ij}^d \cdot \Delta ex_j^d \leq s_i, \quad i = 1, \ldots, n \\ 0 \leq \sum_{j=1}^{n} im_{j'i}^m l_{ij}^d \Delta ex_j^d \leq x_{j'i}^m, \quad i = 1, \ldots, n, \ j' = 1, \ldots, n \end{cases} \tag{4}$$

where λ_1, λ_2 are the weights of the ratio of labor compensation and virtual water export reduction, respectively, to measure the relative importance of labor compensation and virtual water, which satisfy $\lambda_1 + \lambda_2 = 1$.

2.4. Study area overview

Henan Province is one of China's most populous agricultural provinces with severe water scarcity (Dou *et al.* 2015). Figure 1 shows the average *per capita* water resources for each province in China and each city in Henan Province during the 10-year period 2009–2018. The average *per capita* water availability is 353.5 m^3/person, which is only 82% of the national *per capita* water availability, and is always below the extreme water shortage threshold of 500 m^3/person. The 2019 National Grain Bulletin shows that Henan Province produced 66.95 million tons of grain, over 1/10th of the national total. As an emerging industrial province, Henan Province is currently strengthening the implementation of the Interconnected Development of the 'Five Zones', namely: Zhengzhou Airport Economy Zone, China (Henan) Pilot Free Trade Zone, Zhengzhou-Luoyang-Xinxiang National Innovation Demonstration Zone, China (Zhengzhou) Cross-Border E-Commerce Pilot Zone and National (Henan) Big Data Pilot Zone.

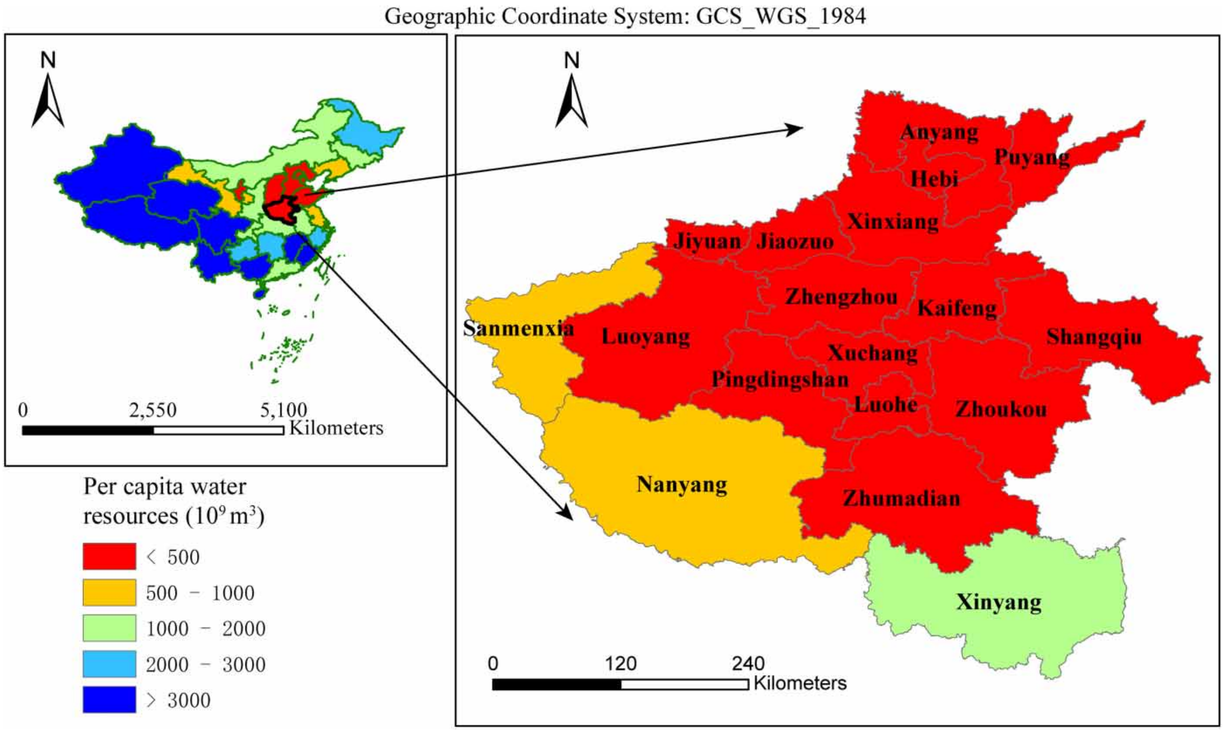


Figure 1 | Overview of water resources *per capita* in Henan Province.

The development of agriculture and industry cannot be separated from the consumption of water resources. According to the China Water Resources Bulletin data, agricultural and industrial water use in Henan Province accounted for 74.3% of total water consumption in 2017. Under the accelerated industrial development in Henan Province, it is inevitable that pressure on water resources in the province will be further increased. However, existing studies (Sun & Liu 2019; Zhang *et al.* 2019b) on the water footprint of Henan Province show that most of the water resources consumed by production activities in the province are used outside the province, which will undoubtedly make the water scarcity situation in Henan Province more severe. Therefore, it is of great significance to clarify the relationship between the production water of various sectors in Henan Province and optimize the allocation of water resources for the export of sectors to reduce the pressure on water resources in Henan Province.

2.5. Data source

The input-output table used for calculation is collected from the 2020 Henan Provincial Statistical Yearbook, which lists 42 sectors. The 2018 China Statistical Yearbook contains information on agricultural water use in Henan Province in 2017. The water consumption data for Henan Province's sub-sectors of industry, construction, and services are based on statistical data from the 2008 China Economic Census Yearbook, the 2017 Henan Province Water Resources Bulletin, and the First Water Census Bulletin of Henan Province, and obtained using the conversion method adopted by Zhang *et al.* (2021). In addition, to make the industries data consistent, the 42 sectors in the input-output table are integrated into 28 sectors in this paper, and the integrated industry classification is shown in Table 2. The translation of each sectoral name is the same as that in the 'China multi regional input-output table 2017' provided by CEADs database (Zheng *et al.* 2020).

3. MODEL ANALYSIS

3.1. Water footprint measurement and structural analysis of sectors in Henan Province

Using the direct water use data of each sector in Henan Province, the water footprint of each sector in Henan Province in 2017 was calculated and shown in Figure 2. From Figure 2, it was found that the sectors where the sectoral water footprint is lower than the sectoral direct water use are agriculture, forestry, animal husbandry and fishery, mining, production and

Table 2 | Sectoral names and codes

Code	Sector
C1	Agriculture, Forestry, Animal Husbandry and Fishery
C2	Mining
C3	Food and tobacco processing
C4	Textile industry
C5	Manufacture of leather, fur, feather, and related products
C6	Processing of timber and furniture
C7	Manufacture of paper, printing and articles for culture, education, and sport activity
C8	Processing of petroleum, coking, processing of nuclear fuel
C9	Manufacture of chemical products
C10	Manufacture of non-metallic mineral products
C11	Smelting and processing of metals
C12	Manufacture of metal products
C13	Manufacture of general-purpose machinery
C14	Manufacture of special purpose machinery
C15	Manufacture of transport equipment
C16	Manufacture of electrical machinery and equipment
C17	Manufacture of communication equipment, computers, and other electronic equipment
C18	Manufacture of measuring instruments
C19	Other manufacturing and waste resources
C20	Production and distribution of electric power and heat power
C21	Production and distribution of gas and tap water
C22	Construction
C23	Wholesale and retail trades
C24	Transport, storage, and postal services
C25	Accommodation and catering
C26	Finance
C27	Real estate
C28	Other services

distribution of electric power and heat power, etc. The products of these sectors are mostly used as raw materials for downstream sectors in the production chain, and some of the water consumed is transferred to other sectors along with inter-industry trade. Thus, from the water footprint perspective, the actual water consumption of these sectors is lower than their direct water consumption. Agriculture, forestry, animal husbandry and fishery, for example, has a direct water consumption of 12.28 billion (12.28×10^9)m^3, which is about 61.96% of the province's water resources. However, the water footprint shows that the real water consumption of the sector is 3.098 billion m^3, which means that the sector transfers 74.8% of its direct water consumption to other sectors through the production chain. In addition, sectors with a higher water footprint than direct water use include food and tobacco processing, textile industry, manufacture of leather, fur, feather and related products, construction, accommodation, and catering, among others. These sectors are mostly at the tail end of the production chain, consuming large amounts of virtual water embedded in raw materials from water-intensive sectors like agriculture and mining. Thus, from a water footprint perspective, the actual water consumption of these sectors is much higher than their direct water consumption. For example, the food and tobacco industry has a direct water consumption of 522 million m^3, which is about 2.64% of the province's water resources. However, the water footprint shows that the real water consumption of the sector is 6.374 billion m^3, which is 11 times more than direct water use. The calculation shows that the variance of direct water uses, and water footprint of sectors are 5.2676 and 1.6663 billion m^3 respectively,

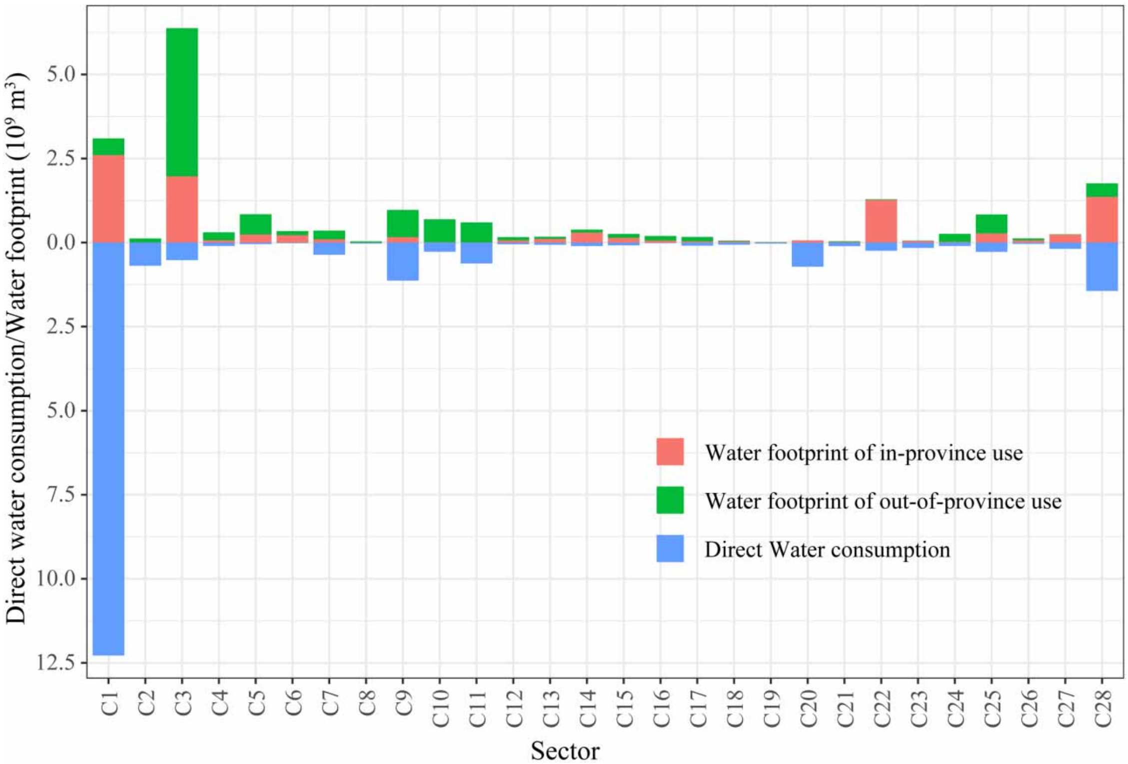


Figure 2 | Water footprint and direct water consumption by sector in Henan Province, 2017.

which shows that the water consumption of sectors is more balanced from the water footprint perspective. Considering that water footprint tracking calculates all water resources consumed by sectoral products in the production process and can present the real water consumption of products, it is more scientific to analyze the sectoral water use from the perspective of water footprint.

Figure 2 shows differences in the water footprint of sectors in Henan Province in terms of in-province use and out-of-province use. Sectors producing essential goods have a larger water footprint for in-province use. For example, agriculture, forestry, animal husbandry and fishery, food and tobacco processing, construction, and other services have a larger water footprint for in-province use. The total water footprint of in-province use in the four sectors accounts for 77% of the total water footprint of in-province use in Henan Province. On the other hand, traditional industries have a larger water footprint for out-of-province use. Food and tobacco processing, textile industry, manufacture of leather, fur, feather and related products, manufacture of chemical products, manufacture of non-metallic mineral products, and smelting and processing of metals all have a large water footprint for out-of-province use. The total water footprint of out-of-province use in the six sectors accounts for 77% of the total water footprint of out-of-province use in Henan Province. Calculations show that the water footprint for the out-of-province consumption accounts for 52.75% of the province's total water use, meaning that more than half of the water used in Henan Province is used outside the province. The Heckscher-Ohlin trade theory states that regions in trade exchange export their rich resources. However, water is a scarce resource in Henan Province, and most of it is exported outside the province, leading to a more serious water scarcity in the province. Hence, to relieve the pressure on Henan Province's water resources, it is essential to optimize the export structure of sectors and reduce the large outflow of water resources from the province with trade.

Currently, most water-intensive sectors have a relatively large water footprint of out-of-province use. Since a larger virtual water multiplier indicates a higher water footprint consumption per unit of product, we classify sectors into water-intensive and non-intensive sectors by whether the virtual water multiplier is greater than 25. As we can see from Figure 3, there are 10 water-intensive sectors classified, including agriculture, forestry, animal husbandry and fishery, food and tobacco processing, textile industry, manufacture of leather, fur, feather and related products, etc. The products of these sectors consume a large amount of water resources and controlling their exports can effectively save water resources in the province. Figure 3 shows

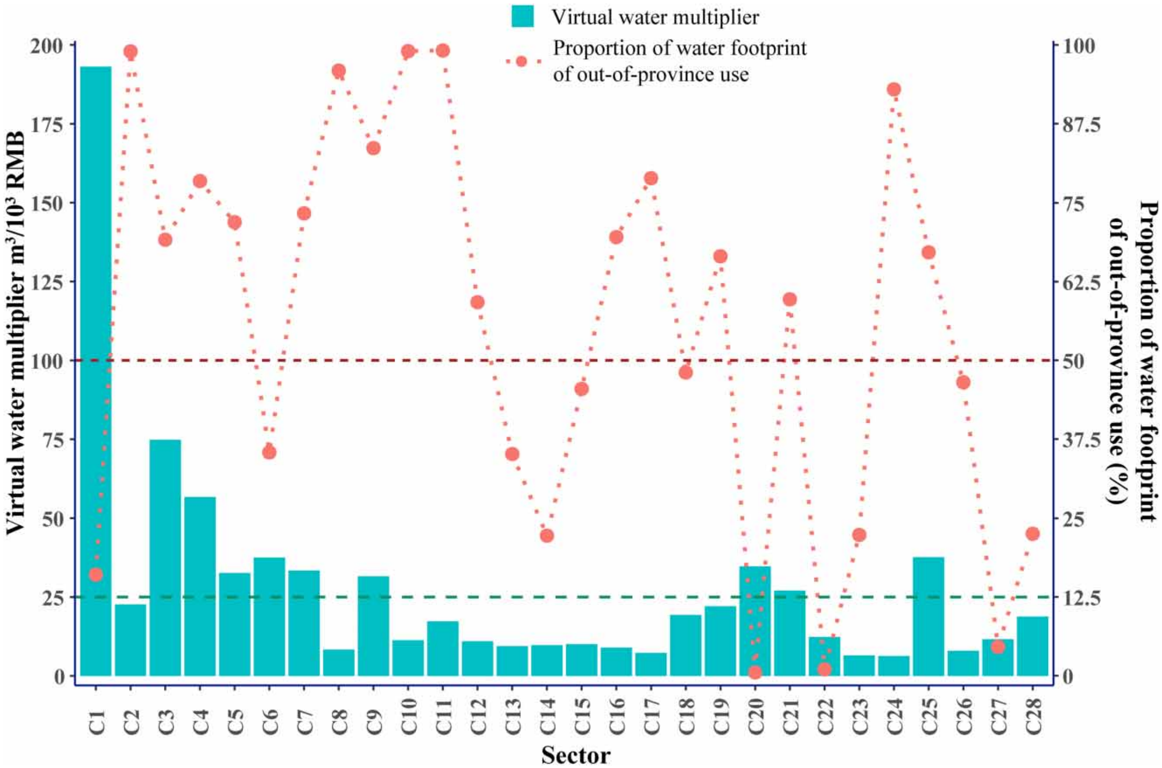


Figure 3 | Virtual water multiplier and proportion of export water footprint of sectors in Henan Province, 2017. *Note:* RMB is the abbreviation of Renminbi and is also commonly known as CNY (Chinese Yuan).

that of the 28 sectors classified in this paper, 16 sectors use over 50% of the total water footprint of that sector outside of the province. Among them, mining, petroleum processing, coking and nuclear fuel processing, non-metallic mineral product manufacturing, and metal smelting and processing were the four sectors that the water footprint of out-of-province use accounted for over 90% of their total water footprint. It was discovered that the water footprint of out-of-province use in 7 of the 10 water-intensive sectors accounted for a large proportion of their total water footprint. As a result, the current sectoral export structure in Henan Province will result in a large outflow of water resources from the province. It is critical to optimize the sectoral export structure from the perspective of water conservation.

3.2. Sectoral export optimization program development

Model (4) was used to solve the current optimal sectoral export adjustment scheme in Henan Province under the objectives of minimizing water outflow and maximizing labor compensation. Before solving the model, the values of the model parameters p_j, λ_1, λ_2 needed to be set. After consolidating the 42 sectors into 38 valid sectors, we found that 9 of the sectors in Henan Province took negative values for the average export change rate from 2012 to 2017, with an average value of −25%. The remaining 29 sectors have a positive growth rate with an average value of 37%. Given this, $p_j = 0.3,\ j = 1,\ \ldots, n$ was set in the simulation. Since both water resources and economic development are important to people's lives, it is assumed that water resources have the same status as workers' compensation, and $\lambda_1 = \lambda_2 = 1/2$ was set as a parameter. Finally, the optimal export adjustment scheme for Henan Province was found as shown in Table 3.

First, it was found that optimizing the export structure of sectors in Henan Province can bring dual benefits of water conservation and economic development. Table 3 shows that adjusting the export value of sectors in the province within the constraints can increase the export GDP of Henan Province by 170.607 billion RMB, accounting for 3.52% of the export value of Henan Province in 2017. The compensation of laborers in the province increases by 39.763 billion RMB, accounting for 1.79% of the total labor compensation. Meanwhile, the outflow of water resources in the province was reduced by 151,7.44 million m^3, accounting for about 14.65% of the total exported water resources in Henan Province in 2017. As can be seen, there is still a lot of room to improve in terms of water resource utilization efficiency in the province using

Table 3 | Optimized industry export adjustment scheme

Sector	Export Adjustment (10^9 RMB)	Change of water footprint of out-of-province use(10^9 m^3)	Change of labor remuneration (10^9 RMB)
C1	−77.27	−14,921.43	−499.98
C2	−156.46	−3,549.97	−22.03
C3	−1,765.81	−132,175.37	−138.92
C4	−127.12	−7,206.31	−35.46
C5	−557.65	−18,205.24	−41.22
C6	−96.35	−3,615.75	−8.24
C7	−233.09	−7,791.24	−16.42
C8	122.26	1,019.21	7.24
C9	−770.78	−24,355.40	−46.93
C10	1,825.11	20,585.38	130.23
C11	−1,032.93	−17,891.20	−33.83
C12	263.30	2,899.16	28.37
C13	191.89	1,811.39	24.80
C14	263.93	2,576.99	20.16
C15	348.11	3,491.30	40.32
C16	453.82	4,078.01	32.37
C17	546.52	3,988.13	107.91
C18	−42.46	−821.51	−2.99
C19	40.53	232.69	1.41
C20	−0.32	−11.17	3.00
C21	−24.93	−674.36	1.10
C22	32.78	404.65	6.44
C23	60.37	393.48	14.26
C24	1,148.99	7,214.17	328.54
C25	447.59	16,842.40	149.67
C26	214.63	1,709.59	53.51
C27	29.34	340.47	7.99
C28	632.05	11,887.87	286.33
Total	1,706.07	−151,744.05	397.63

current production technology. Adjusting the export structure of the province's sector has a positive impact on improving people's living standards and protecting the province's water environment.

Second, it was found that the sectors that need to reduce exports in Henan Province are mainly located in traditional industries, and the sectors that need to increase exports are mainly located in sectors with high technology content and services. Table 3 shows the current need to reduce exports in Henan Province in a total of 12 sectors; most of these sectors belong to the traditional industries. Among them are food and tobacco processing, manufacture of leather, fur, feather and related products, chemical products, and smelting and processing of metals. Four traditional industries have an export adjustment volume which is large, and these sectors' exports should be reduced by 176.581 billion RMB, 55.765 billion yuan, 77.078 billion RMB and 103.293 billion RMB, respectively. The total downward adjustment of these four sectors accounts for about 84.48% of the reduction in all export downward adjustment industries. Restricting the export of these sectors can substantially reduce the outflow of water from the province. Currently, there are 16 sectors that need to increase exports, and these sectors are mostly located in sectors with high technology content and services. Among them, the seven sectors whose exports are adjusted to a larger amount are manufacture of non-metallic mineral products (C10), manufacture of transport equipment (C15), manufacture of electrical machinery and equipment (C16), manufacture of communication equipment, computers and other electronic equipment (C17), transport, storage, and postal services (C24), accommodation and catering (C25), and other services (C28), which increased, respectively, by 182.511 billion RMB, 34.811 billion RMB, 45.382 billion RMB, 54.652 billion yuan, 114.899 billion RMB, 44.789 billion RMB and 63.205 billion RMB. The total upward adjustment of these seven sectors accounts for about 81.96% of the increase in all export upward adjustment industries. Increased support for these sectors can assist the province in implementing the Interconnected Development of the 'Five Zones,' which will cause better and faster economic development.

Third, it was found that the current focus on labor compensation in optimizing the export adjustment of Henan sectors helps achieve the dual goals of water conservation and economic growth. In this paper's solution, we take the parameters of model (4) as $\lambda_1 = \lambda_2 = 1/2$. In practice, the government can change the values of the two parameters according to the specific situation in the province. If more importance is given to water resources, then increase λ_1 and decrease λ_2, and if more importance is given to workers' compensation, then decrease λ_1 and increase λ_2. With other settings held constant, Figure 4 shows the variation of export water footprint and labor compensation in relation to the weight λ_1 in Henan Province. As the emphasis on water resources has increased, the total export water footprint has decreased, and the corresponding total labor compensation has decreased. The amount of change in the water footprint export in the optimization results turns positive to negative when λ_1 is taken somewhere in the interval [0.35,0.40], and the amount of change in labor compensation turns from positive to negative when it is taken somewhere in the interval [0.50,0.55]. When the value of λ_1 is between [0.40,0.5], it is possible to increase workers' compensation while significantly reducing water outflow. Therefore, it is better to pay attention to labor compensation when optimizing the export scheme. In the simulation, it was found that when the parameter λ_1 varies between [0.4,0.5], the optimal adjustment schemes all indicate that the products of several sectors, such as food and tobacco processing, textile industry, manufacture of paper, printing and articles for culture, education and sport activity, and manufacture of chemical products, should be exported less. Manufacture of nonmetallic mineral products, manufacture of metal products, manufacture of general-purpose machinery, manufacture of special purpose machinery, manufacture of communication equipment, computers and other electronic equipment should be exported more. This again shows that Henan Province is in urgent need of a downward adjustment of exports for the traditional industries and an upward adjustment of exports for industries with high technology content.

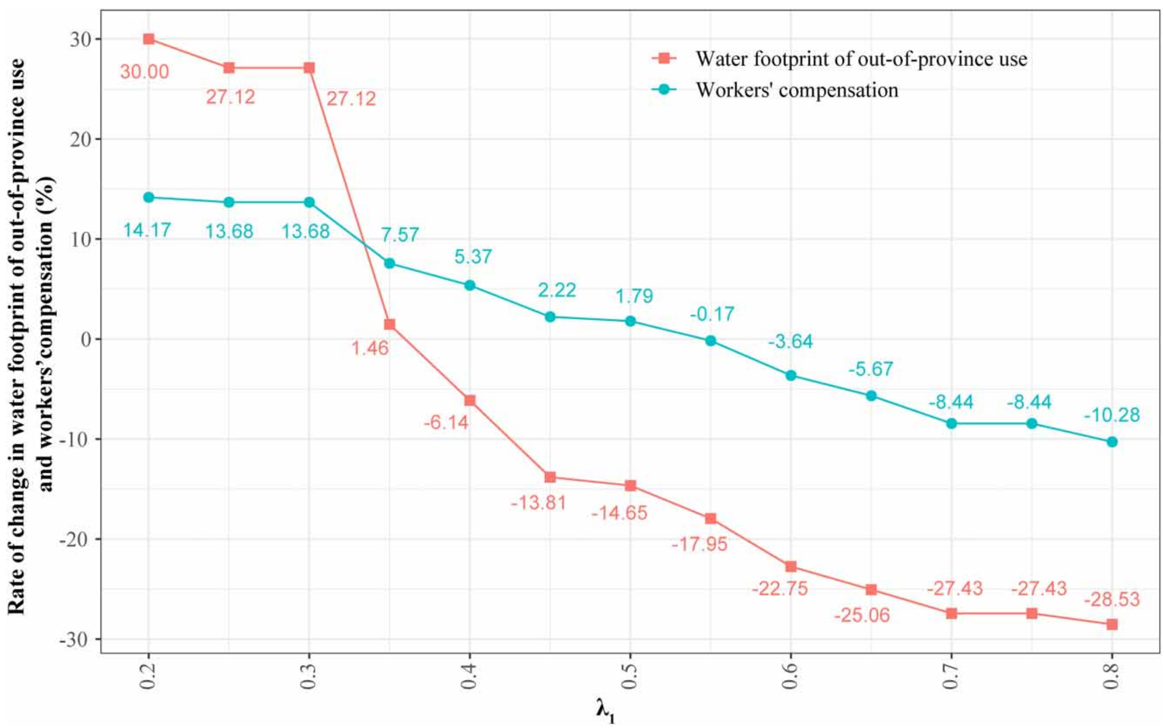


Figure 4 | Water footprint of out-of-province use and workers' compensation in relation to λ_1.

4. DISCUSSION AND LIMITATIONS

4.1. Discussion

Basing data on the non-competitive input-output table can accurately measure the water footprint of sectors in the region, which helps to analyze the real consumption of water resources of each sectoral products. Due to the limitation of statistical data structure, few scholars currently use non-competitive input-output techniques to measure the water footprint of sectors in Henan Province. This paper accurately measures the water footprint of sectors in the province within the framework of non-competitive input techniques and finds that the food and tobacco processing has the largest water footprint. This is different from the results of Yang *et al.* (2019) for Henan Province in 2012, where the largest sector in terms of water footprint was agriculture, for two reasons: (1) this paper uses the most recent input-output table; the production linkages among sectors in Henan Province have changed in five years, and at the same time the water consumption of different sectors has also changed; (2) the input-output table of Henan Province in 2017 was transformed into a non-competitive input-output table by excluding imported products in the intermediate use section, which measures products containing provincial water resources in each sector more accurately.

Currently, scholars are already optimizing regional sectoral export structures based on water footprint results. Zhu *et al.* (2016) conducted a study on optimizing the export structure of Chinese sectors, but this research differs from it. First, this research analyzes water resources in water-scarce areas, arguing that only a non-competitive input-output table can accurately depict the flow of water resources within the region. Second, this paper's optimization goal is to maximize workers' compensation rather than GDP because workers' compensation, as the primary source of income for many workers, has a significant impact on people's employment, livelihood, and regional economic development. Like Zhu *et al.*, our findings also conclude that improving the sectoral export structure positively impacts regional water use and economic development. The difference is that this paper discusses the optimal selection interval of model parameters to provide regional managers with a more flexible adjustment scheme.

Since Henan Province has a scarcity of water resources, the water footprint accounting results in this paper only calculate the water resources within the province, not the water footprint introduced by products from outside the province. This is because different regions have different water reserves, and thus different provinces do not pay the same attention to the same amount of water footprint. More attention will be paid to the destination of water resources in water-scarce regions such as Henan Province. At the same time, each province has the sole authority to plan and manage the water resources under its jurisdiction and has no right to plan or use the water resources of other provinces. As a result, only the export of water resources within the province should be considered, rather than introducing water resources from other provinces. Furthermore, the upper limit of export adjustment at 30% was setted for the annual average rate of change in the export value of each sector from 2012 to 2017. The export adjustment cap does not have to be uniform across sectors. Depending on the current state of sectors, the government can increase or reduce the adjustment cap, resulting in more desirable economic and water-saving benefits.

In summary, compared with related studies, the method of this paper has the following advantages: (1) the use of non-competitive input-output techniques makes the measurement of water footprint more accurate; (2) the sectoral export adjustment scheme can more accurately reflect the strength of the impact on people's lives after the implementation of the scheme; (3) through the adjustable parameters of export restrictions, the government can control the strength of export adjustment in each sector according to the actual situation of the region.

4.2. Limitations and future research

There are some limitations to the methodology of this paper. For example, (1) although this paper uses the latest input-output tables provided by the government, in China the government updates the input-output tables every five years, so there will still be some lag in the research results; (2) the method in this paper is suitable for analyzing the state of water resource flow in this region in recent years but does not have the ability to predict the state of water resource flow in this region in the future.

There is a close relationship between water use and supply. In future research, researchers can try to predict the state of future water supply and consumption of a region by some method (Valis *et al.* 2017; Studziński & Pietrucha-Urbanik 2019), and provide more accurate implementation plans for future export adjustment of various sectors in the region by combining the methods in this paper. This paper mainly uses the blue water footprint to optimize the export structure of sectors in a region. In future research, green and gray water footprint could be included in the model of this paper to provide a comprehensive optimization plan for the export structure of regional sectors.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

This paper improves the accuracy of water footprint measurement in Henan Province by calculating the province's water footprint using a non-competitive input-output technique. It is pointed out that the water consumption of sectors in Henan Province differs significantly from a direct water use perspective, and that the water consumption of sectors is more balanced from a water footprint perspective.

In Henan Province, the water footprint of sectors is distributed differently between in-province use and out-of-province use. Sectors producing essential goods dominate the in-province water footprint, while traditional industries dominate the water footprint of out-of-province use. Meanwhile, the water footprint of out-of-province use accounts for 52.75 percent of the province's total water consumption, implying that more than half of the water consumed in Henan Province is consumed outside of the province, which puts additional strain on the province's water resources.

A dual-objective planning model for minimizing water exports and maximizing labor compensation is developed and applied to Henan Province by constructing the change in imported intermediate use and labor compensation caused by the change in provincial exports. It was discovered that improving Henan's sectoral export structure could save 1.52 billion cubic meters of water while also increasing labor compensation by 39.76 billion RMB, resulting in a win-win situation of economic development and water conservation.

5.2. Recommendations

Henan is currently accelerating the implementation of the 'Five Zones Interconnected Development,' and the province's rapid economic development has also increased demands on the use of water resources. The findings of this paper can be used to make practical recommendations for Henan Province's water resource management and long-term economic development. The specific recommendations are as follows.

From the perspective of the water footprint, the outflow of a large amount of water resources in Henan Province has further increased the pressure on water resources in the province. To reduce the large outflow of water resources from the province, the government should reasonably reduce the export volume of products from several sectors, including food and tobacco processing, textile industry, paper, printing, and articles for culture, education, and sports activity, and chemical product manufacturing. Furthermore, the government should boost exports of nonmetallic mineral products, general-purpose machinery, special-purpose machinery, communication equipment, computers, and other emerging industries. This has the potential to save a significant amount of water while also providing significant economic benefits.

Another reason for the large export footprint of Henan Province is the high-water consumption intensity of the sectors with a large proportion of exports. The government should adopt policies to improve water use efficiency in the high-water consuming sectors, including agriculture, forestry, animal husbandry and fishery, food and tobacco processing, textile industry, manufacture of leather, fur, feather and related products, etc. For example, governments can increase investment in modern irrigation and production water technologies to reduce water waste in production processes.

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AUTHOR CONTRIBUTIONS

Faguang Wen and Xue Fang developed the research idea and supervised the study. Xue Fang obtained the data. Faguang Wen conducted the data analyses. Faguang Wen drafted the initial manuscript and Xue Fang and Ribesh Khanal critically reviewed and revised the manuscript. All authors reviewed and approved the final manuscript.

CONFLICT OF INTEREST

The authors declare there is no conflict.

DATA AVAILABILITY STATEMENT

1. Input-Output Table: https://oss.henan.gov.cn/sbgt-wztipt/attachment/hntjj/hntj/lib/tjnj/2020nj/zk/indexch.htm.
2. Agricultural water consumption: https://oss.henan.gov.cn/sbgt-wztipt/attachment/hntjj/hntj/lib/tjnj/2018/zk/indexch.htm.
3. Sub-sectoral water consumption of industry, construction and service industries: http://www.stats.gov.cn/tjsj/pcsj/jjpc/2jp/left.htm; https://slt.henan.gov.cn/bmzl/szygl/szygb/2017nszygb/; https://slt.henan.gov.cn/2019/12-28/1190983.html.

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