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A Study on Water Rights Allocation in Transboundary Rivers Based on the Transfer and Inequality Index of Virtual Water

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Abstract: Virtual water exerts an essential effect on water resources, yet such effect is rarely considered in current studies on water rights allocation in transboundary rivers. Hence, this paper ran a case study on Taihu Lake Basin, collecting data from 2017 to make clear the physical water rights of four regions—Jiangsu Province, Zhejiang Province, Anhui Province, and Shanghai City—in the Basin. After that, the multiregional input–output (MRIO) approach was utilized to measure the trade in value-added (TiVA) transfer and virtual water transfer (VWT) and construct an inequality index of VWT (VWI). Next, water efficiency coefficient was employed to convert the VWT into riparian level. Finally, VWT and VWI were incorporated into the water rights allocation model to form up a water rights allocation scheme for Taihu Lake Basin. Results showed: (1) Jiangsu enjoys the most allocated physical water rights, followed by Zhejiang, and Anhui ranks the lowest; (2) Anhui and Jiangsu are net virtual water exporters (2.259 billion m^3 and 1.78 billion m^3, respectively), while Zhejiang and Shanghai are net importers (2.344 billion m^3 and 1.695 billion m^3, respectively); (3) Anhui suffers the most inequality—0.4401—followed by 0.5076 of Jiangsu, while Zhejiang has the most equal environment—0.7012; (4) after the inclusion of virtual water, the quantity of water rights allocation changes, whereas Anhui experiences the largest growth—144 million m^3—due to the dual effects from the highest VWT and inequality. In conclusion, the effect of virtual water is indispensable, so VWT and VWI should both be considered in the physical water rights allocation of transboundary rivers.

Keywords: virtual water; inequality index of virtual water transfer; water rights allocation

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1. Introduction

Water shortage leads to disputes over water resources between upper and lower parts of a drainage basin or even regional intense competition for water rights, such as the Maipo River in Nile and the Tennessee Valley in USA [1–4]. Hence, with the water rights fairly determined and allocated, such conflicts could be greatly relieved, beneficial to establish an equitable water trading market and transregional ecological compensation. In light of overseas attempts, the key to initial water rights allocation is to adhere to multiple objectives of social equity, economic benefit, ecological preservation, and risk control [5–7]. Scholars have discovered a variety of allocation methods such as linear programming, dynamic programming, multi-model methodology, the multi-objective method, collaboration, and game, and gained experience in exploring rules for initial water rights allocation in drainage basins [8–24].

Virtual water refers to the water hidden in trading products and varies according to regional trade cooperation [25–39]. Frequent trading leads to an increase in virtual water transfer (VWT) between upper and lower parts of a basin, which exerts an indirect impact on the actual amount of water resources [25–39]. Therefore, it is necessary to incorporate virtual water into initial water rights allocation [25,40–42]. However, most current studies are centered around physical water resources, evading the invisible effect of virtual water [8–24]. In this case, this paper included virtual water into the exploration of water rights allocation in transboundary river basins.

To include virtual water in physical water rights allocation, an underlying issue—unfairness between economic benefit and environmental cost—must be considered. So, this paper is grounded in the inequality index of VWT (VWI). Methodologies such as the Gini coefficient, Theil index, Lorenz curve, and coefficient of variation were utilized to measure inequality [43–48], and focused on the holistic perspective of trade–environmental inequality. Some scholars have probed into the equivalence between the implicit resource cost and economic value added of trade [49–52]. On such basis, this paper employed the environmentally extended multiregional input–output (MRIO) model to measure VWT and trade in value-added (TiVA) transfer to construct VWI, to analyze the imbalance between them and integrate it into an allocation model.

The principles of consensus among scholars regarding physical water rights allocation are domestic water first, food security, respect for the history and status quo, and sustainable development [5–7]. In terms of methodology, this paper, drawing from previous studies, thus constructed an index system grounded in principles of status quo, equity, efficiency, sustainability, and macro regulation. Second, as for VWT methodology, many scholars found that the multiregional input–output approach can clarify the interdependence among sections of an entire supply chain in an economy [53–60]. It provides a clearer quantification of the amount of water deployed in trade and makes the virtual water calculation more intuitive and accurate [53–60]. Therefore, this paper drew an input–output tablet for modelling to calibrate water resources allocation in trade [35–45]. Third, VWT is measured among provinces, while water rights allocation is measured in the riparian areas of a transboundary drainage basin. So, VWT needs to be converted. However, there are only a few studies to refer to. Some scholars have adopted water efficiency coefficient to convert from a qualitative perspective [41,61,62]. Considering this, we also measured and converted VWT using the proportion of the water efficiency coefficient of basin area to that of the corresponding province.

In general, many studies have proven the VWT included in trade and its influence, yet still mainly taken physical water into consideration while formulating water rights allocation schemes. Therefore, to fill this gap, this paper first makes clear the physical water rights allocation in the transboundary river, then calculates provincial VWT and constructed VWI and convert provincial VWT into riparian VWT. Last, the converted VWT and VWI are integrated into the water rights allocation model.

So, based on the preceding analysis, the research framework underpinning this paper is meticulously assembled (Figure 1). First, according to the allocation rules, this paper makes clear the physical water rights allocation in the transboundary river. Next, the MRIO approach is employed to measure the VWT and TiVA transfer, and VWI is constructed accordingly. Third, considering that the provincial VWT was predicted at the provincial level, while the physical water allocation at the basin level within the provincial jurisdiction, a conversion of provincial VWT into riparian VWT with water efficiency coefficient is necessitated to reduce errors. Last, the converted VWT and VWI are integrated into the water rights allocation model.

This paper makes the following contributions: (1) integrating virtual water into physical water rights allocation to enrich the theories of initial water rights allocation of transboundary rivers; (2) constructing VWI to make allocation schemes more equal and reasonable.

The rest of this paper is arranged as follows: Section 2 introduces the methodology and data collection; Section 3 summarizes the main results; Section 4 is discussion; Section 5 presents the conclusion.

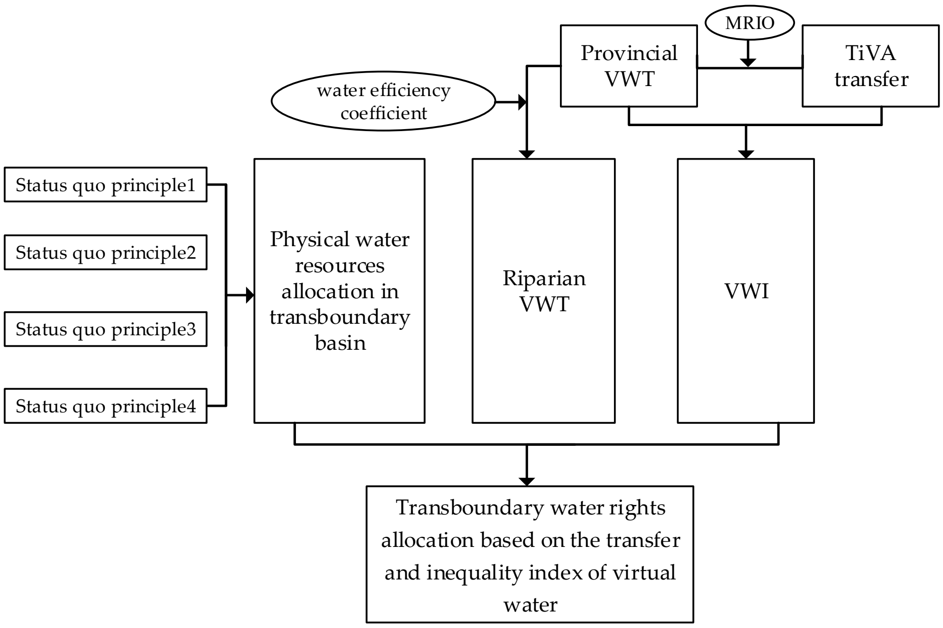

Figure 1. Research framework.

2. Methodology and Data Collection

2.1. Methodologies

2.1.1. Modelling of Physical Water Rights Allocation

Constructing an Index System of Physical Water Rights Allocation

Drawing from previous research [5–8], this paper builds an index system of physical water rights allocation (Table 1).

Table 1. Index system of physical water rights allocation.

Scheme	Principle	Indicator	Units	Symbol	Attribute
Physical water rights allocation scheme A	Status quo B_1	Current water use	Billion m^3	P_{11}	Benefit-based
		Water use per capita	m^3/person	P_{12}	Benefit-based
		Water use per farmland unit	m^3/mu	P_{13}	Benefit-based
		Current water supply scale	10,000 m^3	P_{14}	Benefit-based
	Equity B_2	Annual average runoff volume	Billion m^3	P_{21}	Benefit-based
		Population	10,000 people	P_{22}	Benefit-based
		Effective Irrigated area	m^3	P_{23}	Benefit-based
	Efficiency B_3	GDP per capita	10,000 yuan	P_{31}	Benefit-based
		Industrial output per capita	10,000 yuan	P_{32}	Benefit-based
		Agricultural output per capita	10,000 yuan	P_{33}	Benefit-based
		Water consumption per 10,000 yuan GDP	m^3	P_{34}	Cost-based
		Water consumption per 10,000 yuan agricultural output	m^3	P_{35}	Cost-based
		Water consumption per 10,000 yuan industrial output	m^3	P_{36}	Cost-based
	Sustainability B_4	Economic growth rate	%	P_{41}	Benefit-based
		Greening rate	%	P_{42}	Benefit-based
		Population growth rate	%	P_{43}	Benefit-based
		Proportion of waste water meeting discharge standards	%	P_{44}	Benefit-based
	Macro regulation B_5	Priority of regional development	points	P_{51}	Benefit-based
		Protection of vulnerable groups	points	P_{52}	Benefit-based

In Table 1, the lower grades of cost-based coefficients mean that more initial water rights should be allocated, while the higher grades of benefit-based coefficients mean that more initial water rights should be allocated.

Allocating Physical Water Rights

(1) Decision making matrix

Suppose n regions in a drainage basin are involved in the initial water rights allocation, each having a total of $m(m = 1, 2, \cdots, 19)$ indicators, so m indicators of n regions constitute a decision making matrix below:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} = (x_{ij})_{m \times n} \tag{1}$$

(2) Data normalization

The matrix X needs to be normalized to unitize the indicator standards.

For cost-based indicators, Formula (2) is used for standardization to eliminate the influence of inconsistent dimensions:

$$y_{ij} = \frac{\max\limits_{i} x_{ij} - x_{ij}}{\max\limits_{i} x_{ij} - \min\limits_{i} x_{ij}}, i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \tag{2}$$

For benefit-based indicators, Formula (3) is used for standardization to eliminate the influence of inconsistent dimensions:

$$y_{ij} = \frac{x_{ij} - \min\limits_{i} x_{ij}}{\max\limits_{i} x_{ij} - \min\limits_{i} x_{ij}}, i = 1, 2, \cdots, m; j = 1, 2, \cdots, n \tag{3}$$

where $\max\limits_{i} x_{ij}$ represents the maximum of indicator i in region n, and $\min\limits_{i} x_{ij}$ is the minimum.

(3) Project indicator function

Matrixes of both positive-ideal and negative-ideal solutions are below:

$$\begin{aligned} Y_j^+ &= \max\{y_{1j}, y_{2j}, \cdots, y_{mj}\} \\ Y_j^- &= \min\{y_{1j}, y_{2j}, \cdots, y_{mj}\} \end{aligned} \tag{4}$$

Distance from every region to the positive-ideal solution is:

$$d_j^+ = \left[\sum_{i=1}^{m} \omega_i (y_{ij} - y_{ij}^+)^2\right]^{0.5} \tag{5}$$

where ω_i stands for the weight of indicator i, and the smaller d_j^+ is, the closer region $j, j = 1, 2, \cdots, n$ is to the positive-ideal point, and the more water rights should be allocated to the region.

Similarly, the distance from every region to the negative-ideal solution is:

$$d_j^- = \left[\sum_{i=1}^{m} \omega_i (y_{ij} - y_{ij}^-)^2\right]^{0.5} \tag{6}$$

where the bigger d_j^- is, the further region j is from the negative-ideal point, and the more water rights should be allocated to the region.

Relative proximity is used according to TOPSIS:

$$D_j = \frac{d_j^-}{d_j^- + d_j^+} \tag{7}$$

In terms of ω_j, qualitative indicators (p_{51}, p_{52}) and quantitative indicators are included, so an analytic hierarchy process (AHP) combining both indicators is employed to calculate the weights of indicators.

(4) Water rights allocation scheme

Based on Equations (5)–(7), the quantity of water rights allocated for every region is:

$$\varphi_j = \frac{D_j}{\sum\limits_{j=1}^{n} D_j} \tag{8}$$

Quantity of initial water rights is:

$$C_r = \varphi_r \cdot C_0 \tag{9}$$

where C_0 stands for the available water resources, and $(C_1, C_2 \cdots C_n)$ is the initial water rights allocation schemes.

2.1.2. Model for Calculating VWT and VWI

2.1.2.1. Provincial VWT Calculation

Provincial VWT is calculated based on the MRIO model. By constructing input–output matrices between regions, it can determine the virtual water input–output relationship generated in the trade of intermediate and final products between regions and reflect the distribution of virtual water in different sectors of different regions. Additionally, according to the CEADs' MRIO database, the VWT of each region is calculated. The specific steps are as follows:

A transboundary basin contains n provinces –province $1, 2, \ldots, n$. Other provinces are treated as province $(n+1)$. In addition, this paper modified the MRIO table, as shown in Table A1 in Appendix A.

Based on the modified MRIO table, we can obtain

$$Z^{rs} = \sum_{p=1}^{n+1} W^r L^{rp} F^{ps} \tag{10}$$

To be specific, r and s refer to basin provinces, p stands for the provinces trading with province r and s, and $n+1$ is the number of provinces trading with province r and s. When $p = r$, VWT is included in the direct trade from province r to province s. When $p \neq r$, province r exports semifinished products to province p, which then further process into final products and export to province s, transferring water resources from province r to province s. It is, in other words, indirect VWT from province r to province s.

Z^{rs} represents VWT from province r to province s, W the direct water coefficient matrix, and W^r the direct water coefficient matrix of province r, which is directly obtained from the *China Statistic Yearbook*. L stands for the well-known Leontief inverse, representing the gross output generated throughout the production process of one unit of consumption; L^{rp} refers to the submatrices of Leontief inverse matrix for province r to province p, which is calculated by MRIO; F is the final demand matrix, and F^{ps} represents the submatrices of the final demand matrix for province p to province s, which is directly obtained by MRIO.

In the same way, VWT from province s to province r can be attained:

$$Z^{sr} = \sum_{p=1}^{n+1} W^s L^{sp} F^{pr} \tag{11}$$

where W^s stands for the direct water coefficient matrix of province s, L^{sp} the submatrices of the Leontief inverse matrix for province s to province p, and F^{pr} the submatrices of the final demand matrix for province p to province r.

In conclusion, the net VWT from province r to other provinces via trade is represented as follows:

$$kz^r = \sum_{s=1}^{n} (Z^{rs} - Z^{sr}) \tag{12}$$

If $kz^r > 0$, province r is a net exporter of virtual water; if $kz^r < 0$, it is a net importer.

VWI

Trade brings economic benefits to all parties involved, and the most direct benefits is domestic economic growth, namely, an increase in domestic value added. However, the value added of each country exists in two forms: imports and exports. Imports represent an increase in value added in other countries, while exports represent an increase in value added in one's own country. The net transfer of value added can be expressed as the difference between the value added of exports and imports. A positive value indicates that the country is in generally economic benefit, while a negative value results in economic losses.

From an environmental perspective, trade brings virtual water to different countries in either imported or exported forms. Countries with a net import of virtual water are the beneficiaries, while those with a net export are the losers. However, when two trading partners divide up the work differently in the global supply chain, the "hidden" water and added value in their traded goods also differ greatly. This means that the water and environmental costs that the trading countries pay can be much more than the economic benefits they receive, which is known as the unfairness of virtual water transfer, also known as the unfairness of trade value-added and virtual water transfer.

Therefore, this paper constructed the VWI based on the input–output of virtual water and trade value-added, and measured the gains (losses) of regions.

(1) Model of provincial TiVA transfer

By using a MRIO model, we can calculate the impact of each region's trade on the value added of other regions, that is, TiVA transfer. The TiVA transfer of each region is decomposed to track the impact of final demand from other regions on the implied TiVA of the region. Meanwhile, if a region has a net output of value-added in its trade with other regions, it indicates that other regions are driving the economic growth; conversely, if a region is driving the economic growth of other regions, it indicates that the region is a net importer of value-added.

In the way mentioned in Section 2.1.2.1, TiVA transfer matrix (from province r to province s) is obtained:

$$V^{rs} = \sum_{p=1}^{n+1} (\text{TiVA})^r L^{rp} F^{ps} \tag{13}$$

where $(\text{TiVA})^r$ stands for the trade value added matrix of province r, which is obtained from MRIO directly. V^{rs} means TiVA transfer matrix.

The TiVA transfer matrix from province s to province r is

$$V^{sr} = \sum_{p=1}^{n+1} (\text{TiVA})^s L^{sp} F^{pr} \tag{14}$$

Net TiVA transfer from province r to other provinces via trade is

$$kv^r = \sum_{s=1}^{n} (V^{rs} - V^{sr}) \quad (15)$$

If $kv^r > 0$, province r is a net exporter of TiVA; if $kv^r < 0$, province r is a net importer.

(2) Model of Inequality Index

TiVA estimates the value added in the production of goods and services for trade. Net TiVA transfer equals export minus import—if the result is positive then the province profits; if negative, the province loses. The relations between VWT and TiVA transfer, as shown in Figure 2, mainly fall into two categories: same direction and opposite direction. On such basis, suppose province r has positive net VWT and either positive or negative net TiVA transfer, then three relations can be formed—AA′, BB′ and CC′—as shown in Figure 3.

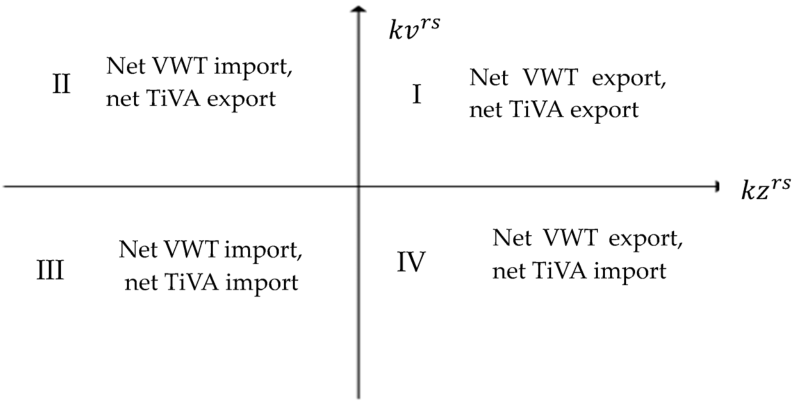

Figure 2. Relations between VWT and net TiVA transfer.

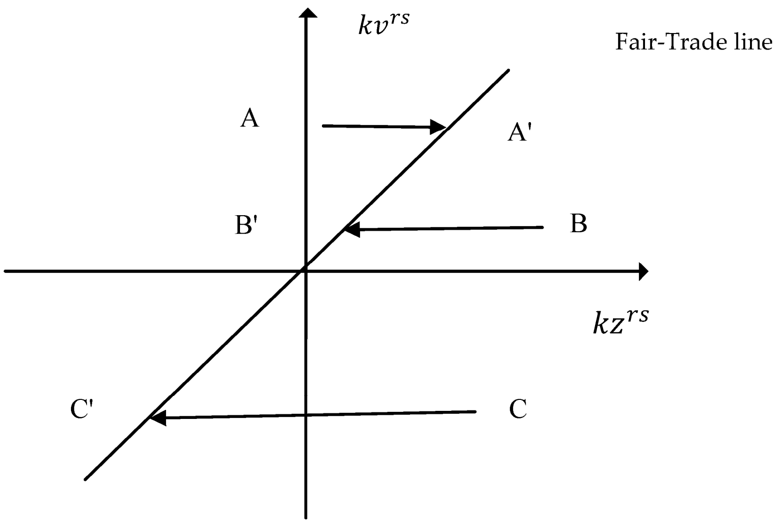

Figure 3. VWI.

In general, suppose the straight line cutting through the origin in Figure 3 is the fair-trade line, and the dots on it stand for the national mean of the relation between VWT and TiVA transfer. Namely, the net TiVA export (import) from unit net virtual water export (import) is up to the national mean. So, TiVA transfer caused by unit net VWT—slope of the fair trade line, is:

$$\beta = \sum_{r=1}^{m} \sum_{s=1, r \neq s}^{m} |kv^{rs}| \Big/ \sum_{r=1}^{m} \sum_{s=1, r \neq s}^{m} |kz^{rs}| \quad (16)$$

where β represents the slope of the fair trade line for TiVA-VWT and $\beta \geq 0$; $|kv^{rs}|$ represents the absolute value of TiVA transfer from province r to province s; $|kz^{rs}|$ represents the absolute value of VWT from province r to province s; $\sum_{r=1}^{m}\sum_{s=1,r\neq s}^{m}|kv^{rs}|/2$ stands for the sum of net TiVA transfer of all provinces/cities in China; and $\sum_{r=1}^{m}\sum_{s=1,r\neq s}^{m}|kz^{rs}|/2$ stands for the sum of net VWT of all provinces/cities in China.

This paper hypothesized $kz^{r} > 0$ so that the dots only show up to the right of the Y-axis in Figure 3, namely Quadrant I. The dots A, B, and C away from the fair trade line are counterparts of A′, B′, and C′ on the line, and segments AA′, BB′, and CC′ refer to the net VWT to be added or subtracted for the dots to reach the line. Furthermore, DP, deflection distance, represents the deviation degree from the fair trade line:

$$DP = \begin{cases} \frac{\frac{kv^{rs}}{\beta} - kz^{rs}}{\frac{kv^{rs}}{\beta}} = 1 - \frac{\beta kz^{rs}}{kv^{rs}},\ \frac{kv^{rs}}{\beta} > kz^{rs} > 0, 0 \leq DP < 1 \\ \frac{kz^{rs} - \frac{kv^{rs}}{\beta}}{kz^{rs}} = 1 - \frac{kv^{rs}}{\beta kz^{rs}},\ 0 < \frac{kv^{rs}}{\beta} < kz^{rs}, 0 \leq DP < 1 \\ \frac{kz^{rs} - \frac{kv^{rs}}{\beta}}{kz^{rs}} = 1 - \frac{kv^{rs}}{\beta kz^{rs}},\ \frac{kv^{rs}}{\beta} < 0,\ DP > 1 \end{cases} \tag{17}$$

where if the TiVA transfer and VWT are in Quadrant I, DP is $[0, 1)$; if in Quadrant IV, DP is $[1, \infty)$; the higher DP is, the further away the dot is from the fair trade line; if DP = 0, the dot is on the line, standing for equality.

On such basis, this paper constructed the exponential function $y = e^{-x}$ to build the VWI within $(0, 1]$ as follows:

$$\mathrm{VWI} = e^{-DP} = \begin{cases} e^{-(1-\frac{\beta kz^{rs}}{kv^{rs}})},\ \frac{kv^{rs}}{\beta} \geq kz^{rs}, \text{Dot above fair}-\text{trade line} \\ e^{-(1-\frac{kv^{rs}}{\beta kz^{rs}})},\ \frac{kv^{rs}}{\beta} \leq kz^{rs}, \text{Dot below fair}-\text{trade line} \end{cases} \tag{18}$$

The closer VWI gets to 1, the more equal it is; the closer VWI gets to 0, the more unequal it is. In conclusion, the inequality between VWT and TiVA transfer is obtained and integrated into the initial water rights allocation model to make the model more equal and reasonable.

2.1.3. Coupling of Physical and Virtual Water

Regional VWT

Based on water use coefficient, the provincial VWT was then converted into the riparian level—VWT of the riparian area of each province:

$$KZ_b^r = \tau KZ^r \tag{19}$$

where τ is the conversion percentage and KZ_b^r is the net VWT of basin r.

Model Integrated with Virtual Water

Higher VWI means higher influence from VWT. As a result, once the physical water transfer, VWT, and VWI are made clear, a model of water rights allocation in a transboundary river included with virtual water is constructed below:

$$C_r' = C_r + kz_b^r \times \left| \frac{1}{n} - \frac{VWI_r}{\sum\limits_{r=1}^{n} VWI_r} \right| \tag{20}$$

where C_r' is the amount of water allocation for region r with virtual water included.

2.2. Data Collection

2.2.1. Study Area

Taihu Lake Basin covers Jiangus Province, Zhejiang Province, Anhui Province, and Shanghai City. Additionally, the Taihu Lake Basin lies in the central area of the Yangtze River Delta region, bordered by the Yangtze River to the north, the East China Sea to the east, the Qiantang River to the south, and Tianmu and Maoshan Mountain to the west. It covers a water surface area of 2338 square kilometers, with an average water depth of 1.89 m and a maximum of 2.60 m. Its annual average water level and annual average water storage capacity are 3.21 m and 4.956 billion m^3 [63]. Water areas and administrative boundaries within the Taihu Lake Basin are shown in Figure 4.

Figure 4. Map of Water Areas and Administrative Boundaries in the Taihu Lake Basin.

Additionally, Taihu Lake is situated in the subtropical zone with a mild and humid monsoon climate and interacts with more than 50 major inflowing and outflowing rivers. Figure 5 depicts the main water inflow and outflow in the Taihu Lake in 2021 [63].

In addition, in order to better manage the Taihu Lake Basin, China established the Taihu Lake Basin Authority, which oversees multiple administrative regions. It monitors the Taihu Lake Basin areas across three provinces and one city. Since the surface water is main water source for Taihu Lake, with an average annual supply 33.78 billion m^3 (groundwater sources and other sources supply 0.023 billion m^3 and 0.526 billion m^3, respectively) [63]. Therefore, the Authority mainly considers the surface water of these regions in its assessment indicators to ensure that the total amount of surface water used is within acceptable limits.

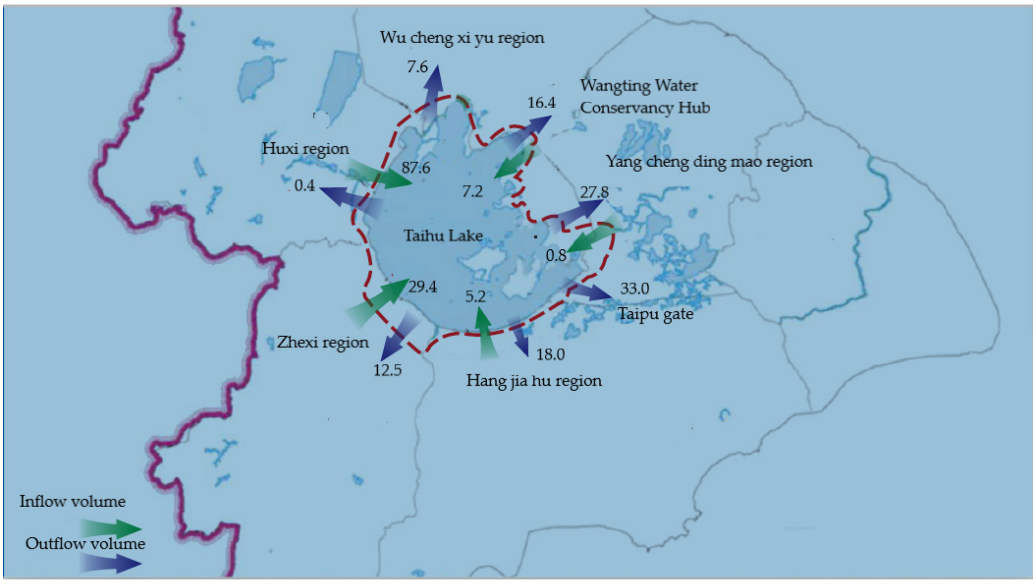

Figure 5. Water inflow and outflow quantity in the Taihu Lake in 2021 (100 million m^3).

In 2021, the total population of the Taihu Lake Basin was 68.11 million, accounting for 4.8% of China's total population. The regional gross domestic product (GDP) was 11.2736 trillion yuan, accounting for 9.9% of the national GDP. The per capita GDP was 165,000 yuan, double the national average [63]. As of 2021, the annual water resource consumption along the Basin reached 34.23 billion m^3, while it only supplied 28.99 billion m^3 of water, leading to a huge supply–demand gap [63]. The specific water consumption of the three provinces and one city is shown in Table 2.

Table 2. The specific water consumption of the three provinces and one city (billion m^3).

Water Use / Region	Domestic Water	Industrial Water	Total Water Consumption
Anhui	0.002	0.016	0.018
Jiangsu	1.59	18.27	20.02
Zhejiang	0.77	3.43	4.32
Shanghai	1.37	8.42	9.87

We know that the Basin is under tremendous pressure of worsening water scarcity, water pollution, and carrying capacity. Therefore, to facilitate cross-regional ecological compensation and water rights trading in the Taihu Lake Basin, it is imperative to establish an initial allocation of water rights based on the allocation plans from various provinces and regions. A well-designed water rights allocation plan is essential for promoting the development of the water rights market and ensuring its sustainability [8].

Meanwhile, the four regions constitute integral parts of the Regional Integrated Development Plan for Yangtze River Delta and contribute to many VWT and transactions, which produces an invisible effect on the actual virtual water amount. Therefore, this paper incorporated VWI and VWT into the initial water rights allocation scheme of the Taihu Lake Basin.

2.2.2. Data Sources

This paper chose data on virtual water in 2017—the latest public data on virtual water from Carbon Emission Accounts & Datasets (CEADs) [64]. The CEADs' input–output intermediate use table covers the input and output scenarios of various industries, and these industries can be classified as manufacturing, agriculture, and services. Therefore, this paper mainly combined specific industries of agriculture, manufacturing, and services for VWT calculation.

Data on physical water of Taihu Lake Basin from the communiques on water of the four regions and the Taihu Basin Authority in 2017 as well as the *China Statistic Yearbook* (2017) [63,65–68].

3. Result

3.1. Physical Water Allocation

3.1.1. Characteristic Value of Indicators

The characteristic values of indicators in Table 1 were attained based on relevant datasets, as detailed in Table 3.

Table 3. Indicator characteristic value of physical water allocation.

Indicator	Anhui N_1	Jiangsu N_2	Zhejiang N_3	Shanghai N_4
P_{11}	0.24	195	47.1	98.2
P_{12}	503	802	370	418
P_{13}	331	446	381	524
P_{14}	1.3	94.6	82.6	28.4
P_{21}	0.12	10.68	6.66	2.84
P_{22}	36.35	3186.51	1987.02	848.12
P_{23}	11.75	1030.43	642.55	274.26
P_{31}	2.8	7.02	13.6	18.6
P_{32}	1.91	4.81	7.97	9.82
P_{33}	0.37	0.45	0.24	0.06
P_{34}	214	52	35	33
P_{35}	1.85	0.011	0.01	0.0052
P_{36}	72	82	21	75
P_{41}	8.5	7.2	7.8	6.9
P_{42}	0.082	0.028	0.06	0.028
P_{43}	58.03	39.84	37.8	30
P_{44}	58.3	60.4	57.2	70.53
P_{51}	6	8	8	7
P_{52}	7	6	6	6

3.1.2. Normalization

Next, the characteristic values above were normalized using Equations (2) and (3) to formulate the following matrix:

$$X = \begin{bmatrix} 0.00 & 1.00 & 0.24 & 0.50 \\ 0.31 & 1.00 & 0.00 & 0.11 \\ 0.00 & 0.60 & 0.26 & 1.00 \\ 0.00 & 1.00 & 0.87 & 0.29 \\ 0.00 & 1.00 & 0.62 & 0.26 \\ 0.00 & 1.00 & 0.62 & 0.26 \\ 0.00 & 1.00 & 0.62 & 0.26 \\ 0.00 & 0.28 & 0.68 & 1.00 \\ 0.00 & 0.37 & 0.77 & 1.00 \\ 0.79 & 1.00 & 0.46 & 0.00 \\ 0.00 & 0.90 & 1.0 & 1.00 \\ 0.00 & 0.10 & 0.10 & 1.00 \\ 0.16 & 0.00 & 1.00 & 0.11 \\ 1.00 & 0.19 & 0.56 & 0.00 \\ 1.00 & 0.00 & 0.593 & 0.00 \\ 1.00 & 0.35 & 0.28 & 0.00 \\ 0.08 & 0.24 & 0.00 & 1.00 \\ 0.00 & 1.00 & 1.00 & 0.50 \\ 1.00 & 0.00 & 0.00 & 0.00 \end{bmatrix}$$

3.1.3. Indicator Weight

Then, AHP was utilized to make clear of the indicator weights, as detailed in Table 4.

Table 4. Indicator weight.

	B_i	P_i	ω_i
A	B_1	P_{11}	0.1472
		P_{12}	0.0503
		P_{13}	0.0503
		P_{14}	0.0172
	B_2	P_{21}	0.0983
		P_{22}	0.1967
		P_{23}	0.1967
	B_3	P_{31}	0.0272
		P_{32}	0.0272
		P_{33}	0.0272
		P_{34}	0.0136
		P_{35}	0.0272
		P_{36}	0.0136
	B_4	P_{41}	0.0363
		P_{42}	0.0140
		P_{43}	0.0140
		P_{44}	0.0054
	B_5	P_{51}	0.0251
		P_{52}	0.0125

3.1.4. Physical Water Allocation

The quantity and ratio of physical water allocation are calculated using Equations (6)–(10). Specifically, Anhui accounts for the least quantity (1.683 billion m^3) and ratio (5.51%) in the Taihu Lake Basin, whereas Jiangsu ranks the first, taking up 14.491 billion m^3 of physical water, followed by Zhejiang of 9.018 billion m^3 and then Shanghai of 6.318 billion m^3 (17.43%). Details are shown in Table 5.

Table 5. Result of physical water allocation in Taihu Lake Basin.

Region	Distance to Positive-Ideal Solution d_k^+	Distance to Negative-Ideal Solution d_k^-	Relative Proximity D_k	φ_k Ratio φ_k	Quantity (Billion m^3)
Anhui	0.8659	0.0992	0.1028	5.51%	1.683
Jiangsu	0.1070	0.8233	0.8850	47.50%	14.491
Zhejiang	0.2810	0.3444	0.5507	29.56%	9.018
Shanghai	0.4767	0.2293	0.3248	17.43%	6.318

3.2. VWT among Regions in Taihu Lake Basin

3.2.1. Provincial VWT Calculation

The import, export, and net import of virtual water among regions in Taihu Lake Basin are calculated using Equations (10)–(12), as detailed in Figures 6 and 7.

In accordance with Figures 4 and 5, Anhui exports the most virtual water, 4.285 billion m^3; Anhui and Jiangsu are the top net exporters -2.259 billion m^3 and -1.78 billion m^3, respectively—and they share a similar mutual VWT. Zhejiang, on the other hand, imports the most virtual water, 3.424 billion m^3, while Anhui the least, 2.505 billion m^3. Zhejiang and Shanghai are net importers 2.344 billion m^3 and 1.695 billion m^3, respectively.

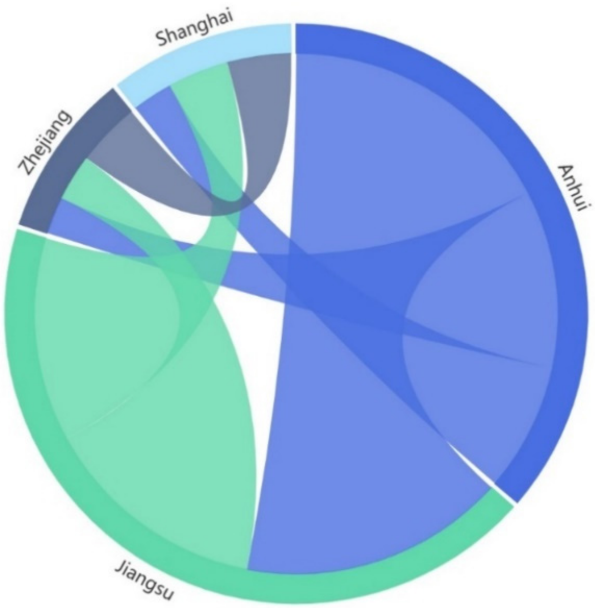

Figure 6. VWT of Taihu Lake Basin (100 million m^3).

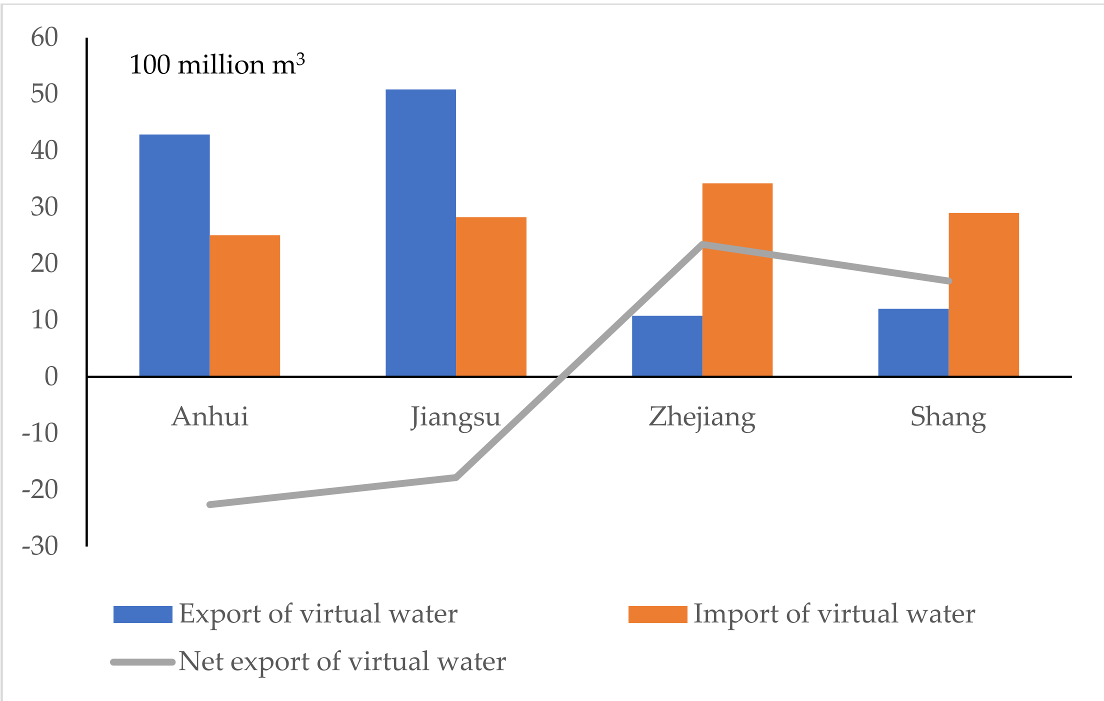

Figure 7. VWT within Taihu Lake Basin (100 million m^3).

3.2.2. VWI

VWI of the four regions was measured using their TiVA and VWT. Anhui has the lowest VWI 0.4401, indicating that it suffers the highest inequality between TiVA and VWT, while Zhejiang has the highest VWI 0.7012, indicating that VWT and TiVA in Zhejiang are in the most equal relation (Table 6).

Table 6. VWI of the four regions.

Region	VWI	$\frac{VWI}{\sum_{r=1}^{n} VWI}$	$\frac{1}{n} - \frac{VWI}{\sum_{r=1}^{n} VWI}$
Anhui	0.4401	0.1957	0.0543
Jiangsu	0.5076	0.2257	0.0243
Zhejiang	0.7012	0.3118	−0.0618
Shanghai	0.5999	0.2668	−0.0168

3.3. The Water Allocation Coupling Physical and Virtual Water Resources

Equations (19) and (20) lead to the result of water rights allocation considering both VWT and VWI, as detailed in Table 7.

Table 7. Water rights allocation of Taihu Lake Basin with virtual water included.

Region	Net VWT (KZ^r) (Billion m^3)	τ	Ratio φ_k	Quantity (Billion m^3)
Anhui	2.259	1.17	5.73%	1.827
Jiangsu	1.780	0.96	45.58%	14.533
Zhejiang	−2.344	1.03	28.15%	8.869
Shanghai	−1.695	1.34	19.93%	6.280

In detail, in terms of absolute quantity, Jiangsu still enjoys the most allocated water—14.533 billion m^3, accounting for 45.58%—followed by Zhejiang—8.869 billion m^3 and 28.15%. Anhui suffers the highest inequality and exports the most virtual water, so it witnesses the largest growth in water allocation, increasing by 1.683 billion m^3 to 1.827 billion m^3, whereas Shanghai drops to 6.28 billion m^3. Moreover, Zhejiang, even though boasting the most equal VWT, declines by 149 million m^3 of allocated water, even more than that of Shanghai, because it exports the most virtual water.

4. Discussion

4.1. Physical Water Allocation

To sum up, the allocation results in this paper are fundamentally in line with the findings of other scholars, except Anhui. Anhui Province was not considered in previous studies for its little-to-no share of the basin area. As for the allocation quantity of other regions, Jiangsu has the most allocated water, followed by Zhejiang and Shanghai; as for allocation ratio, Jiangsu declines by 6.44% while Zhejiang and Shanghai grow by 5.30% and 6.65%, respectively, in comparison with previous studies. When it comes to total ratio, however, Jiangsu still takes the largest proportion, 47.50%, while Shanghai takes the least, 17.43%, as shown in Table 8. The results above are basically in line with the actual conditions—Jiangsu takes the largest share of cities in the Basin and needs the most water; Anhui, on the other hand, only takes 0.6% of the basin area so it needs the least water, which also accords with the principle of status quo.

Table 8. Physical water rights allocation of Taihu Lake Basin.

Region / Allocation Amount	Anhui	Jiangsu	Zhejiang	Shanghai	Units
Amount in this paper	16.83	144.91	90.18	53.18	100 million m^3
Amount in previous studies	0	147.33	125.07	86.39	100 million m^3
Proportion in this paper	5.52	47.50	29.56	17.43	%
Proportion in previous studies	0	41.06	34.86	24.08	%

Comparing with Table 8, it is found that the absolute amount of water allocation and the allocation ratio in this paper is in line with that of previous studies. This can explain that the results of the physical water allocation in this paper are applicable and consistent with reality (Jiangsu has the largest water area, followed by Zhejiang, Shanghai, and Anhui). The difference is that previous studies ignored the Anhui. This is unfair to Anhui province, especially in the context of China's strict water resources management and control over water withdrawals in various regions. Therefore, we included the Anhui region in the allocation process. Additionally, this is one main contribution of this paper in terms of physical water allocation.

4.2. VWT

As for VWT of the four regions, Anhui exports the most virtual water (see Table 7 and Figure 7); as for VWI, Anhui trades a relatively large number of VWT for little economic benefit, indicating that Anhui accommodates many water-consuming yet few high-tech and water-saving industries, and thus is in greater need of economic structure reshaping. Meanwhile, Jiangsu, in comparison with Zhejiang and Shanghai, is also a net exporter, with its inequality ranking second (see Table 6 and Figure 7), mainly because Jiangsu also houses many water-consuming industries, especially in northern Jiangsu. As a result, Anhui and Jiangsu need to be allocated more water rights. On the other hand, Zhejiang and Shanghai are net importers—2.344 billion m^3 and 1.695 billion m^3, respectively. Hence, the two regions need to relinquish some water rights to Jiangsu and Anhui.

Additionally, the increased (decreased) amount in water rights allocation of the four regions experience certain changes after the inclusion of virtual water and VWI, as detailed in Figure 8. It illustrates the significant impact of virtual water on physical water and proves the necessity of including virtual water in physical water rights allocation. At the same time, after including the effect of virtual water, Anhui suffers the most loss in trade with the other regions and thus has the largest compensation, as Figure 8 suggests. It conforms to China's Regional Integrated Development Plan for Yangtze River Delta.

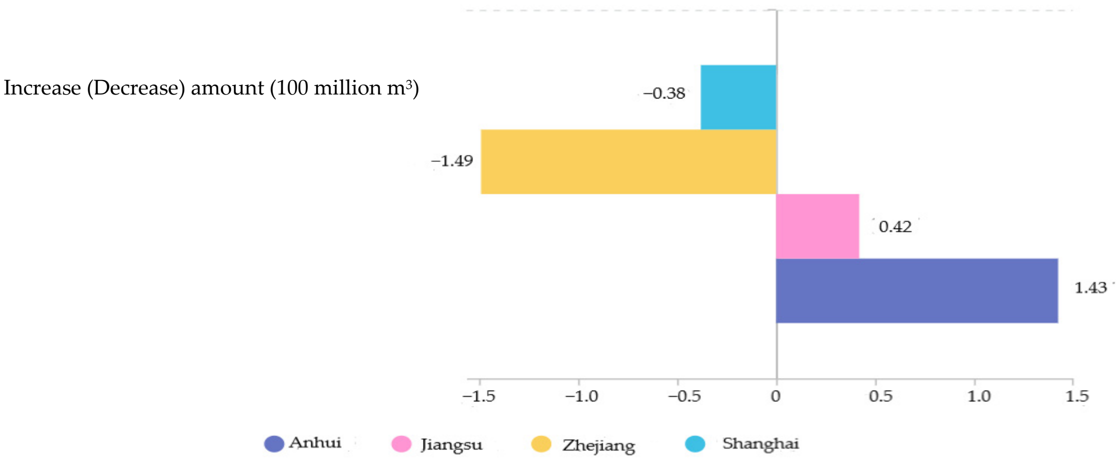

Figure 8. Increased (decreased) amount in water rights allocation of Taihu Lake Basin before and after embedded virtual water.

According to Tables 5 and 7, and Figure 8, we can see that the change quantity of allocation of the three provinces and one city is not significant before and after virtual water transfer. Although the Anhui, Jiangsu, Zhejiang, and Shanghai changes in volume are close to 100 million m^3, especially Anhui and Zhejiang, the changes exceeded 100 million m^3. In the case of abundant water, 100 million m^3 is a small proportion of Taihu Lake. However, in the case of water scarcity, it becomes extremely important. For example, in 2022, a severe drought occurred in the Yangtze River Basin, and water resource was scarce in each region; 100 million m^3 of water could provide water for one million people for one year. Therefore, 100 million m^3 of water becomes extremely precious.

Additionally, as strict water resource management and total water consumption control policies are implemented in China, the water consumption in Anhui, Zhejiang, and Shanghai have been included in the assessment. Failure to pass the assessment results in punishment. Therefore, even slight fluctuations in water consumption alert local governments.

Thirdly, the data in this paper are based on 2018. With the implementation of the *Yangtze River Integration Strategy*, the trade between these four regions will become closer. The VWT may increase, and the impact of virtual water would also become greater. This is also a topic that will be studied in the future to dynamically track the impact of virtual water.

Finally, the data in this paper are based on riparian VWT. If only the impact of provincial VWT was considered, the impact would be greater than it is now.

So, the transfer of interprovincial virtual water has an invisible impact on the absolute amount of water resources in the regions surrounding Taihu Lake. Therefore, virtual water should be incorporated into the allocation of physical water resources.

To conclude, virtual water yields a considerable invisible effect on physical water. If a region produces higher net export (net import) of virtual water with higher inequality, it suffers a higher imbalance between economy and environment, and it needs more compensation. Thus, virtual water must be included in ecological compensation as well as water rights allocation of transboundary rivers.

5. Conclusions

Increased transactions lead to higher interregional VWT, which further yields a higher impact on regional water resources. However, the role of virtual water is not considered in current studies on water rights allocation of transboundary rivers. On such basis, this paper ran a case study on Taihu Lake Basin to make clear the physical water rights of the four regions—Jiangsu, Zhejiang, Anhui, and Shanghai—along the Basin, then built a model on VWI. After that, the water use coefficient was employed to convert the provincial VWT into riparian VWT. Last, VWT and VWI were included in the model of physical water rights allocation, to form up a comprehensive allocation scheme for the Basin.

(1) Jiangsu enjoys the most allocated water, followed by Zhejiang, Shanghai, and then Anhui.
(2) Anhui and Jiangsu are net exporters of virtual water (Anhui > Jiangsu), whereas Zhejiang and Shanghai are net importers (Zhejiang > Shanghai).
(3) Anhui suffers the highest inequality, while Zhejiang boasts the most equal environment where economic benefit and environment are most matched.
(4) VWT and VWI exert an impact on the water rights allocation of the four regions. Anhui in particular experiences the largest growth in allocated water rights due to the dual effects from VWT and VWI.
(5) Anhui and Jiangsu are net exporters of virtual water, indicating that the two regions need economic structure reshaping more urgently.

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Appendix A

Table A1. Multi regional input–output table.

Input \ Output			Intermediate Use						Final Demand			Total Output
			Basin Province 1		Basin Province (*n*)		Basin Province (*n* + 1)		Basin Province 1	Basin Province *n*	Other Province (*n* + 1)	
			Industry 1	Industry m	Industry 1	Industry m	Industry 1	Industry m				
Intermediate use	Basin province 1	Industry 1	y_{11}^{11}	y_{1m}^{11}	y_{11}^{1n}	y_{1m}^{1n}	$y_{11}^{1(n+1)}$	$y_{1m}^{1(n+1)}$	f_1^{11}	f_1^{1n}	$f_1^{1(n+1)}$	y_1^1
		Industry m	y_{m1}^{11}	y_{mm}^{11}	y_{m1}^{1n}	y_{mm}^{1n}	$y_{m1}^{1(n+1)}$	$y_{mm}^{1(n+1)}$	f_m^{11}	f_m^{1n}	$f_m^{1(n+1)}$	y_m^1
	Basin province *n*	Industry 1	y_{11}^{n1}	y_{1m}^{n1}	y_{11}^{nn}	y_{1m}^{nn}	$y_{11}^{n(n+1)}$	$y_{1m}^{n(n+1)}$	f_1^{n1}	f_1^{nn}	$f_1^{1(n+1)}$	y_1^n
		Industry m	y_{m1}^{n1}	y_{mm}^{n1}	y_{m1}^{nn}	y_{mm}^{nn}	$y_{m1}^{n(n+1)}$	$y_{mm}^{n(n+1)}$	f_m^{n1}	f_m^{nn}	$f_m^{1(n+1)}$	y_m^n
	Other province (*n* + 1)	Industry 1	$y_{11}^{(n+1)1}$	$y_{1m}^{(n+1)1}$			$y_{11}^{n(n+1)}$	$y_{1m}^{(n+1)(n+1)}$	$f_1^{(n+1)1}$	$f_1^{n(n+1)}$	$f_1^{(n+1)(n+1)}$	$y_1^{(n+1)}$
		Industry m	$y_{m1}^{(n+1)1}$	$y_{mm}^{(n+1)1}$			$y_{m1}^{(n+1)(n+1)}$	$y_{mm}^{(n+1)(n+1)}$	$f_m^{(n+1)1}$	$f_m^{(n+1)n}$	$f_m^{(n+1)(n+1)}$	y_m^{n+1}
Added value			v_1^1	v_m^1			v_1^{n+1}	v_m^{n+1}				
Total input			y_1^1	y_m^1			y_1^{n+1}	y_m^{n+1}				
Direct water input					w_n^r							

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