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Analysis of Virtual Water Flow Patterns and Their Drivers in the Yellow River Basin

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Abstract: Virtual water flows have a profound impact on the natural water system of a country or region, and they may help conserve local water resources or exacerbate water scarcity in some areas. However, current research has only focused on the measurement of virtual water flows, without analysis of the causes of virtual water flow patterns. This study first obtained virtual water flow patterns across provinces by constructing a multi-regional input—output (MRIO) model of the Yellow River basin in 2012 and 2017, and then analyzed its driving factors by applying the extended STIRPAT model to provide directions for using virtual water trade to alleviate water shortages in water-scarce areas of the basin. We found the following: (1) The Yellow River basin as a whole had a net virtual water inflow in 2012 and 2017, and the net inflow has increased from 2.14 billion m^3 to 33.67 billion m^3. (2) Different provinces or regions assume different roles in the virtual water trade within the basin. (3) There is an obvious regional heterogeneity in the virtual water flows in different subsectors. (4) Per capita GDP, tertiary industry contribution rate, consumer price index, and water scarcity are the main positive drivers of virtual water inflow in the Yellow River Basin provinces, while primary industry contribution rate, per capita water resources, and water use per unit arable area promote virtual water outflow. The results of this paper present useful information for understanding the driving factors of virtual water flow, which could promote the optimal allocation of water resources in the Yellow River basin and achieve ecological protection and high-quality development in this area.

Keywords: virtual water flows; water resources; MRIO model; Yellow River Basin; extended STIRPAT model; driving factors

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1. Introduction

The water crisis is now ranked as one of the most important global risks, as it may threaten the sustainable development of human societies [1,2]. In the coming decades, climate and social changes are expected to further exacerbate water scarcity in many parts of the world [3]. China is generally facing water shortages due to the uneven spatial and temporal distribution of water resources [4]. As an important ecological barrier and economic zone in China, the Yellow River Basin has a very important position in China's economic and social development and ecological security. However, with the in-depth development of industrialization and urbanization in the Yellow River Basin that has occurred, the conflict between the growing water demand and limited water resources has intensified the competition between different water-using regions and industries [5,6]. To a certain extent, this has hindered the sustainable socio-economic development of the Yellow River Basin. Therefore, optimizing water resource allocation through a reasonable assessment of water resource utilization in the Yellow River Basin is an important way to achieve ecological protection and high-quality development in the Yellow River Basin.

The introduction of virtual water theory provides a new perspective on water resource management, regulation, and security of water supply and demand. It was first proposed by Professor Allan in 1998 and refers to the amount of water needed to produce goods and services [7]. Unlike the traditional concept of water resources, virtual water is an integrated concept involving hydrology, socio-economics, and ecology [8]. The types of virtual water are further divided into blue water, green water, and gray water, where the blue water footprint is the amount of surface runoff and groundwater consumed in production processes; the green water footprint refers mainly to the amount of rainfall stored in the soil consumed by plants; and the gray water footprint refers to the amount of water needed to dilute discharged effluent to meet water quality requirements [9,10]. The virtual water strategy refers to the trade of water-scarce countries or regions through imports of water-intensive products (mainly food) to obtain food security and water resource security [11]. Virtual water research combines economic and social systems with water resource systems, grasping the in-depth patterns of water resource utilization in the process of regional economic and social development more precisely. It is of great practical significance to ensure the security of water supply and demand and to alleviate the contradiction of water shortages in the region [12].

The quantification of virtual water is the foundation of virtual water research. There are two types of virtual water quantification methods commonly used internationally: the bottom-up method, represented by the production tree method, and the top-down method, represented by the input-output method. The production tree method accumulates the water use of each link in the final product production chain and can reflect the water use of a certain sector in detail, while it ignores the network or relationship between some industrial sectors. Therefore, when accounting for the virtual water of products in multiple industrial sectors at the same time, there is a risk of unclear delineation of water use responsibilities, omissions, or double counting [13]. Input-output analysis was first proposed by the economist Leontief [14]. It can reflect the direct and indirect links between the production activities of various industrial sectors in the national economic system [12], and it is divided into a single-region input-output model and a multi-region input-output model. However, the former can only reveal the dynamics of virtual water flows in a single closed region, ignoring the highly interconnected nature of the virtual water trade system, whereas a multi-regional input-output model can reflect inter-regional trade linkages of products and services [5]. Based on multi-regional input-output models, environmental extended input-output analysis (EEIOA) incorporates environmental elements and can capture resource flows in a given economic system from a macro perspective [15]. Therefore, this paper added water resource elements to the traditional MRIO model, constructing a multi-regional water resources input-output model for the Yellow River Basin to provide a more convenient channel for analyzing the water resources flow accompanying economic trade.

In recent years, domestic and foreign researchers have undertaken many studies on the virtual water trade pattern at different levels. In the study of virtual water flow patterns at the global level, Wu (2019) found that about 40% of the freshwater resources consumed in China end up in foreign economies, while only 20% of China's virtual water use is from external inflows [16]. Chen (2021) calculated, based on a world multi-regional input–output model, that many of the world's extremely water-scarce countries are net exporters of virtual water, which exacerbates the uneven distribution of water resources [17]. At the national level in China, An (2021) simulated the inter-provincial virtual water flow embedded in grain transportation and evaluated the water stress caused by the virtual water flow. The results show that the virtual water flow in North China will severely exceed the local water resource carrying capacity and have a significant negative impact on its sustainable development [18]. Lin (2019) examined the virtual water implied by trade in the energy sector in China by province, and the flow pattern suggested that energy consumption in the more developed provinces is supported by water use in the less developed provinces, which are severely water-scarce [19]. At the regional level, Zhang (2021) calculated and assessed the reliance of the Yellow River Delta on external water resources and found that the virtual water trade exacerbates the water shortage in the Yellow River Delta [20]. Tian (2019) calculated and analyzed the virtual water flow pattern of the Yangtze River economic zone, and the results showed that the virtual water flow patterns in many parts of the Yangtze River basin are not coordinated with the local water resource carrying capacity [12]. An (2021) simulated the inter-provincial virtual water flow embedded in grain transportation and found that the virtual water flow in North China will seriously exceed its water resource carrying capacity by 2030, which will have a significant negative impact on local sustainable development [18]. Previous studies have shown that virtual water trade has not really played a role in alleviating water scarcity in China, and that virtual water flows incompatible with water endowments have instead exacerbated water shortages in some areas.

However, the current research has only focused on the measurement of virtual water flows, without analysis of the causes of virtual water flow patterns. In recent years, water shortages have become the biggest bottleneck limiting the high-quality economic development of the Yellow River Basin. There is an urgent need to identify the driving factors of virtual water flow and provide potential solutions to alleviate the water shortages in the basin. The IPAT model can visualize the combined effects of population, affluence, and technology on environmental issues, but it lacks flexibility [21]. The STIRPAT model is an extension of the IPAT model that was developed by Dietz and Rosa [22], which has good flexibility and scope for studying virtual water issues. The extended STIRPAT model can add more drivers and is now widely used in the fields of virtual water and water footprints [23,24]. Therefore, the extended STIRPAT model was applied in this paper to identify the main positive driving factors of virtual water flows, from which we explore possible options for using virtual water trade to improve the status of water scarcity in the basin.

Based on this, this study aimed to answer the following two questions: How are the virtual water trade patterns of the Yellow River Basin spatially distributed and how do they temporally vary, and what factors have contributed to the formation of virtual water trade patterns of the Yellow River Basin? Therefore, this study took the virtual water flow in nine provinces of the Yellow River Basin as the object of study and constructed a multi-regional input-output (MRIO) model of water resources of the Yellow River Basin to measure and analyze the virtual water flow pattern. Then, an extended STIRPAT model was constructed with 11 possible drivers selected from four aspects (demographic, economic, technological, and natural) to reveal where the driving forces for the formation of the virtual water flow pattern in the Yellow River Basin lie. It is expected to provide reasonable suggestions for the optimal allocation of water resources in the Yellow River Basin, thus achieving the dual goals of ecological protection and high-quality development in the Yellow River Basin.

2. Study Area

The Yellow River is the second largest river in China. The main stream is 5464 km long, with a total basin area of 795,000 km^2 (including 42,000 km^2 of inland flow area). The Yellow River basin is located in the east, at longitude 96°~119°, north latitude 32°~42°. The Yellow River originated in the northern foothills of the Tibetan Plateau Bayankara Mountains, in the ancient Zongli basin, and flows through Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shanxi, Shaanxi, Henan, and Shandong [25]. The Yellow River basin is often divided into the following three parts [26,27]: upstream provinces (Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia), midstream provinces (Shanxi, Shaanxi), and downstream provinces (Henan, Shandong) (Figure 1).

The per capita water resources of the Yellow River are 473 m^3, less than 1/4 of the national average. However, it meets the water needs of 15% of China's arable land and 12% of the population [28]. Although the Yellow River basin has scarce water resources, it plays a very important role in China's economic and social development, as well as ecological security [29,30]. An assessment of water resources in the Yellow River Basin showed that the natural runoff in the Yellow River Basin has decreased by 20% since the beginning of the 21st century. The actual exploitation rate of water resources has reached 86%, far exceeding the ecological alert of 40% for a typical river basin, which is exacerbating the current water shortages in the region [31].

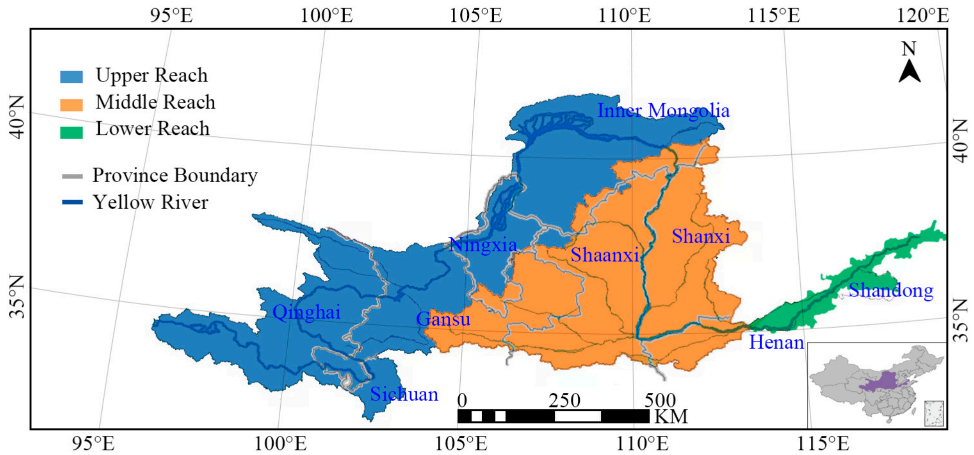

Figure 1. Upper, middle, and lower reaches of the Yellow River Basin.

Internationally recognized water scarcity standards are divided into four levels, with per capita water resources below 3000 m^3 for mild water scarcity, below 2000 m^3 for moderate water scarcity, and below 1000 m^3 for severe water scarcity. Below 500 m^3, the water shortage is extreme [32]. According to this standard, the provinces in the Yellow River Basin are in water shortage, except for Qinghai and Sichuan. Specifically, Shaanxi and Inner Mongolia are in moderate water shortage; Gansu is in severe water shortage; and Ningxia, Shanxi, Shandong, and Henan are in extreme water shortage [28].

There is also an imbalance between the elemental endowments and the degree of utilization of water resources in each region of the Yellow River Basin. From the comparison of the average total water resources and the average total water consumption of each province in the Yellow River Basin in recent years, Gansu, Ningxia, Shanxi, Henan, and Shandong, as water-scarce regions, use more than half of their total water resources each year, and the total water consumption of Ningxia, which is in the upper reaches, far exceeds their total water resources (Figure 2). Qinghai, Sichuan, and Inner Mongolia have abundant water resources; their total water consumption only accounts for a very small part of their total water resources. This indicates that some areas in the Yellow River Basin have abundant water resources to be further developed and utilized, or transferred to other water-scarce areas, thus alleviating the water shortage in other areas and realizing the full utilization of water resources. In some areas, however, there are problems of over-exploitation despite severe shortages or excessive transfer of water resources to other areas, which aggravates water shortages.

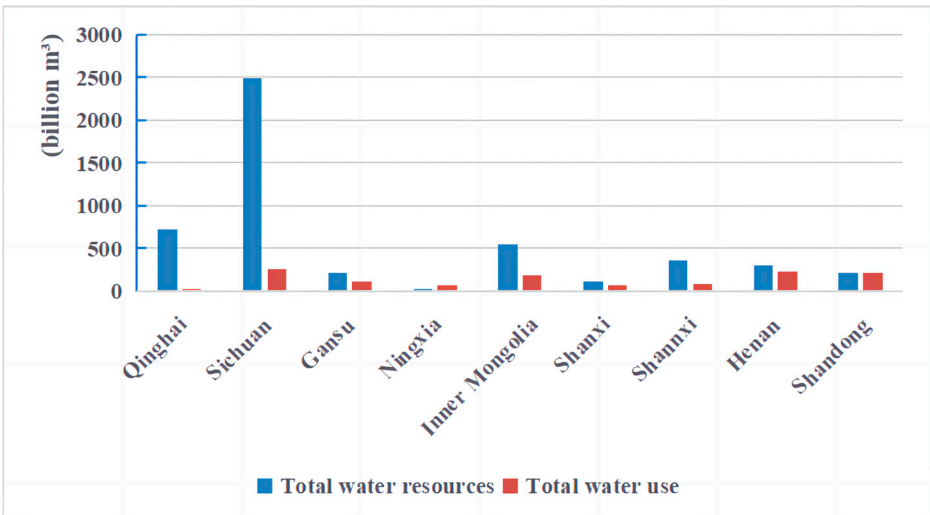

Figure 2. Water resources and water consumption in the Yellow River Basin provinces.

3. Materials and Methods

3.1. Multi-Regional Input-Output Model

Input-output analysis, first proposed by the economist Leontief [14], has been widely used to measure the virtual water volume implied by trade because it can reflect the direct and indirect linkages of production activities in various industrial sectors in the national economic system. Based on the multi-regional input-output tables of 42 industrial sectors in 31 provinces/autonomous regions/municipalities directly under the Central Government of China (except Taiwan, Hong Kong, and Macao SAR), this paper constructed a multi-regional input-output table for the Yellow River Basin (Table 1). The table contains 10 regions (nine regions for each of the nine provinces in the Yellow River Basin, and one region for the 22 provinces outside the Yellow River Basin). In the multi-regional input-output model of the Yellow River Basin, the balance of production activities in region r can be expressed as:

$$x_i^r = \sum_{s=1}^{10} \sum_{j=1}^{42} z_{ij}^{rs} + \sum_{s=1}^{10} f_i^{rs} + e_i^r \tag{1}$$

where x_i^r is the total output of the i sector in the r region, z_{ij}^{rs} is the input of the i sector in the r region to the intermediate use of the j sector in the s region, f_i^{rs} is the input of the i sector in the r region to the end use of the s region, and e_i^r is the export volume of the i sector in the r region.

Table 1. Multi-regional input–output table for the Yellow River Basin.

			Intermediate Use											Final Use				Export	Total Output
			Qinghai			…	Shandong			Other Provinces			Qinghai	…	Shandong	Other Provinces			
			Sector 1	…	Sector 42	…	Sector 1	…	Sector 42	Sector 1	…	Sector 42							
Intermediate Use	Qinghai	Sector 1	$z_{1,1}^{1,1}$	…	$z_{1,42}^{1,1}$	…	$z_{1,1}^{1,9}$	…	$z_{1,42}^{1,9}$	$z_{1,1}^{1,10}$	…	$z_{1,42}^{1,10}$	$f_1^{1,1}$	…	$f_1^{1,9}$	$f_1^{1,10}$		e_1^1	X_1^1
		…	…	…	…	…	…	…	…	…	…	…	…	…	…	…		…	…
		Sector 42	$z_{42,1}^{1,1}$	…	$z_{42,42}^{1,1}$	…	$z_{42,1}^{1,9}$	…	$z_{42,42}^{1,9}$	$z_{42,1}^{1,10}$	…	$z_{42,42}^{1,10}$	$f_{42}^{1,1}$	…	$f_{42}^{1,9}$	$f_{42}^{1,10}$		e_{42}^1	X_{42}^1
	...	…	…	…	…	…	…	…	…	…	…	…	…	…	…	…		…	…
	Shandong	Sector 1	$z_{1,1}^{9,1}$	…	$z_{1,42}^{9,1}$	…	$z_{1,1}^{9,9}$	…	$z_{1,42}^{9,9}$	$z_{1,1}^{9,10}$	…	$z_{1,42}^{9,10}$	$f_1^{9,1}$	…	$f_1^{9,9}$	$f_1^{9,10}$		e_1^9	X_1^9
		…	…	…	…	…	…	…	…	…	…	…	…	…	…	…		…	…
		Sector 42	$z_{42,1}^{9,1}$	…	$z_{42,42}^{9,1}$	…	$z_{42,1}^{9,9}$	…	$z_{42,42}^{9,9}$	$z_{42,1}^{9,10}$	…	$z_{42,42}^{9,10}$	$f_{42}^{9,1}$	…	$f_{42}^{9,9}$	$f_{42}^{9,10}$		e_{42}^9	X_{42}^9
	Other Provinces	Sector 1	$z_{1,1}^{10,1}$	…	$z_{1,42}^{10,1}$	…	$z_{1,1}^{10,9}$	…	$z_{1,42}^{10,9}$	$z_{1,1}^{10,10}$	…	$z_{1,42}^{10,10}$	$f_1^{10,1}$	…	$f_1^{10,9}$	$f_1^{10,10}$		e_1^{10}	X_1^{10}
		…	…	…	…	…	…	…	…	…	…	…	…	…	…	…		…	…
		Sector 42	$z_{42,1}^{10,1}$	…	$z_{42,42}^{10,1}$	…	$z_{42,1}^{10,9}$	…	$z_{42,42}^{10,9}$	$z_{42,1}^{10,10}$	…	$z_{42,42}^{10,10}$	$f_{42}^{10,1}$	…	$f_{42}^{10,9}$	$f_{42}^{10,10}$		e_{42}^{10}	X_{42}^{10}
Import			I_1^1	…	I_{42}^1	…	I_1^9	…	I_{42}^9	I_1^{10}	…	I_{42}^{10}							
Value added			V_1^1	…	V_{42}^1	…	V_1^9	…	V_{42}^9	V_1^{10}	…	V_{42}^{10}							
Total input			X_1^1	…	X_{42}^1	…	X_1^9	…	X_{42}^9	X_1^{10}	…	X_{42}^{10}							

The direct input coefficient $a_{ij}^{rs} = z_{ij}^{rs}/x_j^s$ indicates that the region s sector j requires direct input from the region r sector i to produce a unit of product, where x_j^s is the total output of the sector j in the region s, then Equation (1) can be written as:

$$x_i^r = \sum_{s=1}^{10} \sum_{j=1}^{42} a_{ij}^{rs} x_j^s + \sum_{s=1}^{10} f_i^{rs} + e_i^r \tag{2}$$

Expressing (2) in matrix form and deforming it by shifting the terms, it can be expressed as:

$$X^r = (I - A^{rs})^{-1}(F^{rs} + E^r) = L(F^{rs} + E^r) \tag{3}$$

where X^r is the total output matrix, I is the unit matrix, A^{rs} is the direct input coefficient matrix, F^{rs} is the final demand matrix, E^r is the export matrix, $L = (I - A)^{-1}$ is the Leontief inverse matrix, and the elements within the matrix l^{rs} denote the total output that region r needs to input to meet the final demand of a unit in each sector in the regions, with the following equation:

$$L = (I - A)^{-1} = \begin{bmatrix} l^{1,1} & l^{1,2} & \cdots & l^{1,10} \\ l^{2,1} & l^{2,2} & \cdots & l^{2,10} \\ \vdots & \vdots & \ddots & \vdots \\ l^{10,1} & l^{10,2} & \cdots & l^{10,10} \end{bmatrix} \quad (4)$$

The direct water use coefficient $y_i^r = w_i^r / x_i^r$ represents the direct water use per unit of product produced in sector i in the region r, where w_i^r is the direct water use required for production in sector i in the region r, and x_i^r is the total output of sector i in the region r. Then, the direct water use coefficient vector for the region r is

$$y^r = \begin{bmatrix} y_1^r & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & y_{42}^r \end{bmatrix} \quad (5)$$

The direct water use coefficients for each region form the direct water use coefficient matrix:

$$Y = \begin{bmatrix} y^1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & y^{10} \end{bmatrix} \quad (6)$$

From Equations (4) and (6), the full water use factor matrix can be calculated as follows:

$$Q = YL = Y(I - A^{rs})^{-1} = \begin{bmatrix} q^{1,1} & q^{1,2} & \cdots & q^{1,10} \\ q^{2,1} & q^{2,2} & \cdots & q^{2,10} \\ \vdots & \vdots & \ddots & \vdots \\ q^{10,1} & q^{10,2} & \cdots & q^{10,10} \end{bmatrix} \quad (7)$$

The element q^{rs} in the matrix represents the total amount of water provided in the r area to meet the final demand of the s area for each sector one unit.

According to the constructed multi-regional input-output model, the virtual water trade flow from region r to region s within the Yellow River Basin can be expressed as (8), the virtual water input from region r within the basin to the outside can be expressed as (9), and the virtual water output from region r within the basin to the outside can be expressed as (10).

$$VWT^{rs} = \sum_{i=1}^{10} q^{ri} f^{is} \quad (8)$$

$$VWI^r = \sum_{i=1}^{10} q^{10,i} f^{ir} \quad (9)$$

$$VWO^r = \sum_{i=1}^{10} q^{ri} f^{i,10} \quad (10)$$

3.2. Extended STIRPAT Model

The STIRPAT model is a stochastic regression impact model developed by York [33] from the IPAT equation. The model is commonly used to analyze the effects of population, affluence, and technology level on environmental stress, and is also widely used in fields such as virtual water and water footprints. This study used the STIRPAT model to explore the drivers of virtual water flows in the Yellow River Basin. The basic form of the STIRPAT model is as follows:

$$I = aP^bA^cT^de \tag{11}$$

where, I represents the environmental pressure, a represents the constant term, P represents the population size, A represents the affluence, T represents the technology level, b represents the population index, c represents the wealth index, d represents the technology index, and e represents the model error.

In most studies, to solve the heteroscedasticity problem and to facilitate regression analysis, the natural logarithm is usually taken simultaneously for both sides of the equation, and the STIRPAT model after logarithmization is given by the following equation:

$$\ln I = \ln a + b(\ln P) + c(\ln A) + d(\ln T) + \ln e \tag{12}$$

A major advantage of the STIRPAT model comes from its flexibility [34,35], and the extended STIRPAT model can add other drivers based on the above equation. Considering the Yellow River Basin's own characteristics, the drivers that are expected to have a greater impact on the virtual water trade flows in the basin provinces were selected. Four major categories of indicators were selected in this study, including population indicators, economic indicators, technical indicators, and natural indicators, and a total of 11 drivers were used to construct the model (Table 2).

Table 2. Definition of drivers for the extended STIRPAT model.

Indicator Category	Driving Factors	Variable Symbols	Definition	Unit
Demographic indicators	Population size	x_1	Population size	10,000 people
Economic indicators	GDP per capita	x_2	GDP/Population Size	Yuan/person
	Primary industry contribution rate	x_3	Primary sector GDP/Total GDP	%
	Tertiary industry contribution rate	x_4	Tertiary sector GDP/Total GDP	%
	Consumer Price Index	x_5	Trends and extent of changes in consumer prices	/
	Agricultural production price index	x_6	Trends and extent of changes in the price level of agricultural products	/
	Government expenditure level	x_7	Government spending	Billion
Technical specifications	Water use efficiency	x_8	Water consumption/water withdrawal	%
	Water consumption per unit of arable land area	x_9	Water consumption per unit of arable land area	m^3/ha
Natural indicators	Water resources per capita	x_{10}	Total water resources/population size	m^3/person
	Water scarcity level	x_{11}	Current year's water resource change from the previous year/previous year's water resources	%

Considering the Yellow River Basin's characteristics, this study selected the drivers that were expected to have a large impact on the virtual water trade flows in each province. People consume a large amount of virtual water by means of consuming products and services, so the population size is an important factor influencing the amount of virtual water transfer in each province [36]. The regional economic development level is commonly reflected by the regional GDP per capita [37] and the consumer price index [28]. The industrial structure also has an impact on the size of virtual water trade flows [38]. The Yellow River Basin is traditionally an intensive agricultural region in China, and most provinces are dominated by irrigated agriculture. Agricultural water consumption accounts for a very large proportion of the water consumption in the Yellow River Basin, so indicators such as the contribution of primary industry and the agricultural production price index of agricultural products were chosen. Government expenditure expands the virtual water outflow and inflow by stimulating production and consumption [39], so the government expenditure level was also included in this paper as a factor to measure the economic level. Regional water endowment is also an important factor affecting the inter-regional virtual water trade [40]. In this study, water resources per capita and the water scarcity level were used to measure the natural endowment of water resources in each region. Water-intensive agricultural trade is the most important component of the virtual water trade, so the level of agricultural production technology also affects the pattern of the virtual water flow of agricultural products. According to the calculation method of virtual water consumption of agricultural products, the level of technology can be reflected by water use efficiency [38]. In addition, water use per unit of arable land was added as another technical indicator in this paper. Considering all the above drivers, the extended STIRPAT model can be expressed as follows, taking the virtual water trade flow between provinces and regions within the Yellow River Basin (VWT) as an example:

$$\ln VWT = \ln a + \sum_{i=1}^{11} b_i \ln(x_i) + \ln e \tag{13}$$

where b_i ($i = 1 \sim 11$) is the elasticity coefficient, indicating the percentage change in VWT when x_i changes by 1%.

3.3. Data Sources

The data used in this study can be divided into two parts: the data required to construct the multi-regional input–output (MRIO) model of water resources in the Yellow River Basin, and the data required to construct the extended STIRPAT model. The data required for the MRIO model were divided into input-output data and water use data for each province and each sector. Since there is no official water use data for each sector, this study decomposed the total water use in physical units for the industry, construction, and service sectors based on the proportion of intermediate inputs in monetary units for the "water production and supply" sector extracted from the provincial input-output tables for each industry, construction, and service sector. The data needed to calculate the drivers in the extended STIRPAT model included population size, GDP per capita, and the value-added of tertiary industry, etc. The specific data sources are shown in Table 3.

Table 3. Data classification and data sources.

Model Used	Data Classification	Data Sources
Multi-regional input-output model	Input and output data by province and region	*China Regional Input–Output Tables (2012 and 2017)* [41]
	Water use data by sector in each province and region	*China Statistical Yearbook (2012 and 2017)* [42], *China Water Resources Bulletin (2012 and 2017)* [43], *China Urban and Rural Construction Statistical Yearbook (2012 and 2017)* [44]
Extended STIRPAT model	Population size, GDP per capita, Value added of primary industry, Consumer price index, Water resources per capita, Water consumption per unit arable land area	The official website of the National Bureau of Statistics [42]
	Value added of tertiary industry, Government expenditures	*China Statistical Yearbook (2012 and 2017)* [42]
	Total water resources, Water supply and consumption data	*Yellow River Water Resources Bulletin (2012 and 2017)* [45]
	Agricultural production price index	*China Agricultural Yearbook (2012 and 2017)* [42]

4. Results

4.1. Virtual Water Flow Patterns within and Outside the Yellow River Basin

The results of virtual water trade flow measurement in nine provinces and regions in the Yellow River Basin are shown in Table 4. The Yellow River Basin was in a state of net virtual water inflow in both 2012 and 2017, and the inflow has increased. In 2012, the virtual water inflow to the Yellow River Basin from outside the region was 160.238 billion m^3, and the virtual water flow to the outside of the Yellow River Basin was 158.094 billion m^3, for a net virtual water inflow overall. In 2017, a net inflow of virtual water still occurred, with a total net inflow of 33.672 billion m^3, a large increase compared to 2.144 billion m^3 in 2012.

Table 4. Virtual water trade flows in nine provinces of the Yellow River Basin.

Year	Virtual Water Flow Direction		Upper Reaches						Middle Reaches			Lower Reaches		
			Qinghai	Sichuan	Gansu	Ningxia	Inner Mongolia	Total	Shanxi	Shaanxi	Total	Henan	Shandong	Total
2012	Virtual water inflow	In-basin inflow	19.33	53.78	36.72	16.81	70.52	197.16	92.13	83.62	175.75	85.21	14.70	99.91
		Out-of-basin inflow	124.39	213.76	61.81	22.82	50.87	473.65	64.87	160.84	225.71	350.99	552.03	903.02
		Total inflow	143.72	267.55	98.53	39.64	121.39	670.82	157.00	244.46	401.46	436.20	566.73	1002.93
	Virtual water outflow	In-basin outflow	6.36	43.59	54.82	21.00	114.33	240.11	20.64	50.26	70.90	19.82	242.00	261.82
		Out-of-basin outflow	62.25	322.37	107.85	35.55	50.40	578.43	107.55	130.70	238.25	245.35	418.91	664.25
		Total outflow	68.61	365.96	162.67	56.56	164.74	818.54	128.19	180.96	309.15	265.16	660.91	926.08
	Virtual water net outflow		−75.11	98.42	64.14	16.92	43.35	147.72	−28.81	−63.50	−92.31	−171.04	94.19	−76.85
2017	Virtual water inflow	In-basin inflow	2.74	33.38	5.56	6.75	52.37	100.79	47.76	6.74	54.50	36.95	8.39	45.33
		Out-of-basin inflow	26.29	199.90	54.53	64.21	14.92	359.84	26.99	55.98	82.97	182.64	323.15	505.79
		Total inflow	29.03	233.28	60.09	70.96	67.28	460.63	74.76	62.71	137.47	219.59	331.53	551.13
	Virtual water outflow	In-basin outflow	7.86	14.76	37.62	45.71	20.63	126.58	16.52	9.87	26.40	19.16	28.48	47.65
		Out-of-basin outflow	24.96	110.80	94.24	72.25	39.71	341.96	71.52	33.03	104.55	94.64	70.73	165.37
		Total outflow	32.82	125.57	131.86	117.96	60.34	468.55	88.04	42.90	130.94	113.80	99.21	213.02
	Virtual water net outflow		3.79	−107.71	71.77	47.01	−6.94	7.91	13.29	−19.82	−6.53	−105.79	−232.32	−338.11

In terms of individual provinces and regions within the Yellow River Basin, Gansu, and Ningxia were net virtual water outflow regions in 2012 and 2017, Shaanxi and Henan were net virtual water inflow regions, and the virtual water flow dynamics of Qinghai, Sichuan, Inner Mongolia, Shanxi, and Shandong were reversed. Qinghai and Shanxi changed from net virtual water inflow areas to net outflow areas, and Sichuan, Inner Mongolia, and Shandong changed from net virtual water outflow areas to net inflow areas.

4.2. Virtual Water Flow Patterns between Provinces within the Yellow River Basin

Since the Yellow River Basin as a whole was in a state of net virtual water inflow and increased inflow in both 2012 and 2017, which was mainly due to the fact that provinces and regions outside the basin were delivering virtual water to the Yellow River basin, it was not possible to identify the role played by provinces inside the basin in virtual water trade. Therefore, it was important to measure the virtual water flow pattern among the nine provinces within the Yellow River Basin to clarify the role of each province in the virtual water trade.

The virtual water input from other provinces within the Yellow River Basin in 2012 from Qinghai, Sichuan, Shanxi, Shaanxi, and Henan was greater than their virtual water output, and they played the role of virtual water consumers in the Yellow River Basin (Figure 3). Among them, Shanxi, Shaanxi, and Henan are the three major virtual water consumers within the Yellow River Basin, and their main sources of virtual water are the geographically adjacent Inner Mongolia and Shandong. Gansu, Ningxia, Inner Mongolia, and Shandong export more virtual water to other provinces in the Yellow River Basin than they import, and play the role of virtual water supplier in the Yellow River Basin. Inner Mongolia is the main source of virtual water within the Yellow River Basin, and its virtual water mainly flows to Shanxi, Shaanxi, and Henan in the middle and lower reaches of the Yellow River Basin. In 2017, Qinghai and Shaanxi changed from virtual water consumers to virtual water suppliers, and Inner Mongolia changed from virtual water supplier to virtual water consumer.

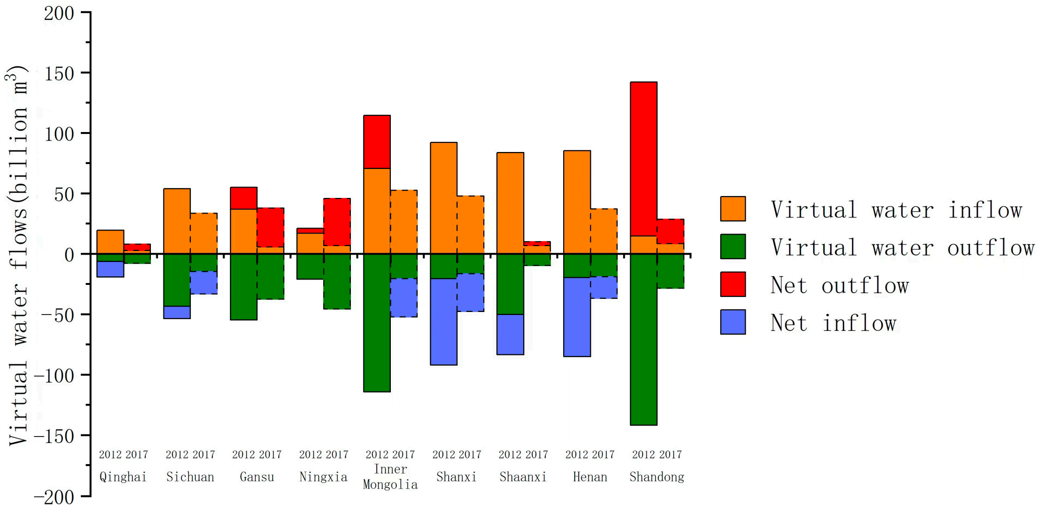

Figure 3. Virtual water flow patterns between provinces within the Yellow River Basin.

4.3. Virtual Water Flow Patterns in the Yellow River Basin by Sector

In order to further clarify the impact of the virtual water trade on each province and sector in the Yellow River Basin, it was also necessary to measure the virtual water trade flows of each province by sector based on the premise of measuring the virtual water trade pattern between provinces and regions within and outside the basin. This will be conducive to the development of reasonable virtual water trade policies by sector according to the development stage and advantageous industries of each province, so as to optimize water resource management and meet the needs of regional economic development. Considering that the 42 sectors in the input-output table were too redundant to calculate, and some sectors had little trade in products and services between them, for the convenience of calculation and analysis this paper combined them into seven major sectors according to sectoral characteristics, as shown in Appendix A (Table A1).

The composition of the virtual water trade volume by sector in each province of the Yellow River Basin is shown in Figure 4. The virtual water trade in each province and region has a very high sectoral similarity. Agriculture, forestry, and fishery and manufacturing are the two major virtual water inflow and outflow sectors in the Yellow River Basin provinces. Among them, the virtual water trade in agriculture, forestry, animal husbandry, and fishery far exceeds that of the other sectors, with an average flow of 75.46% of the total trade in 2012 and 2017. The shares of virtual water flows in the extractive industries, electricity, heat and water supply, transportation, and services are small.

Although the volume of virtual water trade in the Yellow River Basin has some sectoral similarities, the sectoral structure of virtual water trade also has regional heterogeneity under the influence of many factors, such as geographical location, factor endowment, and development stage. The virtual water inflow of agriculture, forestry, animal husbandry, and fishery in Henan and Shandong in the lower reaches of the Yellow River accounts for 85.18% of their total virtual water inflow, while in the upper reaches of the basin, this sector accounts for 78.11% of its total outflow. In terms of virtual water flows in the manufacturing sector, the virtual water outflow of the sector in the upper Yellow River provinces is larger, while the inflow of it in the middle and lower reaches of the provinces is larger.

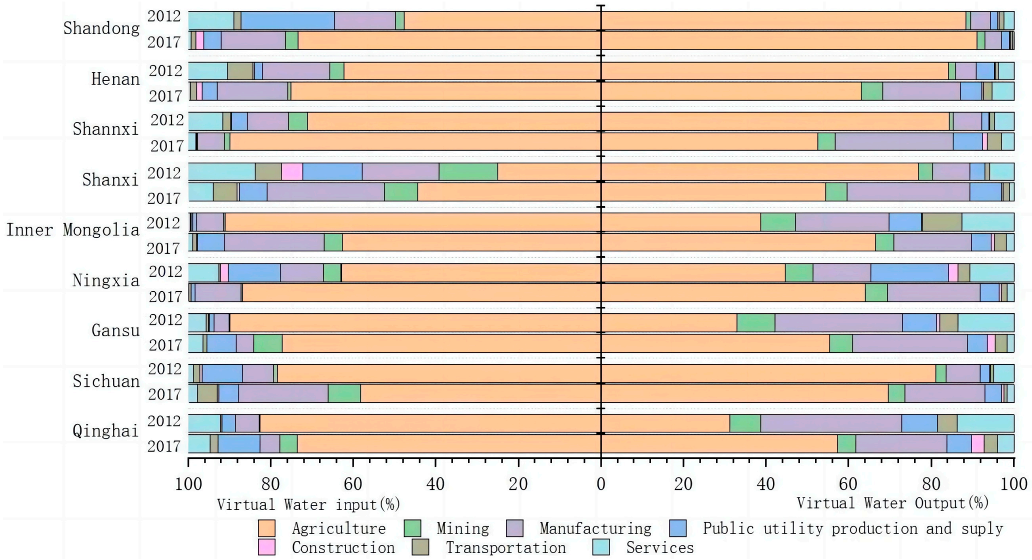

Figure 4. Virtual water flow in the Yellow River Basin by sector.

4.4. Analysis of Drivers of Virtual Water Flow Patterns in the Yellow River Basin

The covariance expansion factor was used to diagnose the covariance of each driver, and if the variance expansion factor (VIF) $\leq$ 10 there was no significant covariance among the factors. Most of the independent variable coefficients had VIF > 10 and reached a maximum of 275.3, which indicated that there was relatively serious multicollinearity among the explanatory variables of this regression equation, and the effect of multicollinearity among the variables must be eliminated in order to obtain reliable fitting results (Table 5). Without eliminating the explanatory variables, the ridge regression estimation method was chosen to effectively solve the problem of multicollinearity [46]. In this paper, the fitting results of the ridge regression at k = 0.6 were selected to determine the ridge regression equation, and the specific procedure is shown in Appendix B.

Table 5. Driving factors and covariance statistics.

Indicator Category	Driving Factors	Variable Symbols	Tolerances	Variance Inflation Factor
Demographic indicators	Population size	x_1	0.005	203.34
Economic Indicators	GDP per capita	x_2	0.062	16.10
	Contribution rate of primary industry	x_3	0.184	5.45
	Tertiary industry contribution rate	x_4	0.045	22.03
	Consumer price index	x_5	0.067	14.89
	Agricultural production price index	x_6	0.068	14.75
	Government spending levels	x_7	0.004	275.32
Technical Specifications	Water use efficiency	x_8	0.184	5.45
	Water consumption per unit of arable land area	x_9	0.039	25.58
Natural Indicators	Water resources per capita	x_{10}	0.129	7.78
	Water scarcity level	x_{11}	0.154	6.48

The results of the elasticity coefficients calculated using the extended STIRPAT model are shown in Table 6. The driving force analysis showed that GDP per capita, tertiary industry contribution rate, consumer price index, and water scarcity were the main positive drivers of virtual water inflow in the Yellow River Basin provinces. For the total virtual water outflow, net outflow, and net outflow of intra-basin trade in the Yellow River Basin provinces, the effects of each factor were approximately the same. The contribution of primary industry, water resources per capita, and water use per unit of arable land area were the main positive drivers of virtual water outflow. Based on the magnitude of the regression coefficient, relevant policies can be formulated to improve the current water shortage in water-scarce regions by enhancing the positive drivers of virtual water inflow and controlling the positive drivers of virtual water outflow.

Table 6. Regression results of the extended STIRPAT model.

Indicator Category	Driving Factors	Variable Symbols	Virtual Water Inflow	Virtual Water Outflow	Net Virtual Water Outflow	Net Virtual Water Outflow between Internal Provinces
Demographic indicators	Population size	x_1	0.054	0.174	−0.349	−0.002
Economic Indicators	GDP per capita	x_2	1.179	−0.278	−1.236	−0.053
	Primary industry contribution rate	x_3	−0.374	0.054	0.045	1.404
	Tertiary industry contribution rate	x_4	0.520	−0.795	−2.493	0.247
	Consumer price index	x_5	3.692	0.234	−3.433	−0.043
	Agricultural production price index	x_6	−1.172	−1.273	−0.043	−0.162
	Government expenditure level	x_7	0.023	0.034	0.034	0.002
Technical Specifications	Water use efficiency	x_8	−0.021	0.017	−0.043	−0.156
	Water consumption per unit of arable land area	x_9	0.002	−0.198	0.253	0.057
Natural Indicators	Water resources per capita	x_{10}	−0.138	0.280	0.035	−0.026
	Water scarcity level	x_{11}	2.303	−1.765	−3.490	−2.267

5. Discussion

The virtual water trade only relieves the water-poor pressure in some parts of the Yellow River Basin. Some water-scarce areas have a large net export of virtual water, while some water-rich areas have a net inflow of the virtual water trade. The virtual water flow status is not coordinated with the local water resource endowment. As shown in Figure 5, the net virtual water outflow of Ningxia, which is an area of extreme water shortage, was 4.701 billion m^3 in 2017, much greater than that in 2012. What is more, Shanxi turned into a net virtual water outflow area in 2017, and this shift was contradictory to the current situation of severe water shortage in Shanxi. Therefore, the virtual water flows implied in the trade of products and services not only do not alleviate the current water shortages in these areas, but may also exacerbate their water stress. On the contrary, Qinghai, which is relatively rich in water resources, had a large net inflow of virtual water in 2012, and maintained a balance of incoming and outgoing water in 2017. This indicates that the virtual water trade does not fully optimize water allocation.

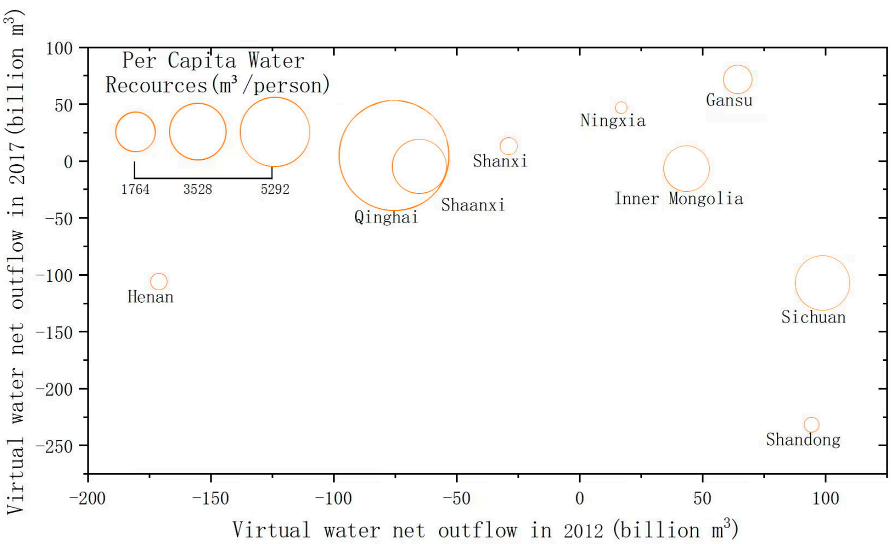

Figure 5. Relationship between per capita water resources and net virtual water outflow.

Decomposing the virtual water trade results into individual sectors, Henan and Shandong, which are water-poor regions, accounted for a large share of the trade output of agricultural products, which have the highest water use coefficients. In contrast, Qinghai and Inner Mongolia, which are relatively rich in water resources, import a large amount of agricultural products, while manufacturing industries, which have lower water consumption coefficients, have a strong output intensity. Such an industrial structure layout is not conducive to alleviating the water shortages caused by the uneven distribution of water resources in the Yellow River Basin. This will require comprehensive planning for the rational use of water resources, adjusting the industrial layout, and establishing a scientific industrial structure according to the natural endowment of water resources in each region.

The extended STIRPAT model provides theoretical support for the formulation of corresponding industrial and trade policies. Per capita GDP, consumer price level, tertiary industry contribution rate, and water scarcity level are the main positive drivers of virtual water inflow in the Yellow River Basin. GDP per capita and consumer price level respond to the regional economic development level, while high-quality economic development is the goal rather than the means to optimize water allocation; therefore, relevant policies are mainly considered from the perspective of increasing the contribution rate of the tertiary industry. At present, the overall industrial structure of the Yellow River Basin is heavy, and the economic development model is mainly based on resource and energy-consuming development, with high environmental pressure. Therefore, under the development premise of ecological protection, water-scarce regions should accelerate the transformation of their regional economic development mode and vigorously develop low water-consumption intensity industries, in order to reduce the pressure on water resources in water-poor areas. The contribution rate of primary industry, per capita water resources, and water use per arable area are the main positive drivers of virtual water flow out in the Yellow River Basin. Per capita water resources reflect regional water resources endowment, and it is generally difficult to make corresponding policy adjustments. Therefore, policies are mainly formulated from the perspective of primary industry contribution rate and water use per unit of cultivated land area to control virtual water outflow in water-scarce areas. As agriculture is a highly water-consuming industry, water-scarce regions can appropriately reduce the production of local water-consuming crops and encourage the import of water-intensive agricultural products, so as to control the virtual water outflow in the region within a reasonable range. Water consumption per unit arable area reflects the level of agricultural production technology. Water-scarce areas should vigorously develop water conservation technology, promote the cultivation of low-water-consuming crops according to local conditions, and reduce water consumption per unit area, so as to alleviate the local water stress.

The unreasonable structure of the virtual water trade is a common problem in Chinese regions. This requires an integrated planning of the virtual water trade from a national perspective, timely adjustment of the industrial layout based on the natural endowment of water resources and other production conditions in each province and region, and the establishment of a reasonable regional industrial structure to form a sustainable virtual water trade pattern.

6. Conclusions

This study calculates the virtual water flow patterns in the Yellow River Basin by constructing a multi-regional input-output (MRIO) model of water resources in the Yellow River Basin. The extended STIRPAT model is then applied to analyze their driving factors and provide directions for using virtual water trade to alleviate the current water shortage in the basin.

The results showed that the Yellow River Basin as a whole was in a state of net virtual water inflow in both 2012 and 2017, and the net inflow has increased, which has alleviated the current water shortage situation in the Yellow River Basin to some extent. However, the virtual water flow status in some provinces and regions within the Yellow River Basin is not coordinated with the regional water resource endowment, and the unreasonable industrial layout drives a large amount of virtual water flow from water-poor areas to water-rich areas, which exacerbates the water shortage status in water-scarce areas.

This leads to relevant policy recommendations: water-scarce regions should accelerate the transformation of regional economic development and vigorously develop tertiary industries, especially low-water consumption intensity industries. At the same time, water-scarce regions can encourage the import of water-intensive agricultural products, develop water-saving technologies, and promote the cultivation of low-water-consumption crops in accordance with local conditions. More importantly, the national virtual water trade should be planned in an integrated manner, with local conditions of each province and region taken into account, thus establishing a reasonable regional industrial structure to form a sustainable virtual water trade pattern.

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Appendix A

Table A1. Division of 42 sectors in the Yellow River Basin.

No.	Industry	Sector
1	Agriculture	Agriculture, Forestry, Animal Husbandry, and Fishery
2	Mining	Mining and washing of coal; extraction of petroleum and natural gas; mining and processing of metal ores; mining and processing of nonmetal and other ores
3	Manufacturing	Food and tobacco processing; textile industry; manufacture of leather, fur, feather, and related products; processing of timber and furniture; manufacture of paper, printing, and articles for culture, education, and sports activities; processing of petroleum, coking, processing of nuclear fuel; manufacture of chemical products; manufacture of non-metallic mineral products; smelting and processing of metals; manufacture of metal products; manufacture of special purpose machinery; manufacture of transport equipment; manufacture of communication equipment, computers, and other electronic equipment; manufacture of measuring instruments; other manufacturing and waste resources; repair of metal products, machinery, and equipment
4	Public utility	Production and distribution of electric power and heat power; production and distribution of gas; production and distribution of tap water
5	Construction	Construction
6	Transportation	Transport, storage, and postal services
7	Services	Wholesale and retail trades; accommodation and catering; information transfer, software, and information technology services; finance; real estate; leasing and commercial services; scientific research; polytechnic services; administration of water, environment, and public facilities; resident, repair, and other services; education; health care and social work; culture, sports, and entertainment; public administration, social insurance, and social organizations

Appendix B

Taking the regression of the virtual net water outflow from nine provinces in the Yellow River Basin as an example, let the ridge regression coefficient k be between (0, 1) with a step size of 0.01, to obtain the trend diagram of the decidable coefficient with the value of k (Figure A1) and ridge trace diagram (Figure A2). It can be seen that when the value of k is between 0 and 1, R^2 is always greater than 0.85, which indicates that the explanatory power of the respective variables on the dependent variable is greater than 0.85 as long as k takes a value between 0 and 1, which has good explanatory power. From Figure 2, it can be seen that when k ≥ 0.6, the ridge trace plot tends to be smooth, so the fitting results of the ridge regression at k = 0.6 were taken to determine the ridge regression equation in this paper.

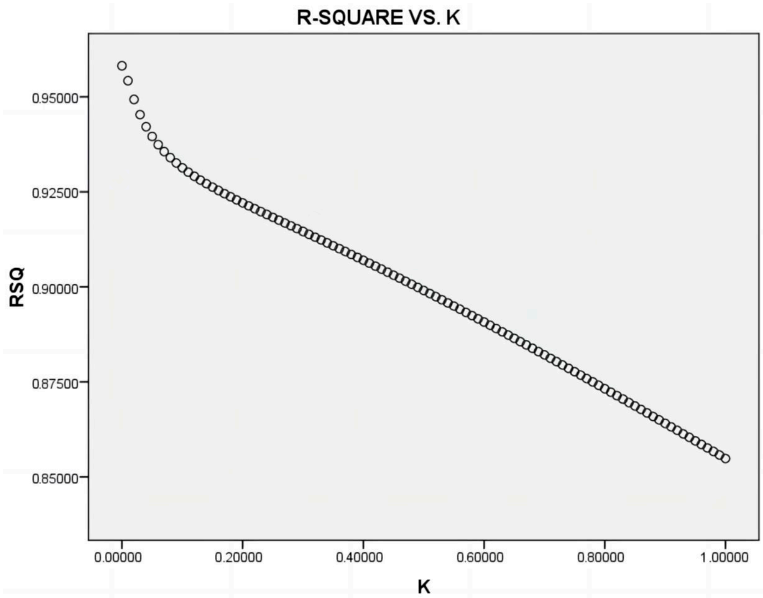

Figure A1. Trend of the decidability coefficient with the value of k.

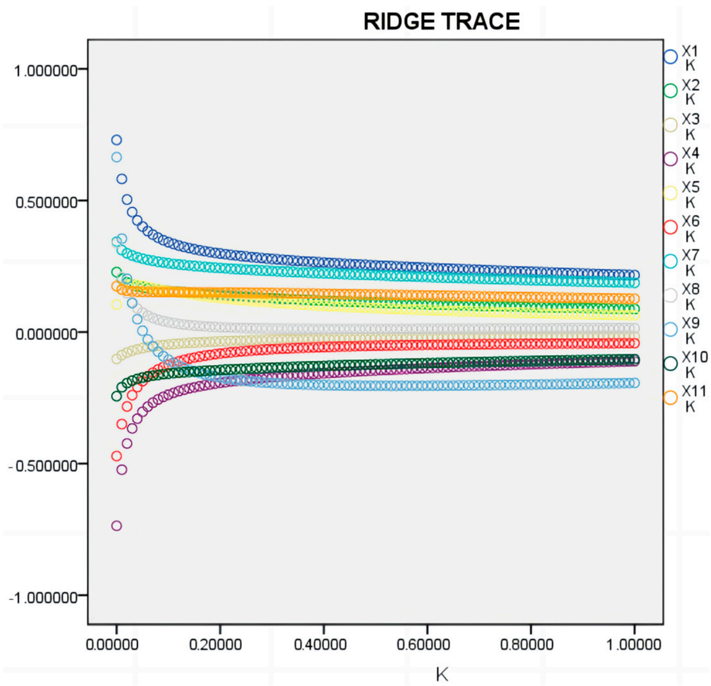

Figure A2. Ridge trace map.

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