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The Influencing Factors of Water Uses in the Yellow River Basin: A Physical, Production-Based, and Consumption-Based Water Footprint Analysis by the Random Forest Model

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Abstract: The strategy of "Basing city, land, population and production on water resources", clarifying the water uses of each province and the influencing factors are crucial to the conservation and intensive use of water resources for the Yellow River basin. In this study, physical water use, the production-based water footprint, and the consumption-based water footprint of nine provinces in the Yellow River Basin from 2007 to 2017 are measured. Then, the key influencing factors of three kinds of water use are analyzed by the random forest model. The results show that (1) the three kinds of water use in the Yellow River basin all showed a trend of first increasing and then decreasing. Physical water use and the production-based water footprint present the geographical differentiation in the declining order from the upper reach to the lower reach, and then the middle reach, while the order for the consumption-based water footprint is the lower reach, the upper reach, and the middle reach. (2) Agriculture, forestry, animal husbandry, fisheries, electricity and hot water production, supply, and chemicals are the dominant sectors of physical water use. Agriculture, forestry, animal husbandry, fisheries, food processing, tobacco, and construction are the key sectors for production-based and consumption-based water footprints. (3) The results of the random forest model show the influencing factors and their interactions of three kinds of water use in the Yellow River basin present obvious sectoral differences. The key influencing factors exhibit a linear or nonlinear response to water use in the three perspectives. The influencing factors of water use are also differentiated among the three perspectives.

Keywords: Yellow River basin; physical water use; production-based water footprint; consumption-based water footprint; random forest model; influencing factors

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1. Introduction

With economic development and population growth, the contradiction between water supply and demand in the Yellow River basin is becoming a more prominent problem, which seriously restricts the sustainable development of the basin [1]. To solve this problem, the Outline of the Yellow River basin's Ecological Protection and High-quality Development Plan has proposed the strategy of "Basing city, land, population and production on water resources" to strengthen the conservation and intensive use of water resources. Thus, water utilization becomes an important breakthrough in coordinating the imbalance between protection and development in the basin. Academic research is increasingly focused on water resources and their connotations.

In the current research, water use has mainly been studied from two perspectives, namely physical water use and virtual water use [2]. Studies on physical water use have been conducted on national [3], provincial [4], and municipal [5] scales, and industrial water use studies focus on sectors such as agriculture [6] and electricity production [7]. The results of former studies show that water use in China increased significantly from

1997 to 2016, with an insignificant increase in agriculture and a large increase in other industries [8]. Water consumption is higher in the south and lower in the north [9]. Water use in the Yellow River basin increased significantly from 1980 to 2000 and stabilized after 2000 [10], and the gap in water use efficiency between regions rapidly narrowed [11].

In contrast to physical water, virtual water estimates the water embodied in commodities and services [2]. Virtual water use can reflect the human occupation of water resources from a new perspective [12] and is often quantified by the water footprint [13]. The accounting of the water footprint can be approached from two perspectives: production and consumption [14], and the quantification methods include bottom-up and top-down approaches [15]. Few studies have been carried out on the water footprint from a production perspective, and they are mainly focused on provincial [14] and municipal [16] levels. The research objects are mainly concentrated on agricultural products [17,18]. More studies were carried out from the consumption-based water footprint perspective, covering national [19], regional [20], provincial [21], and municipal [22] levels. The results reveal that China's production-based water footprint is mainly distributed in the northwest, central, and northeast regions [23]. China's consumption-based water footprint is predominantly located in the northwest, central, and southwest regions [24]. Agriculture is the primary sector for both production-based and consumption-based water footprints [25]. In terms of the Yellow River basin where this study focuses on, the consumption-based water footprint shows an increasing trend, with agriculture accounting for the largest share [20], and the upper, middle, and lower reaches were all net virtual water exporters [20].

Existing studies have explored the effects of economic development level, industrial structure, urbanization, population, water resource endowment, water use structure, technological innovation, and environmental regulation [26–29] on water use. The results of previous studies show that population is a key driver of physical water use and the water footprint [30,31]. Economic development level and technological innovation have a positive impact on water use efficiency [31]. Water resource endowment is negatively correlated with water use efficiency [32]. The effects of environmental regulation, industrial structure, water use structure, and urbanization on water resource utilization vary at different spatial scales.

In summary, studies on physical water use focus on the exploitation and utilization of water resources, while studies on the production-based water footprint concentrate on the real water utilization of industries within the region due to internal and external demands [16,33,34]. Research on the consumption-based water footprint center on how regional water demand is met from the perspective of local consumption [21,35]. By integrating three perspectives, a more comprehensive and systematic understanding of regional water utilization can be obtained. However, in the Yellow River basin, existing studies are mainly carried out from a single perspective. Studies on production-based and consumption-based water footprints concentrated on the period before 2012 [20] and mostly in a single year, making it difficult to track production-based and consumption-based water footprints in recent years. In addition, most studies on the driving mechanism of water use focus on whether different influencing factors have valid impacts on water use, while the different contributions and impact levels of these influencing factors are not sufficiently studied.

Thus, this paper takes the nine provinces in the Yellow River basin (including Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong) as the research object, analyzes the spatial and temporal evolution of physical water use, and the production-based water footprint and consumption-based water footprint from 2007 to 2017. Then, a random forest model is used to identify key influencing factors of the three water uses, and finally, the corresponding policy recommendations are put forward. The study introduces the machine learning method into the analysis of water uses in the Yellow River basin, providing a new perspective for the research on water resource utilization in the Yellow River basin. This will provide a theoretical basis for regional water use reduction and the formulation of related policies.

2. Materials and Methods

This work focuses on investigating water use and its influencing factors in the Yellow River basin in China (Figure 1). In doing so, a framework coupling physical water use, the production-based water footprint, and the consumption-based water footprint is constructed using a series of input–output data. Applying the framework, we have evaluated three water uses for nine provinces in the Yellow River basin and fourteen drivers are examined using a machine learning approach. Related methods and data sources are detailed below.

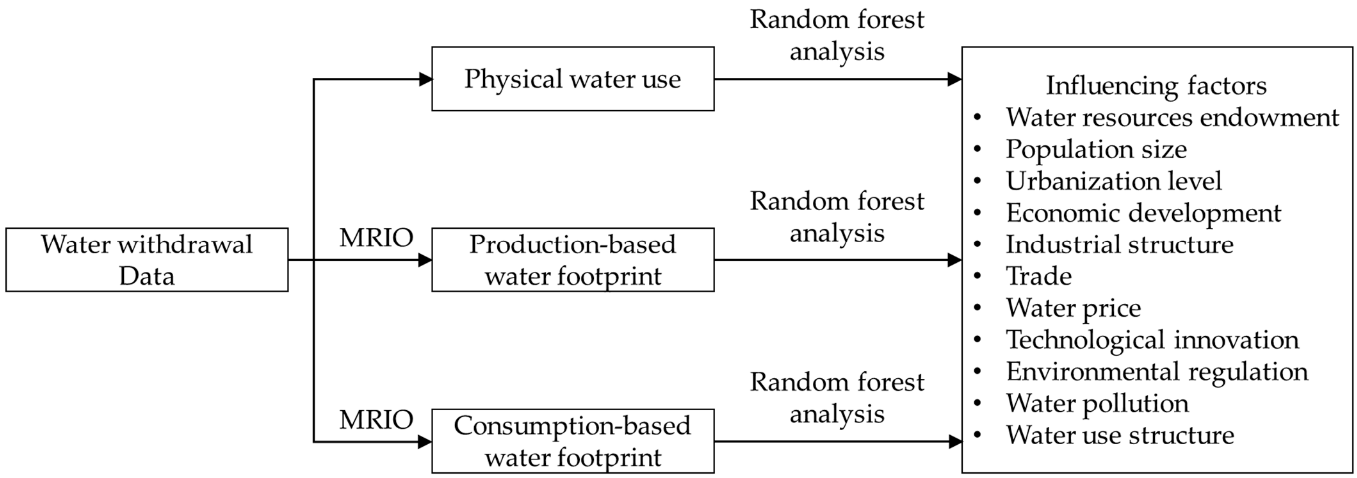

Figure 1. Flowchart of data processing.

2.1. Production-Based and Consumption-Based Water Footprints

By applying a multi-regional input–output model, production-based and consumption-based water footprints are estimated. The basic equation for water footprint calculation is:

$$PBWF = QX = Q\left(I - A\right)^{-1}\left(F + E\right) \tag{1}$$

where *PBWF* is the production-based water footprint, *Q* is the direct water use coefficient matrix, *X* is the total output matrix, *I* is the unit matrix, *A* is the intermediate input coefficient matrix, *F* is the end-use matrix, and *E* is the export matrix.

Equation (1) can be further expressed as:

$$\begin{aligned} PBWF &= Q\left(I - A\right)^{-1} F^{rr} + Q\left(I - A\right)^{-1} \sum_{r \neq s} F^{rs} + Q\left(I - A\right)^{-1} E^{r} \\ &= DWF + VWED + VWEA \end{aligned} \tag{2}$$

where *DWF* is the domestic water footprint, *VWED* is the domestic virtual water outflow, and *VWEA* is the virtual water export.

The consumption-based water footprint CBWF is:

$$\begin{aligned} CBWF &= DWF + \sum_{r \neq s} Q^{s}\left(I - A^{ss}\right)^{-1} F^{sr} + \left(Q^{r}\left(I - A\right)^{-1} AM^{r} + \left(Q^{*}\right)^{r} FM^{r}\right) \\ &= DWF + VWID + VWIA \end{aligned} \tag{3}$$

where AM is the imported products used for intermediate use, $(Q^{*})^{r}$ is the weighted water use coefficient [21], FM is the imported products for final consumption, $VWID$ is the domestic virtual water inflow, and $VWIA$ is the virtual water import.

2.2. Random Forest Model

The random forest model [36] is a machine learning algorithm based on classification trees and used for the analysis of factors influencing water usage in the Yellow River basin. The model first draws multiple samples from the original samples using the bootstrap resampling method, performs decision tree modeling for each bootstrap sample, and then combines the predictions of multiple decision trees and obtains the final prediction result by voting [37]. Random forest regression is performed on the R platform with the following parameters: ntree = 500, mtry = 3, and other defaults.

The model is computed as follows [38]:

$$im_i = \frac{1}{nt}\sum\nolimits_{v\in S_{x_i}} Gain(X_i, v) \tag{4}$$

where im_i is the contribution of variable X_i to the model. In this paper, the %IncMSE is used to represent the important hierarchy of influencing factors. IncMSE indicates an increase in the mean squared error, and a higher value indicates a more critical variable within the model [39]. S_{xi} denotes the set of nodes split in the random forest of the nt regression tree and $Gain(X_i, v)$ is the Gini information gain of X_i at split node v, which is used to identify the predictive variable of the maximum information gain.

2.3. Factors That Influence Water Resource Utilization

Water use is affected by various factors, including natural, social, economic, technological factors, environmental management, etc. Based on previous literature, this paper selects water resources endowment [29,40–42], population size [10,30,43], urbanization level [30,43], economic development [44], industrial structure [42–45], trade [26,44,46], water price [47], technological innovation [43–45], environmental regulation [40], water pollution [48], and water use structure [49] to analyze the factors influencing the three types of water use in the Yellow River basin. Considering data availability and comparability, the indicators of each factor are chosen. (1) For water resources endowment, water resources per capita (WAT) is selected. (2) For population size, the total resident population (POP) is used. (3) For urbanization level, the urbanization rate (URB) is chosen. (4) For economic development, GDP per capita (GDP) is selected. (5) For industrial structure, the proportions of value added of the primary (PRI) and secondary (SEC) industries to regional GDP are used. (6) For trade, the total inflow (IMP) and total outflow (EXP) are chosen. (7) For water price, the industrial water price (PRICE) is selected. (8) For technology innovation, the share of R&D investment in regional GDP (TEC) is used. (9) For environmental regulation, the proportion of industrial pollution control costs to industrial value added (REG) is chosen. (10) For water pollution, COD emissions per capita (POL) is selected. (11) For water use structure, the proportions of agricultural water use (AGR) and industrial water use (IND) to total regional water use are selected.

The data sources of factors are mainly from the Chinese Environmental Statistics Yearbook [50] and Provincial Water Resource Bulletin of China [51], the Chinese Statistical Yearbook [52], input–output tables, etc. Industrial water prices in provincial capitals are chosen as an indicator of PRICE and the data are mainly from the "pkulaw" database (https://www.pkulaw.com/law, accessed on 1 May 2022), the Bureau of Commodity Price and water administrative departments, etc. All prices are converted to constant prices in 2017.

2.4. Data Resources

In this paper, multi-regional input–output tables in China for 2007, 2012, and 2017 that are used for the calculation of water footprints are compiled by previous researchers [53–55]. The clarification and codes of 30 sectors in the input–output tables are shown in Table 1. Water withdrawal is used to calculate water footprints. The computation of physical water use is as follows. Agricultural and industrial water use data are obtained from the Provincial Water Resource Bulletin of China [51]. The calculation of territory water use is based on Zhao et al. [56]. Due to the lack of precise sectoral data for industrial water withdrawal, we acquire detailed sectoral water withdrawals in 2008 from the Chinese Economic Census Yearbook [57]. Then, we assume that water use intensities of industrial sectors in 2007, 2012, and 2017 are the same as that in 2008. Finally, we revise the obtained sectoral water withdrawals with total industrial water use from the water resources bulletin [56]. Sectoral water use in the service industry is allocated based on the assumption that water intensity is the same in all sectors of the service industry [58].

Table 1. Sectors in the input–output table.

Code	Sector Name	Code	Sector Name
S01	Agriculture, forestry, animal husbandry, fisheries	S16	General and specialized machinery
S02	Coal mining, and processing	S17	Transport equipment
S03	Crude petroleum and natural gas extracting	S18	Electric equipment and machinery
S04	Metallic mining	S19	Electronic and telecommunications equipment
S05	Non-metallic and other minerals mining	S20	Instruments, meters, cultural, and office machinery
S06	Food and tobacco processing	S21	Other manufacturing
S07	Textiles	S22	Electricity and hot water production and supply
S08	Garments, leather, furs, and down	S23	Gas and water production and supply
S09	Timber processing and furniture manufacturing	S24	Construction
S10	Papermaking and cultural articles	S25	Transport and storage
S11	Petroleum processing and coking	S26	Wholesale and retailing
S12	Chemicals	S27	Hotel and restaurant
S13	Non-metal mineral products	S28	Leasing and commercial services
S14	Metal smelting and processing	S29	Scientific research
S15	Metal products	S30	Other services

3. Results

3.1. Water Use in the Yellow River Basin

3.1.1. Spatial and Temporal Evolution of Physical Water Use

From 2007 to 2017, the overall physical water use in the Yellow River basin first increased and then decreased, which was 106.4, 110.9, and 108.1 billion m^3 in 2007, 2012, and 2017, respectively. Spatially (Figure 2a–c), physical water use in the Yellow River basin was geographically shown as upstream > downstream > midstream. Sichuan had the largest physical water use, with an annual average of 21.3 billion m^3, followed by Henan and Shandong (19.0 and 18.5 billion m^3, respectively). Qinghai had the smallest water use, which was 2.6 billion m^3. In general, the provinces with large water usage were mainly populated and agricultural provinces. Sectoral water use is presented in Figure 2a. S01 was the largest sector in the Yellow River basin, accounting for 77.2% on average, followed by S22 and S12 (3.7% and 3.7%, respectively).

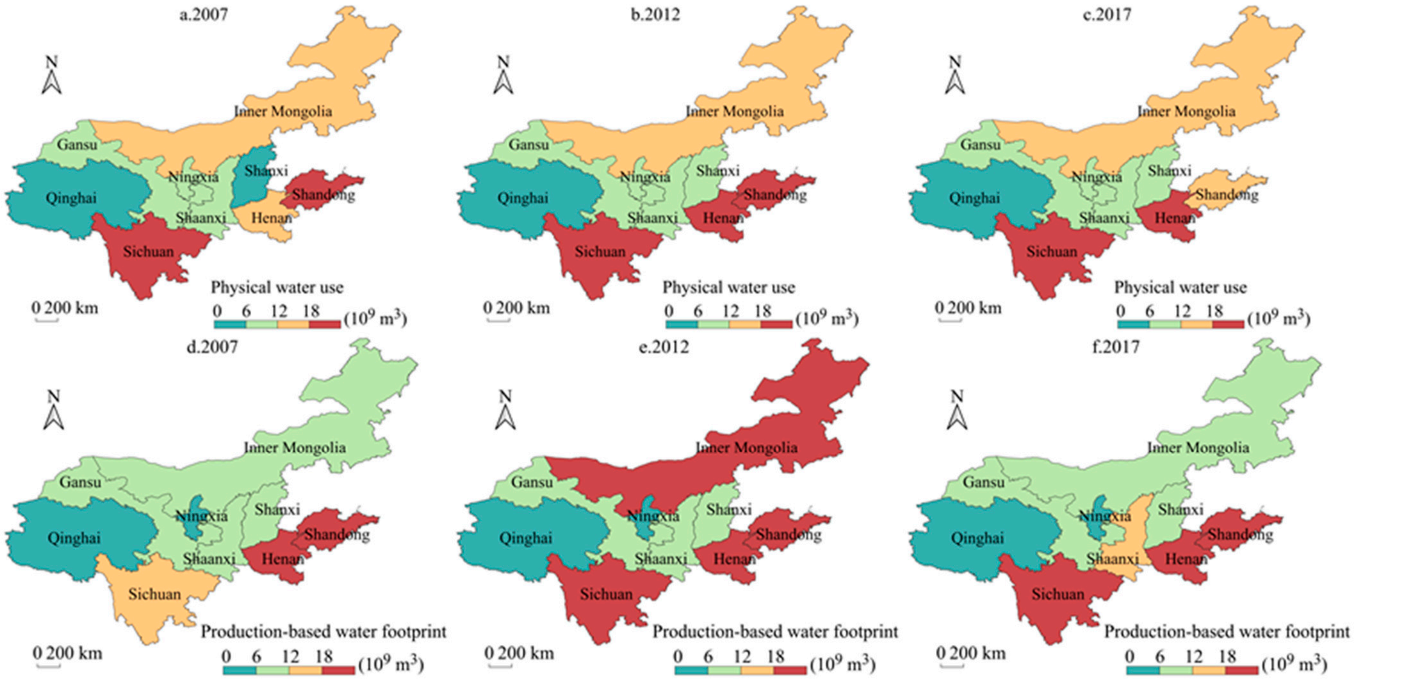

Figure 2. The physical water use and consumption-based water footprint of nine provinces in the Yellow River basin, 2007–2017: (**a**–**c**)-physical water uses in 2007, 2012 and 2017, respectively; (**d**–**f**)-consumption-based water footprints in 2007, 2012 and 2017, respectively.

3.1.2. Spatial and Temporal Evolution of the Production-Based Water Footprint

Because the total physical water use and total production-based water footprint are equal in volume [33], only regional and sectoral production-based water footprints are discussed in this section. At the provincial level, only Henan showed a trend consistent with the basin. Sichuan, Shanxi, and Shaanxi presented an upward trend, but the growth rate in 2012–2017 was slower than that in 2007–2012. Qinghai, Gansu, Ningxia, Inner Mongolia, and Shandong exhibited a decreasing trend. Sectoral water use is presented in Figure 2b. S01 was the largest sector, with an annual average of 39.2%. S06, S24, S30, S07, and S12 all had large production-based water footprints, contributing 21.9%, 7.1%, 5.2%, 3.5%, and 3.0% of the total water footprint, respectively.

Comparing physical water use with the production-based water footprint, S01 was the main sector that exported virtual water to other sectors. The annual average export of virtual water in S01 was 41.3 billion m^3, accounting for 49.3% of its physical water use. This indicates that S01 supplied water to downstream sectors in the form of intermediate products [33], leading to an increase in its physical water use. S06, S24, S30, S07, and S27 were the main sectors receiving virtual water at 22.5, 6.6, 3.9, 3.3, and 2.6 billion m^3, respectively.

3.1.3. Spatial and Temporal Evolution of the Consumption-Based Water Footprint

From 2007 to 2017, the total consumption-based water footprint of the Yellow River basin first increased and then decreased, from 114.9 billion m^3 in 2007 to 134.1 billion m^3 in 2012, and then decreased to 117.1 billion m^3 in 2017. At the provincial level, the trends in Ningxia, Inner Mongolia, and Shandong were consistent with the basin's, while the trend of Henan was the opposite, but the change was small. The consumption-based water footprint rose in Sichuan, Shanxi, and Shaanxi, and decreased in Qinghai and Gansu. Spatially (Figure 2d–f), the consumption-based water footprint in the Yellow River basin displayed a geographical differentiation of upstream > midstream > downstream. Shandong, Sichuan, and Henan had the largest consumption-based water footprints (29.8, 21.5, and 21.4 billion m^3, respectively). Qinghai had the smallest consumption-based water footprint of 2.7 billion m^3. In general, the provinces with large consumption-based water footprints were the provinces with large populations and economies. Sectoral water use is presented in Figure 2c. S01 was the largest sector, with an annual average share of 47.9%. S06, S24, S30, and S12 had large consumption-based water footprints, accounting for 18.4%, 6.7%, 4.9%, and 3.0%, respectively.

3.1.4. Virtual Water Flow

From 2007 to 2017, virtual water outflow and inflow in the Yellow River basin first increased and then decreased. In 2007, 2012, and 2017, virtual water outflow accounted for 44.9%, 45.2%, and 42.2% of the production-based water footprint, and virtual water inflow accounted for 49.0%, 54.7%, and 46.6% of the consumption-based water footprint. This indicates that the water pressure caused by virtual water output [59] and the external water dependence caused by virtual water inflow both decreased. At the provincial level (Figure 3), Inner Mongolia and Gansu had large virtual water outflows, which was due to the development of special agriculture in these two provinces [60]. Shanxi had a large virtual water inflow because its economic development mainly relied on the coal industry and its demand for other products and raw materials was imported from other provinces [61]. Shaanxi, Shandong, and Henan presented both high virtual water input and output. Shaanxi was influenced by the Belt and Road Initiative, and Shandong and Henan were close to the economically developed areas. Thus, three regions had a good foundation for economic development and superior trade conditions. In other provinces, the virtual water outflow and inflow was relatively small, indicating that their water demand was mainly met by locally produced goods.

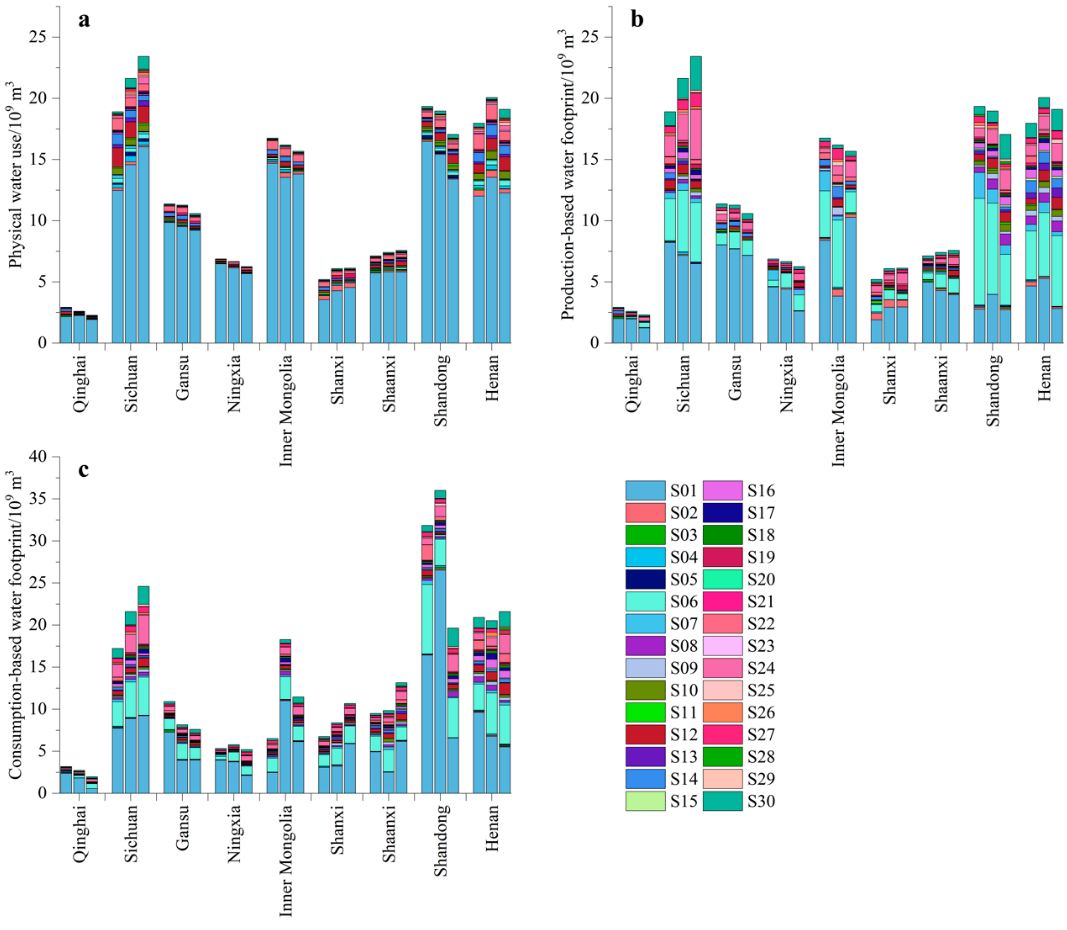

Figure 3. Physical water use (**a**), the production-based water footprint (**b**), and the consumption-based water footprint (**c**) for thirty sectors of the nine provinces in the Yellow River basin, 2007–2017.

Virtual water inflows and outflows within the Yellow River basin for the industrial account are summarized in Figure 3. S01, S06, S07, S12, and S14 were the main sectors of the virtual water outflow, accounting for 75.0% of the virtual water outflow from the Yellow River basin. Virtual water inflow was concentrated in S01, S06, and S12, making up for 77.5% of the virtual water inflow in the Yellow River basin. This indicates that high water-consuming products were the main exported and imported products of the Yellow River basin.

According to the virtual water trade balance, Gansu, Ningxia and Inner Mongolia were net virtual water exporters, Qinghai and Sichuan were in the equilibrium state of virtual water input and output, and other provinces were net virtual water receivers, which led to the spatial difference between the consumption-based water footprint and the physical water use in the Yellow River basin. The virtual water flow relationship between the Yellow River basin and external regions is shown in Figure 4. Virtual water mainly flowed to neighboring provinces and developed regions. For example, in 2007, virtual water from Inner Mongolia flowed to Shandong, Shanghai, Jiangsu, etc. In 2017, the volume of virtual water flowing from Gansu to Shaanxi and Sichuan increased. This was caused by the proximity of the neighboring provinces and the affordable cost of transportation, while developed regions can afford relatively high transport costs. The Yellow River basin imported virtual water from agricultural provinces, such as Xinjiang and Heilongjiang.

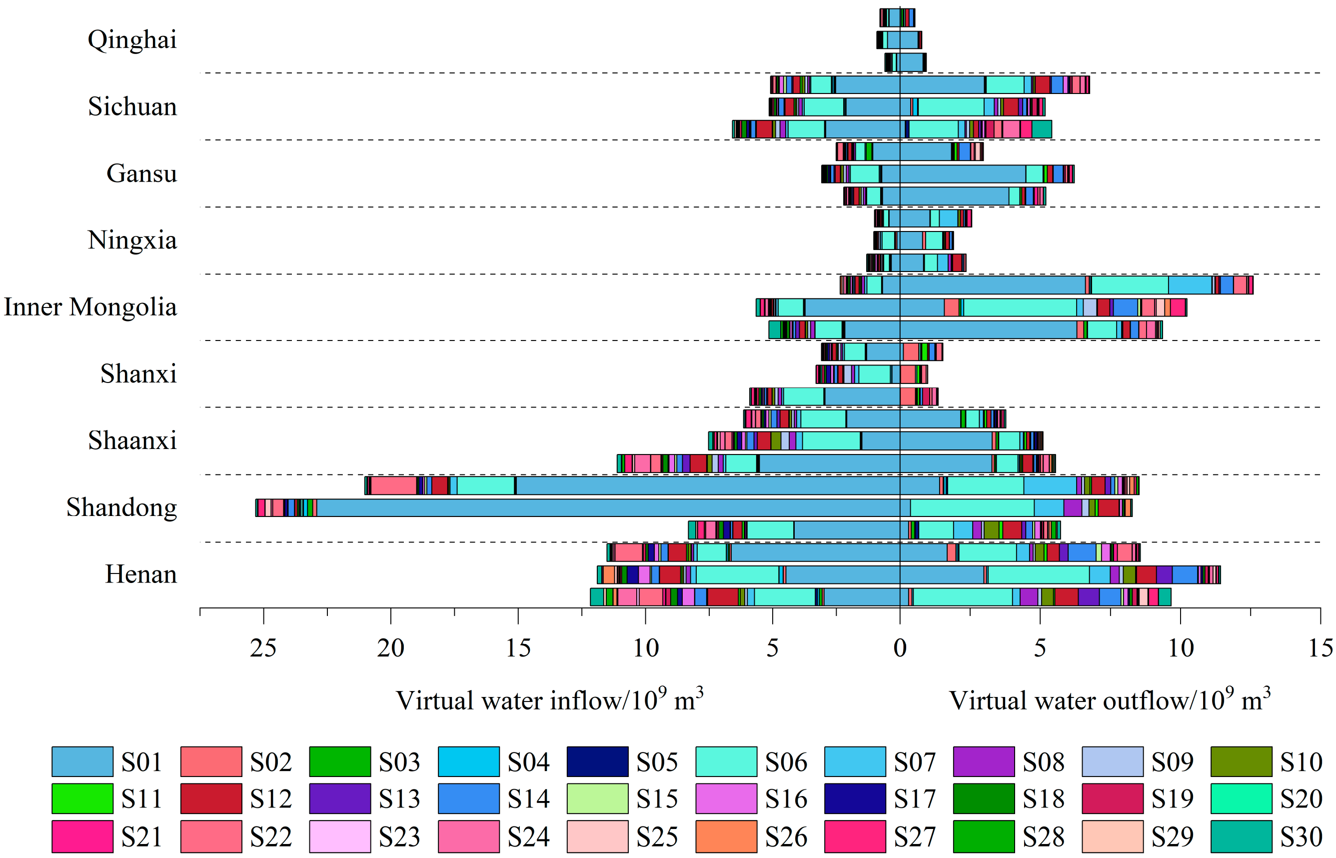

Figure 4. Virtual water inflows and outflows for thirty sectors of the nine provinces in the Yellow River basin, 2007–2017.

In sum, the physical water use, the production-based water footprint, and the consumption-based water footprint in the Yellow River basin have been decoupled from economic growth [62]. Water pressure caused by virtual water outflow and the dependence on external water resources caused by virtual water inflow both declined. The Yellow River basin also benefited from virtual water trade [59]. This means that the

Yellow River basin has achieved some progress toward its goal of high-quality development, but there are still some obstacles to overcome. The physical water use in the Yellow River basin is still dominated by high water-consumption industries. Demand for upstream sectors such as agriculture, forestry, animal husbandry, and fisheries from downstream industries, such as food and tobacco processing, cause an increase in the physical water consumption of upstream sectors. Agriculture and related industries continue to dominate the Yellow River basin's production-based water footprint and virtual water export. Water-deficient provinces, such as Ningxia, Gansu, and Inner Mongolia, have not prevented the water shortage situation from the virtual water trade. It is urgent to change the existing water consumption structure as well as the virtual water outflow structure.

3.2. The Key Influencing Factors of Water Use

To explore the industrial differences of influencing factors of three water uses, random forest regression is used to analyze the importance of influencing factors of physical water use, the production-based water footprint, and the consumption-based water footprint in the first six sectors. Table 2 lists the first six influential factors based on importance. Partial dependence analysis is then used to analyze the relationship between factors and sectoral water uses (Figure 5). It should be noticed that the y-axis values do not refer to the actual water consumption, but the average change of the water consumption across one unit. The reason for choosing the first six industries is that they account for 80% of all three kinds of water use, which is representative.

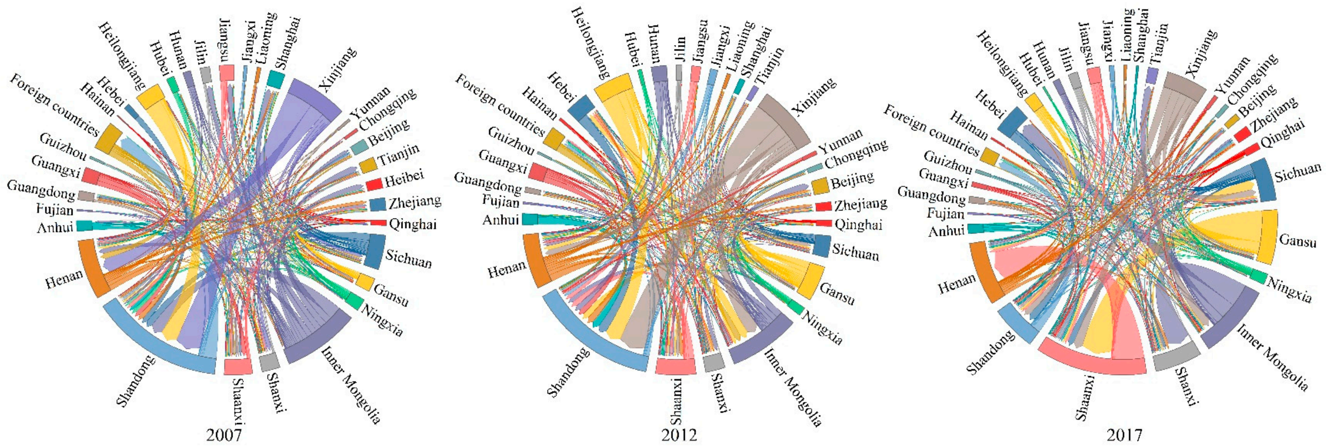

Figure 5. Virtual water flows of the nine provinces in the Yellow River basin, 2007–2017.

3.2.1. Influencing Factors of Physical Water Use

Physical water use in the first six sectors is mainly affected by POP, AGR, IMP, and PRI. Water use in S22, S12, S30, and S10 is affected by POP and AGR. The influence of POP on the water uses of these four sectors presents a stair type to continuously rise (Figure 6b,c,e,f) and 60 million is an important inflection point because the expansion of the population would increase the water resources input in these industries [63]. However, AGR has a negative impact on the water use of these four industries (Figure 6b,c,e,f), indicating that water uses of the four sectors have an extrusion effect on agricultural water use. POP and IMP are the main factors influencing the water use in S01. The influence of POP also shows a stairs type to continuously rise and the influence of IMP increases first and then becomes stable (Figure 6a), indicating the substitution effect of trade inflow on the water use in S01 [46]. The water usage in S14 is mainly affected by AGR and PRI. AGR has a negative impact, while PRI has a positive influence (Figure 6d). Due to the influence of the stage of economic development, the current industrial structure of the Yellow River basin is dominated by agriculture and high-water consumption sectors, and the region with a high proportion of primary industries consuming more water is S14.

Table 2. The importance ranking of factors influencing water use in the Yellow River basin.

Water Use Type	Sector	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Rank 6
Physical water use	S01	POP	IMP	PRI	EXP	WAT	AGR
	S22	POP	AGR	IND	PRI	EXP	IMP
	S12	POP	AGR	REG	TEC	IND	PRI
	S14	AGR	PRI	IND	POP	REG	URB
	S30	POP	AGR	REG	TEC	EXP	POL
	S10	POP	AGR	IND	TEC	REG	IMP
Production-based water footprint	S01	PRI	WAT	POP	SEC	IMP	GDP
	S06	POP	IMP	EXP	WAT	AGR	GDP
	S24	POP	SEC	REG	PRICE	IMP	GDP
	S30	POP	AGR	TEC	IND	REG	EXP
	S07	POP	EXP	AGR	IMP	URB	IND
	S12	POP	EXP	AGR	IMP	GDP	TEC
Consumption-based water footprint	S01	POP	EXP	IMP	IND	PRICE	AGR
	S06	POP	EXP	IMP	AGR	TEC	GDP
	S24	POP	TEC	PRICE	AGR	GDP	REG
	S30	POP	AGR	IMP	EXP	TEC	REG
	S12	POP	EXP	IMP	AGR	IND	TEC
	S27	POP	IMP	WAT	EXP	TEC	PRICE

In addition, REG has a small impact on the water uses in S01 and S22, because S01 is one of the pillar industries in the Yellow River basin and the supply sector of other industries, while S22 is the basic industry for economic development. The Yellow River basin needs the development of the two sectors to meet the demand for economic development. Therefore, the role of environmental regulations in these two industries has not been played. The influence of IND on the water uses in S01 and S30 is relatively small. The current industry structure in the Yellow River basin is dominated by agriculture, so the contribution of industrial water use to the change in water consumption of the two industries has a certain lag. PRI has a small influence on the water use in S30 and S10. This may be due to the small size of the two sectors. For example, the output value of other services accounts for only 16.1% of the basin's GDP in 2017.

3.2.2. Influencing Factors of the Production-Based Water Footprint

Production-based water footprints in the first six sectors are greatly influenced by POP, PRI, SEC, IMP, EXP, WAT, and AGR. The production-based water footprint in S01 is mainly influenced by PRI and WAT. PRI has a positive impact (Figure 6g) and the growth rate of water footprint is faster between 0.10 and 0.15 because the development in S01 will bring about increased resource input. However, the impact of WAT first increases and then decreases (Figure 6g). When the water resource endowment is rich, water use will not be restricted. However, with the further increase in water resource endowment, the water footprint decreases, which may be influenced by regional geography, population, and economic development. For example, from 2007 to 2017, the per capita water resources of Qinghai were the largest in the Yellow River basin, but the population and per capita GDP of this province was the smallest in the basin, and the water footprint in S01 was also the smallest in the basin. The production-based water footprint in S06 is positively affected by POP and IMP (Figure 6h), indicating that population expansion and the substitution effect of trade inflow [46] will lead to an increase in the water footprint of this sector. POP and SEC are the major factors influencing the production-based water footprint in S24. POP has a positive impact, while SEC has a negative impact (Figure 6i). With the industrial structure shifting to secondary industry, economic development improves the water-saving technology, resulting in a decline in the virtual water flowing to S24. S30 is mainly influenced by POP and AGR. The influence of POP shows a stairs type to continuously rise, while AGR has a negative impact (Figure 6i). POP and EXP have a positive impact on the production-based water footprint in S07 and S12 (Figure 6k,l) since S07 and S12 are the main export sectors in the Yellow River basin.

In addition, the importance of IMP to the production-based water footprint in S30 is low because products in S30 are mostly used for local demands in the Yellow River basin. The impact of AGR on the production-based water footprint in S01 and S24 is small because the amount of production-based water footprint in S01 is determined by the sector's physical water use transferred to other sectors and the amount of the production-based water footprint in S24 is influenced by the industrial scale. The impact of GDP on the production-based water footprint in S30 and S07 is small, which may be due to the small scale of these two sectors, the stimulative effect of economic development on the production-based water footprint of the two industries has a certain lag. The contribution of EXP to the production-based water footprint in S01 and S24 is small because the exports in S01 are mainly concentrated in Inner Mongolia, Gansu, and Shaanxi, while the production-based water footprint in S24 is mainly used for local demand.

3.2.3. Influencing Factors of the Consumption-Based Water Footprint

Consumption-based water footprints in the first six sectors are mainly influenced by POP, IMP, EXP, TEC, and AGR. The consumption-based water footprint in S01, S06, and S12 are mainly positively influenced by POP and EXP (Figure 6m,n,q), indicating that the stimulative effect of population and the compensating effect of trade outflow will lead to an increase in the consumption-based water footprint of the three sectors. POP and TEC have a positive influence on the consumption-based water footprint (Figure 6o) since R&D investment in China is used through investment in technology to improve water use efficiency, which leads to a certain lag time in the application of achievements. Thus, R&D investment will bring about input redundancy. The consumption-based water footprint in S30 is mainly influenced by POP and AGR. POP has a positive effect, while AGR has a negative effect (Figure 6p). The consumption-based water footprint in S27 is positively influenced by POP and IMP (Figure 6r).

In addition, TEC has a small impact on the consumption-based water footprint in S01 because S01 is the largest sector of the consumption-based water footprint in the Yellow River basin and one of the main virtual water input sectors. Since there are delays in the level of economic development and water conservation technology compared with developed regions, the basin needs to import a large number of water resources to meet its demand while developing high-water consumption industries. Therefore, the indirect water-saving effect brought by scientific and technological innovation has not yet been played. AGR has a small influence on the consumption-based water footprint in S27. Although S27 receives some water from S01, due to its small scale, the amount of water it receives is also small. EXP and IMP contribute less to the consumption-based water footprint in S24, as the products in S24 are mainly used for local demand.

There are also differences in the influencing factors of water use among the three perspectives. For example, in S01, the key influencing factors of physical water use are POP and IMP, the important influencing factors of production-based water footprint are PRI and WAT, and the critical influencing factors of the consumption-based water footprint are POP and EXP. This is caused by differences in water resource utilization. Expansive development has led to backward water-saving technology and low water price in the Yellow River basin. The industry structure is dominated by water-consuming sectors, such as S01. The basin's development relies heavily on its water resources. Thus, for the physical water use in S01, in addition to the demographic bonus leading to an increase in water use, the more total inflows, the more water resources available for production. The production-based water footprint in S01 is affected by the industrial structure and resource endowment. For the consumption-based water footprint in S01, in addition to population influence, the more total outflow, the more products need to be imported to meet the demand, leading to an increase in the water footprint. In S12 and S30, there is little difference in the influencing factors of water use among the three perspectives. For example, the average annual physical water use, the production-based water footprint, and the consumption-based water footprint in S12 is 4.0, 3.3, and 3.5 billion m^3. Therefore, the results of influencing factors are similar.

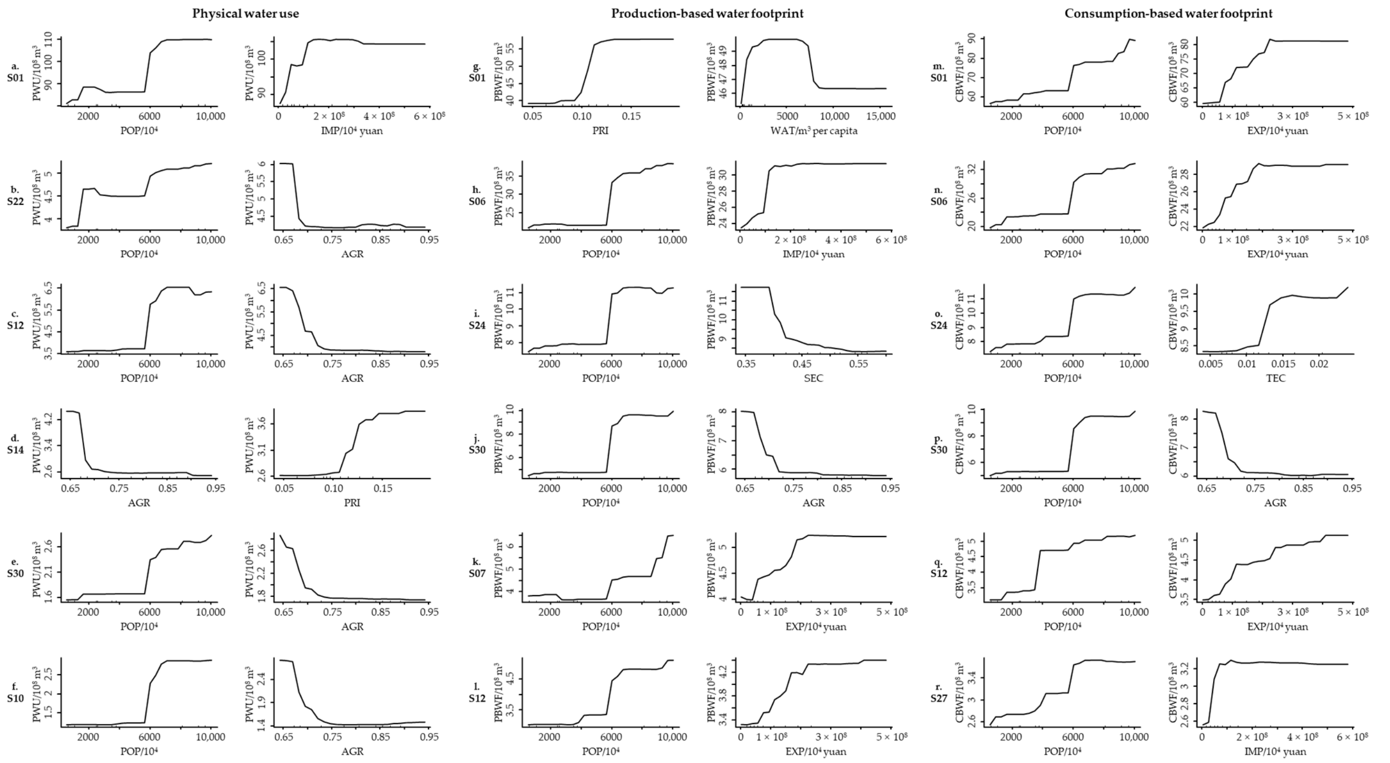

Figure 6. The influence intensity of the top two influencing factors in the top six sectors of physical water use, the production-based water footprint, and the consumption-based water footprint, 2007–2017: (**a**)-S01 in PWU; (**b**)-S22 in PWU; (**c**)-S12 in PWU; (**d**)-S14 in PWU; (**e**)-S30 in PWU; (**f**)-S10 in PWU; (**g**)-S01 in PBWF; (**h**)-S06 in PBWF; (**i**)-S24 in PBWF; (**j**)-S30 in PBWF; (**k**)-S07 in PBWF; (**l**)-S12 in PBWF; (**m**)-S01 in CBWF; (**n**)-S06 in CBWF; (**o**)-S24 in CBWF; (**p**)-S30 in CBWF; (**q**)-S12 in CBWF; (**r**)-S27 in CBWF. (PWU refers to physical water use, PBWF refers to the production-based water footprint, and CBWF refers to the consumption-based water footprint).

4. Discussion

4.1. Comparison with the Literature

In recent decades, water use in the Yellow River basin has been studied by a few scholars. From the physical water use perspective, most relevant studies focus on utilization efficiency [64,65]. Our results are similar to those of Yan et al. [10]. In contrast, after the introduction of the concept of water footprint, many scholars pay more attention to the calculation of the water footprint of the basin. However, there is a large difference between similar studies and our results. The results of Xing et al. [66] and Yang et al. [67] find that the consumption-based water footprint in the Yellow River basin shows an increasing trend. Our results indicate an increasing and then decreasing trend in the water footprint in the Yellow River basin. The difference in the results is likely due to the difference in the scope of research. For example, their studies include the gray water footprint within the water footprint accounting.

Accurate identification of the important factors can provide effective ways to improve regional water utilization. Previous studies have used several quantitative methods to reveal the factors influencing water use. For example, Zhang et al. [68] adopt the LMDI (Logarithmic Mean Divisia Index) method to decompose the driving factors of water use change in Jiangsu province. The Tobit model is also widely used in the study of factors that affect water use [29,69]. Nonetheless, the non-linear relationship between water usage and its influencing factors is not considered in the Tobit model or other traditional methods. In previous studies, many influencing factors such as water resources, population size, environment regulation, economic development, industrial upgrading, technical innovation, and foreign trade have often been used to explore the cause of water use change. Considering the availability of data, this study selects water resource endowment, population size, urbanization level, economic development, industrial structure, trade, water price, technological innovation, environmental regulation, water pollution, and water use structure as the influencing factors. Our results show that physical water use in the first six sectors is mainly affected by POP, AGR, IMP, and PRI. Our results are similar to the studies of Yang and Chen [31], Zhao et al. [43], and Qian and He [46]. Production-based water footprints in the first six sectors are greatly influenced by POP, PRI, SEC, IMP, EXP, WAT, and AGR. Consumption-based water footprints in the first six sectors are mainly influenced by POP, IMP, EXP, TEC, and AGR. Our results are similar to the studies of Zhao et al. [30], Liu et al. [70], and Zhang et al. [71].

As a machine learning method, the random forest model is capable to calculate the nonlinear effects of variables and evaluate the importance of independent variables. In our study, most of the factors are non-linear and correlated with physical water use, the production-based water footprint, and the consumption-based water footprint in the Yellow River basin. For example, the influence of POP on physical water use, the production-based water footprint, and the consumption-based water footprint presents a stair type to continuously rise (Figure 6). It shows that the random forest regression model has a large scope of application for revealing the complex nonlinear effects of natural, social, and economic factors on water consumption.

4.2. Policy Implications

Based on the status of physical water use, the production-based water footprint, and the consumption-based water footprint in the Yellow River basin and the order of importance of the influencing factors of three kinds of water uses, this paper proposes the following policy recommendations.

(1) Population size control. For provinces with large populations, such as Sichuan, Shandong, and Henan, certain population policies can be formulated to control the size of the population and prevent the rapid growth of the population from leading to a sharp increase in water consumption.

(2) Water use structure adjustment. Agricultural water consumption should be restricted, and the scale of low-water consumption and drought-tolerant crops should be expanded. Implementing the total control of agricultural water use, advancing comprehensive price reform, and setting differentiated water prices by level and classification. Increasing industrial water resource input is beneficial for reducing agricultural water consumption, but attention should be paid to limiting water use in high-water consumption sectors. Measures such as the over-quota progressive increase in the water price can be taken for the orderly exit of high-water consumption industries.

(3) Trade structure optimization. For provinces with large virtual water outflows, such as Inner Mongolia, Gansu, Shaanxi, Shandong, and Henan, the existing export structure can be changed by, for example, charging taxes on commodity exports or stimulating local consumption to reduce virtual water exports, thus easing the

pressure on water resources caused by virtual water exports. For regions with large virtual water inflows, such as Shanxi, Shaanxi, Shandong, and Henan, measures can be taken, such as importing high-consumption water products from regions with high water resource utilization levels and giving compensation to the virtual water source areas to help upstream regions reduce their water consumption, thus reducing the dependence on external water resources.

(4) Technological innovation. Increasing investment in technological innovation, intensifying research on water resource utilization, and supporting technological innovation in agriculture and animal husbandry in the Yellow River basin. Accelerating the deployment of technology infrastructure facilities and conducting overall planning for the development of several state key laboratories, industry innovation centers, engineering research centers, and other platforms for technological innovation. Strengthening the training and introduction of personnel of science and technology, engineering, promoting the transformation and application of innovation, and enabling the fundamental transformation of water use from inefficient to economical and intensive.

(5) Investment in pollution control. Promoting the development of sewage treatment, strengthening technical research and financial investment in advanced technology, equipment, and technology, such as industrial pollution prevention, and improving the overall sewage treatment capacity of the region. Based on existing sewage treatment plants, reasonably laying out sewage recycling facilities, promoting the resourceful use of sewage, and ultimately reducing the amount of wastewater discharge and water consumption.

(6) Industrial structure upgrade. Under the premise of safeguarding food security, based on resources, factor endowment, and development foundation to develop the characteristic industry. Actively supporting the development of water-saving facility agriculture, accelerating new and old kinetic energy conversion, and promoting the high-quality development of manufacturing and transformation of resource-based industries. Implementing strict access to high water-consuming industries, supporting the development of high value-added industries with low water consumption, building a modern industrial system that takes advantage of local strengths, and to a certain extent, easing the pressure of water resources brought by rapid economic growth.

4.3. Limitations of the Study

Meanwhile, this study has certain limitations. First, the boundary of our study was restricted to the provinces in the Yellow River basin. However, analyses using downscaled spatial scaled data or taking more regions as samples can provide more details regarding the effects of factors of water use.

Second, the calculation of water footprints was based on the Chinese MRIO for 2007, 2012, and 2017, which means our analysis of water use was influenced by the time of the MRIO. Water usage in 2017 cannot fully represent current water use. The Chinese government publishes input–output tables every 5 years, and the 2017 MRIO is the latest data. Once better data become available, they can be used to update the model.

Another limitation was the selection of factors influencing water use. We did not consider several factors, such as regional differences [29,72] and time effect, due to sample size limitation. There are obvious regional differences in the influencing factors of water resources utilization. For example, the proportions of value added in the primary and secondary industries have significant negative effects on water resource efficiency in the east and the central part of China, while they have positive impacts in the west [29]. The importance of factors may also change with time, which can be seen in a study on carbon intensity [38]. For example, green patent, total population, and economic development rise in the importance rankings on carbon intensity over time, while the industrial structure and population density fall back in the rankings. We speculate that the influencing factors of water resource use also have such a temporal evolutionary phenomenon.

Therefore, future studies need to discuss the effects of geographical factors, factor variation with time, etc., on water use and the problems that can be caused.

5. Conclusions

This study analyzes the spatial and temporal variation of physical water use, the production-based water footprint, and the consumption-based water footprint in the Yellow River basin, and then uses a random forest model to identify the key influencing factors of the three water uses. The conclusions are as follows.

(1) Physical water use, the production-based water footprint, and the consumption-based water footprint in the Yellow River basin increased and then decreased from 2007 to 2017. The upper and lower reaches had large water use, while the middle reach had small water use. Provinces with relatively developed agriculture and a large economic scale have large water usages, such as Shandong, Henan, and Sichuan.

(2) Physical water use in the Yellow River basin was dominated by high-water consumption industries. Agriculture, forestry, animal husbandry, and fisheries consumed the biggest amount of water, followed by electricity, hot water production, supply, and chemicals. The production-based water footprint in the Yellow River basin was dominated by agriculture and related industries. Agriculture, forestry, animal husbandry, and fisheries were the largest sectors, followed by food and tobacco processing, construction, other services, textiles, and chemicals. Demand from downstream industries accounted for about half of physical water use in agriculture, forestry, animal husbandry, and fisheries. The consumption-based water footprint in the Yellow River basin is also dominated by agriculture and related industries. Agriculture, forestry, animal husbandry, fisheries, food and tobacco processing, construction, other services, and chemicals were the main sectors. Overall, achieving high-quality development goals in the Yellow River basin remains a challenge.

(3) According to the results of the random forest model, physical water uses in the first six sectors is mainly affected by total population, the proportion of agricultural water use to total regional water use, total inflow, and the proportion of value added of the primary industry to regional GDP. Production-based water footprints in the first six sectors are mainly affected by total population, the proportion of value added by the primary industry to regional GDP, the proportion of value added by the secondary industry to regional GDP, total inflow, total outflow, water resources per capita, and the proportion of agricultural water use to total regional water use. Consumption-based water footprints in the first six sectors are mainly affected by total population, total inflow, total outflow, the proportion of R&D investment to regional GDP, and the proportion of agricultural water use to total regional water use. The key influencing factors have an obvious linear or nonlinear relationship with the three kinds of water uses. There are also differences in the influencing factors of water use among the three perspectives due to the differences in water resource utilization.

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