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Does aquatic products trade waste or save water resources? An analysis of virtual water trade

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ABSTRACT

China is the largest producer and exporter of aquatic products. While earning foreign exchange, its implied water resources output could not be denied. Against the background of promoting water resources and food security, whether aquatic products trade can also achieve the purpose of water-saving has become a topic worthy of attention. Based on the idea of the quality and energy conservation law, this study uses the physical value input–output table and the fish growth model, and calculates the output and input of China's aquatic products virtual water trade indirectly by fishery water coefficient and virtual water of feed crops. The results show that while China's aquatic products trade is water-saving in general, it is water-wasting in some parts, and its environmental function needs to be improved. In particular, the aquatic products trade with South Asia, Central Asia, Northern Europe, North America, South America and Oceania is virtual water net import, while that with other regions is virtual water net export. The trade of shellfish and marine fish is water-saving, while that of mollusk, crustacean and freshwater fish is water-wasting. China, as a globally responsible power, should try to dynamically optimize the trade structure of aquatic products.

Key words: Aquatic products trade, Fish growth, Input–output table, Water resources

HIGHLIGHTS

- A hot topic is closely related to food security, resource-saving society and sustainable development.
- Both biological and economical models are combined in the analysis.
- The virtual water trade of aquatic products is not centralized and unbalanced.
- It is a reference to change the trade policies of aquatic products and promote the green transformation of fisheries.

GRAPHICAL ABSTRACT

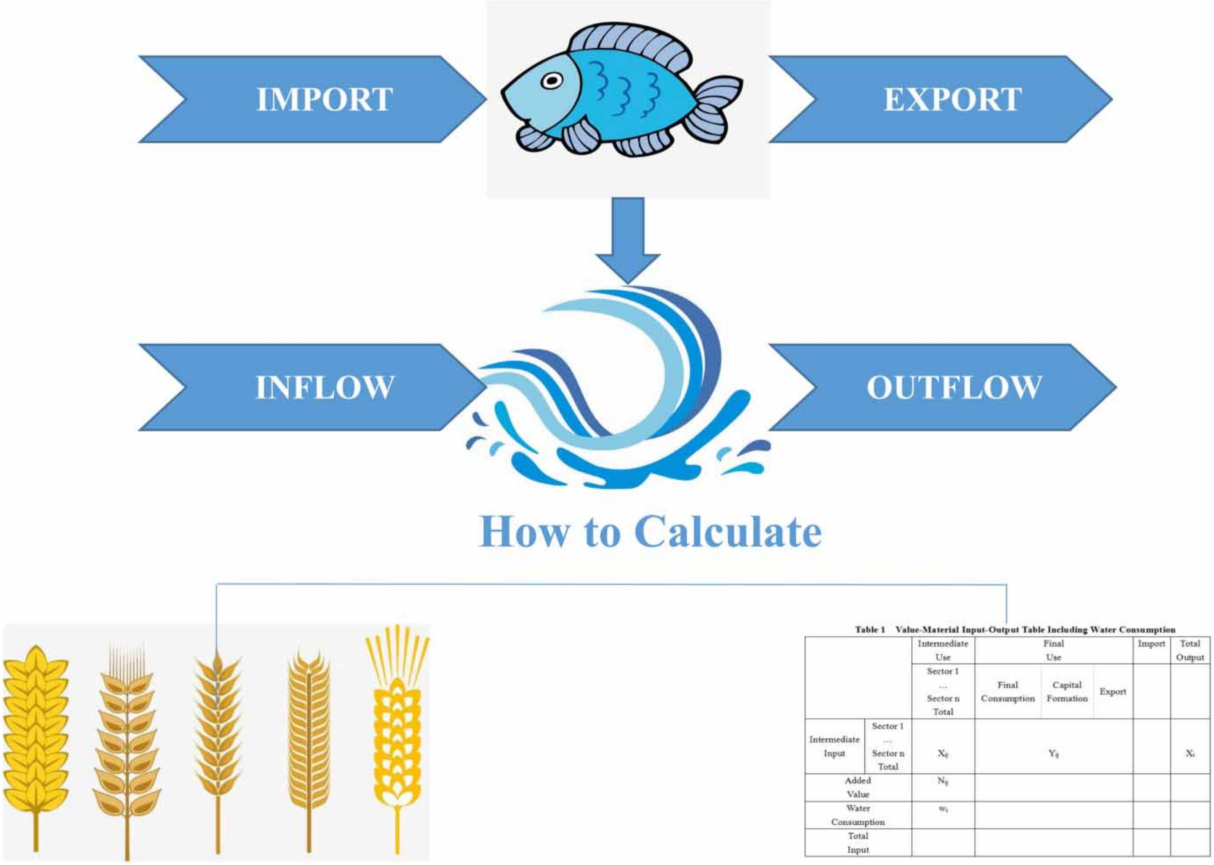

Table 1 Value-Material Input-Output Table Including Water Consumption

		Intermediate Use	Final Use			Import	Total Output
		Sector 1 … Sector n Total	Final Consumption	Capital Formation	Export		
Intermediate Input	Sector 1 … Sector n Total	X_{ij}	Y_{ij}				X_i
Added Value		N_{ij}					
Water Consumption		w_i					
Total Input							

1. INTRODUCTION

1.1. Background

According to the Food and Agriculture Organization (FAO)'s statistics, China has been the largest exporter of aquatic products in the world since 2011. The World Seafood Trade Map 2019 released by Holland Cooperation Bank shows that, in 2017, both China's aquatic products export volume and export amount were nearly two times that of the second country – Norway (Rabobank, 2019). Aquatic products export has brought substantial foreign exchange income to China. According to China's customs statistics, from 2011 to 2019, the price of aquatic products exported by China was about US $50 million per ton, while the price of aquatic products imported in the same period was maintained at US $18–30 million per ton. To some degree, from an economic point of view, the aquatic products trade was cost-effective for China.

However, from the perspective of resources, how about the efficiency of China? China is the country with the largest population in the world, and China's food production (including aquaculture) is facing water resources crises and water pollution issues like other countries. Especially with the aggravation of global warming, the process of urbanization and the increase in people's consumption levels, the problem of water shortage in China is increasingly obvious. How China's fisheries can contribute to both its own country and the world by optimizing its import and export structure is an issue worthy of discussion.

1.2. Question raised

As one of the sayings in China goes, 'fish cannot live without water'. However, the consumption of water resources in the aquaculture sector has not found much interest from the international academic community, and there is a lack of popular and universal evaluation methods and systems. The main reason maybe is that the aquatic products from pelagic fishing do not consume water resources, as it is generally accepted that 'aquatic products are generally considered to have no water footprint, they are high-quality products which could replace terrestrial animal protein and reduce potential water consumption' (Jalava *et al*., 2014). But this viewpoint cannot be applied to China's aquatic products industry. This is because, according to statistics from China's Ministry of Agriculture and Rural, China is the only country in the world that has more aquaculture than fishing, with a ratio of about 8:2. Moreover, the UN FAO pointed out in 'The State of World Fisheries & Aquaculture, 2020', that by 2030, 'with the decline of wild fishing, the output of aquaculture is expected to continue to grow significantly, and aquaculture will become the main driving force for fishery production' (FAO, 2020).

In 1993, British scholar Tony Allan put forward the concept of 'virtual water' for the first time. It has now also become an effective tool for scholars in various countries to analyze the accounting of water resources consumption in the production of planting products.

Generally speaking, studies dealing with accounting and analysis of animal products are relativity insufficient. What is more, the vast majority of recent studies are confined to agricultural production itself, not linked to international trade.

Under the background of global water resources crises and green development of aquaculture and fishery, there is a new challenge for the formulation of aquatic products trade agreements and policies. Then, it is necessary to know: What is the situation of the aquatic products virtual water trade in China? What is the direction of the virtual water flow brought about by the aquatic products trade, and what are the differences in the virtual water content of different kinds of aquatic products? Is it possible to further optimize the import and export structure of aquatic products? If this is still possible, how to optimize it?

1.3. Literature review

1.3.1. The concept of virtual water

In the field of economics, David Ricardo's theory of comparative advantage is well known. When Tony Allan first proposed the concept of 'virtual water' at a seminar at SOAS in 1993, he emphasized that 'virtual water is a derivative of comparative advantage theory' (Allan, 1993). At that time, virtual water was 'invisible' water, the amount was equivalent to the amount of water consumed in the production of agricultural products. With the background of water commercialization and resources globalization, virtual water trade is an effective way to alleviate the pressure of water resources in poor water countries (or regions) (Allan, 1997).

With the deepening of research, the concept and connotation of virtual water have been expanded. Hoekstra and Chapagain proposed the concept of 'water footprint', which expanded the research of virtual water from the field of environmental engineering to the field of economics (Hoekstra & Chapagain, 2006). They suggested that 'water footprint' is a supplementary indicator for water resources consumption evaluation (Hoekstra & Chapagain, 2007). They put forward the concepts of 'blue water', 'green water' and 'gray water'.

There is no clear definition of the research objects of 'virtual water' and 'water footprint'. Zhu thinks that 'virtual water' only includes 'blue water' and 'green water', while 'water footprint' includes 'blue water', 'green water' and 'gray water' (Zhu & Tian, 2012). He thought that the calculation of the consumption of agricultural products under the condition of crop growth and climatic conditions is more convenient than that of the water footprint. Odey *et al*. reviewed available literature about 'virtual water concept', stating different driving factors and their effects on virtual water exchanges (Odey *et al*., 2021). Zhu's view is adopted in this study.

Based on the above literature, in this paper, virtual water trade refers to the situation in which country or region purchases water resource-intensive products from another country or region through commodity trade. The region/country thus imports water resources (virtual water), and it realizes the purpose of saving water resources (virtual water) by focusing on agricultural products trade.

1.3.2. Research methods and scope of virtual water

On the one hand, since 'virtual water' itself is a relatively novel research field, its research methods need to be explored and optimized. At present, there are two methods commonly used: Penman formula and input–output tables. Of course, scholars have carried out some application research and model improvement based on the two methods. For example, based on the Penman formula, Li calculated the virtual water consumption and virtual water trade volume of urban and rural residents in Heilongjiang Province in 2003 by using CROPWAT, crop database and climate database (Li & Wu, 2008). Ahn evaluated the volume of virtual water trade in Korea from 1998 to 2007 by applying the evaluation method of unit virtual water volume to agricultural, livestock and industrial products (Ahn *et al*., 2010). Hristov analyzed direct and indirect relationships in water consumption by Macedonian economic sectors using virtual water in an input–output framework (Hristov *et al*., 2015). Wu constructed a factorial ecologically extended input–output model to evaluate the virtual water flows and reveal ecological inter-connections in virtual water systems (Wu *et al*., 2021).

On the other hand, from the perspective of the research scope, the existing virtual water trade research mainly involves crops, while some involves livestock products such as pork. For example, Mellios *et al*. conducted an analysis of virtual water export through international trade for Greece in order to identify critical 'hotspots' of localized water shortage in the country (Mellios *et al*., 2018). Zheng's paper analyzed the virtual water content of net imports of China's bulk agricultural products with countries along the line of the Belt & Road Initiative (Zheng & Xu, 2019). Brindha assessed the virtual water trade of Germany with the world through the trade of crop and livestock products from 1991 to 2016 (Brindha, 2020).

Recently, some empirical studies began to focus on the impact of and determinations of virtual water trade. Today, 10% of global consumers receive water from private companies, a true global holistic approach to regulate water services is needed (Chaisse & Polo, 2015). After discussing the regulation of the global water services market, both Bailat and Chaisse agree that the economic interests concerning water services are generating a tension with the recognition of the human right to water (Baillat, 2017; Chaisse, 2017). It was pointed out that the relationship between water governance and consumer protection has not been handled properly by regulations (Xu, 2019). The studies gave us a new way to evaluate the importance of global water services and human rights protection.

Then, despite China being the world's largest aquaculture country and the world's largest exporter of aquatic products, research on the importance of 'virtual water' in China focusing on aquatic products is still lacking.

The virtual water trade of various aquatic products needs the attention of academic circles. It is hoped that the study will be of some reference significance for adjusting the trade flows with different countries and the breeding capacity of various fishes, responding to climate change, food security, water resources security and ecological protection.

In the following, the fishery water consumption coefficient, the output and input of fishery virtual water of different destinations and different sources, the virtual water content of different kinds of aquatic products per unit mass and the virtual water trade volume of different kinds of aquatic products will be calculated.

2. METHODOLOGY AND DATA

2.1. Methodological and empirical framework

The input–output method is used to calculate the virtual water of various industries, while the Penman formula calculation method is mostly used to calculate the virtual water of crops.

Model 1 is based on the research hypothesis, that the product of aquaculture water quota and aquaculture area is the aquaculture water consumption in the region. The water consumption of each department is added to the input–output table to form the 'value-physical' input–output table of water resources.

Model 2 is based on the research hypothesis, that the virtual water content of aquatic products is mainly composed of the virtual water content of the feed input in the breeding process, and there is no consumption in the trade process. Therefore, the application scope of the virtual water accounting method is expanded.

2.1.1. Method 1: calculating the virtual water consumption of fishery by the input–output tables

In a broader sense (considering the amount of water exchange in the process of aquaculture), the input–output table method can measure the virtual water content of aquatic products.

The first step is to construct the 'value-material input–output table'. The row vector of water consumption in each sector is added to the value-based input–output table. The second step is to calculate the direct water-use coefficient, the indirect water-use coefficient and the total water-use coefficient. The third step is to calculate the virtual water export and import.

Model 1:

Table 1 is the input–output table for the traditional value-based National Economy. The balance between rows and columns is reflected in the following aspects:

$$\sum\nolimits_{i=1}^{n} x_{ij} + Y_i = X_i \qquad (j = 1, 2, 3, \ \ldots, n) \tag{1}$$

$$\sum\nolimits_{j=1}^{n} x_{ij} + N_i = X_i \quad (j = 1, 2, 3, \ \ldots, n) \tag{2}$$

Lateral equilibrium relationship: in Equation (1), $\sum\nolimits_{i=1}^{n} x_{ij}$ represents the products used in the middle; Y_i refers to the final use part, which comprises the goods and services of each product sector; X_i represents the total output of the i sector, which is equal to the sum of the first two items.

Table 1 | Value-material input–output table including water consumption.

		Intermediate use Sector 1, …, Sector *n* total	Final use				
			Final consumption	Capital formation	Export	Import	Total output
Intermediate input	Sector 1, …, Sector *n* total	$X_{i,j}$	$Y_{i,j}$				X_i
Added value		$N_{i,j}$					
Water consumption		w_i					
Total input							

Vertical equilibrium relationship: in Equation (2), $\sum_{j=1}^{n} x_{ij}$ represents the initial distribution of GNP; N_i represents the total added value of sector i; X_i represents the total input of sector i, which is equal to the sum of the first two items.

Then, the direct water consumption coefficient, the complete water consumption coefficient and the indirect water consumption coefficient are calculated by the above water resources input–output table. The equations are as follows:

$$W_i = \frac{w_i}{X_i} \tag{3}$$

$$T_i^w = W_i(I - A)^{-1} \tag{4}$$

$$S_i^w = T_i^w - W_i \tag{5}$$

In Equation (3), W_i represents the direct water consumption coefficient of the i sector, that is, the water consumption required by the unit output value of the i sector, which is equal to the w_i of the i sector and the output X_i of the i sector.

In Equation (4), T_i^w represents the complete water consumption coefficient of the i sector, that is, the water consumption of the whole economic system for i sector's unit output value, which equals the product of the direct water coefficient W_i and the input–output inverse matrix $(I - A)^{-1}$.

In Equation (5), S_i^w represents the indirect water consumption coefficient of the i sector. It measures the indirect water consumption from other departments to meet the J unit's final use of one unit of J product.

Finally, the calculation equations of China's virtual water export and import of fishery can be formulated:

$$\mathrm{CVWE}_i = T_i{*}\mathrm{CEXV}_i = W_i(I - A)^{-1}{*}\mathrm{CEXV}_i \tag{6}$$

$$\mathrm{CVWI}_i = T_i{*}\mathrm{CIMV}_i = W_i(I - A)^{-1}{*}\mathrm{CIMV}_i \tag{7}$$

In Equations (6) and (7), CEXV_i and CIMV_i represent the total value of China's exports and imports of industry i. CVWE_i and CVWI_i represent China's virtual water export and import volume. T_i represents the complete water consumption coefficient of industry i, that is, the product of the direct water consumption coefficient W_i and the input–output inverse matrix $(I - A)^{-1}$ of China's i industry.

2.1.2. Method 2: calculating virtual water content in the growth cycle of aquatic products by virtual water of feed crops

In the narrow sense (not considering the amount of water exchange in the process of aquaculture), the virtual water consumption (except algae) in aquaculture can be calculated by using data on feed raw materials and feed consumption in the aquaculture cycle.

The first step is to measure the virtual water content of different feed formulations per unit mass. The second step is to determine the feed consumption in the process of breeding different varieties. The third step is to calculate the virtual water content of 22 kinds of aquatic products per unit mass. The fourth step is to calculate the trade data of virtual water exports and imports.

Model 2:

$$\mathrm{VW}_{i,j} = \mathrm{VW}_{a,i,j}{*}\mathrm{F}_i \tag{8}$$

Equation (8) expresses the calculation formula of virtual water quantity of different feed formulas, j is the j water of the i aquatic product, $VW_{i,j}$ is the j water quantity (L) of aquaculture products for every 10,000 g of i species, $VW_{a,i,j}$ is j water amount (L) of feed used for the i aquatic product per 100 g, F_i is the amount of feed (g) needed to feed every 100 g of the i aquatic product. Among them, the virtual water volume of feed is calculated by the international water footprint organization based on the Penman formula:

$$L_t = L_\infty(1 - e^{-K(t-t_0)}) \tag{9}$$

$$W_t = W_\infty(1 - e^{-K(t-t_0)})^B \tag{10}$$

$$w_{i,t} = w_{i,\infty}(1 - e^{-k_i(t_i-t_{i,0})})^{b_i} \tag{11}$$

$$F_i = \alpha_i \int_{t_{i.1}}^{t_{i,2}} w_{i,t}\,dt_i / w_{i,t}(t_{i,2}) * 100 \tag{12}$$

Equations (9)–(12) express the deduction process of feed consumption formula in different breed aquaculture. First, the aquatic product growth equation was used to measure the feed input of different varieties in the breeding period. The von Bertalanffy model, which was proposed by Austrian biologist Bertalanffy (1938), is the approach commonly used to model growth in most fish types, crustaceans and mollusks. It is also recommended by FAO and given by Equations (9) and (10).

In Equations (9) and (10), L_t and W_t are the body length and the weight of aquatic products at the time t; L_∞ and W_∞ are the progressive body length and body weight; t_o is the age when the theoretical body length and weight are 0; K is the average curvature of the growth curve and represents the relative speed of approaching body length or body weight and b is the power exponent coefficient.

Second, by converting Equation (10), the weight $w_{i,t}$ of the i aquatic product at the age of t is derived, which is Equation (11). In this formula, $w_{i,t}$ is the weight of aquatic product i at the age of t (g); $w_{i,\infty}$ is the weight of the i aquatic product at the maximum age (g); k_i is the growth rate parameter of the i aquatic product, $t_{i,0}$ is the theoretical initial growth age of the i aquatic product and b_i is the growth index of the i aquatic product.

Third, through integration, the total feed consumption of aquaculture aquatic products is derived as shown in Equation (12). In this formula, F_i is 100 g of aquatic product i, starting from $t_{i,1}$ to catch $t_{i,2}$ in the whole cycle of feed consumption (g/g); α_i is the feeding rate (%); $w_{i,t}$ is the weight (g) of the i aquatic product at the age of t; $w_{i,t}$ $(t_{i,2})$ is the weight (g) of aquatic product i at t_2.

2.2. Data source

In method 1 of this study, the input–output table data comes from China input–output tables published by the National Bureau of Statistics in 2017. For the intermediate products used in the calculation, the method of 'distribution according to fixed proportion' (Shen & Wu, 2004) is adopted to deduct the imported intermediate products. The water consumption data of fishery departments refer to the data of 'national fishery water quota compilation' and 'China water saving irrigation network'. The national fishery statistics database was searched to obtain the data of fishery culture area.

The import and export volume data were collected from the FAO database. Due to the lack of specific trade flow data in the FAO database, the UN COMTRADE database is used to calculate the fishery virtual water transfer between China and various countries/regions. According to the category of aquatic products, they can be divided into seven categories: eel, Cyprinidae, catfish, perch, trout, salmon and others. According to the geographical location of the countries, they were divided into several plates.

In method 2, there are 22 kinds of aquatic products measured. These 22 products include carp, tilapia, catfish, freshwater perch, sturgeon, eel, salmon, trout, flatfish, flounder, yellow croaker, pufferfish, sea perch, bream, cobia, *Procambarus clarkii*, shrimps and prawns, crabs, oysters, clams, sea cucumbers, sea urchins of major freshwater fish, sea fish, crustaceans, shellfish and cephalopod aquatic products.

The feed formula data come from the 'feed formula parameters' database of the Fishery Science Data Subcenter of the National Agricultural Science Data Sharing Center, China Aquaculture Network. Virtual water data of formula raw materials are from waterfootprint.org ('Water Footprint Assessment Manual' on their website). The data of feeding rate and growth characteristics of aquatic products are obtained from national, regional and industrial standard databases and the weight growth equation of corresponding varieties in relevant literature (Han & Wang, 1991; Ye & Chen, 1996; Zhang *et al*., 2004; China National Agricultural Science Data Sharing Center, 2020a, 2020b, 2020c, 2020d). The aquatic products trade data are based on the FAO database.

3. RESULTS

3.1. Fishery water consumption coefficients

Based on data from China's 'input–output table' in 2010, 2012 and 2017, and the water consumption data of fishery departments, the water consumption coefficients of Chinese fisheries are calculated by using Equations (3)–(5) of Model 1.

The total water-use coefficient of China's fisheries decreased from 0.43 m^3/CNY(2010) to 0.37 m^3/CNY(2012) to 0.25 m^3/CNY(2017), the direct water-use coefficient varied from 0.35 m^3/CNY(2010) to 0.28 m^3/CNY(2012) to 0.18 m^3/CNY(2017). Meanwhile, China's fishery water consumption dropped by 5.3%, and the output of fishery production increased by 87.1%. It reflects that after 2010, China's fishery industry is moving toward the road of green development. The direct water-use coefficient is obviously higher than the indirect water-use coefficient, which indicates that other industries have low dependence on fisheries. Comparing this study with that of Wei & He (2015), it can be concluded that compared with crops, the water consumption coefficient of fishery culture is more than 10 times higher.

3.2. China's fishery virtual water trade volume

From the FAO Database, the trade volume of Chinese aquatic products can be obtained. Applying Equations (6) and (7) in Model 1, it can be concluded that in 2010, 2012 and 2017, the relevant virtual water net export volume reached 2,998,500, 3,118,300 and 2,334,100 m^3, respectively. Although there has been a significant decline, the trend of net output is still significant.

If the UN COMTRADE data are used to study the importing and exporting countries or regions, the virtual water output and input of China's fishery industry to all countries or regions can be measured. Due to space limitations, the following only shows the fishery industry virtual water output of each plate. Detailed calculations are available upon request from the author.

It can be seen from Table 2 that in terms of export destinations, Southeast Asia and North America are the regions where China exported the most fishery virtual water. Among them, Hong Kong and Japan account for 15.8 and 15.6% of the world's total, and Mexico and Canada account for 6.5 and 4% of the world's total. Tilapia and salmon are the most exported virtual water species. The next is Cyprinidae. The least is catfish.

Table 2 also shows that North America and South America are the regions with the largest volume of imports of fishery virtual water for China. Among them, the United States accounted for 31.72% of China's global import of fishery products, and Chile accounted for 22.88%. In terms of the categories of fishery virtual water import products, by species, the rank from the highest to the lowest is salmon, catfish, trout, … , tilapia.

Table 2 | Virtual water output and import of China's fishery export to all plates.

	Eels		Cyprinidae		Catfish		Perch		Salmon		Trout		Tilapia		Others	
	Output	**Input**	**Output**	**Input**	**Output**	**Input**	**Output**	**Input**	**Output**	**Input**	**Output**	**Input**	**Output**	**Input**	**Output**	**Input**
Southeast Asia	1.593	0.056	2.459	0.007	0.056	1.940	0.931	0.153	0.837	0.382	0.612	0.002	0.049	0.000	0.549	0.292
East Asia	0.000	0.014	0.000	0.000	0.000	0.000	0.000	0.015	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.001
South Asia	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000
Western Asia	0.000	0.000	0.012	0.002	0.000	0.000	0.046	0.000	0.020	0.001	0.000	0.000	1.459	0.000	0.001	0.000
Central Asia	0.000	0.000	0.000	0.008	0.000	0.000	0.000	0.000	0.000	1.921	0.000	0.000	0.000	0.000	0.000	0.000
Southeast Europe	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.034	0.899	0.000	0.000	0.035	0.000	0.000	0.000
Eastern Europe	0.000	0.000	0.000	0.000	0.000	0.002	0.000	0.000	0.340	1.779	0.048	0.419	0.387	0.000	0.004	0.000
Southern Europe	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.499	0.001	0.000	0.000	0.215	0.000	0.003	0.000
Western Europe	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.211	5.875	0.000	0.007	0.288	0.000	0.005	0.001
Northern Europe	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.084	3.570	0.000	0.341	0.021	0.000	0.000	0.016
Central Europe	0.047	0.000	0.000	0.000	0.000	0.000	0.000	0.030	1.479	0.000	0.000	0.000	0.324	0.000	0.004	0.000
North America	0.002	0.008	0.011	0.000	0.001	0.000	0.001	0.000	0.732	0.000	0.000	0.000	1.369	0.000	0.013	0.000
South America	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.314	0.000	0.000	0.000	0.287	0.000	0.000	0.000
Central America	0.000	0.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.176	0.000	0.000	0.000
East Africa	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.112	0.000	0.000	0.000
South Africa	0.000	0.009	0.000	0.000	0.006	0.000	0.000	0.008	0.003	1.263	0.000	0.000	0.403	0.000	0.001	0.000
West Africa	0.000	0.000	0.011	0.000	0.057	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.768	0.000	0.000	0.000
North Africa	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.000	0.000	0.000	0.000	0.000	0.002	0.000
Central African	0.000	0.000	0.000	0.000	0.116	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.524	0.000	0.000	0.000
Oceania	0.000	0.000	0.004	0.000	0.000	0.000	0.010	0.000	0.000	0.000	0.000	0.000	0.004	0.000	0.004	0.000

Unit: $1*10^8$ m^3.

From the perspective of geographical location, except for South Asia, Central Asia, Northern Europe, North America, South America and Oceania, China's fishery virtual water trade with the other 14 regions showed a surplus, and overall also showed a surplus. The countries with the largest deficit are the United States, Chile, Vietnam, the Faroe Islands and Australia.

In terms of product categories of fishery virtual water net export, except salmon, catfish and trout, other products showed a surplus of 57 million m^3. Tilapia and Cyprinidae were the main net export categories, while salmon and catfish were the main net import categories.

3.3. Virtual water quantity per 100 g feed formula of different aquatic products $VW_{a,i}$

The contents of blue water and green water in 37 kinds of fish feed ingredients such as rapeseed cake, barley and starch can be found in the water footprint assessment manual on FAO's website. The content of blue water and green water in the corresponding feed can be obtained by multiplying the amount of feed formula required by each type of aquatic product per unit weight and adding them together. Figure 1 shows the calculation results of virtual water per 100 g feed formula for 22 aquatic products.

It is found that the blue water content of most freshwater fish products is higher than that of marine products. It reflects, during the process of aquaculture, the consumption of surface water and groundwater for most freshwater fish products is more than the consumption of marine products. Because the groundwater is a nonrenewable resource, the policies of limiting the aquaculture amount of most freshwater fish products, or improving the technology of it, or changing the feed composition of freshwater fish culture are needed.

3.4. Amount needed to breed different kinds of aquatic products per 100 g F_i

Applying the von Bertalanffy biological curve model shown in Equations (9)–(12) of Model 2, the feed consumptions of the 22 aquatic products in the whole breeding cycle are calculated. Then, according to the fishing time point ($t_{i,2}$), body weight $w_{i,t}(t_{i,2})$, the feed quantity F_i needed as input for each 100 g of different kinds of aquatic products was calculated. The results are shown in Figure 2. The bars of 'Feed Consumption During Growth' refer to the left *y*-axis (g), and the rhombus of 'Average Feed Consumption Per 100 g Body Weight' refers to the right *y*-axis (g).

The results showed that shellfish and crustacean products consume less fish feed than fish products. From the perspective of unit quality, the feed demand of crustacean products is more than that of shellfish, and the feed demand of shellfish is relatively low.

In addition to shrimps and prawns, sea urchins and cobia, there is a high correlation between the 'feed input per 100 g of different aquatic products' and 'feed consumption in the culture cycle'. It shows that the feed demand for most kinds of aquatic products is proportional to the weight of adult fish.

3.5. Virtual water content of different types of aquatic products per 10,000 g $VW_{i,j}$

Based on the above calculations, the virtual water content (L) of 22 kinds of aquatic products per 10,000 g (0.01 ton) could be obtained by using Equation (8). The calculation results are as follows.

Multiply the result of Table 3 by 100 to convert the unit of measurement into L/ton. It is found that the average virtual water content of Chinese aquaculture products is 329,346.66 L/ton. Sturgeons, shrimps and prawns are the most abundant, while clams and sea cucumbers are the least. We should focus on the production, consumption, import and export of cephalopods, crustaceans and marine fish products, and formulate certain quota aquaculture and trade-restrictive policies.

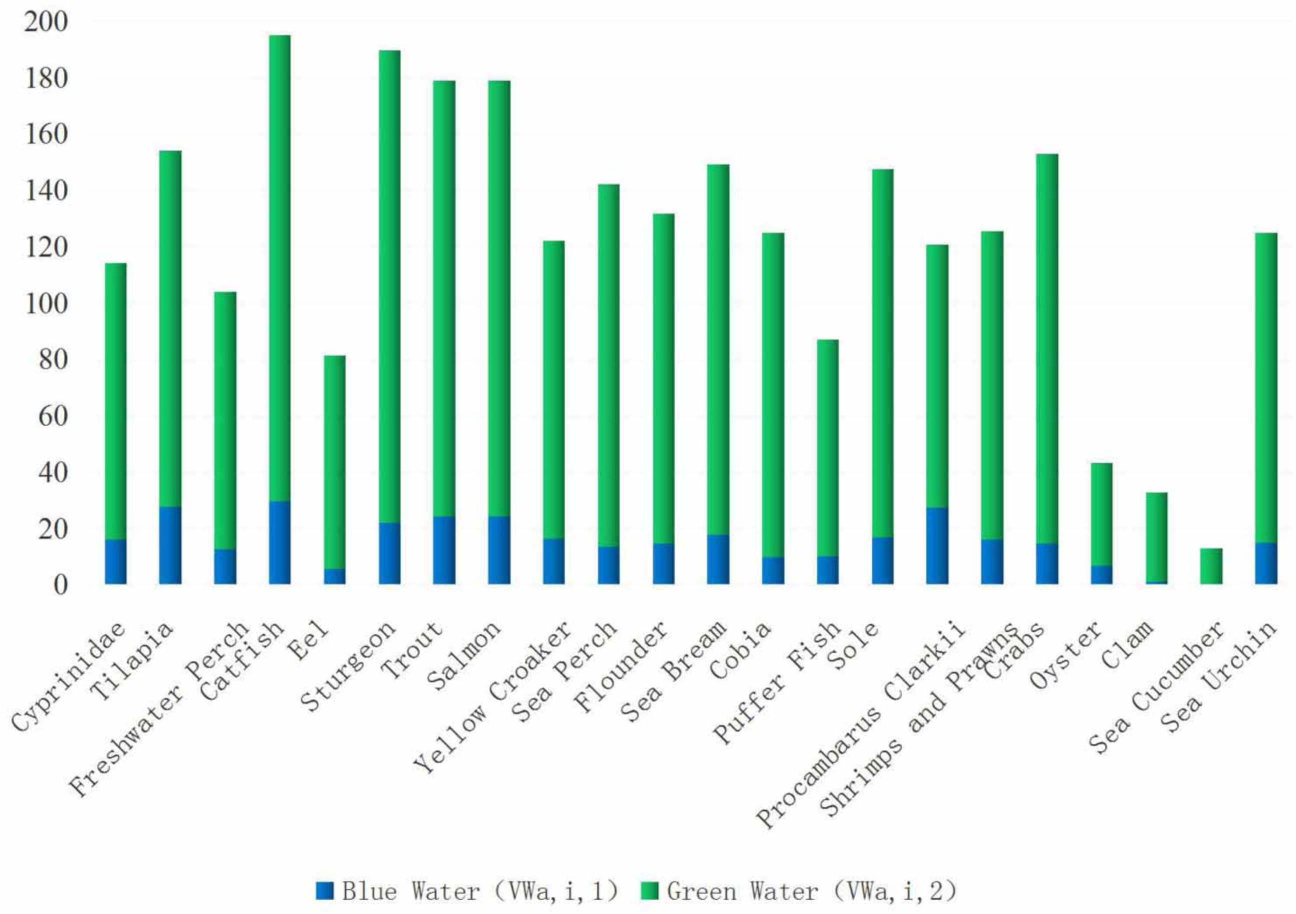

Fig. 1 | Calculation results of virtual water quantity per 100 g feed formula of different aquatic products (unit: L).

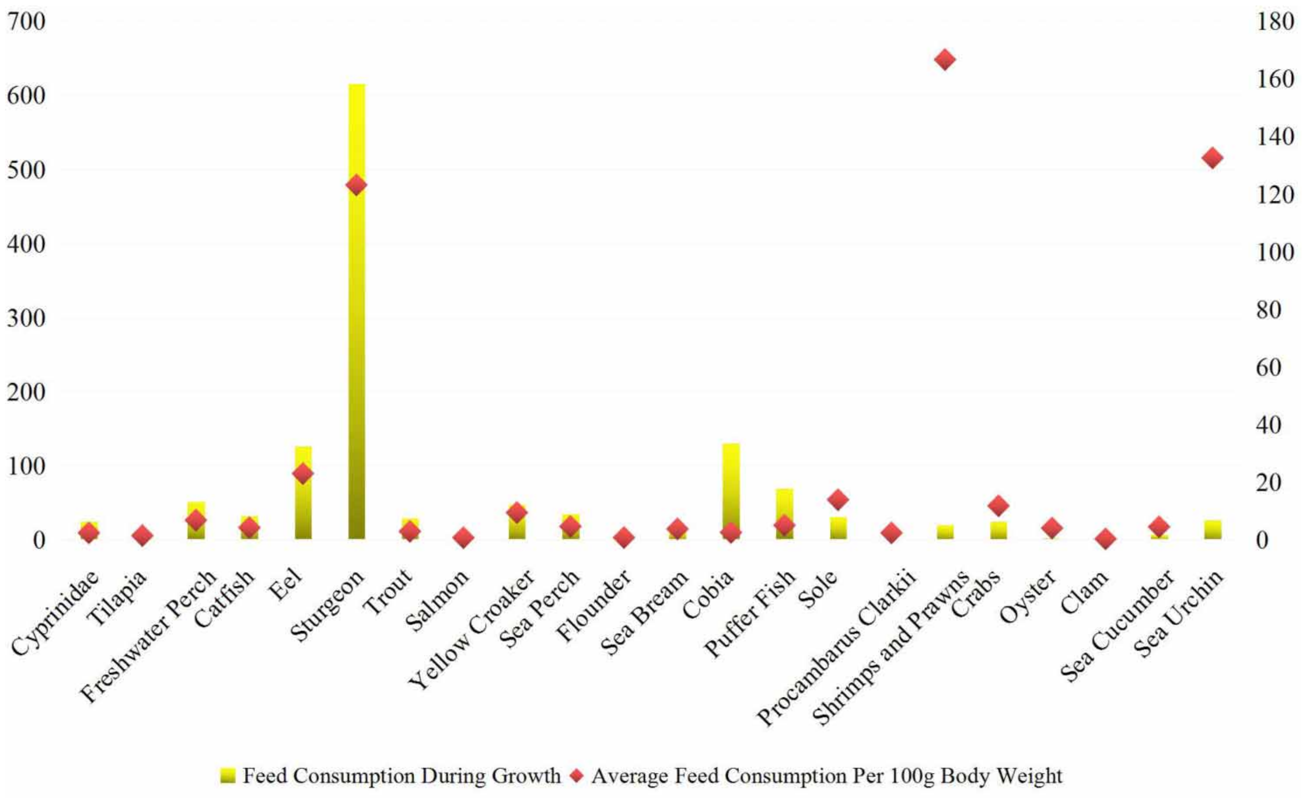

Fig. 2 | Calculation results of feed consumption during growth and feed input per 100 g of different aquatic products (unit: g).

Table 3 | Calculation results of virtual water content per 10,000 g of different aquatic products.

	Cyprinidae	Tilapia	Freshwater perch	Catfish	Eel	Sturgeon	Trout	Salmon	Yellow Croaker	Sea perch	Flounder
Blue water ($VW_{i,1}$)	40.51	42.06	87.13	128.00	131.31	2,718.24	72.79	19.29	157.76	64.55	12.39
Green water ($VW_{i,2}$)	243.85	190.68	627.41	707.04	1,745.54	20,683.36	460.43	122.06	1,004.24	603.33	96.95

	Sea bream	**Cobia**	**Pufferfish**	**Sole**	***Procambarus clarkii***	**Shrimps and prawns**	**Crabs**	**Oyster**	**Clam**	**Sea cucumber**	**Sea urchin**
Blue water ($VW_{i,1}$)	69.09	26.11	52.36	237.85	67.69	2,546.11	222.91	28.74	0.43	0.85	2,011.07
Green water ($VW_{i,2}$)	502.52	298.86	392.55	1,820.59	229.41	17,141.91	2,037.24	149.69	12.07	59.03	14,590.25

Unit: L.

3.6. Virtual water trade volume of China's main aquatic products

Taking the statistics of import and export of the 22 aquatic products, and multiplying with the results of the virtual water quality of their respective units, the output and input of virtual water output in the main aquatic products trade of 2017 in China were shown in the statistics of FAO ISSCAAP, as shown in Figure 3 (due to the limitation of layout, if the proportion of virtual water output and virtual water input is less than 0.1%, it does not appear in the figure).

Shrimps and prawns, sea urchins, crabs, sole, eel, yellow croaker and catfish are import products with large virtual water volumes. Taking 'shrimps and prawns' as an example, the virtual water content for these is 196.88 L/ton (according to Table 3), while the warm-water shrimps and prawns ranked first both in terms of VW input volume and VW output volume. Cold-water shrimps and prawns ranked behind catfish in terms of VW input volume, and ranked behind tilapia in terms of VW output volume. The VW input–output ratios are 1:2.02 and 1:1.80, respectively (Table 4).

Combined with the UN COMTRADE data, it is found that shrimps and prawns are mainly imported from Ecuador, Argentina, Canada and Thailand. Crabs are mainly imported from Russia, Canada, Bangladesh and the United States. Flounder is mainly imported from the United States, Russia, Japan and Canada. Eel is mainly imported from Japan, the United States, Russia and Hong Kong. Catfish are mainly imported from Vietnam, Cameroon, the Democratic Republic of Congo and Mali. With the exception of India and Bangladesh, China has fewer water resources per capita than these countries, according to Global Renewable Resources List (Mauro & Paolo, 2019). However, the virtual water volume of China's imported aquatic products is only 60% of that of its export. In addition, the export volume of most aquatic products with high water factor density is larger than that of low water factor intensive aquatic products, and the corresponding trade volume of this product is also higher. Therefore, the virtual water factor is one of the sources of comparative advantage of China's international trade of aquatic products.

From the analysis of the types of virtual water trade, there are several characteristics. First, China exports and imports similar products at the same time. Second, the intra-industry trade characteristics of virtual water trade are obvious. Third, the virtual water trade of China's aquatic products showed a net outflow and a net inflow of individual aquatic products.

From the theoretical basis of virtual water trade, the net output of China's aquatic products trade is 1.66 times the input, and the surplus of product weight is 1.95 times the imports. Through the virtual water trade of aquatic products, China can generate, to a certain degree, resource income. The virtual water element flow implied in China's foreign trade of aquatic products reflects the application of the H–O–V model: 'a country with relatively abundant endowment of one factor will become a net exporter of that factor and a net importer of another' (Vanek, 1968).

3.7. A brief summary of the results

Although the net output of aquatic products has decreased significantly, China is still a country with a virtual net output of aquatic products. The main destinations for China's fishery virtual water resources output are Southeast Asia (36%) and North America (11%). China's fishery virtual water resources are mainly imported from the American continent, with South America accounting for 23% and North America accounting for 34%.

The import–export weight ratio of freshwater fish is 1:2.43, and the import–export ratio of virtual water is 1:2.80, which does not indicate a water-saving effect. The import and export weight ratio of marine fish is 1:0.77, and the virtual water import–export ratio is 1:0.68, which can have a water-saving effect. The import and export weight ratio of crustaceans is 1:1.57, and the import–export ratio of virtual water is 1:1.75, which cannot have a water-saving effect. The import and export weight ratio of shellfish is 1:15.44, and that of virtual

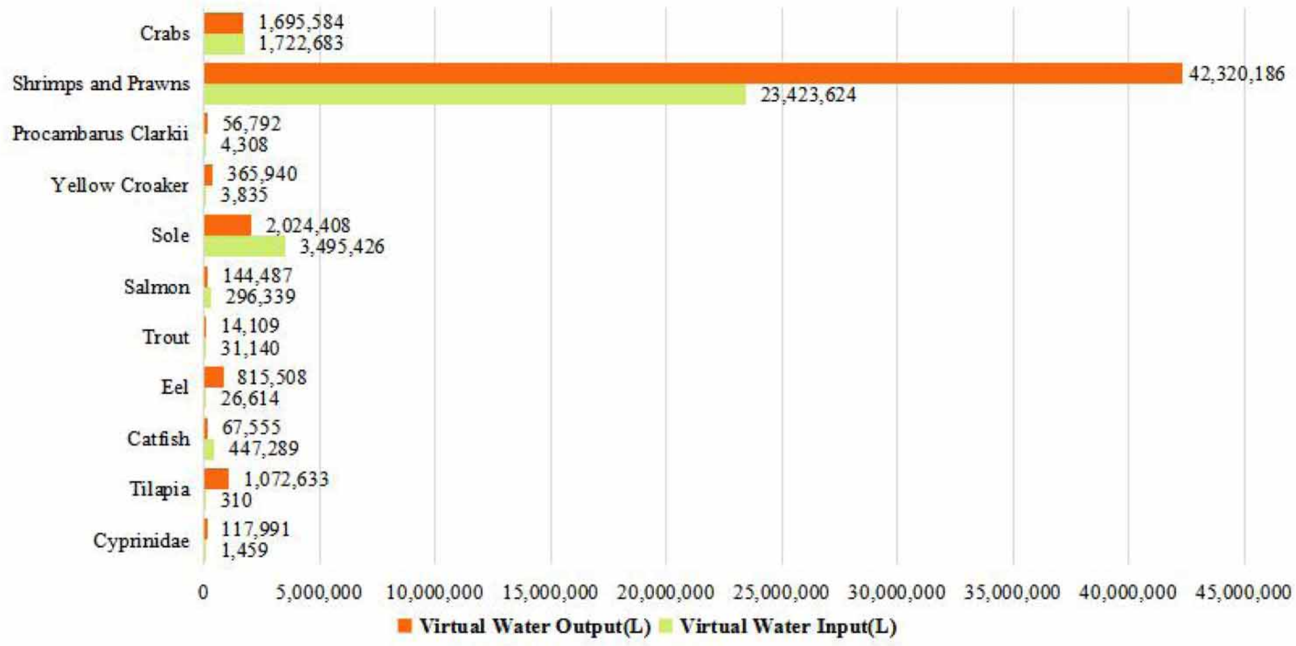

Fig. 3 | Volume of virtual water trade of China's main aquatic products in 2017 (unit: L).

Table 4 | Volume and proportion of virtual water trade of China's shrimps and prawns in 2017.

Item	Cold-water shrimps and prawns	Warm-water shrimps and prawns
Import volume (*t*)	2,132	116,842
Proportion of imported aquatic products (%)	0.33	17.91
VW input volume (*L*)	419,748	23,003,853
Proportion of VW input from aquatic products trade (%)	1.42	78.04
Export volume (*t*)	4,304	210,650
Proportion of exported aquatic products (%)	0.34	16.59
VW output volume (*L*)	847,371	41,472,772
Proportion of VW output from aquatic products trade (%)	1.74	84.97

water is 1:5.13, which cannot have a greater water-saving effect. The import–export weight ratio of mollusks is 1:0.16, and the import–export ratio of virtual water is 1:2.90, which cannot have a water-saving effect in particular. Therefore, at present, China's aquatic products trade is not generally water-saving, so the water-saving function of aquatic products trade needs to be improved.

4. DISCUSSION

Although there are some differences between the two methods from the perspective of industry and species, there are two things in common: First, China is still a net exporter of aquatic products virtual water trade. Second, the virtual water trade of aquatic products in China is not centralized and unbalanced. Method 1 shows that the flow of virtual water resources in China is related to spatial distance, economic development, eating habits, consumption psychology and resource endowment. The output of China's fishery virtual water resources is mainly due to the large export of tilapia products, and the input is mainly dependent on the large quantity import of salmon products; Method 2 shows that shrimps and prawns, eel, yellow croaker, oyster and sea perch in export trade all belong to the products with larger virtual water volume, while salmon, sea cucumber and crabs in import trade belong to aquatic products with smaller virtual water volume.

This implies that the environmental policies should be made differently to suit the local conditions and species, rather than crossing the board. The central government could give the policy-making power to provincial or county-level governments. The underlying economic model should be flexible and adaptable to various practical situations, with the support of not only the ministry of natural resources, but also the fishery administration department, customs and local government.

Second, about the methods, Method 1 can contribute to adjusting import and export policies, such as increasing/reducing tariffs on certain products and setting/removing environmental trade barriers. For FAO, the result could be a reference of sustainable fishery virtual water resources using global valuation to put forward some suggestions on the change of diet structure and consumption structure for human beings. Method 2 contributes to examining the value of aquatic products trade from the view of sustainable utilization of water resources, not only from the view of general goods trade value, in a country/region, even on a global scale.

Third, about the limitations of this study, in the UN COMTRADE database, the classification is relatively simple and can only reflect the virtual flow of trade in seven categories of freshwater fish. The deficiencies are mainly due to a lack of data. With the increasing emphasis on the virtual water issue, the coverage in relevant databases may improve in future.

Fourth, regarding the policies to make, in order to uphold the scientific concept of sustainable development, maintain the security of water resources and food security and promote the green transformation of China's fisheries, it is necessary to optimize the trade structure of aquatic products. Reducing the export of products with high virtual water content and animal products that cannot play a water-saving role (mollusks, shrimps and spawns and freshwater fish), increasing the export of products with low virtual water content that can have water-saving effects (marine fish and shellfish), and increasing the import of products with high consumption of virtual water resources (shrimps and spawns, sturgeon and sea urchins) are necessary from the viewpoint of virtual water. Raising the tariff levels of the VW aquatic products, so that the scarce water resources are appropriately valued in the products; taxing the aquaculture products exporting firms, in order to contain the use of freshwater and other types of waters; and incentivizing the firms to adopt the water-saving technologies/processing practices help reduce the water footprint of the products.

Moreover, investment in fishery science and technology should be increased, and the level of water-saving efficiency of fish feed and aquaculture mode with intensive and environment-friendly cultivation techniques should be lifted.

Most importantly, we should help fishermen establish environmental awareness, and appropriately change people's eating habits and needs. At present, the water consumption of the fishery sector accounts for about 30% of the agricultural sector, and the water consumption coefficient of fishery breeding is more than 10 times that of crop planting. Whether the fishery can do a good job of water-saving is related to the water-saving efficiency of the whole large-scale agriculture.

Last, as water sustainability is a global issue, virtual water trade should be planned considering water as a common good. An 'Aquatic Virtual Water Balance Plan' could be proposed. First, the virtual water quantity of different kinds of aquatic products can be calculated by the virtual water method of feed formula, and the results of each country and globally should be published to the public. The results will be beneficial to the shopping choices of ordinary people and the policy choices of the government. Secondly, it is hoped a global aquatic virtual water trade market will be established. The market mechanism is introduced into the allocation of water resources to stimulate endogenous water-saving power.

5. CONCLUSION

Nowadays, the 'virtual water' concept provides a new idea for saving water for product production and service, optimizing industrial structure and trade structure.

Do aquatic products trade waste or save water resources? It's a question that has been overlooked in the former studies focusing on the aquatic products trade. Based on the fishery resources endowment, this literature mainly discussed the global optimal allocation of aquatic products, without consideration of water resources. The case of China is a typical example: as the most important contributor to global aquatic products, her fishery resources are abundant, but her water resources are very scarce. Therefore, it is important to analyze the virtue water related to her aquatic products trade.

In the end, two improved methods were grafted into this paper, which connected the water resources with the aquatic products trade. It was found that China's aquatic product trade is water-saving in general, from the perspective of species distribution and regional distribution, it is not centralized and unbalanced. This result implies that through aquatic products trade, a country may be able to save water resources, but the specific degree is not equal in different trade varieties and different trade partners. It may depend on spatial distance, economic development, eating habits, consumption psychology, resource endowment and a lot of other factors. The idea of the study casts a new light on the aquatic products trade. The study could be a scientific reference to make water policies and carry out water-saving actions, especially trade agreements and environmental laws with respect to water services and human rights protection. When dealing with relevant issues, it is suggested that we should consider the power from technology innovation, market mechanisms, collaboration between government departments and fishermen's cooperation.

But at present, the research on the calculation method of virtual resources is still limited, and it is necessary to pay attention to it. In future studies, virtual cultivated land and other virtual resources can also be included in the model and analysis framework. The works will not only enrich the theory of virtual resource accounting and sustainable development, but also make valuable contributions to a community with a shared future for mankind.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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