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Social network analysis of virtual water trade among major countries in the world

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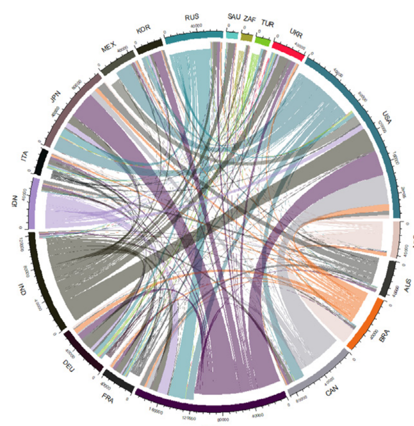
HIGHLIGHTS

- Multi-region input–output model is adapted to calculate the virtual water trade.
- This paper uses social network analysis to study virtual water trade networks.
- The Out-Degree and In-Degree of the virtual water trade network increased in 2006–2015.
- Reduce the logistics cost of trade to expand virtual water trade.
- Expand the virtual water trade to alleviate the pressure on water supply.

GRAPHICAL ABSTRACT



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ABSTRACT

This study utilizes multi-region input–output model to calculate the virtual water trade among 19 major countries (the Group 20 countries, except the EU) from 2006 to 2015. Moreover, this paper uses network analysis method to study the characteristics of virtual water trade networks. Results show that: (1) the import and export of the virtual water trade among 19 major countries in 2015 increased in varying degrees. Among them, the growth rates of China's import and Russia's export were the highest. (2) The density(average value) and asymmetry(differences between import and export)of the virtual water trade network among the major countries in 2006–2015 increased throughout the whole industry and the three major industries. In comparison with the secondary and tertiary industries, the virtual water trade network formed by the primary industry is denser. (3) The Out-Degree(corresponding to export) and In-Degree(corresponding to import)of countries in the virtual water trade network of the whole industry increased in varying degrees in 2015. Major countries exhibited the largest export and import within the primary industry, except for Japan and South Korea. Therefore, in order to alleviate the contradiction between supply and demand of water resources in various countries, it is necessary to further strengthen the construction of transportation facilities and reduce the logistics cost of trade in industrial and agricultural products, especially the trade cost of agricultural products such as grain, so as to further expand the virtual water import and export trade to expand the import and export trade of the virtual water network further.

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1. Introduction

Water is an indispensable resource for human survival and economic development, which is widely used in industrial and agricultural production and for residential purposes. Most importantly, water maintains the balance of the ecological environment. The current uneven distribution of global water resources has seriously affected the economic development of various countries. Thus, a new virtual water trade strategy[1] has been formulated to alleviate the gap between water supply and demand. The virtual water trade strategy refers to a strategy in which water-scarce countries (regions) import industrial and agricultural products or services from water-rich countries (regions) to replace their own production (Allan, 1993).In order to better implement the virtual water trade strategy, it is necessary to account for virtual water trade between major countries (regions) around the world. As the virtual water trade between major countries (regions) in the world and the virtual water trade network can reflect import and export trade balance of each country; it also has a realistic importance to analyze the network characteristics of the virtual water trade.

Allan's (1993) study makes the first effort to propose the concept of virtual water trade. Hoekstra and Hung (2002) have been the first to study the accounting method of virtual water trade in food crops. They pointed out that the key to calculating the virtual water trade volume of food crops is to calculate the virtual water content. Based on the calculated virtual water content of food crops, the virtual water trade volume of food crops can be obtained by multiplying the virtual water content by the product trade volume. Virtual water trade can be obtained by multiplying virtual water content by the trade volume of products. Chapagain and Hoekstra (2003) have further proposed an accounting method to obtain the virtual water trade of living animals and their products. This method aggregates the amount of water consumed by each animal during each stage of growth and specifically considers the value factor of the weighted calculation of the product with the scale factor. Subsequently, researchers used the above methods to conduct empirical research on the virtual water trade of agricultural products in various countries (Zhang et al., 2016; Antonelli et al., 2017; Zhang et al., 2018; Taherzadeh and Caro, 2019; Liu et al., 2020).

The method proposed by Hoekstra and Hung (2002) and Chapagain and Hoekstra (2003) to calculate the virtual water trade volume according to product production steps is an effective method for calculating the virtual water trade volume of agricultural products, but it is inconvenient in calculating the volume of industrial products and service industry products due to its complicated calculation process. Thus, some researchers propose to use the input-output method to calculate the virtual water trade volume of various industries, which method can be divided into a single-region input-output model and a multi-regional input-output model according to the number of research areas. The steps adopted by these two models are basically the same. In the input–output model, the water use data of each industry divided by the total output is used to obtain the coefficient of direct water use. Then, the coefficient of direct water use is multiplied with the Leontief inverse matrix. Finally, the import and export in the input–output table is used to obtain virtual water trade volume in various industries (Deng et al., 2015; Zhao et al., 2015; Serrano et al., 2016; Tian et al., 2018; Wiedmann and Lenzen, 2018; Sun et al., 2019).

In addition, researchers have also studied the network characteristics of virtual water trade among countries (regions) around the world. Konar et al. (2011) have studied the virtual water trade of food products in various countries in 2000. They pointed out that the US plays a key role in maintaining the global network architecture. Dalin et al. (2012) have studied the evolution of virtual water trade networks of food among countries from 1986 to 2007. They have found that China's virtual water imports of agricultural products increased sharply after 2000. Fang and Chen (2015) have used the network analysis method to study the virtual water trade network among the regions located at the Heihe River Basin in China from 2002 to 2010. They have determined that the virtual water trade network among the regions around the basin tends to be symbiotic and synergistic. Tuninetti et al. (2017) established a prediction model for the virtual water trade network of agricultural products, pointing out that population, geographical distance, and agricultural efficiency are the main factors driving the existence of bilateral trade.

Existing literature has conducted considerable research on virtual water trade (especially the virtual water trade of agricultural products) in various countries. However, the research does not involve the virtual water trade of industrial products and service products among major countries. A lack of corresponding research on network characteristics also exists. The main innovation of this paper is to use social network analysis method to study the virtual water trade network among the main countries in the world, as none of the existing literatures use this method to analyze the network characteristics of virtual water trade network. In addition, the virtual water trade network diagrams (Figs. 2 to 3 and 5 to 7) also incorporate the network characteristics indicators involved in social network analysis. In order to better implement the virtual water trade strategy, it is necessary to further calculate the virtual water trade between the major countries (regions) in the world, and to explore the balance of virtual water trade among countries (regions) in combination with network characteristic indicators. To fill this research gap, this study uses the multi-regional input–output table data and water use data obtained from the EORA database[2] to conduct virtual water trade across the whole industry and three other major industries among major countries (the Group 20 countries, except the EU) from 2006 to 2015. The accounting and analysis of the network characteristics of the virtual water trade are discussed in the following sections.

2. Methods and data sources

2.1. Multi-regional input–output model

First, we set the following direct water coefficient w:

$$w_i^r = \frac{W_i^r}{X_i^r} \tag{1}$$

where the superscript r represents the first country (region), the subscript i represents the primary industry. W is the water consumption, and X is the total output amount.[3] The formula for the balance of the world input–output tables in the EORA database (Lenzen et al., 2012; Lenzen et al., 2013) is written as:

$$AX + Y = X \tag{2}$$

where A is the $mn \times mn$ order coefficient matrix of direct consumption (m is the total number of countries (regions), whereas n is the total number of industries). X is the $mn \times 1$ order of the total output column vector, and Y is the $mn \times 1$ order of the final used column vector. According to Formula (2), the formula can be rewritten as:

$$X = (I-A)^{-1}Y = LY \tag{3}$$

where $L = (I - A)^{-1}$ is the $mn \times mn$ order of the Leontief inverse matrix. Referring to Jiang et al. (2015) and Duarte et al. (2018), the virtual water trade matrix H can be obtained by multiplying the direct water coefficient diagonal matrix W, the Leontief's inverse matrix L, and the final used matrix Z.

[1] Compared with real water trade, virtual water trade is a new strategy.

[2] https://www.worldmrio.com/

[3] The meaning of W and X can be more clearly understood by considering the structure of the input-output table in the EORA database.

$$H = \hat{W}LZ \tag{4}$$

where the order of the final matrix is the $mn \times m$ order, and the column vector Y finally can be obtained by summarizing each row element in the matrix Z. According to the $mn \times m$ order of the virtual water trade matrix H calculated by Formula (4), we can obtain the $m \times m$ order virtual water trade matrix T by further merging each country (region) by industry. The diagonal elements of the matrix T are the virtual water consumption of the products produced by the countries (regions), whereas the non-diagonal elements are the virtual water import and export trade. This study only considers the non-diagonal elements of the matrix T, where $t^{rs}(r \neq s)$ indicates the bilateral trade volume between country r and country s, which can be seen as the virtual water export from country r to country s, or the virtual water import from country r to country s.

2.2. Characteristics of trade network

Various indicators are used to represent the characteristics of the trade network (Wasserman and Faust, 1994). This study examines the density, asymmetry, Out-Degree, and In-Degree of the virtual water trade network.

The network density considered in this paper is the average of the elements on the off-diagonal line of the virtual water trade matrix T, which is expressed as follows:

$$D = \frac{\sum_{r \neq s, r=1}^{m} \sum_{s=1}^{m} t^{rs}}{m(m-1)}. \tag{5}$$

A greater density of network entails a greater average value of the virtual water trade among countries and a closer relationship. The virtual water imports of countries are generally not equal to the virtual water outlets. Thus, the matrix T is generally an asymmetric matrix. The following indicators are defined to measure the asymmetry of the matrix T[4]:

$$S = \frac{\sum_{r \neq s, r=1}^{m} \sum_{s=1}^{m} | t^{rs} - t^{sr} |}{m(m-1)} \tag{6}$$

The greater the value S, the greater the virtual water trade deficit (or surplus) among major countries. Outreach refers to the sum of virtual water outlets (i.e., the sum of the elements in row r in matrix T corresponding to the virtual water trade network), whereas the degree of entry refers to the sum of virtual water imports (i.e., the sum of the elements in the s column of the matrix T corresponding to the virtual water trade network). They are expressed by the following formula:

$$OD = \sum_{s \neq r, s=1}^{m} t^{rs} \tag{7}$$

$$ID = \sum_{r \neq s, r=1}^{m} t^{rs} \tag{8}$$

The greater the Out-Degree (OD), the more virtual water exports in the country. Greater In-Degree (ID) indicates that a country has more virtual water imports. A greater Out-Degree than In-Degree indicates a virtual water trade surplus in the country. Otherwise, the country faces deficit. OD (ID) can reflect the overall situation of imports and exports of countries in the virtual water trading network, but it cannot reflect the bilateral and multilateral trade between countries. Multilateral virtual water trade between countries needs to be displayed through network visualization graphics (Figs. 2, 3, 5, 6, and 7).In addition, virtual water trade exists between two major countries, thus the virtual water trade matrix T is strongly connected.

It should be noted that there are many indicators that can reflect the network characteristics. This article only selects indicators that are closely related to the virtual water trade network. More network characteristic indicators (such as point centrality, near centrality, intermediate centrality, agglomerate subgroups, block models, structural holes, and core-edge analysis) can be found in Wasserman and Faust (1994) and Liu (2004, 2009). If these characteristic indicators are used to analyze the virtual water trade network between the major countries (regions) in the world, the elements in the initial virtual water trade network need to be 0–1 transformed. i.e., the virtual water trade network is transformed into non-connected, which will lead to the losing of some information of the original virtual water trade network. So, under the premise of not losing network information, this paper only selects the characteristic indicators closely related to the virtual water trade network for research.

2.3. Data sources

The input–output tables and water use data in this study are obtained from the EORA database (Lenzen et al., 2012; Lenzen et al., 2013). The EORA26 version includes a multi-regional, multi-sector input–output table composed of 26 departments in 190 countries (regions) from 1990 to 2015. The data includes the use of green water, blue water, and grey water in 26 sectors of each country (region) (the specific data please refer to https://www.worldmrio.com/ or the Annex of this paper). In this study, water use is the sum of the use of green water, blue water, and grey water. Moreover, the data from 19 countries (regions) with a large amount of virtual water import and export trade from 2006 to 2015 are selected for the network characteristics of virtual water trade analysis. The 19 countries (regions) are as follows: Argentina(ARG), Australia(AUS), Brazil(BRA), Canada(CAN), China(CHN), France(FRA), Germany(DEU), India(IND), Indonesia (IDN), Italy(ITA), Japan(JPN), Korea(KOR), Mexico(MEX), Saudi Arabia (SAU), South Africa(ZAF), Turkey(TUR), the UK(UKR), the US(USA), and Russia(RUS). These countries (regions) are included in the G20 (except the EU), whereas the other countries (regions) are merged into ROW in the table.

3. Results and discussions

3.1. Accounting results of virtual water trade among major countries (regions)

The whole industry of virtual water imports and exports of the major countries (regions) in 2006 and 2015 is calculated by utilizing the multi-region input–output model as shown in Table 1.

The virtual water imports and exports of major countries (regions) have increased in varying degrees, especially in 2015 due to the further improvement of transportation facilities in recent years. Moreover, the logistics costs are continually decreasing. Thus, the trade volume of each country is further expanding. Among the data for imports, the growth rate of China's virtual water import is the highest, which accounts to 267.94%.[5] This rate is due to the large increase in imports of agricultural products, especially soybeans, and the high virtual water content of agricultural products in recent years. The growth of virtual water imports in South Africa is relatively slow, with a growth rate of only 31.62%. For exports, Russia's virtual water exports have the highest growth rate of 131.04%. By contrast, Mexico has the lowest growth rate

[4] Given that the virtual water outlet of the country r to the country s is equal to the virtual water inlet of the country s from the country r, the sum is equal to 0 after the summation if the absolute value is not taken in Formula (6).

[5] The growth rate of this part is not an annual growth rate. There is a 9-year gap between 2006 and 2015, and the growth rate in this paper refers to the growth rate of virtual water trade in 2015 compared to 2006.In this paper, Growth rate of virtual water imports = (imports of 2015 –imports of 2006) / imports of 2006 × 100%; Virtual water export growth rate = (exports of 2015– exports of 2006) / export of 2006 × 100%.

Table 1
Virtual water import and export of the whole industry among major countries (regions) in 2006 and 2015 (Unit: Mm^3 and %).

Countries (Regions)	2006		2015		Growth Rate	
	Imports	Exports	Imports	Exports	Imports	Exports
Argentina	4350.02	26,168.44	10,575.52	49,983.43	143.11	91.01
Australia	9826.02	26,565.41	17,263.60	56,092.01	75.69	111.15
Brazil	17,665.17	37,121.06	42,795.95	66,874.17	142.26	80.15
Canada	23,977.12	57,359.51	42,120.29	70,363.28	75.67	22.67
China	58,211.15	122,508.74	214,184.51	179,470.19	267.94	46.50
France	57,114.45	19,075.54	84,206.92	24,558.17	47.44	28.74
Germany	106,626.98	11,754.03	160,776.48	16,086.13	50.78	36.86
India	32,199.46	95,652.94	73,794.43	192,988.25	129.18	101.76
Indonesia	13,163.25	34,941.79	27,410.33	67,339.65	108.23	92.72
Italy	43,849.33	15,015.26	61,245.57	19,412.72	39.67	29.29
Japan	164,476.34	671.94	251,222.32	858.65	52.74	27.79
Mexico	25,962.37	12,838.73	43,409.88	15,745.29	67.20	22.64
South Korea	27,995.41	921.73	56,067.79	1434.08	100.27	55.59
Russia	61,825.80	45,243.50	135,256.59	104,532.72	118.77	131.04
Saudi Arabia	18,173.41	461.65	45,421.14	756.71	149.93	63.91
South Africa	13,770.77	9906.95	18,125.00	15,865.80	31.62	60.15
Turkey	17,307.86	12,349.76	35,412.51	16,227.88	104.60	31.40
UK	64,421.82	2756.66	93,927.93	3542.63	45.80	28.51
USA	202,576.37	61,280.80	271,706.88	110,194.47	34.13	79.82
ROW	179,120.90	550,019.54	344,642.53	1,017,239.95	92.41	84.95
Total	1,142,613.97	1,142,613.97	2,029,566.17	2,029,566.17	77.62	77.62

Note: Import and export in ROW refers to the import and export of 19 countries, such as Argentina, in other parts of the world, excluding trade among countries (regions) in other parts of the world.

of only 22.64%. In addition, the virtual water export of country A to country B is equal to the virtual water import of country B from country A. Thus, from the total value, the virtual water import volume per year is equal to the virtual water export volume. In addition, the growth rate of imports is equal to the growth rate of exports.

The country with the largest virtual water import in 2006 was the US, with a total of 202,576.37 Mm^3. Argentina's virtual water imports were the lowest at 4350.02 Mm^3.The country with the largest virtual water export volume was China, with a total of 122,508.74 Mm^3. By contrast, Saudi Arabia's virtual water exports were the lowest at 461.65 Mm^3. The country with the largest virtual water imports in 2015 was still the US, with a maximum of 271,706.88 Mm^3. By contrast, Argentina's virtual water imports were the lowest at 10,575.52 Mm^3. The country with the largest virtual water exports was India, with a total of 192,988.25 Mm^3. By contrast, Saudi Arabia's virtual water exports were the lowest at 756.71 Mm^3. In addition, the proportion of virtual water imports in the 19 major countries reached more than 80%, whereas the proportion of virtual water exports in total was approximately 50%. These results showed that the virtual water trade in the world was mainly concentrated in these 19 major countries (regions).

In 2006 and 2015, virtual water exports were larger than virtual water imports. Specifically, countries (regions) with virtual water trade surpluses included Argentina, Australia, Brazil, Canada, India, Indonesia. However, China had a virtual water trade surplus in 2006 and a virtual water trade deficit in 2015.

Due to the further improvement of transportation facilities in various countries in the world in recent years, the cost of logistics is getting lower and lower, so the product trade volume of each country is further expanding, and the virtual water trade volume is also increasing. As China's imports of agricultural products, especially soybeans, have increased substantially in recent years, and the virtual water content of agricultural products is relatively high,[6] China's virtual water import growth rate is the highest. In addition, since the virtual water export from country A to country B is equal to the virtual water import from country A from country B, in terms of total value, not only the annual virtual water import volume is equal to the virtual water export volume, but also the growth rate of imports it is equal to the growth rate of exports. A similar phenomenon also has been found by Deng et al. (2016) in the study of virtual water trade among eight regions of China.[7]

At present, some literatures have examined the balance of global virtual water trade (Konar et al., 2011; Dalin et al., 2012; Wiedmann and Lenzen, 2018). The balance of imports and exports of countries in this article can be used to reflect the balance of virtual water trade. In addition, the export and imports of countries in the virtual water trade network are also indicators corresponding to virtual water exports and virtual water imports. The trade balance of each country can also be comprehensively reflected by the asymmetry index of the virtual water trade network (ie, Formula 6) in this paper. In fact, the data matrix corresponding to the virtual water trade network reflects the multilateral virtual water trade between multiple countries, and the elements t^{rs} in the matrix reflect the country s 's virtual water exports to the country r (that is, the country r 's virtual water imports from the country s), and t^{rs} reflects the country r's virtual water import from the country s (ie, the country s's virtual water export to the country r), and the difference between the elements in the matrix (t^{rs} - t^{sr}) reflects the virtual water trade surplus of country r (ie, the country s's virtual water trade deficit).

It should be noted that there may still be a large number of net virtual water exports in areas with water shortages. According to the accounting results in Table 1, China had a large number of net virtual water exports in 2006, but China had a serious water shortage problem, which phenomenon has also been found in the literature that originally proposed virtual water trade accounting methods (Hoekstra and Hung, 2002; Chapagain and Hoekstra, 2003), Deng et al. (2018) also pointed out that there was a net virtual export of water in China in 2012.In addition, even in different regions within a country, there may be virtual net transfers of water to regions with abundant water resources (Deng et al., 2016).Therefore, the pattern of global virtual water trade is not determined by the shortage of water resources. A reasonable explanation for this phenomenon is that the production of a product not only consumes water resources, but also requires the input of multiple factors such as capital, labor, land and energy. If there is capital, labor,

[6] Compared with industrial products, it need more water resource for producing one unit of agricultural products. That is, the virtual water content of agricultural products is higher.

[7] Deng et al. (2016) pointed out that if only domestic trade is considered, the sum of transfer-out amount of the virtual water in the eight major regions of China is equal to the sum of the transfer-in amount of virtual water.

Table 2
Density and asymmetry of the entire industry virtual water trade network among the 19 major countries from 2006 to 2015 (unit: Mm^3).

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Density	1208.99	1353.62	1612.79	1303.77	1636.52	1987.48	2007.31	2042.26	2071.85	1952.29
Asymmetry	1811.92	1984.42	2368.58	1889.80	2368.35	2866.02	2880.64	2913.22	2965.72	2791.40

land or energy Comparative advantage may still exist in net virtual water exports (Ansink, 2010; Reimer, 2012), and it is wrong to simply assume that net virtual water exports will not exist in areas with water shortages. Based on the above reasons, this paper does not calculate the water shortage index of each country, and uses this index to study the virtual water trade network between the major countries in the world (Pfister et al., 2009; Feng et al., 2014; Liao et al., 2018; Zhao et al., 2018).

Table 1 reveals the virtual water trade volume of the 19 major countries (regions). However, the table does not reveal the mutual trade among these major countries (regions). Therefore, in this study, we further analyze the network characteristics of virtual water trade among these 19 major countries (no longer considering the rest of the world).[8]

3.2. Characteristic analysis of virtual water trade network among the 19 major countries

In this section, we first analyze the characteristics of virtual water trade networks in all industries among the 19 major countries. Then, we describe the characteristics of virtual water trade networks among the 19 major countries according to the division of three major industries. As ROW includes multiple countries (regions), the virtual water trade volume between ROW and major countries in the world is very large (Table 1 shows that the total amount of virtual water imports or exports of ROW to major countries in the world are large). If ROW is added to the virtual water trade network diagram, the virtual water trade volume among the main countries looks very small in the figure (i.e, only highlight the virtual water trade between ROW and major countries in the world), which will affect the expressive effect of the diagram (it's neither to represent it by the string diagram). In addition, the purpose of this paper is to study the virtual water trade network among the major countries in the world, so ROW is excluded in Section 3.2.

3.2.1. Analysis of the characteristics of virtual water trade network in the entire industry

The calculation results of the density and asymmetry indicators of the entire industry of the virtual water trade network among the 19 major countries from 2006 to 2015 are shown in Table 2.

As shown in Table 2, the density and asymmetry indicators of the whole industry of the virtual water trade network among the 19 major countries showed an increasing trend from 2006 to 2015 (except for 2009 and 2015). This finding indicates that the world's virtual water trade among the 19 major countries is getting closer annually. Moreover, the gap between virtual water imports and exports is growing. The direct cause of the low virtual water trade among the 19 major countries in 2009 and 2015 was the decline in product and service trade; the deeper reason was the impact of the financial crisis. In addition, there is a certain lag in the impact of the financial crisis on trade, so the financial crisis in 2008 led to the decline of virtual water trade volume. According to Formula (5), the network density of the virtual water trade network is actually the average value of the non-diagonal elements in the trade matrix formed by the virtual water trade between two countries. Therefore, when the virtual water trade between countries increases (decreases), the network density of the virtual water trading network must also increase (decreases).

This study takes 2006 and 2015 as examples to illustrate the calculation results of the Out-Degree and In-Degree of the industry-wide virtual water trade network among the 19 major countries, as shown in Table 3.

The import and export in Table 1 correspond to the degree of entry and exit in Table 3, respectively. However, the corresponding data in Tables 1 and 3 are different. For example, the volume of virtual water imports of Argentina in 2006 was 4350.02 Mm^3, whereas Table 3 shows that Argentina's In-Degree rate in 2006 was 2438.48 Mm^3. Argentina's virtual water imports from 18 countries accounted to 2438.48 Mm^3, and from other parts of the world accounted to 1911.54 Mm^3.

As shown in Table 3, (1) the country with the largest Out-Degree rate in 2006 and 2015 is China, with a total of 85,873.68 Mm^3 and 117,272.95 Mm^3, respectively. The country with the smallest expenditures in 2006 and 2015 was Saudi Arabia, with a total of 354.66 Mm^3 and 549.65 Mm^3, respectively. These findings show that in 2006 and 2015, China's virtual water exports were the largest in the virtual water trade among the 19 major countries. By contrast, Saudi Arabia's virtual water exports were the smallest. (2) In 2006 and 2015, the country with the highest In-Degree rate was the US, with a total of 119,889.7 Mm^3 and 145,884.71 Mm^3, respectively. The countries with the smallest In-Degree rates were Argentina and Saudi Arabia, with the values of 2437.48 Mm^3 and 6424.46 Mm^3, respectively. These findings show that in 2006 and 2015, the US had the largest virtual water imports in the virtual trade among the 19 major countries. In 2006, Argentina's virtual water imports were the smallest. In 2015, Saudi Arabia's virtual water imports were the smallest. (3) The Out-Degree and In-Degree rates of all countries increased in 2015. With the construction of convenient transportation, the trade links among major countries increased. According to Formula (7) and Formula (8), the Out-Degree in the virtual water trading network corresponds to the virtual water export, and the In-Degree corresponds to the virtual water import. Therefore, when the virtual water imports and export of each

Table 3
Out-Degree and In-Degree of the industry-wide virtual water trade network among the 19 major countries in 2006 and 2015 (unit: Mm^3).

Countries	2006		2015	
	Out-Degree	In-Degree	Out-Degree	In-Degree
Argentina	19,377.74	2438.48	36,936.53	6466.67
Australia	17,943.94	3875.88	36,178.98	7723.75
Brazil	25,595.34	10,798.34	43,684.96	26,594.61
Canada	51,811.05	15,350.99	61,657.07	27,044.77
China	85,873.38	19,536.85	117,272.95	72,572.29
France	11,364.39	18,418.50	14,126.78	27,390.27
Germany	6134.93	37,571.77	8361.72	54,575.82
India	62,524.04	3450.12	115,508.58	8545.13
Indonesia	24,341.74	6626.84	46,983.87	14,882.84
Italy	9030.53	15,089.18	11,374.59	20,783.29
Japan	487.74	77,205.89	614.35	107,220.22
Mexico	11,928.92	17,977.73	14,257.83	31,927.83
South Korea	714.81	16,336.60	1102.17	31,775.71
Russia	24,822.37	7259.04	55,971.47	15,865.30
Saudi Arabia	354.66	5653.51	549.65	13,986.06
South Africa	5191.09	3520.91	7451.30	6424.46
Turkey	7952.64	3890.74	9829.86	8515.95
UK	1455.62	28,582.46	1789.05	39,504.01
USA	46,568.61	119,889.70	84,031.98	145,884.71

[8] According to the calculation results in Table 1, in 2006, the major 19 countries' virtual water imports accounted for 84.32% (963,493.07 / 1,142,613.97) of the world's total amount, and the virtual water exports accounted for 51.86% of the world's total amount, which are 83.02% and 49.88% in 2015. Therefore, for the sake of convenience, this paper only studies the virtual water trade among the 19 most important countries in the world.

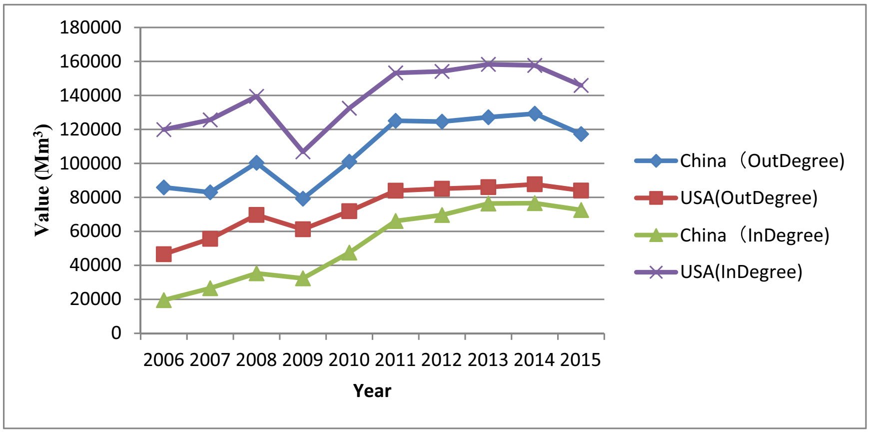

Fig. 1. Out-Degree and In-Degreerates of China and US from 2006 to 2015.

country increases, the in-degree and out-degree index values of the virtual water network of countries in the network will also increase.

According to the results in Table 3, in 2006 and 2015, the country with the most out flow in the virtual water trading network was China, and the country with the most outflow was the United States. Therefore, this article takes the two countries with the highest outflow and inflow as examples to further analyze the changes in the out-degree and in-degree of the virtual water trading network of the entire industry from 2006 to 2015.

As shown in Fig. 1, (1) the Out-Degree and In-Degree rates of China and the US generally shows an increasing trend in 2009 and 2015. A short-term decline existed, which was consistent with the calculation of the density and asymmetry of the virtual water trade network in Table 2. (2) From 2006 to 2015, the US entered the largest degree rate, followed by China's outreach, US' outreach, and China's minimum In-Degree rate.

According to the characteristics of Out-Degree and In-Degree, the virtual water trading network of the whole industry in major countries in 2015 is shown in Figs. 2 and 3.

There are connections lines between each two countries in Figs. 2 and 3 (connections lines are called Edges in the analysis of trade networks) because that Argentina and other 18 major countries have virtual water trade between each other in 2015. Figs. 2 and 3 are industry-wide virtual water trade networks between major countries in the world, and the size of the nodes in the network reflects the size of the degree and the degree of ingress respectively. In addition, the thickness of the trade links between countries in Figs. 2 and 3 reflects the amount of virtual water import and export trade between countries. The greater the bilateral trade volume between countries, the thicker the connection.

The total amount of virtual water exports varied from country to country. Likewise, the export destinations of each country also differed. Thus, the size of each node (representing country) and the thickness of the connections in Fig. 2 are different. According to the calculation results in Table 3, China, India, and US have the largest Out-Degree in 2015. Thus, the nodes corresponding to these countries were larger. In addition, given the large amount of virtual water trade among China, US, Japan, India in 2015, the corresponding line in Fig. 2 is relatively thick.

Similarly, given the difference in the total amount of virtual water imports and the difference in the source of imports of each country, the sizes of each node (representing country) in Fig. 3 are different. Moreover, thickness of the connection was also different. According to the calculation results in Table 3, the In-Degree of USA and Japan is larger in 2015, so the nodes corresponding to the USA and Japan are larger. Thus, the nodes corresponding to these two countries were larger. In addition, given the large amount of virtual water trade among China, Japan, the US, and India in 2015, the corresponding line in Fig. 3 is relatively thick.[9]

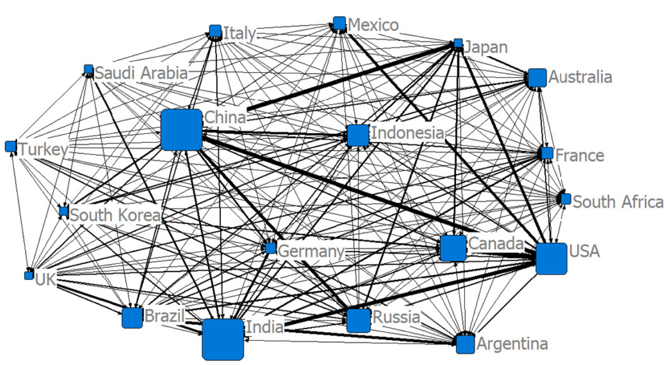

Fig. 2. Industry-wide virtual water trade network among the major countries in 2015 with Out-Degree as a characteristic indicator.

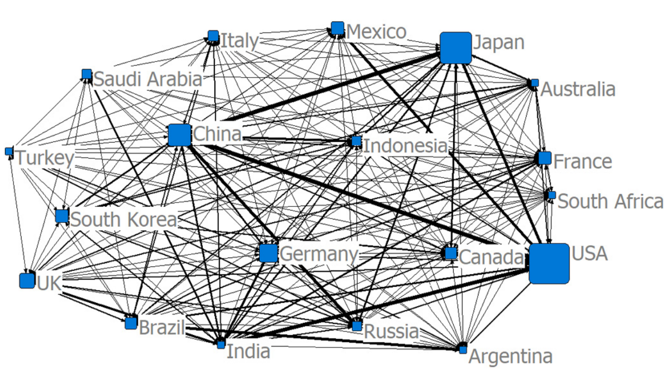

Fig. 3. Industry-wide virtual water trade network among the major countries in 2015 with In-Degree as a characteristic indicator.

[9] It should be pointed that, the arrows in Figs. 2–3 and 5–7 represent the virtual water export from country A to country B (i.e., virtual water imports of country B from country A). As there are virtual water imports and exports between each two major countries in the world, in turn, country B also has virtual water exports to country A (that is, country A imports virtual water from country B). The arrows in the figure are bidirectional.

Table 4
Density and asymmetry of the three-major industrial virtual water trade networks among the 19 major countries from 2006 to 2015 (Unit: Mm^3).

Year	Density			Asymmetry		
	Primary Industry	Secondary Industry	Tertiary Industry	Primary Industry	Secondary Industry	Tertiary Industry
2006	980.71	221.53	6.75	1512.51	309.07	12.21
2007	1083.34	262.02	8.26	1641.70	359.87	14.96
2008	1298.18	304.69	9.92	1968.48	419.31	18.01
2009	1054.06	241.98	7.73	1580.96	322.43	13.96
2010	1324.71	302.44	9.38	1985.49	401.26	16.92
2011	1606.60	369.38	11.50	2399.44	488.55	20.77
2012	1620.48	375.22	11.61	2408.31	498.26	20.94
2013	1648.25	382.15	11.87	2435.90	503.74	21.38
2014	1663.25	396.09	12.51	2466.24	527.66	22.66
2015	1561.69	378.75	11.86	2313.04	505.20	21.45

3.2.2. Analysis of the characteristics of virtual water trade network in three major industries[10]

The calculation results of the density and asymmetry indicators of the three-major industrial virtual water trade networks among the 19 major countries from 2006 to 2015 are shown in Table 4.

As shown in Table 4, (1) regardless of density or asymmetry, the value of the primary industry is the largest, followed by the secondary industry and the tertiary industry, given that the primary industry is agriculture. The production of agricultural products requires a large amount of water resources. This production is much larger than the industrial water consumption and service industry water consumption. In addition, the industrial water consumption is also greater than the service industry water consumption. Therefore, among the three major industries, the virtual water trading network of the primary industry among the 19 major countries has the largest average value on the off-diagonal line from 2006 to 2015. The difference between the virtual water import and export of the primary industry in each country is also the largest.(2) From 2006 to 2015, the density and asymmetry of the virtual water trade network corresponding to the three major industries generally showed an increasing trend (except in 2009 and 2015). This finding shows that the virtual water trade was closer among the 19 major countries.

Considering the data in Tables 2 and 4, the sum of the density values of the three major industries was equal to the density value of the whole industry. However, the sum of the asymmetry indicators of the three major industries was not equal to the value of the whole industry, such as the value of the three major industrial density values in 2006, which was equal to 1208.99 Mm^3. However, the sum of the three major industry asymmetry indicators was equal to 1383.79 Mm^3, which was larger than the industry-wide value of 1811.92 Mm^3.

In Formula (5), the virtual water exports of entire industry t^{rs} ($r \neq s$) from country r to country s is equal to the sum of the virtual water exports of the three industries. However, Formula (6) takes the absolute value of the difference between the virtual water inlet and the virtual water outlet. Thus, the sum of the values S calculated by the three major industries according to Formula (6) is not equal to the value corresponding to the whole industry.

This study takes 2015 as an example to illustrate the calculation results of the Out-Degree and In-Degree of the three-major industrial virtual water trade networks among the 19 major countries, as shown in Table 5.

Under normal circumstances, the agricultural water consumption is greater than the industrial water consumption. The industrial water consumption is greater than the service industry water consumption. Thus, the primary industry has the highest direct water consumption coefficient even if the product trade volume of the primary industry is lower than the secondary industry and the tertiary industry. For the majority of countries, the amount of virtual water in and out of the primary industry is greater than the virtual water imports and export volume of the secondary industry and the tertiary industry. Moreover, the output and In-Degree of the primary industry is the largest. In Table 5, except for Japan and South Korea, the output of the primary industry is less than that of the secondary industry. The export volume of agricultural products from Japan and South Korea was much lower than that of industrial products. The output value of Japan's primary industry was 134.83 Mm^3, whereas the output value of the secondary industry was 451.45 Mm^3. The output value of the Korean primary industry was 397.54 Mm^3, whereas the output value of its secondary industry was 700.36 Mm^3.

For the Out-Degree, India had the largest value (97,322.34 Mm^3) in the primary industry. China had the largest value in the secondary and tertiary industries, with a total of 32,918.35 Mm^3 and 2151.25 Mm^3, respectively. The value of Japan in the primary industry was the smallest, with a total of 134.83 Mm3. Saudi Arabia had the smallest

Table 5
Out-Degree and In-Degree of the three-major industrial virtual water trade networks among the 19 major countries in 2015 (Unit: Mm^3).

Countries	Out-Degree			In-Degree		
	Primary Industry	Secondary Industry	Tertiary Industry	Primary Industry	Secondary Industry	Tertiary Industry
Argentina	34,168.09	2763.67	4.77	4207.51	2229.98	29.18
Australia	29,148.25	7027.75	2.98	6085.83	1491.41	146.51
Brazil	30,668.82	12,992.82	23.32	23,744.79	2815.75	34.08
Canada	55,409.10	6032.64	215.33	20,563.82	6393.15	87.80
China	82,203.35	32,918.35	2151.25	61,013.84	11,457.91	100.54
France	11,979.89	2044.94	101.95	21,319.42	5938.68	132.16
Germany	6459.94	1858.37	43.41	44,533.08	9420.26	622.47
India	97,322.34	18,094.13	92.10	5072.00	3359.11	114.02
Indonesia	43,809.20	3170.40	4.27	12,710.56	2094.16	78.13
Italy	6124.42	5164.39	85.78	16,200.72	4318.39	264.18
Japan	134.83	451.45	28.07	87,552.29	19,236.93	431.00
Mexico	10,877.50	3317.04	63.29	27,775.38	4120.94	31.51
South Korea	397.54	700.36	4.27	26,126.58	5411.73	237.40
Russia	36,714.99	18,139.86	1116.62	12,869.77	2956.20	39.32
Saudi Arabia	316.16	218.22	15.28	11,237.21	2692.07	56.78
South Africa	6761.75	688.94	0.61	5058.41	1330.67	35.37
Turkey	8391.94	1424.51	13.42	5247.30	3181.44	87.20
UK	1247.45	539.50	2.10	30,961.20	8224.38	318.43
USA	71,960.82	11,984.93	86.23	111,816.66	32,859.07	1208.98

[10] We divide the 26 industries in the world input-output table into three major industries. The first industry includes Agriculture(c1), Fishing(c2); and the second industry includes Mining and Quarrying(c3), Food & Beverages(c4), Textiles and Wearing Apparel (c5), Wood and Paper(c6), Petroleum, Chemical and Non-Metallic Mineral Products(c7), Metal Products(c8), Electrical and Machinery(c9), Transport Equipment(c10), Other Manufacturing(c11), Recycling(c12),Electricity, Gas and Water(c13), Construction(c14); and the third industry includes Maintenance and Repair(c15), Wholesale Trade(c16), Retail Trade(c17), Hotels and Restaurants (c18),Transport(c19),Post and Telecommunications(c20), Financial Intermediation and Business Activities(c21), Public Administration (c22), Education, Health and Other Services(c23), Private Households(c24), Others(c25), Re-export & Re-import(c26).

value (218.22 Mm^3) in the secondary industry, and South Africa (0.61 Mm^3) in the tertiary industry. For the In-Degree, the primary, secondary, and tertiary industries were the largest in the US, with 111,816.66 Mm^3, 32,859.07 Mm^3, and 1208.98 Mm^3, respectively. In the primary and tertiary industries, Argentina had the smallest value, with a total of 4207.51 Mm^3 and 29.18 Mm^3, respectively. The value of South Africa in the second industry was the smallest (1330.67 Mm^3).

In addition, combined with the data in Tables 3 and 5, the sum of the output values of the three major industries was equal to the output value of the whole industry. The sum of the In-Degree values of the three major industries was equal to the In-Degree of the whole industry.

Corresponding to Fig. 1, this study still takes China and US as examples to analyze the trends of the Out-Degree and In-Degree of the virtual water trading network of the primary industry from 2006 to 2015, as shown in Fig. 4.

The indicators in Figs. 1 and 4 almost have the same trend. Only differences in numerical values are observed. The virtual water trade volume of the primary industry in China and US accounted for the whole industry. Furthermore, the proportion of virtual water trade in the industry was large.

Taking the sum of the Out-Degree and In-Degree (that is, the sum of the import and export of virtual water) as the characteristic index, the virtual industrial trade network of the three major industries among the 19 major countries in 2015 is shown in Figs. 5 to 7.

The size of each node in Figs. 5 to 7 represents the sum of Out-Degree and In-Degree of each industry's virtual water trading network. The larger the total amount of virtual water import and export, the larger the country node. The connection thickness represents the virtual state between the two countries. If the amount of virtual water trade between the two countries is greater, then the connection is thicker. In Fig. 5, the US has the largest node, followed by China and India. This finding indicates that the US, China, and India's primary industries had a large amount of virtual water imports and exports in 2015. Among China, the US, and Japan, the connection is relatively thick, indicating that the virtual water trade volume of agricultural products in 2015 was relatively large among these countries. In Fig. 6, China and the US have the largest nodes, reflecting that the virtual water imports and export of China's and the US' secondary industry in 2015 were large. The connection between China and the US, and China and Russia is relatively thick. This finding indicates that the amount of virtual water trade of these countries in the industrial industry was large in 2015. In Fig. 7, China has the largest node, followed by the US and Russia. This finding shows that in 2015, China, the US, and Russia had the largest amount of virtual water imports and exports. In addition, the links between China and US are relatively thick. This finding shows that the virtual water trade volume of service industries between these countries was the largest in 2015.

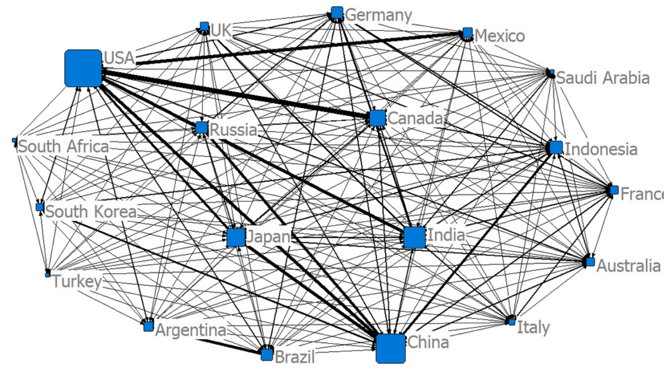

Fig. 5. Primary industry's virtual water trade network among 19 major countries in 2015.

3.3. Further discussions

We use social network analysis instead of complex network analysis (Watts and Strogatz, 1998; Albert and Barabási, 2002). There are significant differences between them. Although both are based on graph theory, social network analysis is a sociological study, which mainly analyzes the characteristics of network structure. In this paper, we use this method to analyze the virtual water trade networks of major countries in the world. Complex network theory belongs to the study of network dynamics, which reflects the evolution of network structure and the interaction between network structure and network behavior (Li, 2009).

Except of using the social network analysis software UCINET6 to draw a virtual water trade network diagram, we can also use R software to draw a chordal graph of virtual water trade network. With the previous one we can draw the virtual water trade network map based on network characteristic indicators, but with the latter one we can more clearly represent the virtual water trade volume between each two countries. The chordal graph of to the virtual water trade network of the whole industry in major countries (regions) is as follows (The virtual water trading networks of the three major industries can be similarly analyzed and will not be repeated) (Fig. 8):

In this figure, the connecting line of the two arcs represents the virtual water trade relationship between the two countries, and the width of the connecting line represents the size of the virtual water trade volume between the two countries. The arc of a certain country imitates the water export and water import following the clockwise direction. It can be seen from the figure that the width of the arc of USA is wider than that of other countries, which means, in 2015, the United States had the largest total amount of virtual water imports and exports from 18 other countries, but its exports amount was the imports

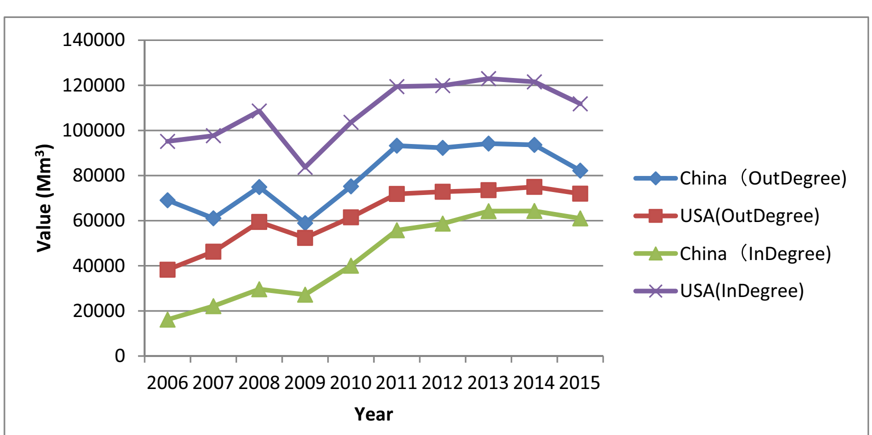

Fig. 4. Out-Degreeand In-Degree of the primary industry in China and US from 2006 to 2015.

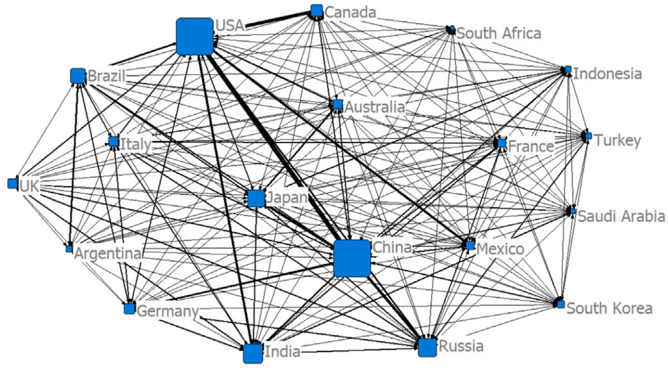

Fig. 6. Secondary industry's virtual water trade network among the 19 major countries in 2015.

amount. In addition, the connection lines between China and USA, and between China and Japan are wide, which means, in 2015, China exported a large amount of virtual water to the United States (Japan), that is, the United States (Japan) imported a large amount of virtual water from China.

In fact, according to the calculation method in this paper, the virtual water trade networks corresponding to green water, blue water and grey water among countries (regions) in the world can be obtained separately, moreover, the virtual water trade network corresponding to 26 industries in various countries (regions) in the world can be obtained. Due to space limitations, this article only shows the virtual water trading network corresponding to all water use (sum of green water, blue water and grey water) of the whole industry among the major countries of the world, which is also part 3.2.1 (Analysis of the characteristics of virtual water trade network in the entire industry)of the paper. The virtual water trade network data corresponding to the green water, blue water, grey water and all water uses of 26 industries in all countries (regions) of the world of 2015 are shown in Annex (both are 4915×190 order matrix, $4915 = 189 \times 26 + 1$, including the virtual water consumed by itself). According to the data in Annex, we can compile the virtual water trade volume of the green water, blue water and grey water of the 19 major countries in the world in 2015 (corresponding to Table 1 in the paper), and construct the water trade network of the green water, blue water and grey water among the 19 major countries (corresponding to Figs. 2 and 3 in the paper), and analyze its network characteristics, such as network density, symmetry, out-degree and in-degree (corresponding to Tables 2 and 3 in the paper), and analyze the virtual water trade network of green water, blue water and grey water of the three major industries (corresponding to Tables 4 and 5 in the paper and Figs. 5 to 7).This article takes China as an example to illustrate the difference in virtual water trade volume corresponding to green water, blue water and grey water. According to the data in Annex, the imports of virtual water of China's green water, blue water

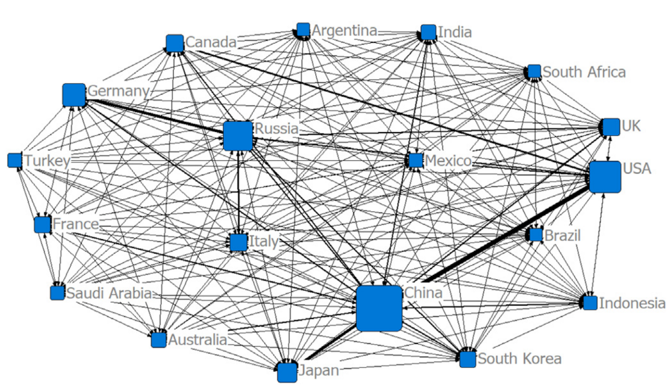

Fig. 7. Tertiary industry's virtual water trade network among 19 major countries in 2015.

and grey water in 2015 can be collated as 181,360.59 Mm^3, 16,707.27 Mm^3, and 16,116.65 Mm^3 (the sum of these three is equal to the import volume of China's 2015 virtual water in Table 1, which is 21,4184.51 Mm^3), and the exports amount of three types of water are 103,175.42 Mm^3, 20,540.43 Mm^3 and 55,754.34 Mm^3 (the sum of these three is equal to the export volume of China's 2015 virtual water in Table 1, which is 179,470.19Mm^3). In addition, similar to 2015, the virtual water trade volume corresponding to green water, blue water and grey water in 26 industries in other countries can be calculated according to the research method used in this paper.

4. Conclusions and implications

This study uses the input–output table and water use data obtained from the EORA database to calculate the virtual water trade among 19 major countries (except the Group 20 countries and the EU countries) from 2006 to 2015. Moreover, this study aims to investigate the characteristics of the virtual water trade network. After analysis, the results show that: The virtual water import and export of major countries in the world increased in 2015 in varying degrees. Among them, China's virtual water import and Russia's virtual water export growth rates were the highest. The density and asymmetry of the virtual water trade network among the 19 major countries increased from 2006 to 2015 regardless of which industry. Compared with the secondary and tertiary industries, the virtual water trading network formed by the primary industry is denser. The Out-Degree and In-Degree of countries in the virtual water trading network of the whole industry increased in varying degrees in 2015. Major countries have the largest export and import in the primary industry, except for Japan and South Korea.

Considering the conclusions of the above research, the following policy implications can be obtained: First, water-deficient countries (regions) can alleviate the pressure on water supply by importing products and services from countries (regions) with abundant water resources (that is, virtual water trade). For more convenient implementation of virtual water trade strategy, it's necessary to further strengthen the construction of transportation facilities and reduce the logistics cost of industrial and agricultural products, thereby expanding the import and export trade of virtual water. It should be noted that in addition to water resources, the production of a product also requires the input of multiple factors such as capital, labor, and land, so there is still a phenomenon that existing a large number of net virtual water exports in some countries which have a shortage of water resources (such as China). In addition, countries with a large amount of bilateral trade in virtual water, such as China and the United States, China and Japan, and the United States and India should strengthen trade ties and cooperation to give play to their respective comparative advantages, and achieve complementary advantages.

Second, although the trade volume of agricultural products in various countries may be lower than the volume of trade in industrial products and services, the amount of water consumed per unit of production of agricultural products is much greater than that of industrial products and services. In most countries (e.g China, the United States), the virtual water trade volume of agricultural products is greater than the virtual water trade volume of industrial products and service products. Therefore, in alleviating the contradiction between water supply and demand, focusing on agricultural trade products, such as grain, is necessary. However, the production of agricultural products also needs to consume products produced in other industries, such as fertilizers and pesticides; the production of products in other industries also requires agricultural products as raw materials, such as the food manufacturing industry. Therefore, while emphasizing the virtual water trade of agricultural products, it is necessary to pay attention to the production and production of related industries and trading.

It should be pointed out that the green water, blue water, and grey water data in the EORA database are integrated data and are not specific to the product level. For example, the agricultural sector's data is not

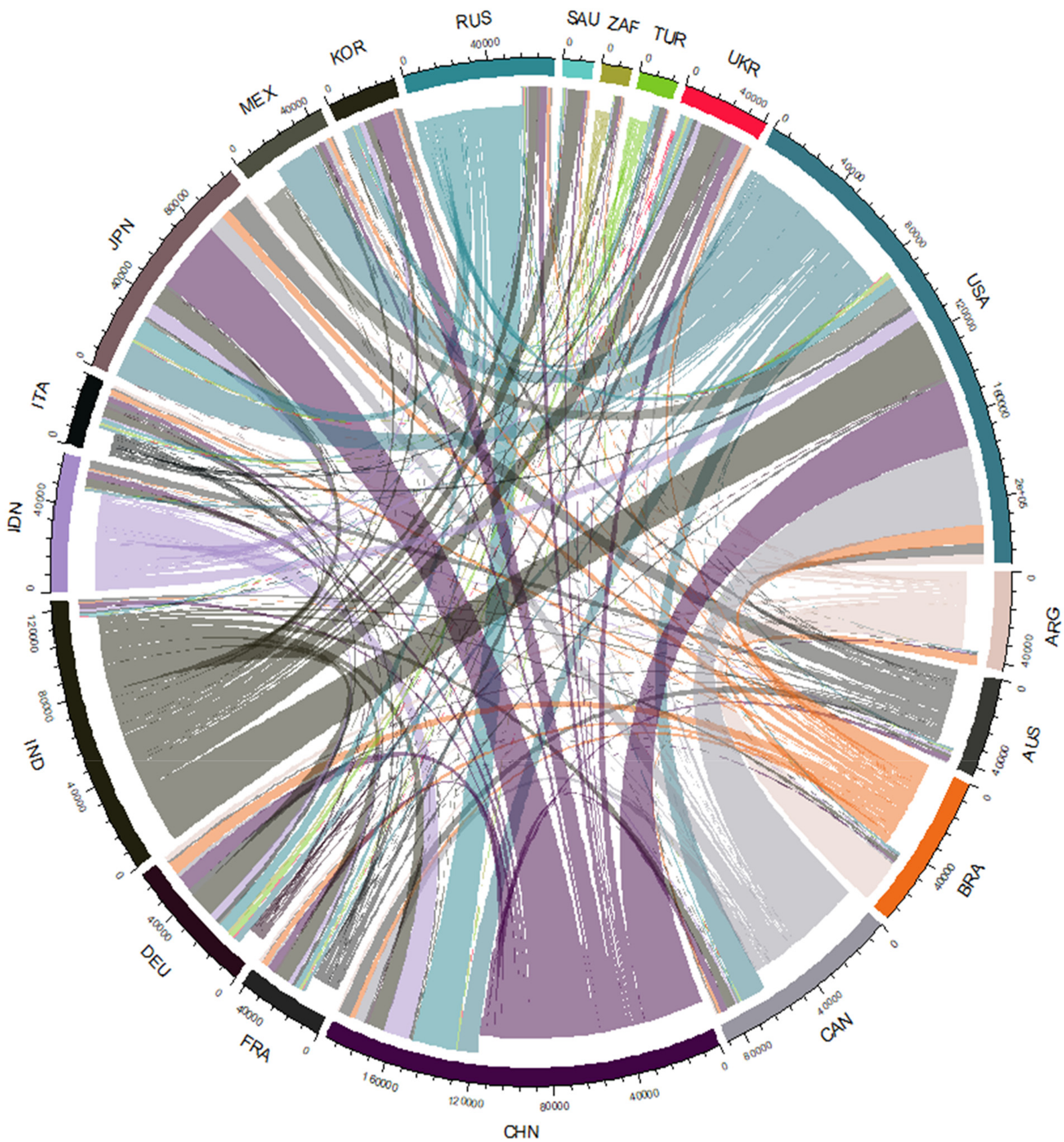

Fig. 8. The chordal graph corresponding to the virtual water trade of the whole industry in major countries (regions) (unit: Mm3).

subdivided into plantation products, livestock products, forest products, and fishery products. According to the method of production tree, the virtual water trade situation of specific agricultural products such as rice, wheat, and corn can be further obtained. Using the world input-output table and water footprint data in the EORA database, it can only analyze the virtual water trade network of the macro-sectors of each country (region), but cannot analyze the virtual water trade network of specific agricultural products such as rice, wheat, and corn, which constitutes the shortcomings of this paper.

Currently there are three main types of world input-output table databases: WIOD, EXIOBASE and EORA. There are big differences in the number of countries (regions) involved in the above three types of databases.WIOD2016 and EXIOBASE3 mainly involve EU28 and other larger economies in the world, while the EORA database involves 190 countries (regions).The environmental accounting account of WIOD2016 does not include detailed water usage data, but both EXIOBASE3 and EORA databases contain them. EXIOBASE3 includes 13 categories for water consumption in agricultural activities for both green and blue water, and 12 categories of blue water consumption in livestock production (Merciai and Schmidt, 2018; Stadler et al., 2018). EORA26 database does not subdivide the usage of water in the agricultural sector to the product level, so water data in EXIOBASE3 is much better than the one in the EORA26 database, in terms of sectoral resolution and transparency of the data sources. However, the EXIOBASE3 database only includes the world input-output tables and water resources data from 1995 to 2011 (the water resources data only includes green water and blue water, but no grey water), while the data in the EORA database is as of 2015 and includes green water, blue water and grey water data. As this article only studies virtual water trade at the macro-sector level, not at the specific product level, it is sufficient to use EORA data. Based on the reasons above, this paper uses the EORA database to calculate the virtual water trade of major countries (regions) in the world from 2006 to 2015.

CRediT authorship contribution statement

Guangyao Deng: Data curation, Writing - original draft, Writing - review & editing. **Fengying Lu:** Conceptualization, Methodology, Software. **Lingping Wu:** Writing - review & editing. **Chao Xu:** Writing - review & editing, Supervision.

Declaration of competing interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.142043.

References

Albert, R., Barabási, A.L., 2002. Statistical mechanics of complex networks. Rev. Mod. Phys. 74 (1), 47–97.
Allan, J.A., 1993. Fortunately there Are Substitutes for Water Otherwise our Hydro-Political Futures Would Be Impossible. Priorities for Water Resources Allocation and Management. ODA, London.
Ansink, E., 2010. Refuting two claims about virtual water trade. Ecol. Econ. 69 (10), 2027–2032.
Antonelli, M., Tamea, S., Yang, H., 2017. Intra-EU agricultural trade, virtual water flows and policy implications. Sci. Total Environ. 587, 439–448.
Chapagain, A.K., Hoekstra, A.Y., 2003. Virtual Water Trade: A Quantification of Virtual Water Flows between Nations in Relation to International Trade of Livestock and Livestock Product. Research Report SeriesIHE Delft, The Netherlands, p. 12.
Dalin, C., Konar, M., Hanasaki, N., Rinaldo, A., Rodriguez-Iturbe, I., 2012. Evolution of the global virtual water trade network. P. Natl. Acad. of Sci. USA. 109 (16), 5989–5994.
Deng, G., Wang, L., Song, Y., 2015. Effect of variation of water-use efficiency on structure of virtual water trade-analysis based on input–output model. Water Resour. Manag. 29 (8), 2947–2965.
Deng, G., Ma, Y., Li, X., 2016. Regional water footprint evaluation and trend analysis of China—based on interregional input–output model. J. Clean. Prod. 112, 4674–4682.
Deng, G., Wang, L., Xu, X., 2018. Linkage effect of virtual water trade in China's industrial products—based on generalized hypothetical extraction method. Ecol. Indic. 93, 1302–1310.
Duarte, R., Pinilla, V., Serrano, A., 2018. Factors driving embodied carbon in international trade: a multiregional input–output gravity model. Econ. Syst. Res. 30 (4), 545–566.
Fang, D., Chen, B., 2015. Ecological network analysis for a virtual water network. Environ. Sci.Technol. 49 (11), 6722–6730.
Feng, K., Hubacek, K., Pfister, S., Yu, Y., Sun, L., 2014. Virtual scarce water in China. Environ. Sci. Technol. 48 (14), 7704–7713.
Hoekstra, A.Y., Hung, P.Q., 2002. Virtual Water Trade: A Quantification of Virtual Water Flows between Nations in Relation to International Crop Trade. Value of Water Research Report Series 11IHE Delft, The Netherlands.
Jiang, Y., Cai, W., Du, P., Pan, W., Wang, C., 2015. Virtual water in interprovincial trade with implications for China's water policy. J. Clean. Prod. 87, 655–665.
Konar, M., Dalin, C., Suweis, S., Hanasaki, N., Rinaldo, A., Rodriguez-Iturbe, I., 2011. Water for food: the global virtual water trade network. Water Resour. Res. 47 (5), 1–17.
Lenzen, M., Kanemoto, K., Moran, D., Geschke, A., 2012. Mapping the structure of the world economy. Environ. Sci. Technol. 46 (15), 8374–8381.
Lenzen, M., Moran, D., Kanemoto, K., Geschke, A., 2013. Building Eora: a global multi-regional input-output database at high country and sector resolution. Econ. Syst. Res. 25 (1), 20–49.
Li, J., 2009. Trilogy of network research: graph theory, social network analysis and complex network theory. Journal of South China Normal (Social Science Edition) 2, 136–138 (In Chinese).
Liao, X., Chai, L., Pang, Z., 2018. Water resource impacts of future electric vehicle development in China. J. Clean. Prod. 205, 987–994.
Liu, J., 2004. An Introduction of Social Network Analysis. Social Science Academic Press (In Chinese).
Liu, J., 2009. Lectures on Whole Network Approach: A Practical Guide to UCINET. Trust & Wisdom Press (In Chinese).
Liu, X., Shi, L., Engel, B.A., Sun, S., Zhao, X., Wu, P., Wang, Y., 2020. New challenges of food security in Northwest China: water footprint and virtual water perspective. J. Clean. Prod. 245, 118939.
Merciai, S., Schmidt, J., 2018. Methodology for the construction of global multi-regional hybrid supply and use tables for the EXIOBASE v3 database. J. Ind. Ecol. 22 (3), 516–531.
Pfister, S., Koehler, A., Hellweg, S., 2009. Assessing the environmental impacts of freshwater consumption in LCA. Environ. Sci. Technol. 43 (11), 4098–4104.
Reimer, J.J., 2012. On the economics of virtual water trade. Ecol. Econ. 75 (5), 135–139.
Serrano, A., Guan, D., Duarte, R., Paavola, J., 2016. Virtual water flows in the EU27: a consumption-based approach. J. Ind. Ecol. 20 (3), 547–558.
Stadler, K., Wood, R., Bulavskaya, T., Sodersten, C.J., Simas, M., Schmidt, S., Usubiaga, A., Acosta-Fernandez, J., Kuenen, J., Bruckner, M., Giljum, S., Lutter, S., Merciai, S., Schmidt, J.H., Theurl, M.C., Plutzar, C., Kastner, T., Eisenmenger, M., Erb, K., de Koning, A., Tukker, A., 2018. EXIOBASE 3: developing a time series of detailed environmentally extended multi-regional input-output tables. J. Ind. Ecol. 22 (3), 502–515.
Sun, S., Bao, C., Tang, Z., 2019. Tele-connecting water consumption in Tibet: patterns and socio-economic driving factors for virtual water trades. J. Clean. Prod. 233, 1250–1258.
Taherzadeh, O., Caro, D., 2019. Drivers of water and land use embodied in international soybean trade. J. Clean.Prod. 223, 83–93.
Tian, X., Sarkis, J., Geng, Y., Qian, Y., Gao, C., Bleischwitz, R., Xu, Y., 2018. Evolution of China's water footprint and virtual water trade: a global trade assessment. Environ. Int. 121, 178–188.
Tuninetti, M., Tamea, S., Laio, F., Ridolfi, L., 2017. To trade or not to trade: link prediction in the virtual water network. Adv.WaterResour. 110, 528–537.
Wasserman, S., Faust, K., 1994. Social Network Analysis: Methods and Applications. Cambridge university press.
Watts, D.J., Strogatz, S.H., 1998. Collective dynamics of 'small-world' networks. Nature 393 (6684), 440–442.
Wiedmann, T., Lenzen, M., 2018. Environmental and social footprints of international trade. Nat. Geosci. 11 (5), 314–321.
Zhang, Y., Zhang, J., Tang, G., Chen, M., Wang, L., 2016. Virtual water flows in the international trade of agricultural products of China. Sci.Total Environ. 557, 1–11.
Zhang, Y., Zhang, J.H., Tian, Q., Liu, Z.H., Zhang, H.L., 2018. Virtual water trade of agricultural products: a new perspective to explore the belt and road. Sci. Total Environ. 622, 988–996.
Zhao, X., Liu, J., Liu, Q., Tillotson, M.R., Guan, D., Hubacek, K., 2015. Physical and virtual water transfers for regional water stress alleviation in China. P. Natl. Acad. of Sci. USA. 112 (4), 1031–1035.
Zhao, X., Li, Y.P., Yang, H., Liu, W.F., Tillotson, M.R., Guan, D., Wang, H., 2018. Measuring scarce water saving from interregional virtual water flows in China. Environ. Res. Lett. 13 (5), 054012.