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Simulation of the virtual water flow pattern associated with interprovincial grain trade and its impact on water resources stress in China

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ABSTRACT

With fast development of economy and trade globalization, the water resources system has undergone profound changes due to the overconsumption of physical water and the complex virtual water flow. China is poor in water and rich in arable land for the north, but rich in water and poor in arable land for the south. The spatial mismatch of water and food production has posed a great threat to sustainable development. To quantify the virtual water flow with grain trade and evaluate its influence on the regional water resources system, this study simulated the interprovincial virtual water flow embedded in grain transportation based on a linear optimization model and assessed the water pressure induced by virtual water flow. Results show that the annual virtual water flow (as much as 73.46 billion m^3 in 2012) associated with interprovincial grain trade is mainly from the North to the South. The grain output areas are mainly located in the Northeast, Northwest, and the North China Plain, while the grain input areas are mainly distributed in the eastern and southern coastal provinces with well-developed economies. According to the estimation, when China's food demand reaches a peak of 650 million tons in 2030, the virtual water flow will further increase and the volume of virtual water flowing out of Northeast China will be up to 50 billion m^3, accounting for 90% of the total virtual water flow. The increasing the virtual water outflow in North China will severely exceed the local water resources capacity in the arid and semi-arid areas and have an obvious negative impact on sustainable development in Northern China. Further improving the water use efficiency, adjusting the structure of spatial grain production distribution and physical-virtual water coupled management are effective countermeasures to ensure the coordination safety of food and water in China.

1. Introduction

Water and food security are important foundations of modern social and economic development (Wang et al., 2019). Due to the low per capita water consumption, water-related issues are one of the severe challenges facing China's current social development (Niva et al., 2020). China's per capita water availability is approximately 2100 m^3/year, which is a quarter of the global average (Liu et al., 2020). Northern China supports 60% of the total area of arable land and produces more than 50% of the country's wheat and 35% of the corn with only 6% of the total water resources (He et al., 2019). Booming domestic and international trade has had a huge impact on the region's water systems because of virtual water (Hanasaki et al., 2010). As a production link with high water consumption and low economic benefits, grain production plays an important role in the utilization of water resources, economic development and social stability (Ibarrolarivas et al., 2017). Virtual water strategies have changed the traditional thinking of solving

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the water resource shortage problem by means of engineering technology and built a bridge between water resource management and food security (Zhang et al., 2019). Virtual water has been identified as a potentially useful concept for redistributing water from water-rich to water-scarce areas, that is, indirectly through economic linkages (Gao et al., 2019a).

However, the virtual water flow pattern associated with the food trade in China presents a pattern of water flow from the north (with severe water shortages) to the south (with abundant water resources) (Zhuo et al., 2016). The amount of water embedded in grain transported from the north to the south has increased from 9 billion m^3 to more than 50 billion m^3 per year from 1990 to 2016 (Sun et al., 2019). It can be predicted that with the acceleration of urbanization, grain demand in developed regions (e.g., the southeast coast of China) will increase due to the fast urbanization, and the volume of virtual water transported from the North to the South will continue to increase (Fu et al., 2018). The virtual water flow pattern is not matched with the distribution of water resources, which is the result of multiple factors such as the mismatch of water and soil resources, economic development, and population, which affects the sustainability of agricultural water use (Wu et al., 2018). It is very important to clarify the pattern of virtual water flow of grain, analyze the mechanism of regional virtual water transfer, and optimize and regulate the pattern of grain production and trade for the agricultural water security of the social economy.

Virtual water was first proposed by the British scholar Tony Allan (1993). It is a new concept for water resources management, which can completely describe the consumption of water resources in the production process and the transformation and flow process of water resources with virtual water trade after it enters a commodity (Duarte et al., 2016). The virtual water concept provides a new method to identify the crux of water problems in agricultural production in different regions, periods and stages from a broader perspective (Wu et al., 2019). Since the virtual water concept was proposed, the scholars at home and abroad have carried out a number of studies to map the virtual water flow patterns and evaluate its impacts in different regions and products. Hoekstra and Hung (2005) studied the virtual water flows involved in the trade of food and animal products in more than 100 countries and regions in 1995–1999, and found that 13% of the global agricultural water flows between countries and regions in the form of virtual water resources. Chapagain et al. (2006) showed that global virtual water transfer water-saving amount brought by grain trade was as high as 385 billion m^3. Antonelli et al. (2017) found that the EU is a net importer of grain virtual water from the rest of the world, however, intra-regional virtual water accounts for 46% of total imports and 75% of total exports. The volume of virtual water in EU had been growing almost monotonously for years with a sharp increase since 2000. The overall trend of virtual water trade changes is inconsistent with the goals of the Water Framework Directive. Lamastra et al. (2017) studied the bilateral trade of agricultural products between China and Italy and concluded that 91% of the virtual water imports in Italy were related to crop products, while 95% of the virtual water imports in China were related to animal products. The authors suggested that agricultural products were generally traded from regions with low water productivity to those with high water productivity. Zhang et al. (2017) found that the proportion of the gray water footprint of agricultural products exported from China to Trans-Pacific partnership agreement (TPPA) countries is approximately five times higher than that imported from TPPA countries, which reflects the differences in agricultural technology. Zhang et al. (2018) showed that agricultural trade with China is undoubtedly beneficial to the countries along the Belt and Road and China, promoting the allocation of water resources. The above research data were obtained from the trade centers' databases or published reports. In China, many studies have quantified the domestic virtual water trade and evaluated its impact. Zhao et al. (2015) mapped virtual water flows among Chinese provinces in 2007 and 2030 and analyzed physical-virtual water effect on the water stress in water-exporting regions of China. Feng et al. (2012) evaluated the regional virtual water flow between the Yellow River Basin and the rest of China and showed that all three sub-basins are net virtual water exporters. Sun et al. (2016) research showed that Northeast China and Huang-Huai-Hai Region are the main output regions of agricultural virtual water in China, and virtual water flow changes the original distribution of water resources and has a significant impact on the water resources in both the input and output regions. However, due to the difficulty in collecting the interprovincial grain trade data, the methods of quantifying the grain virtual flow remains challenging.

In the current research, the main method used to quantify the virtual water trade pattern was to conduct input-output analysis on water use using the multi-regional input-output model (MRIO) (Feng et al., 2012). This method quantifies the virtual water trade pattern among regions by establishing the relationship between water use and total output in the section and using the industrial economic correlation in the input-output table (Dong et al., 2014). Sun and Liu (2019) used the MRIO and found that the total amount of internal virtual water, the net input virtual water of international trade, and the net export virtual water of interprovincial trade were 481.93 billion m^3, 26.13 billion m^3, and 80.16 billion m^3, by MRIO in 2012. Moreover, interprovincial trade played a leading role in the national virtual water trade. Based on detailed trade data, the advantage of MRIO is that the results are reliable and close to the real values. However, the multi-regional input-output table is difficult to be obtained and of poor time resolution. In China, the input-output table is always released by authorities every five years. To date, the available input-output table data are as early as 2012. It is difficult to carry out the studies in recent years (e.g., 2015–2020). Green water footprint, which accounts for a large proportion of the water used by agricultural production, cannot be calculated by MRIO. Compared with MRIO, the parameters of the linear optimization model are easier to obtain. Ye et al. (2019) and Wang et al. (2019) used a linear optimization model to optimize the virtual water flow pattern, but their researches did not focus on the quantification of the current virtual water flow pattern of social and economic development. In addition, a few scholars have developed some models to quantify virtual water flow of grain production (Gao et al., 2019b; Sun et al., 2019; Wang et al., 2019). Using the gravity method, Sun et al. (2019) calculated that the amount of grain virtual water from north to south in China increased from 72.99 billion m^3 in 1997 to 124.64 billion m^3 in 2014, which aggravated the water resource pressure, gray water footprint and greenhouse gas emissions in the grain virtual water export areas. Most current models use distance as the only factor affecting virtual water flow. But there are few researches on the impact considering two or more factors to simulate the grain virtual water flow patterns. It should be realized that, the selection of the influencing factors is very important for accurately simulating interprovincial grain virtual water flow in a specific year or in the future.

China, with 80% water resources in the South and 65% arable land in the North, is facing a rigorous challenge due to the spatial mismatch between water distribution and grain production to make a balanced development of economy and ecosystem. In the past decades, the North China played a prominent role in maintaining national food security. In contrast, the lack of water resources in this region poses a great threat to the sustainable development. The quantitative analysis of the current pattern of virtual water flow in grain is of great significance for evaluating the current virtual water flow with grain trade and planning the future water management strategy. However, due to the lack of grain trade data among different provinces, the relevant researches on grain virtual water flow are rarely carried out in China. This study innovatively used the comprehensive cost of grain production and transportation as the optimization objective, and attempted to establish a linear optimization model to quantify the virtual water flow of interprovincial grain trade. The main contents of this study are (1) to construct a linear optimization model with the comprehensive cost of grain production and transportation as the optimization goal to quantify the virtual water flow of inter-provincial grain trade, so as to overcome the difficulties in data acquisition and expand the scenario and scope of the application of the model; (2) use the MRIO results as real values to verify the model simulation results; (3) use the water stress index (WSI) to analyze the effect of the virtual water flow pattern associated with interprovincial grain trade, and predict the virtual water flow model of grain in 2030. This study lays a foundation for the exploration of sustainable water resources utilization in social and economic systems based on the coordination management of physical water and virtual water.

2. Methods and data

This section introduced the principle of the virtual water simulating model, the calculation method of MRIO, the concept of water stress indices and the specific data sources. A linear model was constructed to quantify the flow pattern of virtual water, and the result obtained by MRIO was used as the real values to verify the model. The effect of virtual water flow was evaluated by water stress index (WSI) and assumed water stress index (WSI*). The methods and the source of data used in this study are described in the following four parts.

2.1. Simulation model of virtual water flow pattern

Since the latest obtained data for MRIO is in 2012, in order to better verify the simulation results of the model, the simulation time was set as 2012 in this study. The research area was the 30 provinces (except Taiwan, Hong Kong, Macao and Tibet due to data limitation) of China corresponding to the MRIO. As China's grain production was larger than the total grain consumption in 2012, domestic grain production could meet the domestic grain demand overall. The research aimed at analyzing interprovincial grain trade, deducting grain import and export trade, and quantifying the amount and direction of virtual water trade flow among different regions in China. Provinces were divided into grain deficit provinces and grain surplus provinces according to their grain production and consumption:

$$\mu_i = P_i - C_i \tag{1}$$

where P_i is the mass of grain production in province i, and C_i is the mass of grain consumption in province i.

When $\mu_i > 0$, province i is a grain surplus province, and its grain surplus is:

$$S_i = P_i - C_i \tag{2}$$

When $\mu_i < 0$, province i is a grain deficit province, and its grain deficit is:

$$D_i = C_i - P_i \tag{3}$$

This method is also used to determine the provincial distribution of surplus and deficit of different grain varieties (rice, wheat or corn). The corresponding data of grain production and consumption need to be replaced during calculation.

The total cost of grain virtual water trade is divided into two parts: grain production cost and transportation cost. This study constructed a linear optimization model to simulate the virtual water flow pattern with the optimization objective function of minimizing the comprehensive cost of grain production and transportation.

$$min\ \ Cost = \sum_{i=1}^{N} \sum_{j=1}^{30-N} x_{i,j} \times \left(Cost_i^c + Cost_{i,j}^t \right) \tag{4}$$

where $Cost$ is the sum cost of the grain production and trade transportation among provinces; $x_{i,j}$ is the mass of grain transfer from province $i$to province j; province i is the grain surplus province; province j is the grain deficit province; N is the amount of grain surplus province; $30\text{-}N$ is the amount of grain deficit province; $Cost_i^c$ is the unit cost of grain production in province i, and $Cost_{i,j}^t$ is the unit cost of grain transportation from province i to province j.

The constraints of the model are as follows:

$$\sum_{i=1}^{N} x_{i,j} \geq D_j \tag{5}$$

$$\sum_{j=1}^{30-N} x_{i,j} \leq S_i \tag{6}$$

$$x_{i,j} \geq 0 \tag{7}$$

Equation (5) is a demand constraint, which means that the total mass of grain transported from other provinces to province j should be greater than or equal to the mass of the grain deficit to meet the grain demand in the deficit province. Equation (6) is a supply constraint, which means that the total mass of grain transported to other provinces in the grain surplus province should be less than or equal to that province's grain surplus and cannot exceed its own supply capacity. Equation (7) is the restriction of variable symbol, which represents that the trade data is positive from province $i$to province j.

The Lingo Software (Linear Interactive and General Optimizer) was first developed by Lindo System Inc. (Lindo Systems, Inc., 2020) in USA, which can be used to solve linear and nonlinear programming. Run the above model mentioned in Equations (4)–(7) using Lingo software to solve the grain trade mass $x_{i,j}$, that is, the amount and direction of virtual water flow associated with interprovincial grain trade. The optimization algorithm code is provided in the supplementary material under the name of CODE. Combined with the grain virtual water content, the virtual water flow pattern caused by the interprovincial grain trade flow was obtained.

$$TVW_{i,j} = x_{i,j} \times VWC_i \tag{8}$$

where $TVW_{i,j}$ is grain virtual water transfer from province $i$to province j. VWC_i is the grain virtual water content in province i, which refers to the total amount of water consumed by grain production in a certain area in a certain period of time, also known as the water footprint (Chapagain and Hoekstra, 2011). Grain virtual water content consists of blue virtual water content (irrigation water consumed during grain growth) and green virtual water content (effective precipitation stored in soil) (Sun et al., 2013).

$$TVW_{i,j}^{blue} = x_{i,j} \times BWC_i \tag{9}$$

$$TVW_{i,j}^{green} = x_{i,j} \times GWC_i \tag{10}$$

where $TVW_{i,j}^{blue}$ is blue virtual water transfer of grain from province $i$to province$j$; BWC_i is the blue virtual water content of grain;$TVW_{i,j}^{green}$ is green virtual water transfer of grain from province $i$to province$j$, and GWC_i is the green virtual water content of grain.

The grain virtual water content is calculated by equation (11).

$$VWC_i = BVW_i + GVW_i \tag{11}$$

The blue virtual water content is the product of irrigation water consumption per unit area of grain and irrigation area.

$$BVW_i = IR_g \times S_{IR} \tag{12}$$

where IR_g is the irrigation water consumption per unit area of grain, and S_{IR} is the irrigated area of grain.

The green virtual water content is the product of the effective precipitation during the growth period of grain and the sown area. When the effective precipitation is greater than the grain water demand in the same period, the effective precipitation should be replaced with the grain water demand.

$$GVW_i = \frac{P_e S_g}{\lambda} \tag{13}$$

where P_e is the effective precipitation; S_g is the grain sown area, and λ is grain multiple cropping index.

The effective precipitation during the grain growth period adopts the method recommended by the United States Department of Agriculture Soil Conservation Service.

$$\text{When } P < 83, P_e = \frac{P(4.17 - 0.02P)}{4.17}. \tag{14}$$

$$\text{When } P \geq 83, P_e = 41.7 + 0.1P. \tag{15}$$

where P is ten-day precipitation.

2.2. Multi-regional water resources input-output model

The net provincial grain virtual water flow obtained by MRIO was used as the real value to verify the simulation results. Since the results obtained by MRIO only contain the blue virtual water flow, the real value is compared with the simulated net blue virtual water flow during the verification process.

The correlation coefficient is used to quantify the degree of linear correlation among variables. The calculation method is shown in equation (16).

$$R\left(NVW^{blue}, NVW^{MRIO}\right) = \frac{Cov\left(NVW^{blue}, NVW^{MRIO}\right)}{\sqrt{Var\left[NVW^{blue}\right] Var\left[NVW^{MRIO}\right]}} \tag{16}$$

where $R(NVW^{blue}, NVW^{MRIO})$ is the correlation coefficient between the variables NVW^{blue} and NVW^{MRIO}; NVW^{blue} is the variable of net blue virtual water flow of grain obtained by simulation, $NVW^{blue} = [NVW_i^{blue}]$; NVW^{MRIO} is the variable of net blue virtual water flow of grain obtained by MRIO, $NVW^{MRIO} = [NVW_i^{MRIO}]$; $Cov(NVW^{blue}, NVW^{MRIO})$ is the covariance between the variables NVW^{blue} and NVW^{MRIO}; $Var[NVW^{blue}]$ is the variance of NVW^{blue}, and $Var[NVW^{MRIO}]$ is the variance of NVW^{MRIO}.

$$NVW_i^{blue} = \sum_{j=1}^{30} TVW_{i,j}^{blue} \tag{17}$$

$$NVW_i^{MRIO} = \sum_{j=1}^{30} TVW_{i,j}^{MRIO} \tag{18}$$

where NVW_i^{blue} and NVW_i^{MRIO} are net blue virtual water flow of grain in province i obtained by simulation and MRIO; $TVW_{i,j}^{MRIO}$ is the grain virtual water transfer from province $i$to province j obtained by MRIO:

$$TVW^{MRIO} = \alpha\theta TVW_a \tag{19}$$

where TVW^{MRIO} is the virtual water transfer matrix for grain obtained by MRIO, $TVW^{MRIO} = [TVW_{i,j}^{MRIO}]$; α is the provincial proportion of farmland irrigation water in agricultural water; θ is the provincial proportion of grain planting area in crop planting area, and TVW_a is the virtual water transfer matrix for agricultural sector, which is obtained by virtual water transfer matrix (TVW). TVW is calculated as follows.

The data is the multi-region input-output table in 2012 compiled by the China Carbon Accounting Database (CEADs) (Mi et al., 2017). As shown in Table 1, the water resource expansion MRIO model can be obtained by adding the direct water consumption of each province and sector into the MRIO model as a separate module.

In the water resource expansion MRIO model, it is assumed that the system consists of m provinces, and each province contains n sectors. The purpose is to verify the grain virtual water flow among provinces, sectors other than agriculture are merged to simplify the calculations.

According to the structure of the input-output model, the total input into production activities of each sector in a province is equal to its total output, that is, the total input of each sector is equal to the sum of the intermediate and final uses and others. The calculation equation is as follows:

$$X_i^a = Y_i^a = \sum_{m=1}^{M} \sum_{n=1}^{N} x_{ij}^{ab} + \sum_{m=1}^{M} f_i^{ab} + \left(EX_i^a + E_i^a\right) \tag{20}$$

where X_i^a is the total input of sector i in province a; Y_i^a is the total output of sector i in province a; x_{ij}^{ab} is the intermediate input provided by sector i in province a to sector j in province b; f_i^{ab} is the input for the final use of province b from sector i in province a; EX_i^a is the exports of sector i in province a, andE_i^a is the others of sector i in province a.

The direct input coefficient, a_{ij}^{ab}, refers to the direct input from sector i in province a to sector j in province b in the production of per unit product. The equation is as follows:

$$a_{ij}^{ab} = x_{ij}^{ab} \Big/ x_i^a \tag{21}$$

Then, equation (20) can be transformed into equation (22):

Table 1
Multi-regional water resources input-output model (MRIO).

			Intermediate use							Final use				Others	Total output
			Province 1			…	Province m			Province 1	…	Province m	Exports		
			Sector 1	…	Sector n		Sector 1	…	Sector n						
Intermediate input	Province 1	Sector 1	x_{11}^{11}	…	x_{1n}^{11}	…	x_{11}^{1m}	…	x_{1n}^{1m}	f_1^{11}	…	f_1^{1m}	EX_1^1	E_1^1	Y_1^1
		…	…	…	…	…	…	…	…	…	…	…	…	…	…
		Sector n	x_{n1}^{11}	…	x_{nn}^{11}	…	x_{n1}^{1m}	…	x_{nn}^{1m}	f_n^{11}	…	f_n^{1m}	EX_n^1	E_n^1	Y_n^1
	…	…	…	…	…	…	…	…	…		…	…	…	…	…
	Province m	Sector 1	x_{11}^{m1}	…	x_{1n}^{m1}	…	x_{11}^{mm}	…	x_{1n}^{mm}	f_1^{m1}	…	f_1^{mm}	EX_1^m	E_1^m	Y_1^m
		…	…	…	…	…	…	…	…	…	…	…	…	…	…
		Sector n	x_{n1}^{m1}	…	x_{nn}^{m1}	…	x_{n1}^{mm}	…	x_{nn}^{mm}	f_n^{m1}	…	f_n^{mm}	EX_n^m	E_n^m	Y_n^m
	Imports		IM_1^1	…	…	…	…	…	…	FM^1	…	FM^m			
Value added			VA_1^1	…	VA_n^1	…	VA_1^m	…	VA_n^m	…					
Total input			X_1^1	…	X_n^1	…	X_1^m	…	X_n^m	…					
Water consumption			W_1^1	…	W_n^1	…	W_1^m	…	W_n^m						

$$X_i^a = \sum_{m=1}^{M}\sum_{n=1}^{N} a_{ij}^{ab} \cdot x_i^a + \sum_{m=1}^{M} f_i^{ab} + \left(EX_i^a + E_i^a\right) \tag{22}$$

The matrix form of equation (23) is:

$$X = AX + F + (EX + E) \tag{23}$$

Equation (23) is transferred to obtain:

$$X = (I - A)^{-1}(F + EX + E) \tag{24}$$

where I is the identity matrix; $(I - A)^{-1} = [\lambda]$ is the Leontief inverse matrix, and the matrix element λ_{ij}^{ab} indicates that the production of a unit of product into sector j in province b requires the total input of sector i in province a.

After deducting the impact of imports and exports, the domestic inter-provincial trade relationship is:

$$XX = (I - A)^{-1}F \tag{25}$$

The direct water consumption coefficient, k_i^a, refers to the amount of water consumption per unit total output. It is expressed as the ratio of water consumption to the total output in the production process of each province and sector:

$$k_i^a = \frac{W_i^a}{X_i^a} \tag{26}$$

where W_i^a is the water consumption of sector i in province a; X_i^a is the total output of sector i in province a, and $K = [k]$ is the row vector for the direct water coefficient.

The complete water consumption coefficient, q_i^a, refers to the amount of water (directly and indirectly) consumed by the final product of the unit of production. $Q = [q]$ is the matrix of the complete water consumption coefficient. The equation is as follows:

$$Q = K(I - A)^{-1} \tag{27}$$

Then the complete water consumption matrix is obtained by:

$$VW = Q \cdot F \tag{28}$$

where $F = [f]$ is the matrix of final use.

$$TVW = VW - (VW)^T \tag{29}$$

where TVW is the virtual water transfer matrix, which is the difference between the complete water consumption matrix and its transpose matrix. TVW is the spatial flow pattern of virtual water (flux and direction of flow) obtained by the MRIO model.

2.3. Water stress index (WSI) and assumed water stress index (WSI*)

The agricultural water stress index (WSI) refers to the ratio of the amount of water used in agricultural production in a province to the amount of water available in the province. To implement the strictest water resources management system, the amount of available provincial water resources is the provincial total water use control target in the strictest water resources management system. In order to better respond to the policy, this study used the total water consumption control target instead of the available water in the province. Two scenarios were set here: the water resource pressure caused by grain production under normal conditions, and a scenario with the assumption that there is no virtual water trade in grain among provinces and that the grain demand of each province depends on its own grain production to meet demand. The difference between two scenarios represents the contribution of the food virtual flow momentum in intensifying or improving water stress in the provinces.

The WSI indicates that its value is equal to the ratio between the water consumption for grain production and the total water consumption control target of the province under current conditions.

$$WSI_i = \frac{WF_i^{grain}}{W_i} \tag{30}$$

where WSI_i is water stress index of province i; W_i is the total water use control target in province i; WF_i^{grain} is the water footprint of grain production in province i, which can be calculated using equation (31).

$$WF_i^{grain} = C_i \times VWC_i \tag{31}$$

The assumed water stress index (WSI*) is expressed as the ratio of the difference between the water consumption for grain production and the net output of grain virtual water flow (which is negative in the grain deficit province) to the total water consumption control target of the province.

$$WSI_i^* = \frac{WF_i^{grain} - NVW_i}{W_i} \tag{32}$$

where WSI_i^* is assumed water stress index of province i, and NVW_i is the net output of grain virtual water flow.

The WSI and WSI* are divided into four levels:0 < WSI/WSI* < 0.2, no stress; 0.2 < WSI/WSI* < 0.4, light stress; 0.4 < WSI/WSI* < 0.6, moderate stress, and 0.6 < WSI/WSI* < 1, severe stress.

2.4. Data source

Corresponding to the China Statistical Yearbook, the grain types of this study included rice, wheat, corn, soybean, and potato. Detailed data sources are presented below.

(1) Gain production and water consumption data

The provincial data of grain production, sown area, effective irrigation area, and population were obtained from the China Statistical Yearbook in 2013(National Bureau of Statistics of China, 2013a). Precipitation data at major meteorological stations were from the China meteorological science data sharing service network (National Meteorological Information Center, 2020). Data on agricultural water consumption, grain water consumption, and irrigation quotas were obtained from the China Water Resources Bulletin and Yearbook of China Water Resources issued by the Ministry of Water Resources and the National Bureau of Statistics in 2013 (China Ministry of Water Resources, 2013; National Bureau of Statistics of China, 2013b).

(2) Data on grain production cost and trade

Grain production cost data were obtained from the Compilation of National Agricultural Product Cost-Benefit Information, which includes direct agricultural production of seeds, fertilizers, films, and other materials as well as service fees, labor costs, and land costs (National Development and Reform Commission, 2013). Grain transportation costs are expressed as the rail freight cost among provincial capitals, and the data were obtained by querying railway freight rates (China Academy of Railway Sciences, 2020).

(3) Grain consumption data

Due to the lack of statistical data on grain consumption, the grain conversion rate method was used to calculate grain consumption. The grain conversion rate represents the grain amount consumed per unit product during the production process. For example, the grain conversion rate of beef is 1:2, which means that it takes 2 kg grain to produce 1 kg beef. Combined with the existing research of Wang et al. (2019), the main demand type and grain conversion rate were determined.

Grain consumption was divided into ration, feed, industrial, and seed consumption.

Ration consumption was divided into household and non-household consumption. Household consumption was obtained by multiplying the provincial population and per capita grain consumption in the China Statistical Yearbook (National Bureau of Statistics of China, 2013a). Non-household consumption was 16% of household consumption.

Feed consumption was calculated using the conversion rate of grains. The conversion rates are: pork 1:2.9, beef and mutton 1:2, poultry 1:2, milk 1:0.4, and eggs 1:1.7. Animal production is obtained from the China Food Industry Yearbook (China Food Industry Association, 2013).

Industrial consumption is mainly beer, liquor, and alcohol, and other industrial products consume 25% of the grain required by these three industries. The conversion rates are: liquor 1:2.3, beer 1:0.172, and alcohol 1:3.

Seed consumption was obtained by multiplying the sown area of each kind of grain by the seed grain per unit area. Data were obtained from the Compilation of National Agricultural Product Cost-Benefit Information (National Development and Reform Commission, 2013).

In addition, grain wastage will also consume some grain, which is mainly composed of three parts: stock, transportation, and processing. The stock wastage is 2% of grain production, and the transportation wastage and processing wastage are 4‰ and 5‰, of the sum of grain ration, feed, and industrial consumption.

3. Results

In order to clearly show the results of the study, the results section was divided into three parts. Firstly, the provincial distribution of grain surplus and deficit was calculated and displayed. Then, the simulated virtual water flow associated with interprovincial grain trade was verified and analyzed. At last, the effects of virtual water flow on regional water stress were evaluated by WSI and WSI*.

3.1. Provincial distribution of grain surplus and deficit

In 2012, China produced a total of 590 million tons and consumed 573 million ton of grain s. According to the grain production and consumption at the provincial level, the provincial distribution of grain surplus and deficit was obtained. There is surplus grain in 13 provinces, which can be used as grain surplus provinces to transport grain to grain deficit provinces. The remaining 17 provinces all have different degrees of grain shortage, and can conduct virtual food water trade with surplus provinces to meet their grain demands.

As shown in Fig. 1(a), the surplus provinces are mainly distributed in northeast China, northwest China and some regions in central China. The southeast coastal area (Guangdong, Fujian, Zhejiang) is the main grain shortage area in China, with a large population and less cultivated land. In addition, economically developed provinces such as Beijing and Shanghai also rely on grain trade as population influx and urbanization reduce farmlands. On the whole, it presents the pattern that the majority of provinces in the north are grain surplus provinces and most provinces in the south are grain deficit provinces. Among them, northeast China is the largest grain producing area in China, with its grain surplus accounting for 54.2% of the total grain surplus. Heilongjiang, located in northeast China, is the largest grain producer in China. Excluding its own grain consumption, the grain (mainly rice and corn) that can be supplied to other provinces reached 34.80 million tons. The second-largest grain surplus is Jilin, also located in the northeast China, with a grain surplus (mainly corn) of 13.34 million tons. Grain surpluses in Anhui, Inner Mongolia and Hebei are also relatively large, reaching 8.51, 7.02 and 4.38 million tons. The total grain surplus of the above provinces exceeds 75% of the total national surplus, and they are the major grain suppliers in the interprovincial grain trade. Guangdong and Sichuan are the provinces with the largest grain deficits, with 15.44 and 11.14 million tons, accounting for 40% of the total grain deficit. Other provinces with grain shortages of more than 5 million tons are Zhejiang, Guangxi, and Fujian. In addition, as the province-level municipality with a high degree of economic development, Beijing, Shanghai, Tianjin, and Chongqing also have large degrees of grain shortages. The total grain deficit of the above provinces exceeded 80% of the total

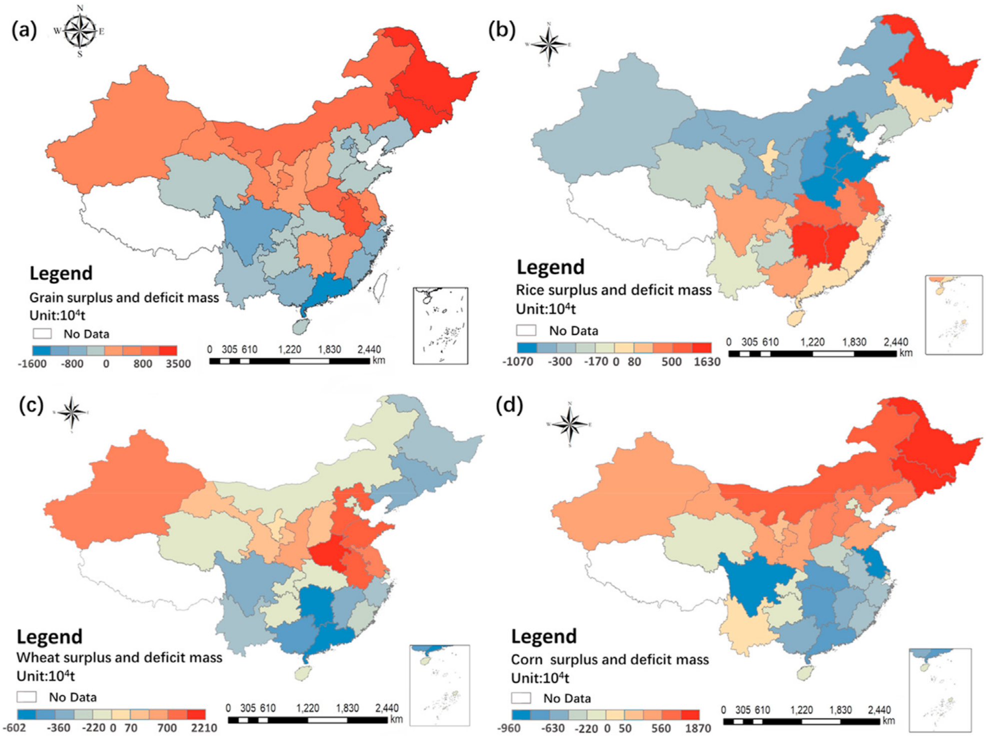

Fig. 1. Provincial distribution of surplus and deficit of (a) grain, (b) rice, (c) wheat, and (d) corn in China in 2012 *(Negative values represent deficit [blue], and positive values represent surplus [red]).* (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

national deficit, and they are the major grain demand provinces in the inter-provincial grain trade.

The provincial distribution of surpluses and deficits for major grain categories (rice, wheat, corn) is shown in Fig. 1[b], [c], and [d]. There are significant spatial differences in the distribution pattern of provincial surplus and deficit among different grain categories. The main rice surplus areas are Heilongjiang, Jilin, and some provinces in the south. The main rice deficit areas are located in northern China. Among them, rice surpluses in Heilongjiang, Hunan, and Jiangxi all exceeded 10 million tons, becoming the main rice supply provinces in the inter-provincial rice trade. The wheat surplus provinces are mainly concentrated in the North China Plain and several provinces which are located close to the same latitude. The remaining regions are all wheat deficit provinces. Provinces with a surplus of more than 10 million tons of wheat include Henan and Shandong, with 22.09 million tons and 13.41 million tons. The provincial distribution of corn surplus and deficit is between the northern China and the southern China. With the exception of a small surplus in Yunnan, the remaining corn surplus provinces are all located in the northern China, and the corn deficit provinces are located in southern China. The largest corn surplus provinces are Heilongjiang and Jilin, with surpluses of 18.64 million tons and 17.04 million tons. The planting and production patterns of different grain categories have jointly formed the spatial distribution of grain surplus and deficit.

Based on the above results, the total grain production in Northern China far exceeds the consumption. The grain demand in the Southern China is much greater than the local production. Although the surplus and deficit relationships for different grain varieties are not consistent spatially, in general, the most areas in Northern China can be self-sufficient and export much more grain to Southern China through the inter-provincial grain trading chain, which finally leads to the present virtual water flow pattern of grain in China. The unbalanced relationship of grain production and consumption is the fundamental driving force of Chinese “North-to-South” virtual water flow embedded in grain trade.

3.2. Virtual water flow associated with interprovincial grain trade

By solving the linear optimization simulation model, combined with the grain virtual water content, details of inter-province grain trade can be obtained. In the verification process, the net virtual water outflows of grain obtained by MRIO was compared with the net blue virtual water outflows of grain by simulation, as shown in Fig. 2.

The verified results show that, the simulated values are well matched with the real values acquired by input-output model, because the value points are mainly distributed along the 1:1 straight line. To further illustrate the simulated results, a correlation coefficient R was introduced to quantitatively describe the consistency between the simulated results and the real values. As shown in Fig. 2, the correlation coefficient R is as high as 0.85, indicating that the correlation between the simulated results and the real values is statistically significant and the simulation accuracy is acceptable and reliable. Based on the above analysis, the reliability of the linear optimization model proposed in this study is convincing and acceptable. The simulation results are feasible and can be used for inter-provincial grain virtual water flow analysis.

Fig. 3 shows the virtual water flow pattern associated with interprovincial grain trade. The virtual water flow direction is mainly from the North (water scarce region) to South (water sufficient area) and the total virtual water flow is as much as 73.46 billion m^3, in which, the blue virtual water flow is 30.23 billion m^3 and the green virtual water flow is 43.23 billion m^3. According to rough estimate, the total virtual water flow accounting for more than 10% of the total water consumption for grain production, just

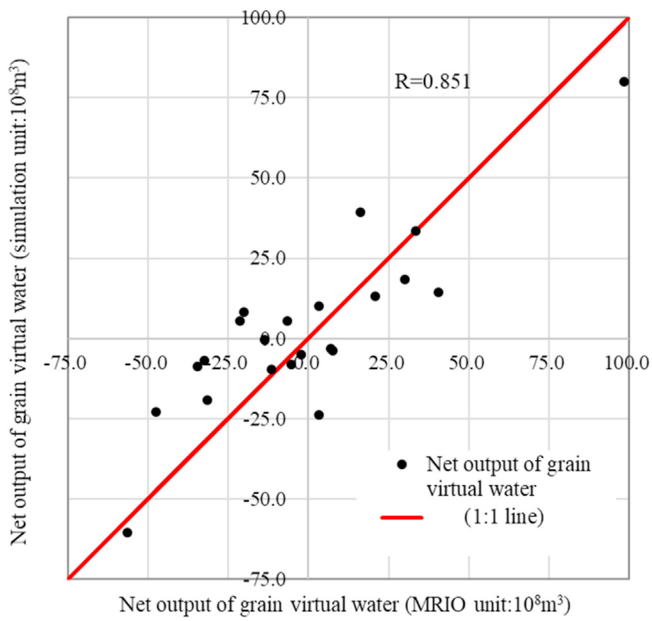

Fig. 2. Comparison of the net grain virtual water outflows by simulation and the multi-regional input-output model (MRIO). *(Note: The x-axis represents the net virtual water outflows of grain obtained by MRIO, and the y-axis represents the net blue virtual water outflows of grain by simulation.R* $\geq$ 0.8, *indicate a strong correlation between the real value and the simulated value.).* (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

like more than one Yellow River (the largest river in Northern China) being flowing from the North to the South. With the inter-provincial grain trade, virtual water flows from the grain surplus provinces to the grain shortage provinces. Heilongjiang is the largest grain virtual water output province. The virtual water outflow in Heilongjiang reaches 20.79 billion m^3, which accounted for 66.6% of its agricultural water consumption, and is the largest in the grain output provinces. Guangdong is the largest grain input province, with grain virtual water inflow of 16.12 billion m^3, mainly from Inner Mongolia (3.04 billion m^3), Anhui (3.73 billion m^3), and Henan (3.21 billion m^3), accounting for 21.9% of the total grain virtual water volume. Overall, the net virtual water flow in Heilongjiang and Guangdong exceed 20% of the total outflow and inflow. Combined with the specific volume of virtual water trade, the virtual water inflow of Guangdong, Sichuan and Zhejiang exceeds 50% of the total inflow. The virtual water outflow from the top 4 grain supply provinces provide 70% of the virtual water outflow, indicating that a few China's provinces are providing important support and guarantee for national security, in other words, the concentration index of China's grain production is so high. This phenomenon is posing huge risks to national food security and regional sustainable development.

3.3. Effects of virtual water flow pattern on regional water stress

Due to the inter-provincial grain trade, a large amount of virtual water is transferred from the main grain production area to the main grain consumption area, which brings great pressure to the regional water system and poses huge influence on the environment and ecosystem. The grain output will dramatically increase the water pressure in the grain output provinces. It will not only make up for the grain shortage but also reduce their water pressure for the grain input provinces. As shown in Fig. 4, the WSIs of almost all the grain output provinces are larger than those of grain input provinces. In particular, the WSI of several major output provinces represented by Heilongjiang, Inner Mongolia, and Jilin are already at moderate stress or severe stress level. It shows that the water used for grain production accounts for a large proportion of the total water used in these provinces. Shanxi, Gansu, and Ningxia have moderate WSI levels due to water resource shortages. By comparing and analyzing the WSI and WSI* of the grain exporting provinces, the difference between them represents the degree to which the virtual grain flow increases the water stress of the provinces. Heilongjiang, Jilin, Inner Mongolia, and Anhui have all produced a large amount of grain for the inter-provincial virtual water trade of grain. This has played an important role in ensuring food security for social and economic development. In order to produce grain for trade, Heilongjiang's grain production water accounts for more than half of its total water consumption. If the inter-provincial virtual water flow is excluded, the severe water stress level in Heilongjiang will decrease to moderate stress and the water stress in Jilin will directly decrease by two levels to a no-stress level.

In contrast to the grain export region, the water stress in the grain virtual water import region benefits from the grain trade among provinces. Without inter-provincial virtual water trade in grain, several major import areas, such as Beijing, Tianjin and Sichuan, would experience moderate stress or even severe stress. The presence of virtual water enables water resources to be redistributed through trade. The water stress in Guangdong and Fujian is also improved due to the virtual water inflow. Through the analysis of GDP and water resources with WSI* and WSI difference changes (Fig. 5). The difference between WSI* and WSI is positively correlated with GDP and water resources. These results show that the virtual water trade of grain in China has a pattern of flowing from poor water areas to rich water areas and from areas with low economic development to those with higher economic development. From the perspective of water and food security, such grain trade is detrimental. Compared with the main grain consumption areas, the main grain production areas are scarcer of water resources, and the outflow of virtual water in the water-deficient northern areas will aggravate the pressure on water resources. Due to the characteristics of high water consumption and low added value of grain production, the current virtual water trade will further widen the regional economic gap between grain output and input areas, which is not conducive to the sustainable development of grain production. It is urgent to establish a compensation system to stimulate the motivation of agricultural production and balance the development between grain producers and consumers.

4. Discussion

The virtual water flow associated with inter-provincial grain trade has a profound impact on regional water resources system. In the following section, the flow pattern of grain virtual water in China in the future was predicted, and the challenges faced by water for grain production in the future and possible countermeasures were discussed. Further, the uncertainty of the study was also discussed, and the research results were compared with those of previous studies.

4.1. Future grain virtual water flow pattern

In order to better analyze grain trade, the future grain virtual flow pattern was predicted. Studies have found that the population growth, accelerated urbanization, changing dietary structure, and industrial grain consumption are the main factors influencing the grain consumption in China (Namany et al., 2020). In the future, China's total grain consumption will continue to show an increasing trend and is expected to peak around 2030, possibly reaching 650

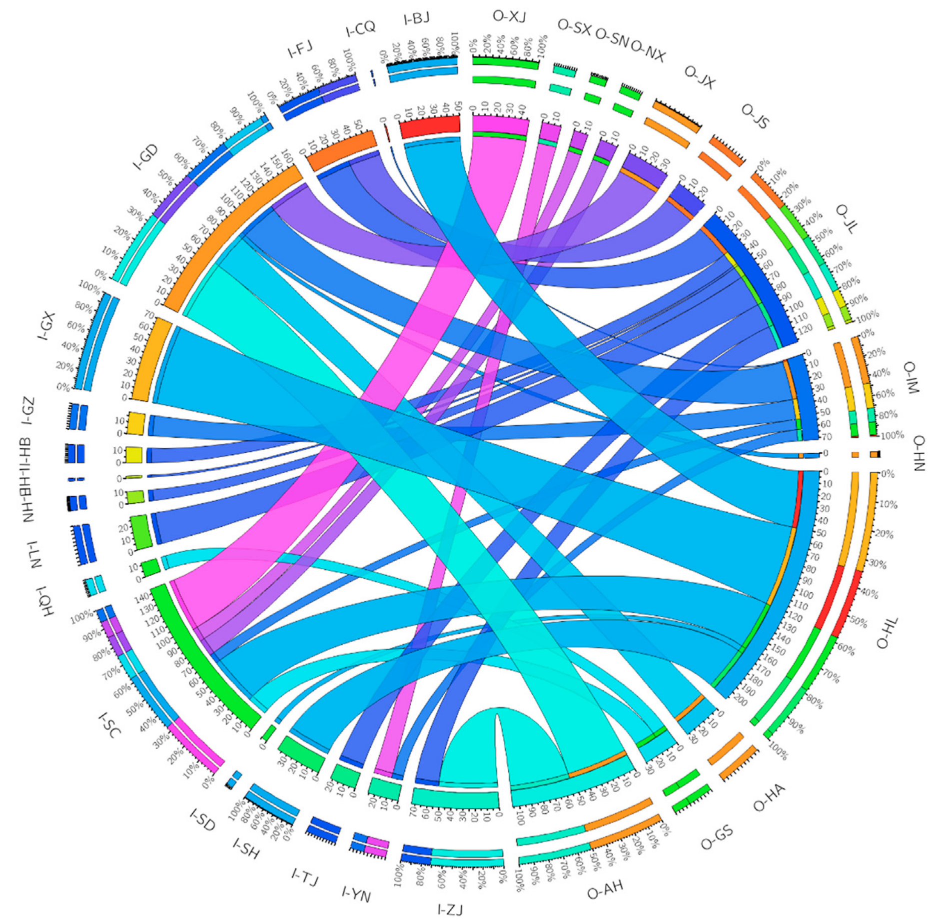

Fig. 3. Virtual water flow pattern associated with interprovincial grain trade *(Note: the province names begin with "I-" or "O-", "I-" represents an input province, "O-" represents an output province, followed by abbreviation of the province, the corresponding relationship is shown in Table S1 in the appendices. The outer circle shows the percentage of the output (or input) of this flow in the total output (or input) of the province, and the inner circle shows the value of the output (or input) of this flow [$10^8 m^3$]).*

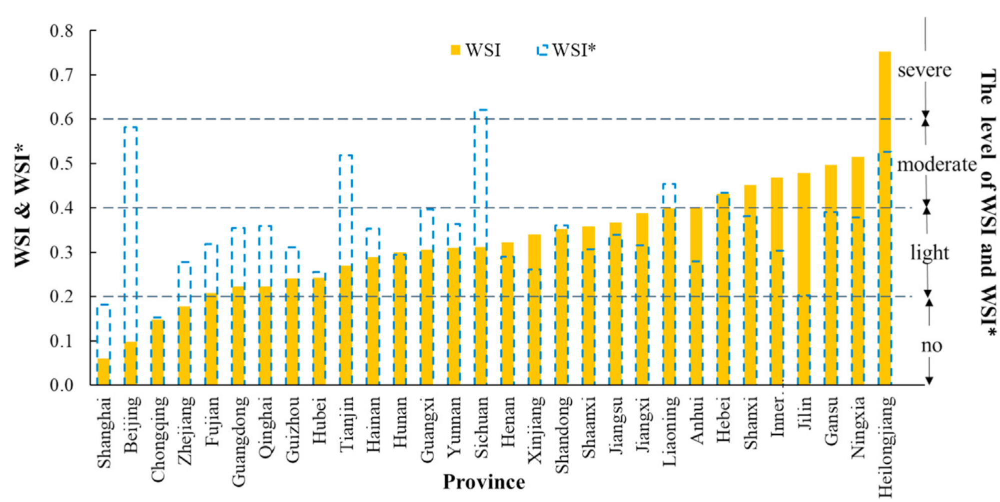

Fig. 4. Comparison between the water stress index (WSI) and the assumed water stress index (WSI*) in provinces in China.

million tons (Xiang and Zhong, 2013). To maintain self-sufficiency of grain production in China to at least 95% of requirements, China's grain output must reach approximately 620 million tons. In 2018, China's grain output was 610 million tons. According to the current grain production capacity, there remains a gap of nearly 10 million tons to meet the peak grain demand.

From the regional distribution of grain production, grain production of the seven major regions (except Southern China) all show upward trends from 1990 to 2018. Northeast China saw the largest increase (104.5%), followed by Northwest China (61%), Northern China (54.5%), and central China (39.7%). According to the change process chart drawn from the seven major grain-producing

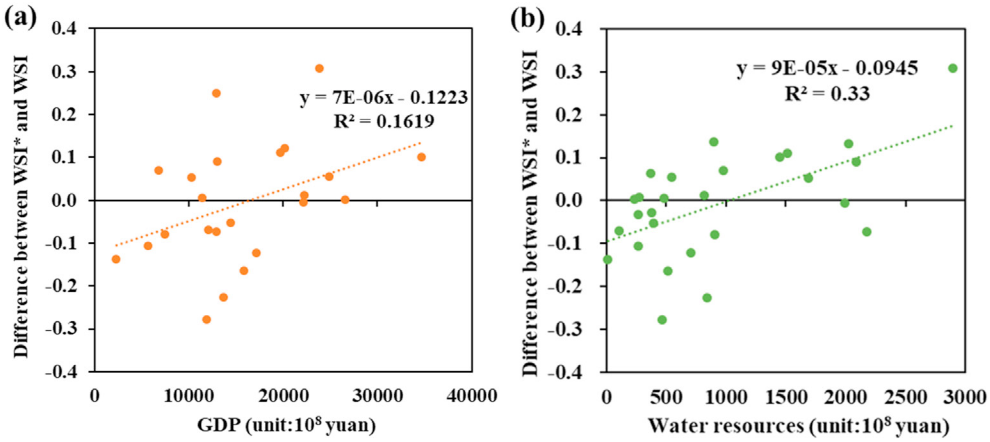

Fig. 5. (a) Gross domestic product (GDP) and (b) water resources change with the difference between the assumed water stress index (WSI*) and the water stress index (WSI).

areas in China from 1990 to 2018 (Fig. 6), the proportion of grain production in Northeast, Northern, Northwest, and Central China shows significant upward trends. Since 2005, total grain production in these regions has reached more than 60% of the total national output. In contrast, the proportion of grain output in Southwest, Southern, and Eastern China have been decreasing annually, and the center of grain production in China has been shifting northward.

Based on the above analysis, the future grain virtual water flow pattern is predicted. China's grain consumption will reach a peak of 650 million tons in 2030. Under the requirement of 95% self-sufficiency rate in grain production, the total grain production should be 620 million tons. To predict the future grain production and consumption in each geographical region, it is assumed that the proportion of grain production and consumption in each geographical region remains the same as that in present when the total grain consumption reaches its peak in 2030. Based on the above assumption, according to the proportion of grain production in seven geographical regions in Fig. 6, the grain production of each region in 2030 can be determined. According to the calculation results of grain consumption in Section 2.4, the regional grain consumption in 2030 is obtained. As shown in Fig. 7, the virtual water flow pattern of grain in China in 2030 is simulated by using the model proposed in this study.

When total grain consumption reaches its peak, the main grain output areas will include Northeast, Northern, Northwest, and Central China. The virtual flow of grain from the north to the south will rise further. The grain virtual water output associated with grain output in Northeast China will exceed 50 billion m^3 in 2030, accounting for a larger proportion of the total output and approaching 90% of the domestic grain virtual water output. In addition, since the grain production self-sufficiency rate in the simulation scenario was 95%, it will be necessary to import as much as 30 million tons of grain from abroad. Southwest and Southern China will become the main grain input areas. The main reasons for the increase of grain demand in Southwest China are the large population base and high growth rate. The main factors causing the gap in grain demand in Southern China are the increase of grain

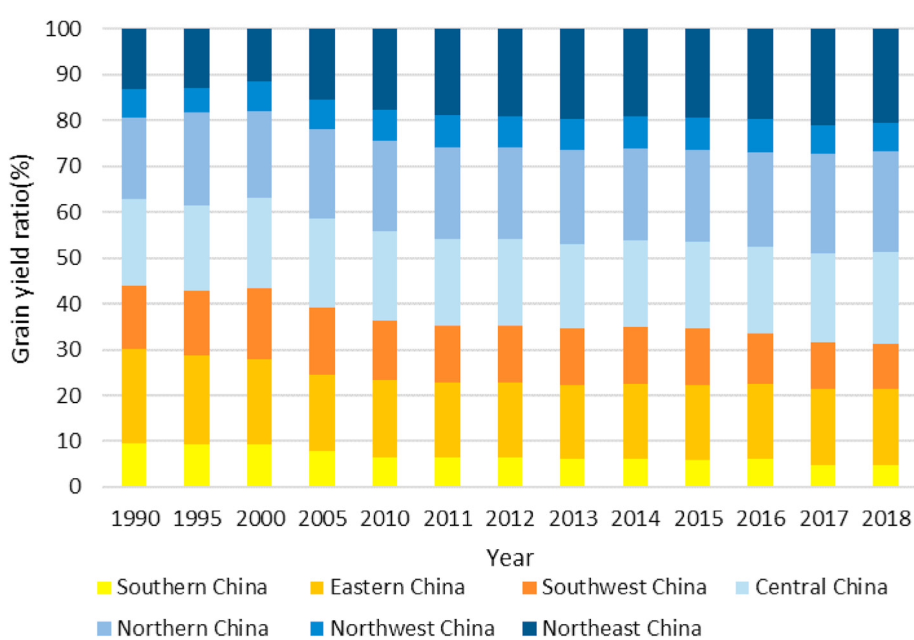

Fig. 6. Change of grain yield proportion in seven geographical regions in China.

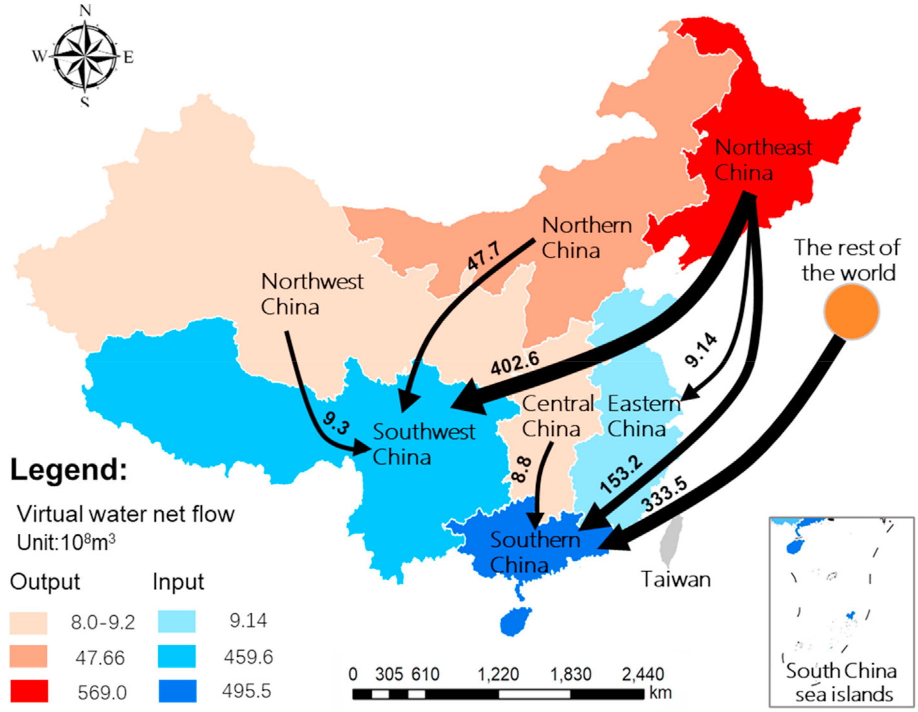

Fig. 7. Future grain virtual water flow pattern in China *(Note: This is the simulation result under the situation of 95% grain self-sufficiency for China. The background color of the map represents the volume of net virtual water flow, the arrow represents the flow direction of virtual water, and the number near the arrow represents the volume of virtual water flow in this direction).* (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

demand caused by the acceleration of urbanization and the low agricultural yield following the agricultural land to industrial land conversion.

4.2. Challenges to grain security

The inter-provincial grain trade effectively solves the problem of unbalanced spatial grain supply and demand. However, grain security in China still faces many challenges. The structural imbalance between supply and demand of grain categories and the limited potential of grain production in major grain-producing areas are problems that must be urgently solved.

As shown in Fig.8, based on the production and consumption of various grains, the demand for staple grain can mainly be guaranteed, however, there is a large demand gap for soybeans. In 2012, China produced more rice and wheat than it consumed. Corn production is roughly equal to consumption, while soybean consumption is much higher than production. The demand gap for soybeans reached 58.93 million tons, which is approximately equal to 66.88 billion m^3 of virtual water. China has only achieved basic self-sufficiency in staple grains, and the supply of soybeans also depends on imports. This is mainly due to feed demand, which accounts for more than 75% of soybean consumption. With rapid economic and social development, residents' incomes continue to increase and urbanization accelerates. The improvement of living standards has led to profound changes in the structure of food consumption (Samireddypalle et al., 2019). Although the consumption of rations has decreased, demands for meat, aquatic products, and alcoholic products have increased, and the overall food demand remains very high. The structural security of grain still faces many challenges.

With the evolution of the national economic pattern, from the perspective of the current development trend, China's future food security will continue to be mainly undertaken by the grain-producing areas in the North. Water shortage has always been the main factor restricting grain production stability and exploitation of the grain yield potential. At present, Northeast China occupies an important position in grain production. The comprehensive grain production capacity in Northeast China is strong and the commodity rate of grain production is high. However, the problems facing food production in this region are also severe. Firstly, with the extensive use of land resources, the decline of soil fertility and the increase of marginal cost of agricultural products, farmers are faced with the serious dilemma that they cannot increase their income. Secondly, water shortages are very serious. The Songnen Plain is a key grain-producing region in Heilongjiang Province. The area of arable land accounts for 45.6% of the province, however, the amount of water resources only accounts for 5.7%. In addition, the problem of agricultural non-point source pollution in Northeast China also increases the risks for sustainable grain production (Ouyang et al., 2012). North China is an important grain-producing region in China and the world. Since the 1970s, with the development of irrigation technology, agricultural output has greatly increased, however, at the same time it has caused a series of environmental problems such as a decline in the water table, river channel interruptions, wetland shrinkage, and land subsidence, which have brought serious threats to future agricultural and social and economic development (Zhao et al., 2019). In Hebei Province, for example, in recent years, the rate of groundwater decline has been very rapid. In the 1950s and 1960s, the underground water level was around 2–3 m, while the groundwater depth is below 30 m in 2016, leading to soil drying, intensified drought, and ecological deterioration (Hu et al., 2016). Northwest China is the main production base of wheat and corn. In addition, located in the northwest, Xinjiang's cotton production has accounted for 85% of the national total production (Gunther et al., 2017). However, Northwest China is also an important energy base. Energy, such as coal and natural gas, also requires a lot of

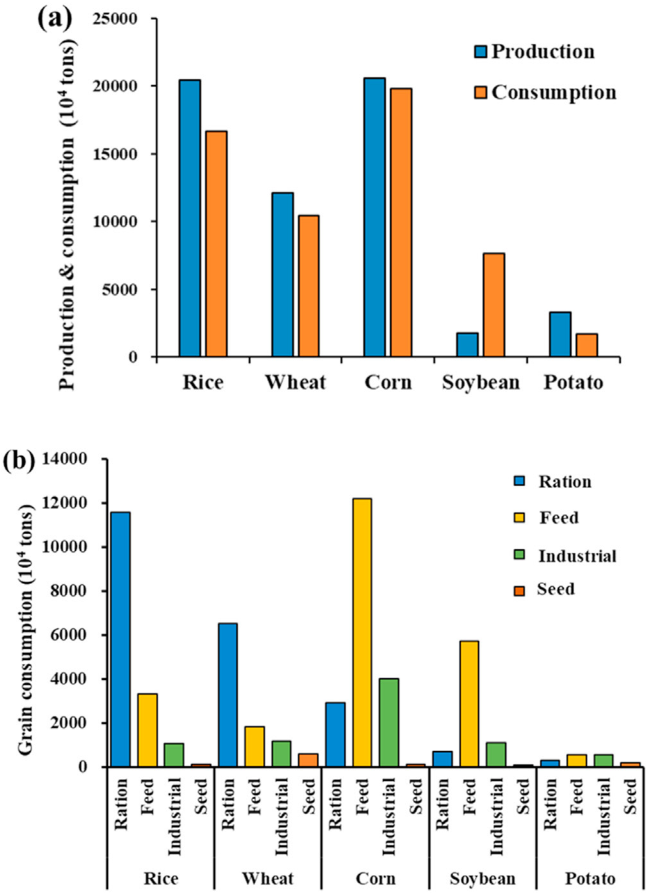

Fig. 8. (a) Total grain production and consumption, and (b) grain consumption by various consumption channels in China in 2012.

water, but it can bring higher profits than agriculture, which limits the increase in grain production in Northwest China. Because of the abundant water resources, the southern region has been the focus of food production since ancient times (Liu et al., 2020). However, since China's reform and opening up, affected by the regional economic pattern and the evolution of production factors, the grain production center has shifted to the North and the proportion of grain production in the southern region has decreased annually. At present, due to the restrictions of land resources and agricultural labor resources, the southern region has been difficult to bear the burden of future food growth.

Economic globalization is deepening and international trade is becoming more extensive (Wu et al., 2019). However, simultaneously, international competition is also intensifying (Xu et al., 2019). The trade war initiated by developed countries against China has brought huge made uncertainty for China's food imports (Wang et al., 2019). In the future, grain demand will continue to rise. Under the scenario of 95% grain self-sufficiency, there is a gap between production and demand of nearly 10 million tons. If grain imports are restricted, the means of filling the demand gap will be shifted from imports to domestic production. The huge demand for water resources will bring greater challenges to the water resources system in grain-producing areas, making it more difficult to guarantee food supply security.

4.3. Countermeasures for the coordinated safety of water and grain

Grain production is related to social stability and is an important foundation for economic development. However, the mismatch between grain production and water resources in China poses a significant threat to water and grain security, especially in the North China. In the face of the huge impact of the current situation and the unsustainable virtual water flow embedded in interprovincial grain trade, the following countermeasures should be urgently implemented to ensure the collaborative safety of water and grain.

The first is to improve the water use efficiency for grain production. The government and scientific research should pay much attention to water-saving agriculture mainly from the following 3 aspects: water-saving engineering, water-saving technology promotion and water-saving breeding. In terms of water-saving engineering, the construction and maintenance of irrigated areas should be enhanced to reduce canal system leakage and improve irrigation water efficiency. In terms of water-saving technology, it should be encouraged to use water-saving irrigation equipment (such as drip irrigation and sprinkling irrigation), and to promote rainwater collection and dry farming. In terms of water-saving breeding, the areas of cold-resistant and drought-resistant crop varieties and high-yielding crops should be enlarged.

The second is to optimize the planting structure and improve the matching degree of water and land resources. In recent years, the North China is producing more and more grain than the South China, which in turn brings about tremendous water scarcity issues and the associated ecological and environmental problems (e.g., ground subsidence caused by overexploitation of groundwater, land desertification and degradation and water and soil erosion, etc.), especially in North China Plain and Northwest China. It is urgent to limit the grain production in Northern areas and change the planting structure aiming at minimizing the irrigation water and expanding the rain-fed agricultural area. The South China should also be encouraged to produce more grain through some policy incentives, especially to restore the grain production capacity in traditional agricultural provinces (e.g., Sichuan, Hubei, Hunan, Jiangsu and Jiangxi) of South China.

The third is to establish a coupled physical-virtual water coupled management framework. Traditionally, managers always focus on the physical-water measures to cope with water scarcity (e.g. increasing the available water resources for irrigation, utilization of reclaimed water and inter-basin water transfer projects). However, these measures are always cost intensive and difficult to implement. In comparison, to implement the virtual water strategy is simpler and convenient. For example, the water-deficient northern areas could buy food and other water-intensive products from the water-rich regions to reduce the local agricultural water consumption and the saved water could be used to support the urbanization and ecological restoration. In addition, a national compensation system is necessary in the framework of coupled physical-virtual water management framework, in which, the government can use transfer payments to compensate the farmers and grain production areas to stimulate the motivation of agricultural production and to construct the infrastructures for water-saving agriculture.

4.4. Uncertainty analysis

In this study, a linear model is constructed to quantify the grain virtual water flow pattern among provinces. As shown in Table 2, a few scholars have previously studied the interregional virtual water flow. Ma et al. (2006) divided China into eight Sub-regions and simulated the virtual water flow of regions with distance as a single factor. Ren et al. (2018) adopted the input-output analysis method. Wang et al. (2019) adopted the linear optimization method, but their purpose was to calculate the virtual flow route. Although it is impossible to compare their studies with this study due to the

Table 2
Comparison among this study and previous studies.

Sources	Theory	Method	Driving factor	Validation	StudyPeriod	Sub-regions in China
This study	Minimize the comprehensive cost	Linear optimization model	Production and Transport cost	Verify by the real value obtained by MRIO	2012	30 provinces
Ma et al. (2006)	Minimize the total distance	Regional distribution	Distance	—	1999	Eight sub-regions
Ren et al. (2018)	Input-output balance	MRIO model	Input-output analysis	—	2007	Beijing-Tianjin-Hebei region and other areas
Wang et al. (2019)	Maximizing opportunity cost	Linear optimization model	Opportunity and Transport cost	—	2014	31 provinces

different study years, regions and objects, it also can be seen through comparative analysis that the model established in this study further improves the model tools on the basis of existing studies, and it proves that the minimization of the comprehensive cost of grain production and transportation as the model optimization objective is a feasible and better way to map the virtual water flow patterns embedded in interprovincial grain trade in China. Compared with the previous studies, this study also has better spatial resolution because this study conducted the analysis for grain virtual water flow among Chinese 31 provinces, but the most previous studies were mainly focusing on the virtual water flow among China's large geographical zones (e.g., the virtual water flow among 8 large regions of China). But at the same time, the difficulty of obtaining the data required by the model in this study is relatively smaller. Compared with MRIO, this model has the advantages of convenient data collection and more flexible application scenarios in quantifying the virtual water flow among regions or provinces.

But it also has some limitations. In this study, since the study area does not have detailed provincial-level grain input and output data, it is assumed that the food produced in each province first meets all local needs and then go out for virtual water trade. However, due to the complexity of grain trade, this assumption does not fully reflect the real situation of grain trade in the study area. For example, corn transported from the north to the south may be made into feed for pigs, and then transported from the south to the north in the form of pork. More detailed virtual water flow paths and processes are worthy of further study later. In addition, this study adopts a distribution scheme that minimizes the cost of grain production and transportation, but this may be contrary to reality. For example, some people will be willing to spend more money to pursue better quality grain. Time and region will affect the transaction cost of food, and ignoring the transaction cost also brings uncertainty to the research results. The real virtual water flow pattern may be more complicated and intertwined than the simulation results. The optimization model that considers more drivers of grain trade and quantifies the contribution rate of each factor should be perfected in the next step.

5. Conclusion

The demand for grain continues to increase due to population growth, urbanization, and improvement of living standards. The mismatch of water resources and cultivated land resources in China has resulted in a virtual water flow pattern that is inconsistent with the distribution pattern of water resources, which has huge impacts on the water resources system in grain-exporting regions. However, research on methodologies for virtual water flow simulation is still in its infancy. At present, a simulation method with simple data acquisition and reliable simulation results is lacking. In this study, grain cost allocation was divided into two parts: grain production cost and transportation cost. With the optimization goal of minimizing the overall allocation cost, a model of the virtual water spatial flow pattern of grain among provinces in China was constructed to simulate the virtual water flow pattern associated with China's inter-provincial grain trade in 2012.

The main conclusions are summarized as follows:

(1) Grain output provinces were distributed in Northeast, Northwest, and Central China. The grain virtual water outputs of Heilongjiang, Jilin, and Anhui were 20.78 billion m^3, 12.73 billion m^3, and 10.59 billion m^3, and were the major grain exporting provinces in China, accounting for 60.0% of the country's total output of virtual water. Grain import provinces were widely distributed in more economically developed areas such as the Beijing-Tianjin-Hebei region, the northern, eastern, and southern coasts, and Southwest China. Guangdong Province had the largest amount of virtual water input for grain, where, in 2012, the amount of virtual water input for grain was 16.12 billion m^3, accounting for 21.9% of the total amount of virtual water input for grain in China. The correlation coefficient $R > 0.85$ between the results obtained by MRIO and the optimized simulation method indicated that the optimized simulation had good simulation results regarding the grain virtual water output in each province.

(2) The WSI and WSI* were used to analyze the influence of the virtual water flow pattern of regional water resources. The results showed that water stress was alleviated in some areas due to the input of virtual water for grain, with the most significant effects in Beijing, Tianjin, and Sichuan. Due to the output of virtual water, water stress increased in many areas. This was most serious in Northeast China, where the water resources system in Heilongjiang Province was under severe water stress. The continuous supply of virtual water for grain not only limits the development of other industries in these regions and restricts the development of the local economy, but it also brings great challenges to the security of the local water resources system.

(3) According to the estimation, when China's food demand reaches a peak of 650 million tons in 2030, the virtual water flow will further increase. Then, the volume of virtual water flowing out of Northeast China will be as much as 50 billion m^3, accounting for 90% of the total virtual water flow. Increasing the virtual water outflow in North China will severely exceed the local water resources capacity in the arid and semi-arid areas and have an obvious negative impact on sustainable development in Northern China. Further improving the water resource efficiency of grain production and adjusting the structure and spatial distribution of grain production are effective countermeasures to ensure the coordination and safety of grain and water.

CRediT authorship contribution statement

Tingli An: Writing - original draft, Constructed the model and wrote the original draft. **Lizhen Wang:** Writing - original draft, The original draft preparation. **Xuerui Gao:** Conceptualization, and modification. **Xinxueqi Han:** Data curation, Data collection and validation. **Yong Zhao:** Formal analysis, Data analysis and figures preparation. **Lixing Lin:** Data curation, Data collection and model construction. **Pute Wu:** Writing - review & editing, Reviewing and editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.125670.

Appendices

Table S1
Province name abbreviations

Province	Abbreviation	Province	Abbreviation	Province	Abbreviation
Beijing	BJ	Zhejiang	ZJ	Hainan	HI
Tianjin	TJ	Anhui	AH	Chongqing	CQ
Hebei	HE	Fujian	FJ	Sichuan	SC
Shanxi	SX	Jiangxi	JX	Guizhou	GZ
Inner Mongolia	IM	Shandong	SD	Yunnan	YN
Liaoning	LN	Henan	HA	Shanxi	SN
Jilin	JL	Hubei	HB	Gansu	GS
Heilongjiang	HL	Hunan	HN	Qinghai	QH
Shanghai	SH	Guangdong	GD	Ningxia	NX
Jiangsu	JS	Guangxi	GX	Xinjiang	XJ

References

Allan, J.A., 1993. Fortunately there are substitutes for water otherwise our hydropolitical futures would be impossible. Priorities Water Resour. Alloc. Manag. 13.
Antonelli, M., Tamea, S., Yang, H., 2017. Intra-EU agricultural trade, virtual water flows and policy implications. Sci. Total Environ. 587–588 (1), 439–448. https://doi.org/10.1016/j.scitotenv.2017.02.105.
Chapagain, A., Hoekstra, A.Y., 2011. The blue, green and grey water footprint of rice from production and consumption perspectives. Ecol. Econ. 70 (4), 749–758. https://doi.org/10.1016/j.ecolecon.2010.11.012.
Chapagain, A., Hoekstra, A., Savenije, H., 2006. Water saving through international trade of agricultural products. Hydrol. Earth Syst. Sci. 10, 455–468.
China Academy of Railway Sciences, 2020. Website. www.12306.cn/yjcx/hybj.jsp.
China Food Industry Association, 2013. China Food Industry Yearbook 2013. Zhonghua Book Company Publishing House, Beijing.
China Ministry of Water Resources, 2013. The China Water Resources Bulletin 2013. China Water & Power Press, Beijing.
Dong, H., Geng, Y., Fujita, T., Fujii, M., Hao, D., Yu, X., 2014. Uncovering regional disparity of China's water footprint and inter-provincial virtual water flows. Sci. Total Environ. 500–501, 120–130. https://doi.org/10.1016/j.scitotenv.2014.08.094.
Duarte, R., Pinilla, V., Serrano, A., 2016. Understanding agricultural virtual water flows in the world from an economic perspective: a long term study. Ecol. Indicat. 61, 980–990. https://doi.org/10.1016/j.ecolind.2015.10.056.
Feng, K., Siu, Y.L., Guan, D., Hubacek, K., 2012. Assessing regional virtual water flows and water footprints in the Yellow River Basin, China: a consumption based approach. Appl. Geogr. 32 (2), 691–701. https://doi.org/10.1016/j.apgeog.2011.08.004.
Fu, Y., Zhao, J., Wang, C., Peng, W., Wang, Q., Zhang, C., 2018. The virtual Water flow of crops between intraregional and interregional in mainland China. Agric. Water Manag. 208, 204–213. https://doi.org/10.1016/j.agwat.2018.06.023.
Gao, X., Sun, M., Zhao, Y., Wu, P., Jiang, S., Zhuo, L., 2019a. The cognitive framework of the interaction between the physical and virtual water and the strategies for sustainable coupling management. Sustainability 11 (9), 2567. https://doi.org/10.3390/su11092567.
Gao, X., Zhao, Y., Lu, S., Chen, Q., An, T., Han, X., Zhuo, L., 2019b. Impact of coal power production on sustainable water resources management in the coal-fired power energy bases of Northern China. Appl. Energy 250, 821–833. https://doi.org/10.1016/j.apenergy.2019.05.046.
Gunther, J., Thevs, N., Gusovius, H., Sigmund, I., Bruckner, T., Beckmann, V., Abdusalik, N., 2017. Carbon and phosphorus footprint of the cotton production in Xinjiang, China, in comparison to an alternative fibre (Apocynum) from Central Asia. J. Clean. Prod. 148, 490–497. https://doi.org/10.1016/j.jclepro.2017.01.153.
Hanasaki, N., Inuzuka, T., Kanae, S., Oki, T., 2010. An estimation of global virtual water flow and sources of water withdrawal for major crops and livestock products using a global hydrological model. J. Hydrol. 384 (3), 232–244. https://doi.org/10.1016/j.jhydrol.2009.09.028.
He, G., Zhao, Y., Wang, J., Li, H., Zhu, Y., Jiang, S., 2019. The water–energy nexus: energy use for water supply in China. Int. J. Water Resour. Dev. 35 (4), 587–604. https://doi.org/10.1080/07900627.2018.1469401.
Hoekstra, A.Y., Hung, P., 2005. Globalization of water resources: international virtual water flows in relation to crop trade. Global Environ. Change 15, 45–56.
Hu, X., Shi, L., Zeng, J., Yang, J., Zha, Y., Yao, Y., Cao, G., 2016. Estimation of actual irrigation amount and its impact on groundwater depletion: a case study in the Hebei Plain, China. J. Hydrol. 543, 433–449. https://doi.org/10.1016/j.jhydrol.2016.10.020.
Ibarrolarivas, M.J., Granadosramirez, R., Nonhebel, S., 2017. Is the available cropland and water enough for food demand? A global perspective of the Land-Water-Food nexus. Adv. Water Resour. 110, 476–483. https://doi.org/10.1016/j.advwatres.2017.09.018.
Lamastra, L., Miglietta, P., Toma, P., De, L., Massari, S., 2017. Virtual water trade of agri-food products: evidence from Italian-Chinese relations. Sci. Total Environ. 599–600, 474–482. https://doi.org/10.1016/j.scitotenv.2017.04.146.
Lindo systems, Inc. www.lindo.com/index.php/company, 2020.
Liu, J., Li, M., Wu, M., Luan, X., Wang, W., Yu, Z., 2020. Influences of the south–to-north water diversion project and virtual water flows on regional water resources considering both water quantity and quality. J. Clean. Prod. 244, 118920. https://doi.org/10.1016/j.jclepro.2019.118920.
Ma, J., Hoekstra, A.Y., Wang, H., Chapagain, A.K., Wang, D., 2006. Virtual versus real water transfers within China. Philos. T. R. Soc. B 361 (1469), 835–842. https://doi.org/10.1098/rstb.2005.1644.
Mi, Z., Meng, J., Guan, D., Shan, Y., Song, M., Wei, Y., Liu, Z., Hubacek, K., 2017. Chinese CO2 emission flows have reversed since the global financial crisis. Nat. Commun. 8 (1), 1712. https://doi.org/10.1038/s41467-017-01820-w.
Namany, S., Govindan, R., Alfagih, L., Mckay, G., Alansari, T., 2020. Sustainable food security decision-making: an agent-based modelling approach. J. Clean. Prod. 255, 120296. https://doi.org/10.1016/j.jclepro.2020.120296.
National Bureau of Statistics of China, 2013a. China Water Resources Bulletin. China Water & Power Press, Beijing.
National Bureau of Statistics of China, 2013b. China Statistical Yearbook 2013. China Statistical Publishing House, Beijing.
National Development and Reform Commission of China, 2013. Compilation of National Agricultural Product Cost-Benefit Information. China Statistical Publishing House, Beijing.
National Meteorological Information Center, 2020. Website. www.cma.gov.cn/2011qxfw/2011qsjgx/.
Niva, V., Cai, J., Taka, M., Kummu, M., Varis, O., 2020. China's sustainable water-energy-food nexus by 2030: impacts of urbanization on sectoral water demand. J. Clean. Prod. 251, 119755. https://doi.org/10.1016/j.jclepro.2019.119755.
Ouyang, W., Huang, H., Hao, F., Shan, Y., Guo, B., 2012. Evaluating spatial interaction of soil property with non-point source pollution at watershed scale: the phosphorus indicator in Northeast China. Sci. Total Environ. 432, 412–421. https://doi.org/10.1016/j.scitotenv.2012.06.017.
Ren, D., Yang, Y., Yang, Y., Richards, K., Zhou, X., 2018. Land-Water-Food Nexus and indications of crop adjustment for water shortage solution. Sci. Total Environ. 626, 11–21. https://doi.org/10.1016/j.scitotenv.2018.01.071.
Samireddypalle, A., Prasad, K.V., Ravi, D., Khan, A.A., Reddy, R.Y., Angadi, U.B., Blummel, M., 2019. Embracing whole plant optimization of rice and wheat to meet the growing demand for food and feed. Field Crop. Res. 244, 107634.

https://doi.org/10.1016/j.fcr.2019.107634.
Sun, C., Liu, S., 2019. Water footprint and space transfer at provincial level of China based on MRIO model. J. Nat. Resour. 945–956, 05.
Sun, S., Wang, Y., Engel, B.A., Wu, P., 2016. Effects of virtual water flow on regional water resources stress: a case study of grain in China. Sci. Total Environ. 550, 871–879. https://doi.org/10.1016/j.scitotenv.2016.01.016.
Sun, S., Wu, P., Wang, Y., Zhao, X., 2013. The virtual water content of major grain crops and virtual water flows between regions in China. J. Sci. Food Agric. 93 (6), 1427–1437. https://doi.org/10.1002/jsfa.5911.
Sun, S., Yin, Y., Wu, P., Wang, Y., Luan, X.B., Li, C., 2019. Geographical evolution of agricultural production in China and its effects on water stress, economy, and the environment: the virtual water perspective. Water Resour. Res. 55 (5), 4014–4029. https://doi.org/10.1029/2018WR023379.
Wang, Z., Zhang, L., Ding, X., Mi, Z., 2019. Virtual water flow pattern of grain trade and its benefits in China. J. Clean. Prod. 223, 445–455. https://doi.org/10.1016/j.jclepro.2019.03.151.
Wu, P., Zhuo, L., Liu, Y., Gao, X., Wang, Y., Zhao, X., Sun, S., 2019. Assessment of regional crop-related physical-virtual water coupling flows. Sci. Bull. 64 (18), 1953–1966. https://doi.org/10.1360/n972018-00997.
Wu, S., Ben, P., Chen, D., Chen, J., Tong, G., Yuan, Y., Xu, B., 2018. Virtual land, water, and carbon flow in the inter-province trade of staple crops in China. Resour. Conserv. Recycl. 136, 179–186. https://doi.org/10.1016/j.resconrec.2018.02.029.
Xiang, J., Zhong, F.N., 2013. Impact of demographic transition on food demand in China: 2010 – 2050, 06 China Population, Resources and Environment 23, 117–121 (in Chinese).
Xu, Z., Li, Y., Herzberger, A., Chen, X., Gong, M., Kapsar, K., Liu, J., 2019. Interactive national virtual water-energy nexus networks. Sci. Total Environ. 673, 128–135. https://doi.org/10.1016/j.scitotenv.2019.03. Sci.Total Environ. 298.
Ye, Q., Li, Y., Zhang, W., Cai, W., 2019. Influential factors on water footprint: a focus on wheat production and consumption in virtual water import and export regions. Ecol. Indicat. 102, 309–315. https://doi.org/10.1016/j.ecolind.2019.02.051.
Zhang, X., Liu, J., Zhao, X., Yang, H., Deng, X., Jiang, X., Li, Y., 2019. Linking physical water consumption with virtual water consumption: methodology, application and implications. J. Clean. Prod. 228, 1206–1217. https://doi.org/10.1016/j.jclepro.2019.04.297.
Zhang, Y., Zhang, J., Tian, Q., Liu, Z., Zhang, H., 2018. Virtual water trade of agricultural products: a new perspective to explore the Belt and Road. Sci. Total Environ. 622–623, 988–996. https://doi.org/10.1016/j.scitotenv.2017.11.351.
Zhang, Y., Zhang, J., Wang, C., Cao, J., Liu, Z., Wang, L., 2017. China and Trans-Pacific Partnership Agreement countries: estimation of the virtual water trade of agricultural products. J. Clean. Prod. 140, 1493–1503. https://doi.org/10.1016/j.jclepro.2016.10.001.
Zhao, Q., Zhang, B., Yao, Y., Wu, W., Meng, G., Chen, Q., 2019. Geodetic and hydrological measurements reveal the recent acceleration of groundwater depletion in North China Plain. J. Hydrol. 575, 1065–1072. https://doi.org/10.1016/j.jhydrol.2019.06.016.
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. A. Sci. USA. 112 (4), 1031–1035. https://doi.org/10.1073/pnas.1404130112.
Zhuo, L., Mekonnen, M., Hoekstra, A.Y., 2016. The effect of inter-annual variability of consumption, production, trade and climate on crop-related green and blue water footprints and inter-regional virtual water trade: a study for China (1978–2008). Water Res. 94, 73–85. https://doi.org/10.1016/j.watres.2016.02.037.