Stochastic Environmental Research and Risk Assessment (2021) 35:147–164
https://doi.org/10.1007/s00477-019-01735-6

ORIGINAL PAPER

# Water and energy circulation characteristics and their impacts on water stress at the provincial level in China

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**Abstract**

Water and energy circulate between provinces and sectors through products and services. The multi-scale input–output method can quantify the resources embodied in direct consumption, domestic trade and foreign trade and the resources in intermediate input and final consumption. In this study, this method is used to calculate the embodied water intensity and embodied energy intensity at the provincial level in China. The impacts of interprovincial water and energy transfers on provincial water stress were analyzed with reference to their water stress index. The results show that direct consumption is the main component of the embodied water intensity, with an average proportion of 52.21%. However, differences among provinces are significant, ranging from 14.82 to 80.11%. The embodied energy intensity is mainly reflected in domestic imports, with a national average of 61.01%. Domestic exports ($3.69 \times 10^{11}$ m$^3$), urban household consumption ($2.01 \times 10^{11}$ m$^3$), and gross fixed capital formation ($1.49 \times 10^{11}$ m$^3$) share the largest proportion of final consumption, and they are also the main components in the final consumption of energy. Provincial water and energy transfers do not play major roles in relieving water stress in the net inflow areas but increase water stress in the net outflow areas. Provinces with high embodied water intensity and energy-induced water intensity tend to transfer more water to other provinces, while provinces with low intensity receive more supplies from other areas. Therefore, it is important to focus on improving the water use efficiency in provinces with active trade and high water and energy intensities, pay more attention to the demand side and avoid the continuous expansion of indirect consumption due to excessive restrictions on direct consumption.

**Keywords** Multi-scale input–output method · Embodied resource intensity · Energy-induced water · Water stress · China

## 1 Introduction

Water and energy are resources crucial to national security and regional economic development, and a close relationship exists between these two resources in terms of their uses. In recent years, the interrelationship between water and energy has become a matter of great concern in the international community (Gaudard et al. 2018; Li et al. 2019; Lv et al. 2018), and research on the energy–water nexus is in a period of vigorous development (Hu et al. 2018; Shang et al. 2018). Many countries and regions in the world have suffered from water shortages (Carole et al. 2014; Ye et al. 2018). In China, especially in the northern provinces, there is increasing pressure on provincial water

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**Electronic supplementary material** The online version of this article (https://doi.org/10.1007/s00477-019-01735-6) contains supplementary material, which is available to authorized users.

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resources (Zhao et al. 2015), and water shortages occur frequently, putting constraints on local municipal, industrial and agricultural development (Avrin et al. 2015). Meanwhile, uncontrolled energy consumption has also had negative effects on the ecological environment (Pata 2018; Sarkodie and Adams 2018). In 2017, China accounted for 23.2% of the global energy consumption and 33.6% of the global energy consumption growth and has ranked first in increment for 17 consecutive years (BP 2018). Energy consumption also involves large amounts of greenhouse gas emissions (Quadrelli and Peterson 2007). Water and energy are important foundations for industrial development. Rapid economic development leads to the consumption of large amounts of water and energy. Therefore, exploring the consumption status and efficiency of water and energy in various provinces of China is of great significance. In addition, the production of energy consumes a large amount of water (Ding et al. 2018; Gerbens et al. 2008, 2009; Zhang et al. 2017). For regions with water shortages, energy consumption undoubtedly aggravates the already severe water pressure. Therefore, understanding the water and energy nexus is crucial for the efficient management of resources and for sustainable development of the national and regional economy.

Industrial sectors are classified according to the homogeneity of products or services. In previous studies, the resource consumption of the entire economic system has often been measured by calculating the resource intensity. The most widely used accounting method is the input–output method, which can be further divided into the single-region input–output method (SRIO), multi-regional input–output method (MRIO), and multi-scale input–output method (MSIO). The SRIO method is simple to use and has low data requirements; however, it ignores the external inflow (Zhao et al. 2016) or assumes that the resource intensity in products from outside areas is the same as the local intensity (Guo et al. 2016; Shao et al. 2017; Zhao et al. 2009), causing an error in the calculation result. MRIO takes resource flows between different regions into account, as the multi-regional input–output table can usually cover the entire production process, so the resource flows in different regions and sectors can be tracked, and the calculation result is more accurate (Wang and Chen 2016; Wang et al. 2018). However, this method cannot accurately reflect the resources embodied in foreign imports (Jiang et al. 2015; Zhao et al. 2015). Chen et al. (2011) proposed the MSIO, which can distinguish the resource intensities from different economies such as foreign countries and domestic provinces. In addition, the results obtained by this method can be used to quantify the resources embodied in final consumption and intermediate input, and the application scope of input–output analysis is greatly expanded. This method provides a more complete and reliable theoretical basis for resource accounting at various scales (Shao 2014) and has been widely applied in carbon emissions (Chen et al. 2011, 2013), water resources (Han et al. 2015; Shao et al. 2017), and energy fields (Chen and Wu 2017; Wu et al. 2016). The research scale also involves economies at different levels, such as those on the world (Chen and Chen 2013; Chen et al. 2010), country (Chen and Chen 2010; Chen and Zhang 2010), subnational (Liu et al. 2017) and urban scales (Li et al. 2014; Shao et al. 2017). When calculating the resource intensity at subnational levels, such as in provinces or cities, MSIO uses the world average and national average resource intensities to account for the inflow from external areas (Shao et al. 2017); therefore, data requirements are reduced. The results of the input–output method have been combined with the water stress index (Zhao et al. 2015) to provide a reference for policy making.

This study accounts for the water stress caused by water and energy transfers embodied in the interprovincial trade in China. Due to its advantages in resource intensity accounting, MSIO is adopted to calculate the embodied water intensity and embodied energy intensity of each province with consideration of direct consumption, domestic imports, and foreign imports. In this study, local water stress refers to provincial water stress. Embodied water refers to the water resources that circulates between provinces and sectors through products and services. Energy-induced water refers to the water resources involved in energy production and processing, and this water circulates between provinces and sectors through energy trade. We analyze the resource intensity characteristics from two perspectives: industrial sectors and interprovincial differences. Subsequently, the final destinations of water and energy are calculated through the resource intensity and input–output tables for each province. The net inflow of embodied water and embodied energy into each province is calculated, and the results are combined with the water stress index. To the best of our knowledge, this study is the first attempt to calculate the embodied water intensity and embodied energy intensity in 30 provinces in China and to consider the changes in water stress caused by interprovincial energy transfers.

## 2 Methods and materials

### 2.1 Multi-scale input–output method

The MSIO is used to calculate the embodied water intensity and embodied energy intensity in individual provinces in China (Li et al. 2016; Liu et al. 2017; Shao et al. 2017). The basic structure of the multi-scale input–output table is shown in Table 1.

The monetary unit in the Input–Output table is 10,000 yuan (1 yuan $\approx$ 0.159 USD in 2012) which is the common unit used in Chinese statistics. In this study, unless otherwise specified, the monetary unit is 10,000 yuan. $z_{i,j}^L$, $z_{i,j}^D$, and $z_{i,j}^M$ represent the intermediate input from sector $i$ to sector $j$ in the local economy, national economy, and world economy, respectively, $y_i^L$, $y_i^D$, and $y_i^M$ represent the final demand of sector $i$ in the local economy, national economy, and world economy, respectively. $ex_i^D$ and $ex_i^M$ represent the economic flows from sector $i$ to other provinces and foreign countries. $E_{p,i}$ and $W_{q,i}$ respectively represent the $p$-th type of energy and $q$-th type of water resource directly consumed by sector $i$ in the study area, and the units are GJ and m$^3$, respectively. $x_i$ represents the total output of sector $i$, and the economic balance relation can be expressed as:

$$x_i = z_{i,j}^L + y_i^L + ex_i^D + ex_i^M \tag{1}$$

The circulation balance relation of resources (representing energy and water in this study) is illustrated in Fig. 1 (Chen et al. 2013; Han et al. 2015; Liu et al. 2017), in which $\varepsilon_{k,j}^L$, $\varepsilon_{k,j}^D$, and $\varepsilon_{k,j}^M$ represent $k$-th embodied resource intensity of sector $j$ in the local economy, national economy, and world economy, respectively. $z_{j,i}^D$ and $z_{j,i}^M$ represent the economic flows from other provinces and countries into sector $i$ in the study area, and the units are GJ and m$^3$. According to the material balance theorem, the total inflow of sector $i$ is equal to the total outflow:

$$\begin{aligned} & E_{k,i} + \sum_{j=1}^{n} \varepsilon_{k,j}^L z_{j,i}^L + \sum_{j=1}^{n} \varepsilon_{k,j}^D z_{j,i}^D + \sum_{j=1}^{n} \varepsilon_{k,j}^M z_{j,i}^M \\ & = \varepsilon_{k,i}^L \left( \sum_{j=1}^{n} z_{i,j}^L + y_i^L + ex_i^D + ex_i^M \right) \end{aligned} \tag{2}$$

By combining Eqs. (1) and (2), Eq. (3) can be obtained:

$$E + \varepsilon^L Z^L + \varepsilon^D Z^D + \varepsilon^M Z^M = \varepsilon^L X^L \tag{3}$$

After some transformations, we obtain:

$$\varepsilon^L = \left( E + \varepsilon^D Z^D + \varepsilon^M Z^M \right) \left( X^L - Z^L \right)^{-1} \tag{4}$$

and

$$\varepsilon^L = \left( E + \varepsilon^D Z^D + \varepsilon^M Z^M \right) \left( X^L \right)^{-1} \left( I - A^L \right)^{-1} \tag{5}$$

where $\varepsilon^L = [\varepsilon_{k,i}^L]_{m \times n}$, $E = [E_{k,i}]_{m \times n}$, $\varepsilon^D = [\varepsilon_{k,i}^D]_{m \times n}$, $\varepsilon^M = [\varepsilon_{k,i}^M]_{m \times n}$, $Z^L = [z_{j,i}^L]_{n \times n}$, $Z^D = [z_{j,i}^D]_{n \times n}$, $Z^M = [z_{j,i}^M]_{n \times n}$, $X^L = [x_{i,j}^L]_{n \times n}$, and $A^L = Z^L (X^L)^{-1}$.

$\varepsilon^L$ is the final three-scale embodied resource intensity, which represents the amount of resources directly and indirectly consumed by each 10,000 yuan value of product (the units of embodied energy intensity and embodied water intensity are GJ/10,000 yuan and m$^3$/10,000 yuan, respectively). The three scales refer to the resource intensity reflected in the local direct use ($E(X^L)^{-1}(I - A^L)^{-1}$), domestic imports ($\varepsilon^D Z^D (X^L)^{-1}(I - A^L)^{-1}$), and foreign imports ($\varepsilon^M Z^M (X^L)^{-1}(I - A^L)^{-1}$), respectively.

## 2.2 Water stress index

The *WSI* is defined as the ratio of water withdrawal to the local renewable water resources. This ratio is used to evaluate the degree of regional water stress (Oki and Kanae 2006; Stephan et al. 2009). It is expressed as follows:

$$WSI = \frac{WW}{Q} = \frac{WU - PW_{net,im}}{Q} \tag{6}$$

where *WW* refers to the local water withdrawal, which equals the actual water use (*WU*) minus the net physical water inflow ($PW_{net,im}$), and $Q$ refers to the local renewable water resources. In water scarcity assessments, 0.4 is the commonly used *WSI* threshold. In general, below 0.2, a region would have no water stress; between 0.2 and 0.4, there is minor water scarcity; and above 0.4, a region suffers from water stress. The higher the value is, the higher the stress (Alcamo et al. 2000; Oki and Kanae 2006; Stephan et al. 2009; Vörösmarty et al. 2000; Yang et al. 2013; Zhao et al. 2015). When the value is above 1, the

**Table 1** Basic structure of the multi-scale input–output table

| Input | | Output | | | | |
|---|---|---|---|---|---|---|
| | | Intermediate use Sector 1 ··· Sector $n$ | Final demand Sector 1 ··· Sector $n$ | Domestic exports Sector 1 ··· Sector $n$ | Foreign exports Sector 1 ··· Sector $n$ | Total output |
| Local intermediate input | Sector 1 ··· Sector $n$ | $z_{i,j}^L$ | $y_i^L$ | $ex_i^D$ | $ex_i^M$ | $x_i$ |
| Domestic intermediate input | Sector 1 ··· Sector $n$ | $z_{i,j}^D$ | $y_i^D$ | | | |
| Foreign intermediate input | Sector 1 ··· Sector $n$ | $z_{i,j}^M$ | $y_i^M$ | | | |
| Direct energy consumption | Energy type | $E_{p,i}$ | | | | |
| Direct water consumption | Water type | $W_{q,i}$ | | | | |

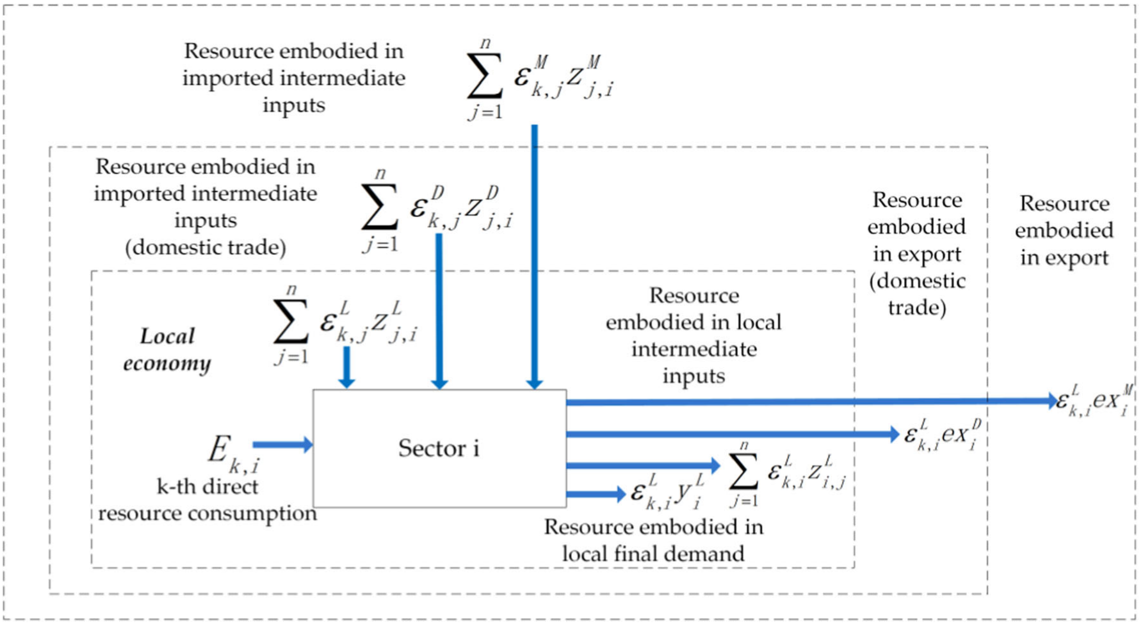


**Fig. 1** Embodied resource flows of sector *i* in an economic system

water use is higher than the water resources, indicating a depletion of nonrenewable water resources.

On the basis of the *WSI*, Zhao et al. (2015) proposed the hypothetical water stress index (*WSI**), which means the hypothetical water stress, assuming that the physical and embodied water transferred from outside is extracted locally and is expressed as:

$$WSI^{*} = \frac{WU + VW_{net,im}}{Q} = \frac{WW + PW_{net,im} + VW_{net,im}}{Q} \quad (7)$$

where $VW_{net,im}$ refers to the net inflow of embodied water. The difference between Eqs. (7) and (6) is $\frac{PW_{net,im}+VW_{net,im}}{Q}$, which refers to the contribution of transferred physical and embodied water toward alleviating the local water stress. When $WSI^* > WSI$, the transferred physical and embodied water alleviates the local water stress, and when $WSI^* < WSI$, the local water stress increases.

In addition, energy consumes water in a series of production processes, such as mining, extraction, and processing. Water resources involved in energy, which are called energy-induced water, circulate between provinces along with energy trade and can be obtained by multiplying the amount of energy exploitation and the water footprints of energy sources. $VWE_{net,im}$ refers to the net inflow of energy-induced water, which is part of $VW_{net,im}$. The net inflow direction may be the same as $VW_{net,im}$ or the opposite, depending on the energy type and the direction of energy trade. The water stress index change caused by the circulation of energy-induced water can be expressed as:

$$WSI\_energy = \frac{VWE_{net,im}}{Q} \quad (8)$$

In summary, the calculation of the provincial water stress in this research involves the following three aspects: (1) the water stress index (*WSI*), which represents the water stress caused by local water withdrawal; (2) the improved water stress index (*WSI**), which represents the water stress caused by transferred physical and embodied water; and (3) the water stress index change caused by the circulation of energy-induced water (*WSI_energy*).

## 2.3 Data sources

The data involved in the study include four aspects, namely, energy exploitation, water withdrawal, water footprints of energy sources, and input–output data at various scales.

### 2.3.1 Energy exploitation

The term energy extraction in this study refers to primary energy extraction. According to the definition in the database used, the process of "energy extraction" means that energy enters the socio-economic system from nature. These processes do not alter the quality of energy that enters the socio-economic system. In the calculation of resource intensity, if primary energy and secondary energy are simultaneously considered, this will lead to a double calculation. To avoid double counting, energy data in this study refers to primary energy extraction, which is directly obtained from nature. Six types of energy are included: raw coal, crude oil, and natural gas, which belong to fossil energy, and hydropower, nuclear energy, and other types of renewable energy (mainly referring to wind energy and abbreviated as others in the following paragraphs), which belong to non-fossil energy. The specific sources are as follows. At the global scale, data on six types of energy in 188 countries are collected from the BP World Energy Statistical Yearbook (BP 2013). At the Chinese scale and the provincial level, the statistics are collected from the China Energy Statistical Yearbook (NBS 2013a). In addition, the non-energy use portion is included in the direct exploitation of coal, oil, natural gas, and nuclear energy, which are consumed as raw materials for production rather than energy. The proportions of the above four types are 1.22%, 14.15%, 9.94%, and 33%, respectively (Wu and Chen 2017), which can be deduced from the calculation.

#### 2.3.2 Water withdrawal

As the physical entry of water into the economic system, water withdrawal, rather than water consumption, is considered in this study. Water withdrawal includes agricultural, industrial, and residential withdrawals. At the global scale, three types of data are collected from the World Bank Statistics Data. At the Chinese scale, agricultural and residential water withdrawal are derived from the China Water Resources Bulletin (2013). There are no detailed water withdrawal data for each industrial sector in 2012. Based on the detailed industrial water withdrawal data in the Chinese Economic Census Yearbook in 2008 (NBS 2010), we assume that the industrial structure and water use efficiency in all provinces did not change significantly in the 4 years and increase the industrial water withdrawal data according to the proportion of total industrial water withdrawals in 2012 and 2008. In this way, the detailed water withdrawal in each sector is estimated. At the provincial level, agricultural and residential water withdrawals are derived from the Water Resources Bulletins in the corresponding provinces, and the estimation of industrial water withdrawal is the same as that on the national scale. Ecological water is not considered in this study because ecological water includes a portion of reclaimed water processed from industrial wastewater or residential sewage, which is not part of direct water withdrawal and accounts for only 1.8% of the total water consumption (NBS 2013c).

#### 2.3.3 Water footprints of energy sources

According to existing research results, the water footprints of raw coal, crude oil, natural gas, hydropower, nuclear energy, and others are 0.14 $m^3$/GJ, 0.29 $m^3$/GJ, 0.11 $m^3$/GJ, 6.75 $m^3$/GJ, 0.19 $m^3$/GJ, and 0.14 $m^3$/GJ (Ding et al. 2018), respectively. Among them, the water consumption of raw coal, crude oil, and natural gas mainly comes from the mining stage, and that of hydropower, nuclear energy, and others mainly comes from the upstream production stage.

#### 2.3.4 Input–output data

The input–output data include three scales: the world economy, national economy, and local economy. The world-scale input–output data are collected from the World Input–Output Table in the 2012 Eora database (Lenzen et al. 2013), which contains economic data for 26 sectors in 188 countries or regions. The national input–output data are derived from the Input–Output Table of China in 2012 (NBS 2015), which covers 42 economic sectors. The input–output data in each province are derived from the Input–Output Table in the corresponding province, which also includes 42 economic sectors.

The energy exploitation, water withdrawal, and input–output database contain 30 provincial-level administrative regions (including 22 provinces, 4 autonomous regions, and 4 municipalities—for simplicity, they are all referred to as provinces). Data for Hong Kong, Taiwan, Macao, and Tibet are not available. In this study, the analysis and results exclude these four regions.

## 3 Results

### 3.1 Embodied water intensity

The embodied water intensity shows different characteristics between different sectors and provinces.

At the sector level, the embodied water intensity is illustrated in Fig. 2 (the codes and names of sectors are shown in “Appendix 1”). The maximum, minimum, and average values refer to the maximum, minimum, and average values in the 30 provinces (the values in Fig. 4 have the same meaning). Although the resource intensity of a single sector varies greatly among provinces, the trend of the average values is consistent with that of the extreme values. Among them, the embodied water intensity of S27 (production and distribution of tap water) is significantly higher than those of the others because most of the industrial and residential water is provided by this sector. For most provinces, the embodied water intensity of S1 (agriculture, forestry, animal husbandry and fishery) ranks second, with water mainly used for irrigation. In addition, S6 (food and tobacco processing), S31 (accommodation and catering), and S25 (production and distribution of electric power and heat power) also have high embodied water intensities. S6 and S31 have close economic relationships with S1 and belong to important downstream sectors of S1, which also shows the important position of

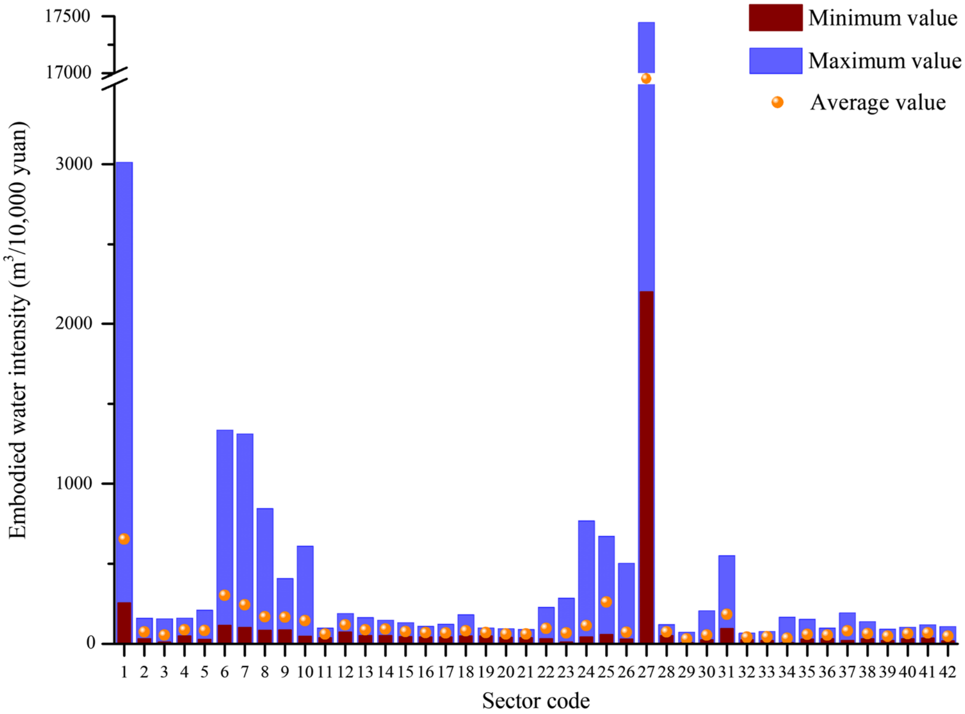


**Fig. 2** Three-scale embodied water intensity in each sector

agricultural withdrawal within total water withdrawal. S25 belongs to the industrial sector with high water intensity, and the water consumed is mainly used for industrial production. The pressures imposed on water by the above 5 sectors are different. The water consumed in S27 and S1 is mainly used for domestic consumption and farmland irrigation, respectively, which places substantial pressure on direct water withdrawal. S6, S31, and S25 belong to the downstream processing industry sectors, and their larger water intensities mean greater water pressure on upstream sectors.

At the provincial level, Fig. 3 illustrates that the average embodied water intensity in all provinces is higher than the world average value (58.81 $m^3$/10,000 yuan). Sixteen provinces have lower values than the Chinese average value (128.18 $m^3$/10,000 yuan), and the remaining fourteen provinces have values higher than the national average. Among them, Tianjin, Beijing, and Shanghai have low values. The water use efficiency is high in these areas, and the water consumption pressure is transferred outside through trade. Shaanxi, Zhejiang, and Liaoning also have low embodied water intensities. These areas have better water endowments and higher water consumption efficiencies, and the embodied water intensity is mainly reflected in direct use. As a province with high embodied water intensity, Xinjiang has abundant light and heat resources and developed agriculture. The evaporation capacity of crops is strong, and the water use efficiency is low. The embodied water intensity of Xinjiang ranks first in China, reaching 525.47 $m^3$/10,000 yuan, which is four times the national average and even eight times greater than those of provinces with lower values. A large amount of embodied water flows to other provinces and countries through agricultural trade, which puts great pressure on local water utilization. Heilongjiang, Guangxi, Ningxia, and Jiangxi also have relatively high embodied water intensities. Among these provinces, Guangxi and Jiangxi have abundant water resources, and the management of water utilization efficiency is relatively lax. While water stress is relatively high in Heilongjiang and Ningxia, they have high levels of embodied water intensity, which is mainly reflected in direct water use, aggravating their already severe water stress. Overall, in provinces with greater embodied water intensities, the proportions of direct use are larger, while the proportions of domestic and foreign imports are small. For provinces with lower embodied water intensities, resources are mainly reflected in imports due to resource constraints. The water intensity embodied in direct use, domestic imports and foreign imports varies greatly among provinces. Overall, direct use is the most important source of embodied water intensity, accounting for 52.21% of the national average. The proportion of domestic imports varies greatly among provinces, ranging from 13.65% (Fujian) to 66.68% (Tianjin). The proportions of foreign imports are relatively large in coastal provinces with active international trade. Conversely, the proportions are relatively low in inland areas with less active international trade (the percentages of embodied water intensity for different types and sources in

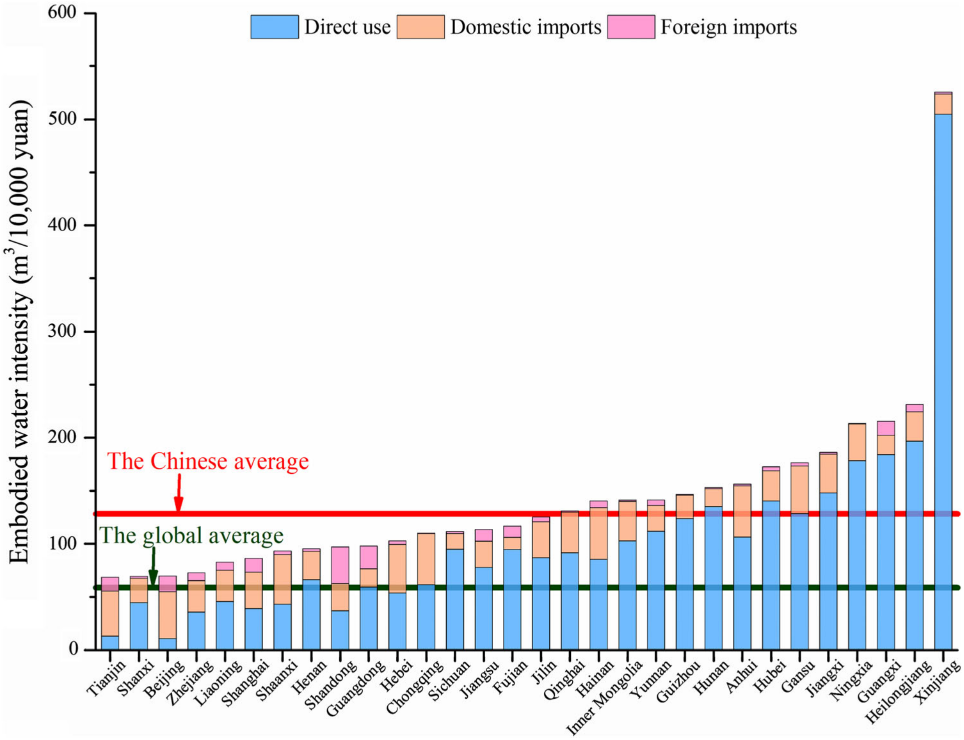


**Fig. 3** Sector-averaged embodied water intensity in each province

each province are illustrated in Fig. S1 in the Supplementary Information).

## 3.2 Embodied energy intensity

At the sector level, the embodied energy intensity is illustrated in Fig. 4. Among all sectors, S2 (mining and washing of coal) ranks first. S25 (production and distribution of electric power and heat), S11 (processing of petroleum, coking, processing of nuclear fuel), S3 (extraction of petroleum and natural gas), S26 (production and distribution of gas), and S13 (manufacturing of nonmetallic mineral products) also have high embodied energy intensities. Among these sectors, S2, S25, and S3 belong to direct energy exploitation sectors; therefore, the higher embodied energy intensity represents greater pressure on direct energy extraction. S11, S26, and S13 belong to downstream processing sectors of the energy exploitation industry, and energy consumption is mainly reflected in indirect use, which may come from local sectors or sectors in other provinces and countries, thus exerting indirect pressure on energy use. Overall, the embodied energy intensity of the tertiary industry sectors (S29–S42) is generally lower than that of the secondary industry sectors (S2–S28).

At the provincial level, Fig. 5 illustrates the average embodied energy intensity of 42 sectors in each province. The embodied energy intensities of northern provinces are generally higher than those of southern provinces, and almost all provinces whose energy intensity is larger than the national average level (37.91 GJ/10,000 yuan) are northern provinces (except Guizhou). Direct use consumes large proportions in these provinces. Raw coal, crude oil, and natural gas are mainly exploited in northern provinces, and the direct exploitation amount of these three types of energy accounts for 86.59% of the national exploitation amount. A sufficient energy supply provides better conditions for the development of energy-intensive industries. Therefore, provinces with large energy production, such as Inner Mongolia and Shanxi, have a large embodied energy intensity. The embodied energy intensity of southern provinces is mainly reflected in domestic imports. Hydropower is abundant in southern provinces but accounts for only 1.00% of the total energy exploitation. Therefore, the embodied energy intensity is low in southern provinces and is generally lower than the national average level. Among all provinces, only Fujian has an embodied energy intensity (16.85 GJ/10,000 yuan) lower than the world average level (18.95GJ/10,000 yuan).

It is also worth noting that Qinghai has a high embodied energy intensity, ranking sixth in China. This result is mainly reflected in direct use. Qinghai is not a major energy supply province in China, as its direct energy production is small, at only $9.56 \times 10^5$ TJ, and it is ranked 22nd among all provinces. Its domestic export is also small, at only $3.15 \times 10^5$ TJ, and it is ranked last among all provinces. According to Eq. (5), the embodied energy intensity is the ratio of energy consumption to the total

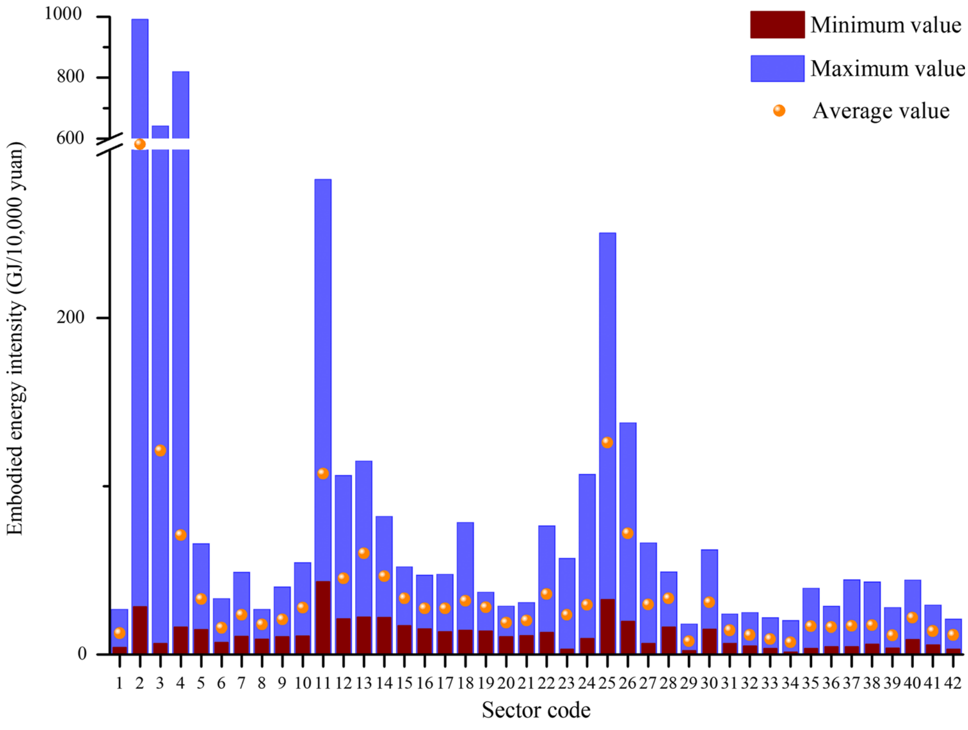


**Fig. 4** Three-scale embodied energy intensity in each sector

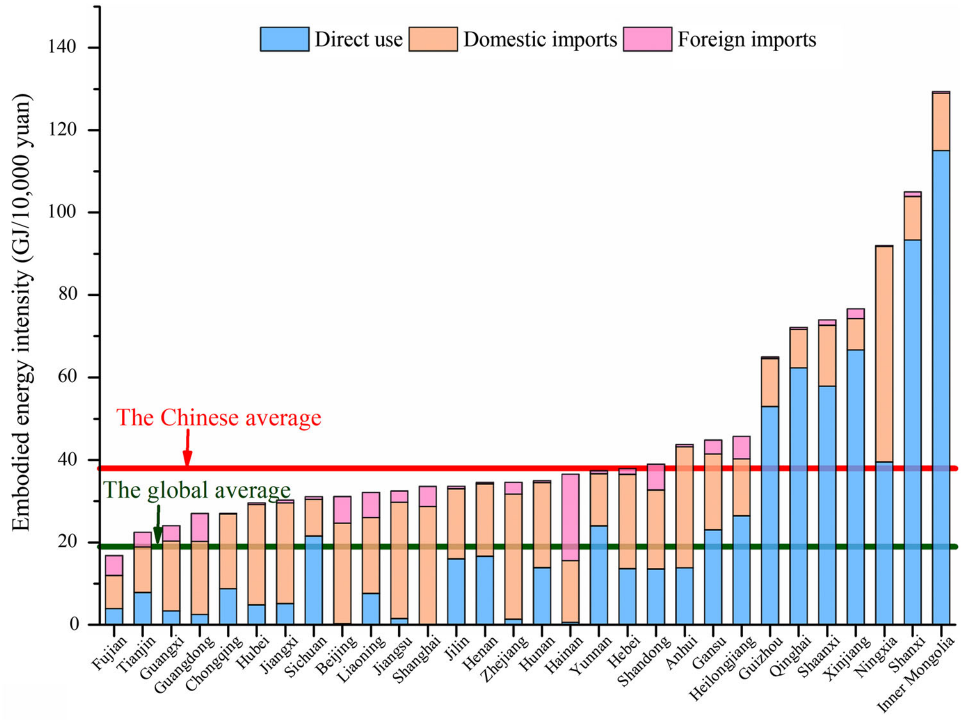


**Fig. 5** Sector-averaged embodied energy intensity in each province

output multiplied by the Leontief inverse matrix. Therefore, the high embodied energy intensity is mainly due to the low total output ($X^L$), especially in energy-related sectors, such as S2, S3, and S25.

In Beijing, to improve the ecological environment, secondary industry sectors with high energy consumption have been gradually removed, and tertiary industry sectors with lower energy consumption are booming. Therefore, the energy intensity embodied in direct use is extremely low, at only 0.27 GJ/10,000 yuan. However, the total embodied energy intensity is 31.13 GJ/10,000 yuan, which is 115 times the amount of direct use. Energy trade transfers local energy pressures to external provinces. If the embodied energy intensity is greater in the external province, the total energy consumption in the whole country increases. The above situation also holds in Shanghai and Zhejiang.

The energy intensity embodied in direct use, domestic imports and foreign imports also varies greatly among provinces. Domestic imports are the most important source of embodied energy intensity, accounting for 61.01% of the national average. The direct use portion ranks second, with a provincial average percentage of 30.44%. Similar to the embodied water intensity, the proportions of foreign imports are relatively large in coastal provinces with active international trade and low in inland areas with less active international trade (the percentages of embodied energy intensity for different types and sources in each province are illustrated in Fig. S2 in the Supplementary Information).

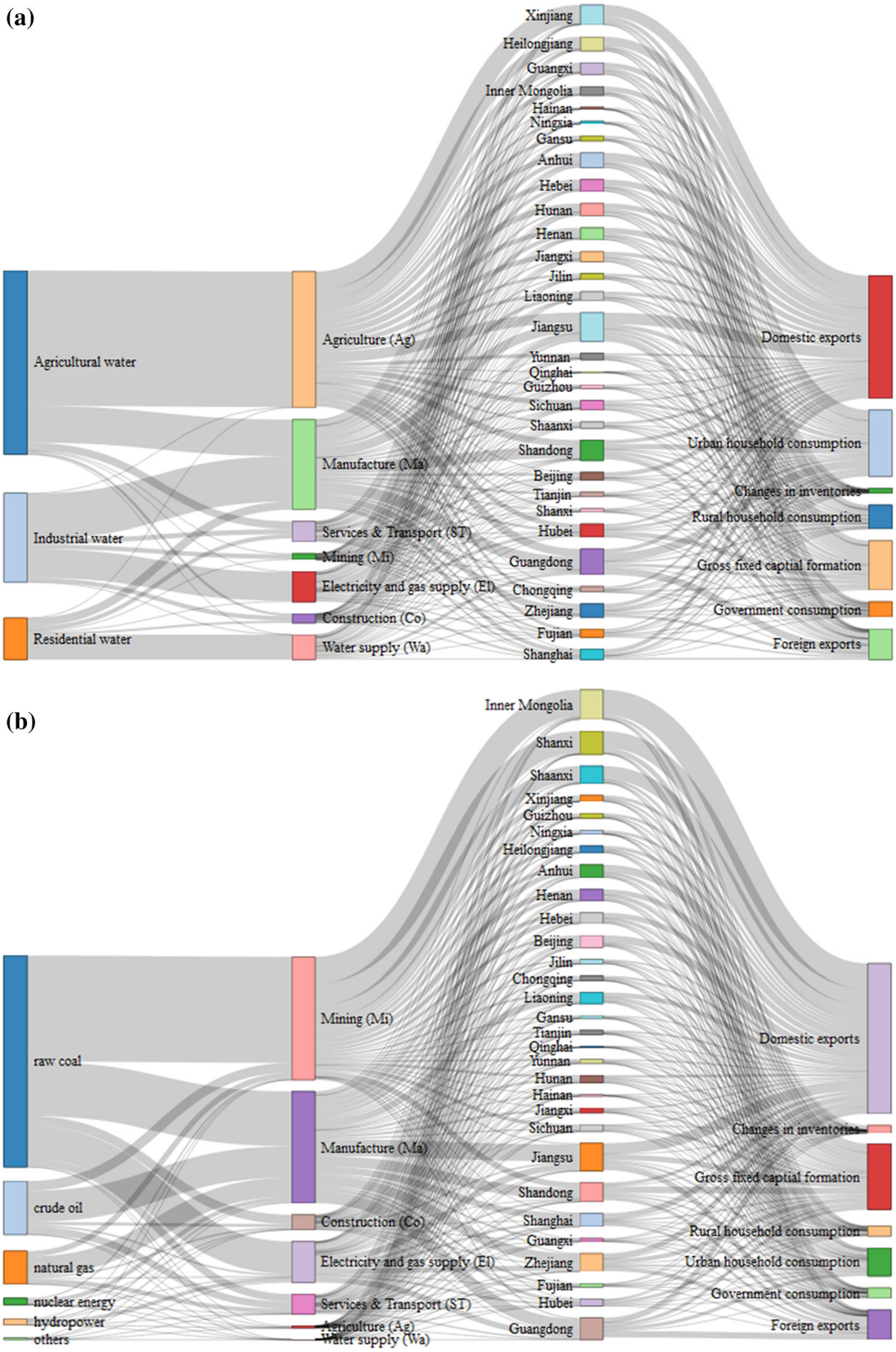
## 3.3 Source-to-sink circulation characteristic of water

According to the provincial input–output table, which covers 42 economic sectors, the final demand is divided into 7 categories: rural household consumption, urban household consumption, government consumption, gross fixed capital formation, changes in inventories, foreign exports, and domestic exports. The amount of resource embodied in each category is obtained by multiplying the embodied resource intensity by the corresponding economic quantity. The characteristics of different types of resources from exploitation to final demand are further illustrated in Fig. 6.

Figure 6a shows the flow characteristics of water. The first column represents the three types of water that enter into the economic system. Among these types, agricultural water is in a dominant position, with a final consumption of $5.55 \times 10^{11}$ $m^3$ accounting for 58.44% of the total. However, in the statistical yearbook (NBS 2013c), the direct water withdrawal by agriculture is $3.89 \times 10^{11}$ $m^3$, accounting for 63.18% of the total. The difference between these two numbers represents the water embodied in foreign trade. The proportions of industrial and residential use are relatively small at 28.27% and 13.29%, respectively. The second column represents water consumption by various sectors in the national economy (to facilitate the presentation of results, 42 sectors are merged into 7 categories according to product characteristics, and specific classifications are presented in "Appendix 1"). The flow between the first and second columns represents the way in which water enters the national economic system. The amounts of water consumed by agriculture (Ag), electricity and gas supply (El), and water supply (Wa) are mainly reflected in the agricultural, industrial, and residential categories, with proportions of 99.35%, 94.01%, and 99.75%, respectively. Manufacture (Ma) and Services and Transport (ST) consume large proportions of water in both agriculture and industry. The third column shows the final demand in each province. Provinces with large values include Jiangsu ($8.75 \times 10^{10}$ $m^3$), Guangdong ($7.80 \times 10^{10}$ $m^3$), Shandong ($6.2 \times 10^{10}$ $m^3$), and Xinjiang ($6.13 \times 10^{10}$ $m^3$), while Qinghai ($3.67 \times 10^{9}$ $m^3$), Hainan ($7.29 \times 10^{9}$ $m^3$), and Ningxia ($8.31 \times 10^{9}$ $m^3$) have low final demands. The fourth column represents the final destination of water resources. Among these destinations, domestic export is the most important component ($3.69 \times 10^{11}$ $m^3$), accounting for 39.01% of the final demand. Urban household consumption ($2.01 \times 10^{11}$ $m^3$) ranks second and accounts for 21.25% of the total value. In contrast, water used in rural household consumption is only $7.56 \times 10^{10}$ $m^3$, which is 37.61% of the urban consumption. In 2012, the rural population was 1.83 times the urban population (NBS 2013b), so the per capita embodied water of the urban area was 4.87 times that of the rural area. This ratio even reached 14.98 and 11.74 in Shaanxi and Guangxi, respectively. This result indicates a huge gap in water use conditions between rural and urban areas in China. The amount of water reflected in gross fixed capital formation is also large, with a value of $1.49 \times 10^{11}$ $m^3$, indicating that China's infrastructure construction was developing rapidly in 2012. The amounts of water reflected in foreign exports, government consumption, and changes in inventories are relatively small at $9.34 \times 10^{10}$ $m^3$ (9.87%), $4.65 \times 10^{10}$ $m^3$ (4.92%), and $1.59 \times 10^{10}$ $m^3$ (1.68%), respectively.

The flow characteristics of energy are illustrated in Fig. 6b. Coal has an absolutely dominant proportion of the final demand, which is 67.54%, while the proportion of direct exploitation is 81.61% in the statistical yearbook (NBS 2013a). The proportions of crude oil and natural gas in the final demand are 17.17% and 10.51%, respectively, while in the statistical yearbook, their proportions are 9.5% and 4.5%, respectively. The above differences stem from the fact that imports are considered in calculating the embodied energy. With the rapid development of the economy, China's external dependence on crude oil and natural gas has gradually increased (Wu and Chen 2017). Imports of these categories account for 42.47% and 28.62% of the total, respectively, and these sources are the two most important imported energy types. Hydropower, nuclear energy, and others account for small proportions, and their total proportion is 4.78%. In the second column, Ma, Mi, and El are the major energy consumption sectors, accounting for 88.30% of the total. The energy consumption of Ma is mainly reflected in coal, crude oil and natural gas, while those of Mi and El are mainly reflected in coal.

**Fig. 6** Source-to-sink flow characteristics of water and energy in China



In the third column, the final demands of Inner Mongolia ($2.64 \times 10^7$ TJ), Jiangsu ($2.46 \times 10^7$ TJ), Shanxi ($2.07 \times 10^7$ TJ), Guangdong ($1.95 \times 10^7$ TJ), and Shandong ($1.71 \times 10^7$ TJ) are large. Among these provinces, the energy consumption of Inner Mongolia and Shanxi is mainly reflected in Mi, namely, in the direct exploitation of energy. For Jiangsu, Guangdong, and Shandong, energy consumption is mainly reflected in Ma, and the development of advanced manufacturing industries benefits from external energy imports. Seven types of final demands are illustrated in the fourth column. Among these categories, domestic exports have the largest proportion (49.65%), which is $1.33 \times 10^8$ TJ, followed by gross fixed capital formation ($5.85 \times 10^7$ TJ) and foreign exports

($2.63 \times 10^7$ TJ). The value of rural household consumption is $9.08 \times 10^6$ TJ, which is only 36.32% of the urban level. The per capita embodied energy in urban areas is 5.09 times that in rural areas, which indicates a large gap in the energy consumption level between urban and rural areas. The energy amounts embodied in government consumption and changes in inventories are relatively small, accounting for 3.48% and 2.49%, respectively.

### 3.4 Energy-induced water analysis

As mentioned previously, energy circulates between provinces through products and services; thus, energy-induced water also circulates between provinces. Figure 7a and b illustrate the inflow and outflow of energy-induced water in each province, respectively. The energy-induced water amounts of coal and hydropower are larger than those of the other energy types. Coal is the most important type of energy in China, and its energy-induced water amount is also large. The average percentages of inflow and outflow are 45.42% and 38.17%, respectively. The large amount energy-induced water of hydropower is mainly due to its water footprint (6.75 $m^3$/GJ), which is significantly larger than those of the other energy types. The average percentages of inflow and outflow of the energy-induced water of hydropower are 41.29% and 47.11%, respectively, which account for large proportions in provinces with abundant hydropower resources, such as Sichuan, Guangxi, and Qinghai. The sum of the proportions of the remaining four types of energy is approximately 14% for both inflow and outflow, and of these types, natural gas consumes a low amount of water. The provincial average proportion of natural gas in the total energy consumption is 10.51%, while the corresponding proportions are only 1.17% (inflow) and 0.97% (outflow) for energy-induced water. Figure 7a and b show the consumption and supply of energy-induced water. The difference between these two figures is mainly because the former depends on the products and services flowing into the province, while the latter is more dependent on the local energy supply.

### 3.5 Analysis of water stress change

Interprovincial transfer of physical and embodied water influences the provincial water stress. At the same time, the interprovincial circulation of energy brings water flow, which also impacts the water stress. To measure the impact of water and energy flows on the provincial water stress, *WSI*, *WSI**, and *WSI_energy* are calculated according to Eqs. (6)–(8). The calculation method for the net embodied water inflows is as follows: net inflows = domestic imports + foreign imports − domestic exports − foreign exports (detailed numerical results are shown in "Appendix 2"). For *WSI_energy*, a positive value indicates that the circulation of energy-induced water causes an increase in the *WSI** index and alleviates provincial water stress. A negative value indicates that the circulation decreases the *WSI** index and increases the provincial water stress.

In Fig. 8, the three bars respectively represent water stress under different assumptions. *WSI** is the water stress index, assuming that all the external transferred physical and embodied water is required by local water sources, as indicated by the blue dashed bar. The *WSI* values are indicated by blue bars. When $WSI^* > WSI$, the transferred physical and embodied water alleviates the local water stress, and when $WSI^* < WSI$, the local water stress increases. Beijing, Tianjin, Shanxi, Liaoning, Shanghai, Zhejiang, Shandong, Chongqing, Shaanxi, and Ningxia have larger *WSI** values than *WSI* values. Benefiting from the transfer of external water resources, water stress in these provinces has been alleviated. Red bars indicate *WSI_energy* values and represent the water stress caused by the circulation of energy-induced water. According to the value of *WSI_energy*, the above provinces can be divided into two categories. One category includes Beijing, Tianjin, Shanghai, Liaoning, Zhejiang, Shandong, and Chongqing.

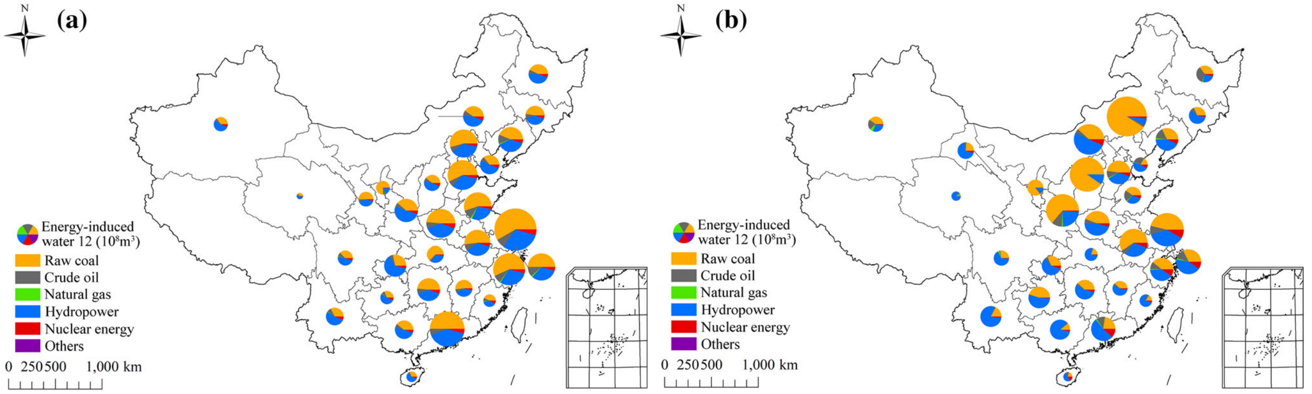


**Fig. 7** Energy-induced water in each province: **a** inflow; **b** outflow

These provinces are also net inflow areas of energy-induced water, and water resources brought by energy transfer have relieved the local water stress. For example, $9.47 \times 10^8$ m$^3$, $3.73 \times 10^8$ m$^3$, and $10.28 \times 10^8$ m$^3$ of water flow into Beijing, Tianjin, and Shanghai due to the interprovincial energy transfer, and the actual water stress indexes are reduced by 0.24, 0.11, and 0.30, respectively, which plays an important role in alleviating the local water stress. Another category includes Shanxi, Shaanxi, and Ningxia. The direction of net inflow of energy-induced water is opposite to that of the net inflow of water in these provinces, that is, the net outflow of energy-induced water offsets a portion of the water inflow, which increases the local water stress. Except for the above provinces, all other provinces have a net outflow of water resources. Net outflow in Xinjiang is the largest, reaching $3.42 \times 10^{10}$ m$^3$, and it is also a net outflow area of energy-induced water—$3.31 \times 10^8$ m$^3$ of water flows out of this area. This province was originally an area with high water stress, and energy exports have further deteriorated this situation.

Figure 9 shows the water stress level in each province. The first row indicates the water stress level in individual provinces when water and energy transfers are not considered. The second row indicates the water stress level after considering energy transfers, and the third row indicates the water stress level after considering physical and embodied water transfers. In Beijing, Tianjin, Shandong, and Ningxia, the water stress levels decrease due to the net inflow of physical and embodied water (the water stress level corresponding to *WSI** is more severe than that of *WSI*). These provinces are all reduced from an extreme level to a severe level. In Heilongjiang, Anhui, Gansu, and Xinjiang, the water stress levels increase due to the net outflow of water resources (the water stress level corresponding to *WSI** is less than that of *WSI*). Among these provinces, there is no water stress ($WSI^* < 0.2$) in Heilongjiang without considering water transfer; however, due to the net outflow of water resources, the water stress level increases to a severe level. Anhui and Gansu change from moderate to severe levels. If considering only the interprovincial transfer of energy-induced water, the water stress levels in two provinces change. The water stress levels in Shaanxi and Ningxia increase due to net outflows of energy-induced water, and no province has a reduced water stress level due to the inflow of energy-induced water. Overall, the interprovincial transfer of physical and embodied water alleviates water stress in some net inflow provinces; however, these provinces are still under severe pressure, and the water stress in net outflow provinces has been further aggravated. In addition, the interprovincial transfer of energy-induced water has not effectively alleviated the water stress in net inflow provinces but has further aggravated the situation in some net outflow provinces.

### 3.6 Circulation characteristic of water and energy-induced water flows among different provinces

The analysis in this study shows that interprovincial water and energy transfers have not effectively alleviated water stress in net inflow provinces but have aggravated the

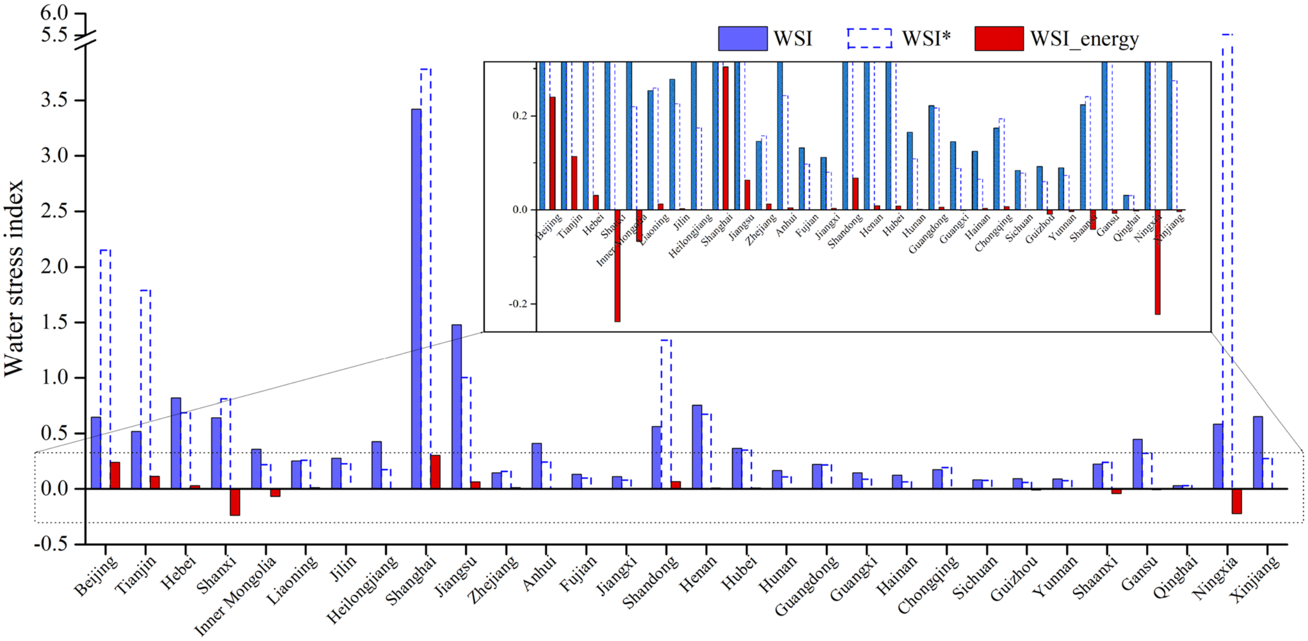


**Fig. 8** Water stress value in each province

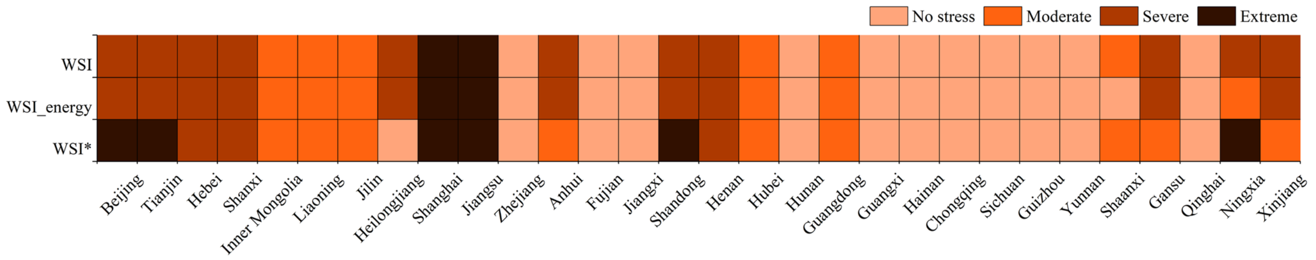


**Fig. 9** Water stress level in each province

pressure in net outflow provinces. The difference in resource intensity between provinces is an important factor. Figure 10 represents the water and energy-induced water flows among different provinces, respectively. The abscissa represents exporting provinces, the ordinate represents importing provinces, and the size of the circle represents the value of the flow. The provinces are ranked according to their water intensity (from high to low, illustrated by the blue arrow). The output values of provinces with high water intensity tend to be higher than those of provinces with low water intensity, while the input values of provinces with low water intensity tend to be higher than those of provinces with large water intensity. This feature also appears in the energy-induced water. For example, in Fig. 10a, Inner Mongolia, Shanxi, and Shaanxi have high water intensities, and the total exported amount from these provinces is 1.03 × $10^{10}$ $m^3$, which is a quarter of the national value; however, the input from other provinces is relatively low, at only 0.33 × $10^{10}$ $m^3$, and accounts for 8.18% of the total. In contrast, provinces with low energy-induced water intensity, such as Jiangsu, Guangdong, Zhejiang, and Shandong, have much more imports than exports, and the imported and exported water totals are 1.26 × $10^{10}$ $m^3$ and 0.68 × $10^{10}$ $m^3$, respectively. This feature is more pronounced in energy-induced water flow. In Fig. 10b, provinces in the upper part of the figure (low energy-induced water intensity) have significantly higher imports than provinces in the lower part (high energy-induced water intensity), and provinces in the left part (high energy-induced water intensity) have significantly higher exports than those in the right part (low energy-induced water intensity). For example, Heilongjiang, Xinjiang, and Jilin have higher energy-induced water intensities, and their exported water is 2.21 × $10^{10}$ $m^3$, while their imported water is only 0.69 × $10^{10}$ $m^3$. In contrast, Shanghai, Tianjin, Zhejiang, Liaoning, and Guangdong have lower energy-induced water intensities, but their imported water (3.02 × $10^{10}$ $m^3$) is 2.03 times their exported water (1.49 × $10^{10}$ $m^3$). The two figures reflect common features: provinces with high water intensity tend to transfer more water to external provinces, while provinces with low intensity are more replenished by external provinces. This situation means that areas with high water consumption need to consume large amounts of water to supply net inflow provinces, increasing the total water consumption in the whole country. Using Shandong, Tianjin, and Shanghai as examples, the volumes of embodied water imported from other provinces are 15.55, 6.84, and 11.42 billion $m^3$, respectively. However, if water-exporting provinces have the same water intensity as these receiving provinces, then the volumes will be 9.16,

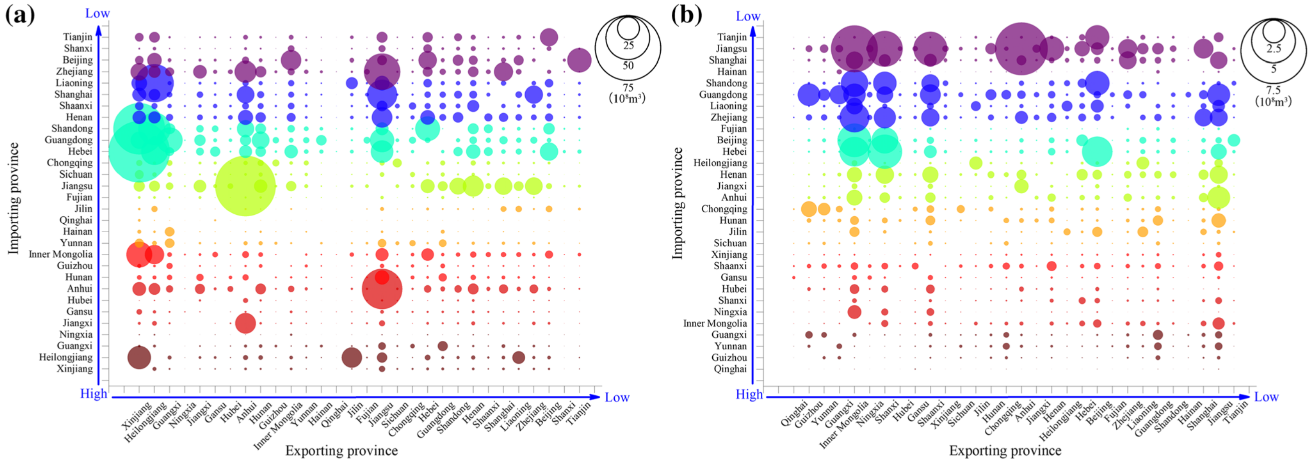


**Fig. 10** Water flow between provinces: **a** water flow, **b** energy-induced water flow

5.32, and 10.8 $m^3$, leading to a reduction in total water use of 6.39, 1.52, and 0.65 $m^3$ in the exporting provinces.

## 4 Discussion

### 4.1 The water–energy nexus in the national economy

The impact of water and energy transfers on water stress shows that the trade-based energy–water nexus has not yet achieved coordinated development. Although interprovincial energy trade alleviates energy consumption pressure, it increases water stress. This is closely related to the resource endowment condition in China, in which water resources are abundant in southern China compared with northern China, while energy resources are abundant in northern areas compared with southern areas. Resource-abundant areas tend to transfer water or energy to resource-deficient areas, and the transfer may be in the form of natural resources or products with high resource intensities. This will increase the pressure on one resource due to the transfer of another. If the overall goal is to relieve the resource pressure across China, then it is necessary to take these two resources as constraints of trade circulation, consider the current economic development situation, and seek a "suboptimal" trade plan to balance the development of two resources. System dynamics models and multilevel decision models could be used to seek the optimal water–energy allocation scheme.

### 4.2 Implications and recommendations for resource management

Currently, many provinces in China, such as Beijing, Tianjin, and Shanghai, have implemented strict water management regulations to achieve the goal of conserving water. For example, Beijing has transferred sectors with high energy and water consumption (such as the coal and manufacturing sectors) to external provinces and imports large amounts of power resources and manufactured finished products to maintain the stable development of regional economies. Although this transfer reduces the direct use of water and energy, it ignores the indirect resource consumption from external sources. The resource intensities in external regions are often higher than that in Beijing, which is why China fails to effectively control the total resource consumption under such strict water and energy management regulations. In addition, some developed provinces have entered a post-industrialization period, and the continuous urbanization process and increasingly prosperous tertiary industry will continuously increase the gap between the direct and indirect use of resources. Therefore, in the implementation of relevant policies, not only the focus on the supply side of resources but also the problem from the perspective of the demand side should be considered to avoid the continuous expansion of indirect consumption due to excessive restrictions on direct consumption. For provinces with large imports from other provinces, such as Tianjin, and Shanghai, the improvement in resource intensity is limited by the relatively high resource intensity in external provinces. Thus, resource management departments should break through the constraints of direct use management and expand the management perspective to the entire industrial chain through interprovincial economic and trade links. Provinces with high development levels and large imports should help their trading partners reduce water intensities (as well as other resource intensities). By doing so, the total water consumption of the country will be reduced. At the same time, developing a circular economy and making full use of the limited resources should be emphasized. For provinces with high embodied water intensities, such as Xinjiang and Guangxi, their high intensity is mainly reflected by direct use. Therefore, these provinces should improve their resource consumption efficiency and limit the total water consumption. For provinces that have increased water stress due to interprovincial energy transfers, such as Shaanxi and Ningxia, more stringent water resource management systems in energy industries (especially in coal industry) should be executed to reduce the energy-induced water.

### 4.3 Limitations and outlook

In this study, the multi-scale input–output method is combined with the water stress index to investigate the water and energy nexus associated with interprovincial trade. Some deficiencies and prospects are summarized as follows. First, databases on the national scale and provincial scale in China include 42 industry sectors with a consistent classification scheme. However, the economic data provided by the Eora World Input–Output Table contain only 26 sectors, and the classification of the sectors is not completely consistent with that in China. For example, Agriculture and Fishing are two separate sectors in the global-scale database, while they are regarded as a whole in China's databases. Mining and Quarrying industry is one sector in the global-scale database, while it is divided into Coal Mining, Oil and Gas Exploration, and Metal Mining industry in China's databases. Therefore, some sectors on the global-scale database were merged and split in connection with the 42 sectors in China's databases, which may have caused certain errors in the quantification of water and energy flows across sectors in this study. Another factor causing uncertainties is that the resource intensity of foreign products is set as the weighted average value of 188 regions/countries except China, rather than the values of the individual countries from which the imports originate. Given the limitation of the data, it is not possible to overcome the uncertainties caused by these two factors in this study. More detailed data on resource intensities in individual sectors in different provinces and countries are needed to reduce the uncertainties. The sectoral consistency is also important to avoid uncertainties arising from the merging and splitting of sectors in different databases. Third, the input–output table for 2012 at the provincial scale in China is the latest version that can be obtained to date, leading to a certain delay in the research, and the current research can provide only a reference for the formulation of relevant policies. Future research will incorporate scenarios under different resource policies and provide more specific and detailed guidance for resource development from the perspectives of exploitation and trade. Finally, bioenergy is not considered in this study because of the lack of data and its currently negligible share in the energy supply in China. However, it should be noted that to alleviate the dependence on fossil energy, China has gradually carried out research and development on bioenergy. The growth of bioenergy crops may increase, heightening the pressure on agricultural water consumption. In the future, water uses in the bioenergy sector may become non-negligible.

## 5 Conclusions

Based on the multi-scale input–output method, this study calculates the three scales of embodied water intensity and embodied energy intensity for each province of China in 2012. The characteristics of resource intensity are analyzed from the perspectives of industrial sectors and interprovincial differences. The sources and final flows of various resources are further calculated, and the results are analyzed with the *WSI* index.

The embodied water intensity and embodied energy intensity of all provinces except Fujian Province are higher than the world average. For most provinces, direct use is the main component of embodied water intensity, with a national average proportion of 52.21%. The embodied energy intensity is mainly reflected in domestic imports, whose national average proportion is 61.01%. Domestic exports, urban household consumption, and gross fixed capital formation are the main final demand types for water and energy. The comprehensive analysis of resource flows and the *WSI* index shows that interprovincial transfers of water resources have alleviated water stress in net inflow provinces but failed to completely change water stress status and further aggravated the situation in net outflow provinces. Interprovincial transfers of energy-induced water also have not effectively alleviated water stress in net inflow provinces but have further aggravated the situation in some net outflow provinces. In China, provinces with high water intensities frequently supply provinces with low water intensities, which means that the output provinces need to consume large amounts of water to meet the consumption needs of input provinces. Therefore, in the implementation of water-saving policies, it is important to improve the water consumption efficiency of provinces with active domestic trade and high resource intensity, pay more attention to the demand side, and avoid the continuous expansion of indirect consumption due to excessive restrictions on direct consumption.

**Author Contributions** The article was mainly written by SH, HY and HW provided many valuable comments. TC collected the data and reviewed the manuscript. All authors read and approved the final version of the manuscript.

**Funding** This research was funded by the National Natural Science Foundation of China (Grant Nos. 51879010, 51479003), the National Key Research and Development Program of China (2018YFC0407900) and the 111 Project (Grant No. B18006).

## Compliance with ethical standards

**Conflict of interest** The authors declare that they have no conflicts of interest to disclose.

## Appendix 1

See Table 2.

**Table 2** Codes and names of sectors

| Sector code | Sector content | Aggregated 7 sectors |
|---|---|---|
| 1 | Agriculture, forestry, animal husbandry and fishery | Agriculture (Ag) |
| 2 | Mining and washing of coal | Mining (Mi) |
| 3 | Extraction of petroleum and natural gas | |
| 4 | Mining and processing of metal ores | |
| 5 | Mining and processing of nonmetal and other ores | |
| 6 | Food and tobacco processing | Manufacture (Ma) |
| 7 | Textile industry | |
| 8 | Manufacture of leather, fur, feather and related products | |
| 9 | Processing of timber and furniture | |
| 10 | Manufacture of paper, printing and articles for culture, education and sport activity | |
| 11 | Processing of petroleum, coking, processing of nuclear fuel | |
| 12 | Manufacture of chemical products | |
| 13 | Manufacture of nonmetallic mineral products | |
| 14 | Smelting and processing of metals | |
| 15 | Manufacture of metal products | |
| 16 | Manufacture of general-purpose machinery | |
| 17 | Manufacture of special-purpose machinery | |
| 18 | Manufacture of transport equipment | |
| 19 | Manufacture of electrical machinery and equipment | |
| 20 | Manufacture of communication equipment, computers and other electronic equipment | |
| 21 | Manufacture of measuring instruments | |
| 22 | Other manufacturing | |
| 23 | Comprehensive use of waste resources | |
| 24 | Repair of metal products, machinery and equipment | |
| 25 | Production and distribution of electric power and heat power | Electricity and gas supply (El) |
| 26 | Production and distribution of gas | |
| 27 | Production and distribution of tap water | Water supply (Wa) |
| 28 | Construction | Construction (Co) |
| 29 | Wholesale and retail trades | Services and transport (ST) |
| 30 | Transport, storage, and postal services | |
| 31 | Accommodation and catering | |
| 32 | Information transfer, software and information technology services | |
| 33 | Finance | |
| 34 | Real estate | |
| 35 | Leasing and commercial services | |
| 36 | Scientific research and polytechnic services | |
| 37 | Administration of water, environment, and public facilities | |
| 38 | Resident, repair and other services | |
| 39 | Education | |
| 40 | Health care and social work | |
| 41 | Culture, sports, and entertainment | |
| 42 | Public administration, social insurance, and social organizations | |

## Appendix 2

See Table 3.

**Table 3** Embodied water and energy-induced water transfers in each province

| Province | Net inflow of embodied water ($10^8$ $m^3$) | Net inflow of energy-induced water ($10^8$ $m^3$) |
|---|---|---|
| Beijing | 56.66 | 9.47 |
| Tianjin | 37.45 | 3.73 |
| Hebei | – 30.63 | 7.24 |
| Shanxi | 17.87 | – 25.28 |
| Inner Mongolia | – 70.54 | – 34.36 |
| Liaoning | 3.22 | 6.61 |
| Jilin | – 25.26 | 1.11 |
| Heilongjiang | – 212.44 | 0.23 |
| Shanghai | 12.06 | 10.28 |
| Jiangsu | – 178.69 | 23.57 |
| Zhejiang | 6.30 | 17.21 |
| Anhui | – 117.39 | 3.10 |
| Fujian | – 51.81 | 0.61 |
| Jiangxi | – 69.34 | 6.99 |
| Shandong | 152.57 | 18.58 |
| Henan | – 58.56 | 2.42 |
| Hubei | – 13.34 | 6.67 |
| Hunan | – 113.23 | 2.13 |
| Guangdong | – 10.28 | 12.28 |
| Guangxi | – 118.44 | – 3.05 |
| Hainan | – 21.55 | 1.10 |
| Chongqing | 9.67 | 3.30 |
| Sichuan | – 16.29 | – 1.25 |
| Guizhou | – 31.27 | – 9.10 |
| Yunnan | – 26.27 | – 5.72 |
| Shaanxi | 6.62 | – 16.18 |
| Gansu | – 35.98 | – 1.95 |
| Qinghai | – 0.22 | – 2.39 |
| Ningxia | – 9.61 | – 2.40 |
| Xinjiang | – 341.91 | – 3.31 |

## References

Alcamo J, Henrichs T, Rösch T (2000) World water in 2025: global modeling and scenario analysis. In: Rijsberman F (ed) World water scenarios. Earthscan Publications, London, pp 243–281

Avrin A-P, He G, Kammen DM (2015) Assessing the impacts of nuclear desalination and geoengineering to address China's water shortages. Desalination 360:1–7

Beijing Water Authority (2013) China water resources bulletin 2012. China Municipal Water Affairs Bureau, Beijing **(in Chinese)**

BP (2013) Statistical review of world energy—June 2013. http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-worldenergy.html

BP (2018) Statistical review of world energy—June 2018. http://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-worldenergy.html

Carole D, Naota H, Huanguang Q, Denise LM, Ignacio R-I (2014) Water resources transfers through Chinese interprovincial and foreign food trade. Proc Natl Acad Sci USA 111:9774–9779

Chen GQ, Chen ZM (2010) Carbon emissions and resources use by Chinese economy 2007: a 135-sector inventory and input–output embodiment. Commun Nonlinear Sci 15:3647–3732

Chen Z, Chen G (2013) Virtual water accounting for the globalized world economy: national water footprint and international virtual water trade. Ecol Indic 28:142–149

Chen GQ, Wu XF (2017) Energy overview for globalized world economy: source, supply chain and sink. Renew Sustain Energy Rev 69:735–749

Chen GQ, Zhang B (2010) Greenhouse gas emissions in China 2007: inventory and input–output analysis. Energy Policy 38:6180–6193

Chen Z, Chen G, Chen B (2010) Embodied carbon dioxide emissions of the world economy: a systems input–output simulation for 2004. Procedia Environ Sci 2:1827–1840

Chen GQ et al (2011) Low-carbon building assessment and multi-scale input–output analysis. Commun Nonlinear Sci 16:583–595

Chen GQ, Guo S, Shao L, Li JS, Chen ZM (2013) Three-scale input–output modeling for urban economy: carbon emission by Beijing 2007. Commun Nonlinear Sci 18:2493–2506

Ding N, Liu J, Yang J, Lu B (2018) Water footprints of energy sources in China: exploring options to improve water efficiency. J Clean Prod 174:1021–1031

Gaudard L, Avanzi F, Michele CD (2018) Seasonal aspects of the energy–water nexus: the case of a run-of-the-river hydropower plant. Appl Energy 210:604–612

Gerbens PW, Hoekstra AY, Van der Meer TH (2008) 2008 Proceedings 13th IWRA world water congress IWRA

Gerbens PW, Hoekstra AY, Tvd Meer (2009) The water footprint of energy from biomass: a quantitative assessment and consequences of an increasing share of bio-energy in energy supply. Ecol Econ 68:1052–1060

Guo S, Shen GQ, Peng Y (2016) Embodied agricultural water use in China from 1997 to 2010. J Clean Prod 112:3176–3184

Han MY et al (2015) Embodied water for urban economy: a three-scale input–output analysis for Beijing 2010. Ecol Model 318:19–25

Hu M-C, Huang T, Yu H-L, Tung C-P (2018) Stochastic competitive analysis of hydropower and water supplies within an energy–water nexus. Stoch Env Res Risk A 32:2761–2769

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

Lenzen M, Moran D, Kanemoto K, Geschke A (2013) Building Eora: a global multiregion input–output database at high country and sector resolution. Econ Syst Res 25:20–49

Li JS, Chen GQ, Wu XF, Hayat T, Alsaedi A, Ahmad B (2014) Embodied energy assessment for Macao's external trade. Renew Sustain Energy Rev 34:642–653

Li JS, Xia XH, Chen GQ, Alsaedi A, Hayat T (2016) Optimal embodied energy abatement strategy for Beijing economy: based on a three-scale input–output analysis. Renew Sustain Energy Rev 53:1602–1610

Li M, Singh VP, Fu Q, Liu D, Li T, Zhou Y (2019) Optimization of agricultural water–food–energy nexus in a random environment: an integrated modelling approach. Stoch Env Res Risk A. https://doi.org/10.1007/s00477-019-01672-4

Liu S et al (2017) A three-scale input–output analysis of water use in a regional economy: Hebei province in China. J Clean Prod 156:962–974

Lv J, Li YP, Shan BG, Jin SW, Suo C (2018) Planning energy–water nexus system under multiple uncertainties—a case study of Hebei province. Appl Energy 229:389–403

NBS (National Bureau of Statistics of China) (2010) China economic census yearbook 2008. China Statistics Press, Beijing **(in Chinese)**

NBS (National Bureau of Statistics of China) (2013a) China energy statistical yearbook 2013. China Statistics Press, Beijing **(in Chinese)**

NBS (National Bureau of Statistics of China) (2013b) China population and employment statistics yearbook 2013. China Statistics Press, Beijing **(in Chinese)**

NBS (National Bureau of Statistics of China) (2013c) China statistical yearbook 2013. China Statistics Press, Beijing **(in Chinese)**

NBS (National Bureau of Statistics of China) (2015) Input–output tables of China 2012. China Statistics Press, Beijing **(in Chinese)**

Oki T, Kanae S (2006) Global hydrological cycles and world water resources. Science 313:1068–1072

Pata UK (2018) The influence of coal and noncarbohydrate energy consumption on $CO_2$ emissions: revisiting the environmental Kuznets curve hypothesis for Turkey. Energy 160:1115–1123

Quadrelli R, Peterson S (2007) The energy-climate challenge: recent trends in $CO_2$ emissions from fuel combustion. Energy Policy 35:5938–5952

Sarkodie SA, Adams S (2018) Renewable energy, nuclear energy, and environmental pollution: accounting for political institutional quality in South Africa. Sci Total Environ 643:1590–1601

Shang Y et al (2018) China' energy–water nexus: hydropower generation potential of joint operation of the Three Gorges and Qingjiang cascade reservoirs. Energy 142:14–32

Shao L (2014) Multi-scale input–output analysis of embodied water and its engineering applications. Peking University, Haidian **(in Chinese)**

Shao L, Guan D, Wu Z, Wang P, Chen GQ (2017) Multi-scale input–output analysis of consumption-based water resources: method and application. J Clean Prod 164:338–346

Stephan P, Annette K, Stefanie H (2009) Assessing the environmental impacts of freshwater consumption in LCA. Environ Sci Technol 43:4098–4104

Vörösmarty CJ, Green P, Salisbury J, Lammers RB (2000) Global water resources: vulnerability from climate change and population growth. Science 289:284–288

Wang S, Chen B (2016) Energy–water nexus of urban agglomeration based on multiregional input–output tables and ecological network analysis: a case study of the Beijing–Tianjin–Hebei region. Appl Energy 178:773–783

Wang S, Liu Y, Chen B (2018) Multiregional input–output and ecological network analyses for regional energy–water nexus within China. Appl Energy 227:353–364

Wu XF, Chen GQ (2017) Energy use by Chinese economy: a systems cross-scale input–output analysis. Energy Policy 108:81–90

Wu XD, Xia XH, Chen GQ, Wu XF, Chen B (2016) Embodied energy analysis for coal-based power generation system-highlighting the role of indirect energy cost. Appl Energy 184:936–950

Yang H, Pfister S, Bhaduri A (2013) Accounting for a scarce resource: virtual water and water footprint in the global water system. Curr Opin Environ Sustain 5:599–606

Ye Q, Li Y, Zhuo L, Zhang W, Xiong W, Wang C, Wang P (2018) Optimal allocation of physical water resources integrated with virtual water trade in water scarce regions: a case study for Beijing, China. Water Res 129:264–276

Zhang X et al (2017) China's coal-fired power plants impose pressure on water resources. J Clean Prod 161:1171–1179

Zhao X, Chen B, Yang ZF (2009) National water footprint in an input–output framework: a case study of China 2002. Ecol Model 220:245–253

Zhao X, Liu J, Liu Q, Tillotson MR, Guan D, Hubacek K (2015) Physical and virtual water transfers for regional water stress alleviation in China. Proc Natl Acad Sci USA 112:1031–1035

Zhao X, Liu J, Yang H, Duarte R, Tillotson MR, Hubacek K (2016) Burden shifting of water quantity and quality stress from megacity Shanghai. Water Resour Res 52:6916–6927