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Quantity and quality of China's water from demand perspectives

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Abstract

China is confronted with an unprecedented water crisis regarding its quantity and quality. In this study, we quantified the dynamics of China's embodied water use and chemical oxygen demand (COD) discharge from 2010 to 2015. The analysis was conducted with the latest available water use data across sectors in primary, secondary and tertiary industries and input–output models. The results showed that (1) China's water crisis was alleviated under urbanisation. Urban consumption occupied the largest percentages (over 30%) of embodied water use and COD discharge, but embodied water intensities in urban consumption were far lower than those in rural consumption. (2) The 'new normal' phase witnessed the optimisation of China's water use structures. Embodied water use in light-manufacturing and tertiary sectors increased while those in heavy-manufacturing sectors (except chemicals and transport equipment) dropped. (3) Transformation of China's international market brought positive effects on its domestic water use. China's water use (116–80 billion tonnes (Bts))[9] and COD discharge (3.95–2.22 million tonnes (Mts)) embodied in export tremendously decreased while its total export values (11–25 trillion CNY) soared. Furthermore, embodied water use and COD discharge in relatively low-end sectors, such as textile, started to transfer from international to domestic markets when a part of China's production activities had been relocated to other developing countries.

1. Introduction

Water crisis has been announced as the 4th global risk with regard to its impact on the society (World Economic Forum, 2019). The world's per capita freshwater capacity has dropped 26% within 25 years (1992–2017) (Ripple *et al* 2017), whereas the water demand was projected to increase by 55% from 2015 to 2050 (IRENA 2015). In 2015, diseases caused by water pollution and unsafe water sources have claimed responsibility for approximately 1.8 million deaths globally (Landrigan *et al* 2018).

[9] Throughout this study, when the authors put two values in one parentheses as (a), (b), value a and b represent water use or COD discharge, or export values in 2010 and 2015, respectively, in order to better reveal their changing patterns.

China, particularly, is facing perilous water challenges. China's remarkable achievements in its accelerating economy sacrifice aquatic environments, attributing to serious resource depletion and water pollution (Guan *et al* 2014, Zhang *et al* 2019). By 2018, 27.6% of its surface water sites had not met Grade III quality standards, the threshold of water quality that enables human beings to swim in (MEEC 2018).

Meanwhile, China has been undergoing profound transitions over the past decade. Its rapid urbanisation since the 1980s has been labelled as 'China's growth miracle' with approximately 1.05% of annual urban population growth from 1980 to 2015 (19.39%–56.10%), which has greatly stimulated China's economy (Zhao and Zhang, 2018, Wang *et al* 2019). In 2014, China has stepped into the 'new normal' phase, and achieved optimisation of economic structures (Mi *et al* 2017). It means that China's development was no longer driven by investment but innovation and environmentally-friendly technology, and the transitions have accomplished from high-speed to medium-high-speed growth, and from rapid growth of scale to intensive- and quality-increasing growth (Meng *et al* 2019, Zhang *et al* 2019, Li *et al* 2019a). Additionally, as the world's largest exporter, China also has its economy driven by international trade. Since the 2008 global financial crisis, its traditional international markets have transformed in order to tackle increasing trade barriers against China (Chandra, 2016). Confronting with more south–south trade in the new phase of globalisation, China has also relocated a part of its production activities to other developing countries (Meng *et al* 2018). Given that water shortage and water pollution are crucial constraints for economic prosperity, China's water quantity and quality require further investigation (Rao and Chandrasekharam 2019).

A series of studies have been conducted to understand the quantity and quality of China's water resources (Jiang, 2009, Han *et al* 2016, Udimal *et al* 2017). However, most existing research has concentrated more on quantity and quality of direct water (production perspective) rather than embodied water (demand perspective), and the negligence would result in emerging water conflicts (De Angelis *et al* 2017). Embodied water captures the total volume of water used to produce products, including both direct and indirect water in the full production chain (Sun and Fang 2019). Embodied water can be categorised by final demands from a demand perspective, which incorporate final consumption (rural consumption, urban consumption and government expenditures) and capital formation (fixed capital formation and inventory change) that can be redistributed as primary inputs to the economy, and export (Wu *et al* 2018, Wu *et al* 2019a, Chen *et al* 2019b). In recent years, increasing attention has been paid to China's embodied water (Guan *et al* 2014), especially water embodied in the inter-regional trade for agriculture (Dalin *et al* 2014, Zhao *et al* 2015, Guo *et al* 2016) and for the whole supply chain (Cai *et al* 2017, Hou *et al* 2018, Tian *et al* 2018, Zhao *et al* 2019). These studies have provided insights into China's water and its contamination from demand perspectives before 2010. Fan *et al* (2019) analysed driving forces of China's embodied water withdrawal categorised by different final demands by 2012. Wu *et al* (2019b) explored water use embodied in China's final consumption and trade balance in 2014 in a global context. Unfortunately, these studies excluded water quality indicators. Thus, we studied China's embodied water quantity and quality from 2010 to 2015, which could greatly benefit China's water studies and policies.

This study successfully bridges the research gaps by obtaining the quantification of the latest available (2010–2015) embodied water quantity and quality in China's economic system. The aims of our study are to: (1) uncover the dynamics of China's embodied water under the above-mentioned backgrounds; (2) quantify the changing patterns of sectoral water structures in input–output analysis to avert emerging water conflicts and to achieve fairer allocation of social responsibilities; and (3) provide holistic points of view towards water policy implications to prevent further environmental deterioration and to improve resilience and mitigation mechanisms based on our analysis. Furthermore, the international relevance in this national-level research lies in the following aspects: (1) Freshwater and water pollutants can be transferred naturally via water run-off (Chen *et al* 2019a) so China's water crisis has an instinct bond with other countries; (2) As the world's largest trade exporter and international environmental 'vandal', China has claimed responsibility for exporting low value-added water- and pollutant- intensive products to imported countries (Cai *et al* 2017), and therefore China's water issues should be prioritised globally to better balance water budgets and catalyse collaboration (Han *et al* 2017); (3) China's case study can be referred in other countries as the methods are replicable, and political implications to address its water crisis can also be mirrored, especially in countries with a similar developing trajectory.

2. Methods and data

2.1. Methods

We conducted environmentally-extended input–output analysis for China in 2010, 2012 and 2015 based on corresponding national input–output tables obtained from Chinese Input–output Association. The methods have been partly elaborated in our previous study (Li *et al* 2019b). In each input–output table, n sectors are included ($n = 42$) as attached in the appendix. Z_{ij} represents transactions between pairs of sectors from sector i to sector j. And x_i, y_i, m_i and f_i can then be denoted as total output, final demands, import and water or COD intensity in sector i. $\mathbf{I}$ indicates a 42×42 diagonal matrix with 1 on its main diagonal, and a_{ij}, technological coefficient, is calculated as $a_{ij} = Z_{ij}/x_j$. $\mathbf{L}$ symbolises Leontief inverse matrix. They can be written as,

$$\mathbf{x} = \begin{bmatrix} x_1 \\ \cdots \\ x_i \\ \cdots \\ x_n \end{bmatrix}, \mathbf{Z} = \begin{bmatrix} Z_{11} & \cdots & Z_{1j} & \cdots & Z_{1n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ Z_{i1} & \cdots & Z_{ij} & \cdots & Z_{in} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ Z_{n1} & \cdots & Z_{nj} & \cdots & Z_{nn} \end{bmatrix},$$

$$\mathbf{y} = \begin{bmatrix} y_1 \\ \cdots \\ y_i \\ \cdots \\ y_n \end{bmatrix}, \mathbf{m} = \begin{bmatrix} m_1 \\ \cdots \\ m_i \\ \cdots \\ m_n \end{bmatrix}, \mathbf{f} = \begin{bmatrix} f_1 & \cdots & f_j & \cdots & f_n \end{bmatrix},$$

$$\mathbf{A} = \begin{bmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{i1} & \cdots & a_{ij} & \cdots & a_{in} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{n1} & \cdots & a_{nj} & \cdots & a_{nn} \end{bmatrix}.$$

We first converted all the input–output tables to 2010 constant prices and removed inflation with the double deflation method, where yearly producer price indexes (PPI) were sourced in Chinese Statistical Yearbooks. The lack of PPI in tertiary sectors was dealt with as follows: (1) PPI was not applicable in scientific research (S36), water conservancy (S37) and public management (S42) as the government services do not comply with market disciplines so their **Z** remain unchanged. (2) In other tertiary sectors, PPI was replaced by consumer price index. Given the p_i denotes the ratio of the current price and the base year price, d_i indicates the reciprocal price ratio, or the deflator in sector i, as $d_i = 1/p_i$. Then **Z** in 2012 and 2015 can be adjusted by multiplying the deflators in each sector.

Second, we ensured the effects of intermediate imports were eliminated with equation (1) (Dietzenbacher *et al* 2013). As α in each sector was negative, no measures need to be further taken to remove re-export.

$$\alpha_i = m_i - \sum_{k=1}^{n} Z_{ik} - y_i. \tag{1}$$

Third, we removed imports imbedded in China's competitive input–output tables to estimate water used or COD discharged solely due to demand by assuming the same proportions of sectoral imports (β_i in equation (2)) were deducted in individual economic sectors and final demands. We can then isolate Z_i and y_i in domestic supply chain, Z_i^d and y_i^d, as expressed in equations (3) and (4) (Meng *et al* 2015).

$$\beta_i = m_i/(x_i + m_i) = m_i/(Z_i + y_i), \tag{2}$$

$$Z_i^d = Z_i(1 - \beta_i), \tag{3}$$

$$y_i^d = y_i(1 - \beta_i). \tag{4}$$

And $\mathbf{A^d}$ can be further obtained in equation (5), where the prime indicates the transposition of the vector **x**.

$$\mathbf{A^d} = \mathbf{Z^d}/\mathbf{x}'. \tag{5}$$

Then, China's embodied water use (**W**) and COD discharge (**C**) can be calculated with equations (6) and (7) in 2010, 2012 and 2015, respectively, denoted with their corresponding subscripts *w* and *c*,

$$\mathrm{W} = \mathbf{f_w L^d y^d} = \mathbf{f_w (I - A^d)^{-1} y^d}, \tag{6}$$

$$\mathrm{C} = \mathbf{f_c L^d y^d} = \mathbf{f_c (I - A^d)^{-1} y^d}. \tag{7}$$

Here, **f** is direct water ($\mathbf{f_w}$) or COD ($\mathbf{f_c}$) intensity, which represents direct water use or COD discharge associated with one unit industry output. And ε is embodied water or COD intensity, a row vector with each element ε_i denoting both direct and indirect water used or COD generated throughout the supply chain to produce per unit of product or service in sector i (Meng *et al* 2015). Thus, ε can be written in equation (8) as,

$$\varepsilon = \mathbf{f(I - A^d)^{-1}}. \tag{8}$$

Lastly, we converted 42 sectors into 18 sectors, attached in the appendix. As for water intensities, we took weighted averages of direct water intensities (with total outputs) and embodied intensities (with total demand) across converted sectors, respectively.

2.2. Data

With regard to direct water use, the total amounts of China's domestic water use in agriculture, industry (except construction) and residential areas (consists of construction, tertiary industry, and rural and urban consumption) were obtained from China Water Resources Bulletins, and water use across industrial sectors (except construction) were down-scaled based on sectoral industrial water use from Annual Statistic Reports on Environment in China (as the total industrial water use in Annual Statistic Reports on Environment in China included water reuse, which was inconsistent with that in China Water Resources Bulletins). The average ratios of water use in construction, tertiary industry and rural/urban consumption in China's 259 cities were calculated as 20.2%, 6.8% and 73% of the total residential water use according to China's provincial and city-level water resource bulletins and statistical yearbooks. We used the ratios above to allocate water use in construction and tertiary industry, and then distributed the water use in tertiary industry into each sector on the basis of the corresponding employee numbers sourced from China Statistical Yearbooks.

Following previous research, COD discharge was taken as the parameter to determine water quality (Guan *et al* 2014, Zhao *et al* 2016, Cai *et al* 2019, Li *et al* 2019a). Fundamentally, COD indicates the amount of oxidant consumed during oxidation of organic substance present in water samples. Regarding COD discharge, the total amounts in agriculture and residential areas, and data across industrial sectors (except construction) were all accessed in Annual Statistic Reports on Environment in China. And the total COD amounts in construction and tertiary industry were estimated by China's total population, employee numbers and their average working hours (8 h). The total COD discharge in tertiary industry was further down-scaled into individual tertiary sectors with the number of employees. The main limitation of this method lied in the rough estimation of water use and COD discharge in tertiary industry. In addition, COD accounted for approximately 15% and 92% of the total water pollutants in primary and secondary industries, respectively (NBS 2010), so the water pollution in primary and tertiary industries was more likely to be underestimated.

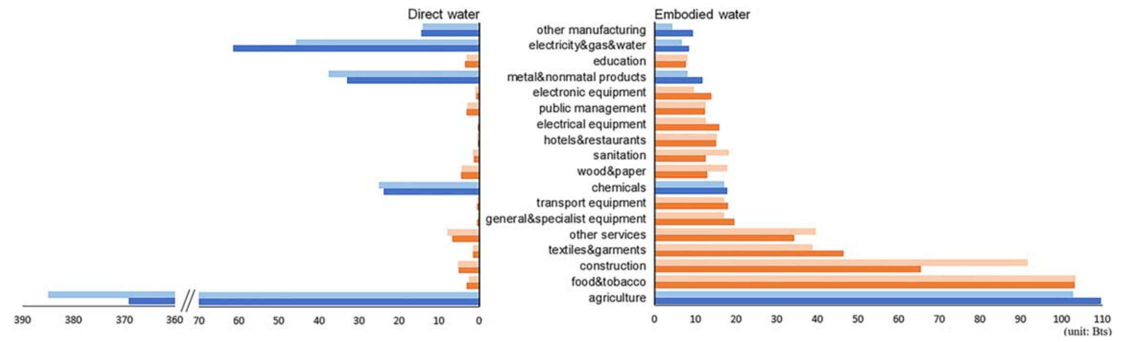

Figure 1. Direct and embodied water use across sectors in primary, secondary and tertiary industries in 2010 and 2015. Blue and orange bars represent producer and consumer sectors, respectively. Bars with dark blue/orange and light blue/orange indicate water use data in 2010 and 2015, respectively.

3. Results

3.1. China's water use from production and demand perspectives

3.1.1. Direct water use versus embodied water use

Producer sectors represent water suppliers (that transfer water to other sectors via trade) in the supply chain, with their direct water use outweighing their embodied water use. On the contrary, consumer sectors are water consumers (that consume water transferred from other sectors via trade) in the supply chain, and these sectors occupy more embodied water use than direct water use.

Figure 1 compares direct and embodied water use across sectors in primary, secondary and tertiary industries in 2010 and 2015. Overall, consumer sectors outweighed producer sectors. Agriculture was the most significant producer sector. Its direct water use accounted for approximately 70% (369 Bts/534 Bts in 2010 and 385/540 Bts in 2015) of China's total amounts, but embodied water use in this sector only took up about 20% (110/534 Bts in 2010 and 103/540 Bts in 2015) of the total, which underlined the irreplaceable role that agriculture played as a dominant producer sector in the virtual water supply chain. Electricity and gas and water was the second largest producer sector (especially electricity), followed by metal and nonmetal products (metallurgy in particular), chemicals and other manufacturing. Conversely, food and tobacco and construction were dominant consumer sectors, followed by textiles and garments and other services. In addition, all sectors in tertiary industry were water consumers.

From 2010 to 2015, gaps of direct and embodied water use have experienced changes in several sectors. As for producer sectors, agriculture's direct water use increased by 16 Bts while its embodied water use declined by 7 Bts. Direct (33–38 Bts) and embodied (12–8 Bts) water use in metal and nonmetal products also showed similar patterns. In contrast, direct water use in electricity and gas and water experienced sharp reduction (62–46 Bts) with its embodied water use fluctuating around 7–8 Bts. Regarding consumer sectors, construction's embodied water use soared (65–92 Bts) while its direct water use remained at around 5 Bts. Similar patterns were also presented in wood and paper, sanitation and other services.

3.1.2. Direct water intensities versus embodied water intensities

Figure 2 depicts the comparison between direct and embodied water intensities. Overall, embodied water intensities outweighed direct water intensities, and both direct and embodied water intensities presented downward trends from 2010 to 2015.

Agriculture occupied the largest direct and embodied water intensities, and the reduction of its intensities was the sharpest, by approximately 40%. It was previously shown that its direct water use was three times the amounts of its embodied water, but its embodied water intensities (724–447 tonne/10 000 CNY) were larger than its direct water intensities (533–330 tonne/10 000 CNY). Electricity and gas and water was ranked as a producer sector with the second largest direct water intensities (129–66 tonne/10 000 CNY), but its embodied water intensities were still larger (188–100 tonne/10 000 CNY). On the contrary, food and tobacco had the second largest embodied water intensities (386–248 tonne/10 000 CNY) but the ranking for its direct water intensities was much lower. Construction and textiles and garments also had far larger embodied water intensities than their direct water intensities. Yet embodied water intensities in construction were smaller than those in textiles and garments even though the amounts of embodied water use in construction were larger.

3.2. Quantity and quality of China's embodied water use

3.2.1. Embodied water use categorised by final demands

From 2010 to 2015, China's total embodied water use fluctuated within a reasonable range from 2010 (534 Bts), 2012 (548 Bts) to 2015 (540 Bts), and its embodied COD discharge dropped gradually during the period (17.74–15.29 Mts). Yet embodied water intensities (113–67 tonne/10 000 CNY) and embodied

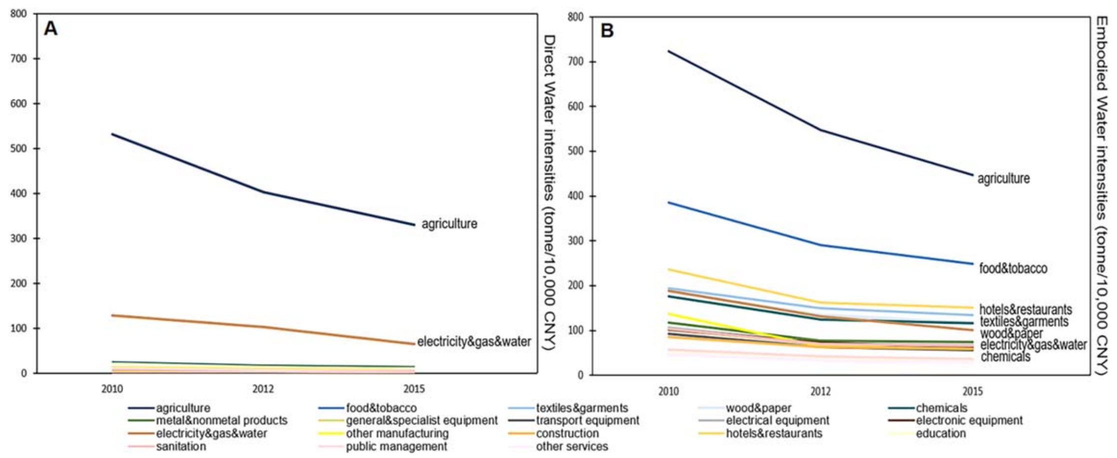

Figure 2. Direct and embodied water intensities across primary, secondary and tertiary industries in 2010, 2012 and 2015. (2A) direct water intensities. (2B) embodied water intensities.

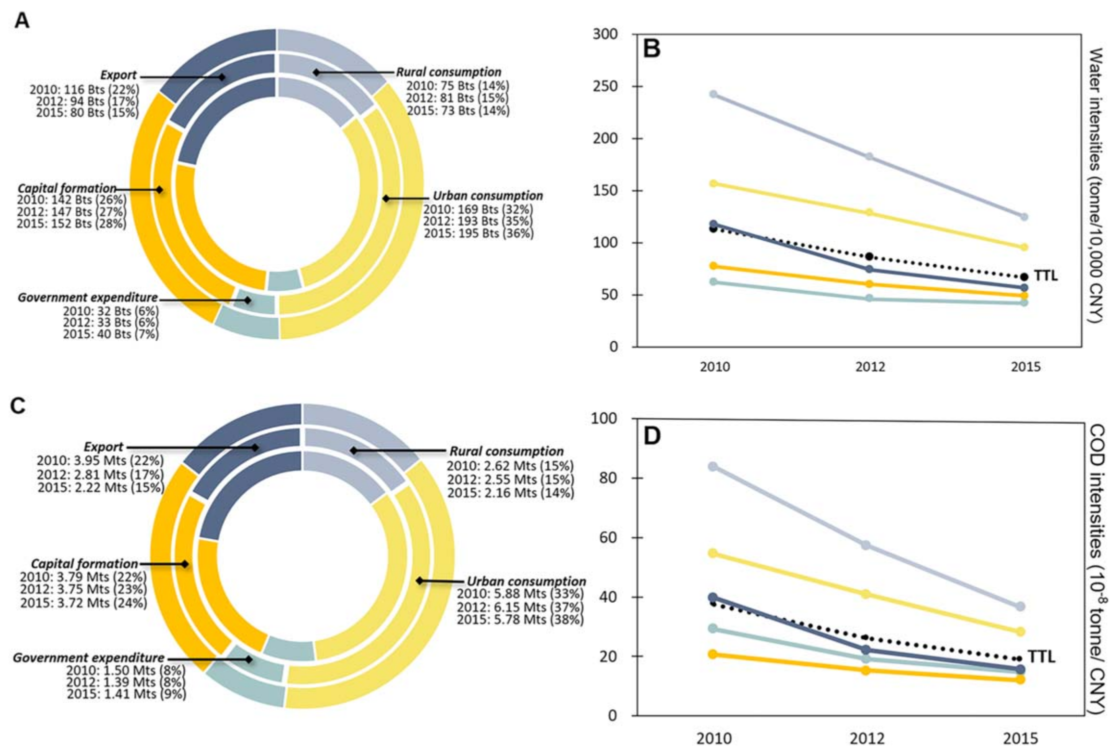

Figure 3. Embodied water use and COD discharge, and their embodied intensities categorised by final demands. (3A) and (3C) depict embodied water used and COD discharged in each final demand, respectively, where the concentric circles from interior to exterior represent 2010, 2012 and 2015, respectively. (3B) and (3D) illustrate embodied water and COD intensities in final demands, indicating embodied water use and COD discharge per unit of each final demand. The dotted black line (TTL) represents total embodied water or COD intensities, calculated as total embodied water use or COD discharge divided by total demand. Colours highlight the final demands remain the same in four graphs.

COD intensities (38–19 tonne/10^{-8} CNY) both declined tremendously during the period.

Figure 3 demonstrates embodied water use and COD discharge contributed by different final demands. Among all the final demands, urban consumption had the largest amounts of embodied water use (169–195 Bts) and embodied COD discharge (5.88–5.78 Mts), followed by capital formation, while government expenditures was the smallest embodied water user (32–40 Bts) and embodied COD discharger (1.50–1.41 Mts). And the dynamics showed that the percentages of water use and COD discharge embodied in export declined dramatically (by 7%) while the percentages in urban consumption grew fast (by 4%–5%). However, government expenditure contributed more for embodied COD discharge (8%–9%) than for embodied water use (6%–7%). Conversely, capital formation held larger percentages in embodied water use (26%–28%) than in embodied COD discharge (22%–24%).

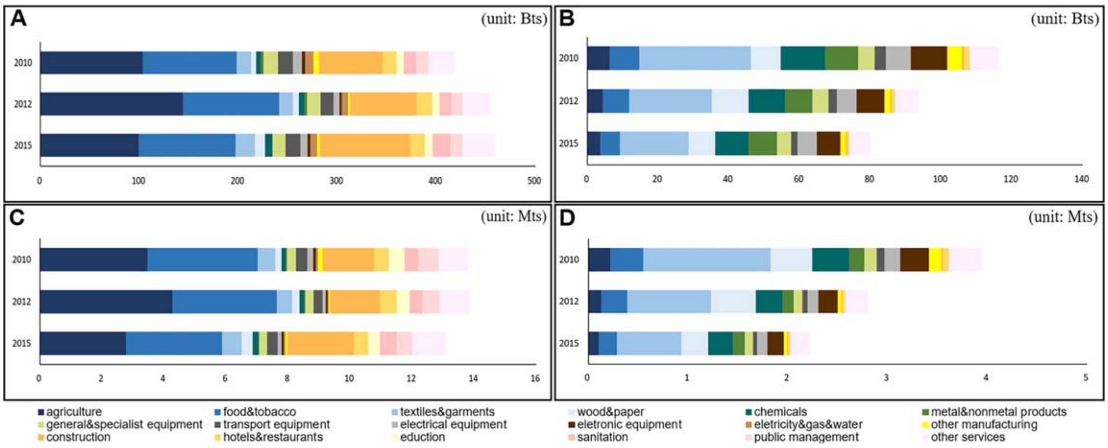

Figure 4. Embodied water use and COD discharge across sectors in domestic demand and in export. (4A) embodied domestic water used for domestic demand. (4B) water use embodied in export. (4C) embodied domestic COD discharged for domestic demand. (4D) COD discharge embodied in export.

Moreover, embodied water and COD intensities in final demands all reduced. Compared with previous research conducted from 1992 to 2010 (Guan *et al* 2014), the overall reduction rates of embodied water and COD intensities tended to be steadier. From 2010 to 2015, the reduction of embodied water and COD intensities during 2012–2015 furthermore slowed compared with 2010–2012, especially in export (117–57 tonnes/10 000 CNY). The dotted black lines (TTLs) represent total embodied water and COD intensities. Embodied water and COD intensities in certain final demand that were higher/lower than these bars meant that it required and generated more/less embodied water use and COD discharge to meet per unit of demand than average national levels. It was clear that only urban and rural consumption sat above the dotted black lines (TTLs), but embodied water and COD intensities were much larger in rural consumption than in urban consumption. Below the TTLs were export, capital formation and government expenditures. Export had the third largest embodied water and COD intensities, and government expenditures and capital formation ranked last in embodied water and COD intensities, respectively.

3.2.2. Sectoral water use embodied in domestic demand and export

Figure 4 presents embodied water use and COD discharge across sectors in domestic demand (including rural and urban consumption, government expenditures and capital formation) and in export in 2010, 2012 and 2015. Regarding domestic demand, agriculture, food and tobacco and construction were the largest embodied water users and COD dischargers. Agriculture experienced ups-and-downs in both embodied water use (103–99 Bts) and embodied COD discharge (3.46–2.77 Bts). And embodied water use (by 26 Bts) and embodied COD discharge (by 0.51 Mts) in construction surged. Besides these sectors, textiles and garments, sanitation, transport equipment, hotels and restaurants, public management, wood and paper also had large amounts of both embodied water use and COD discharge. However, general and specialist equipment was a large embodied water user but not a large embodied COD discharger, while education discharged large amounts of embodied COD but the amounts of its embodied water use were relatively small.

From 2010 to 2015, embodied water use in light-manufacturing sectors for domestic demand presented an upward trend. On the contrary, embodied water use in heavy-manufacturing sectors declined (except chemicals and transport equipment), where the embodied water use in metal and nonmetal products dropped at the fastest speed (by 2 Bts), followed by general and specialist equipment, electrical equipment and electricity and gas and water. Besides, embodied water use in each tertiary sector rose during the period, especially sanitation (by 6 Bts) and hotels and restaurants.

With regard to export, it was apparent that textiles and garments occupied a predominant role in both embodied water use (31–19 Bts) and embodied COD discharge (1.28–0.65 Mts). The amounts of embodied water use and COD discharge were also both large in chemicals, electronic equipment, food and tobacco and wood and paper. Yet for metal and nonmetal products, its embodied water use was ranked as the top, but its embodied COD discharge had a smaller ranking. Furthermore, the largest embodied water users and COD dischargers in domestic demand included sectors across primary, secondary and tertiary industries, while only primary and secondary sectors were listed as the largest embodied water users and COD dischargers in export.

During 2010–2015, both embodied water use and COD discharge for export fell in each sector. The reduction of embodied water uses (32–19 Bts) and embodied COD discharge (1.28–0.65 Mts) in textiles and garments was the sharpest. In the textile sector, both water use (21–9 Bts) and COD discharge (0.86–0.30 Mts) embodied in exported products plummeted even though its embodied water use (1–3 Bts) and embodied COD discharge (0.05–0.11 Mts) for domestic demand increased.

4. Discussions

Agriculture and electricity were the most important producer sectors in the virtual water supply chain (figure 1). Despite agricultural product types and energy types (including renewable energy), irrigation water use and cooling water use were required. And direct water used in agricultural products (including its by-products) and in electricity generation then benefited other production processes and human settlements. Heavy-manufacturing was also a vital producer sector in the virtual water supply chain because water-intensive final or semi- products in this sector were often redistributed to other production lines as raw materials. The above messages can at the same time explain why large-scale sectors, such as food and tobacco, construction, textile and garments occupied the largest amounts of embodied water use (figure 1). It was worth mentioning that Wang *et al* (2018) found that materials used in construction triggered a large amount of embodied CO_2 emissions. In this study, we further validated that these materials in construction also embodied a large amount of water use. However, changing patterns of water use in these sectors differed from 2010 to 2015: (1) agriculture supplied more water to other sectors; (2) electricity transferred less water to other sectors; (3) construction used more water from other sectors (figure 1). The increase of direct and embodied water use in agriculture and construction indicated the growing demand, which can be reflected in the skyrocketing value-added GDP in these sectors from China Statistical Yearbooks. Regarding electricity, the reduction of direct water use in the sector was attributed to higher water efficiency. We observed from China Statistical Yearbooks that from 2010 to 2015, the percentage of China's coal consumption for electricity generation declined from 76.2% to 72.2%, while natural gas and renewable energy consumed to generate electricity grew from 4.1% to 4.8%, and from 10.4% to 14.5%, respectively. As coal required more water use than other energy types during the overall process of electricity generation, direct water use in electricity would inevitably decrease with more efficient water distribution.

We also saw that embodied water intensities tended to surpass direct water intensities in major producer sectors in the virtual water supply chain even though direct water use outweighed embodied water use in these sectors (figure 2). This illustrated our previous point that major producer sectors, especially agriculture and electricity, contributed large water inputs to generate large production outputs. In contrast, major consumer sectors had both larger amounts of embodied water use and embodied water intensities than their direct water use and direct water intensities (figure 2). It meant that the large amounts of embodied water use in these sectors were not only affected by their huge demand but also large embodied water intensities. In construction, its embodied water use soared while its embodied water intensities dramatically decreased from 2010 to 2015 (figure 2), which signified the rapid development of China's infrastructure construction and real estate, and the role it played as a solid measure to stimulate economy, especially in the post financial crisis era (Giang and Pheng 2011).

The overall changing patterns of embodied water use and COD discharge, and embodied water and COD intensities (figure 3) marked the advancement of water-saving and water pollution control in China. The slower reduction of embodied water and COD intensities from 1992 to 2015 (figure 3) was attributed by long-term water management and recent years' economic slowdown (Zhang *et al* 2019). In the future, technology breakthrough would be the most effective approach to obtaining faster reduction of embodied water and COD intensities. From demand perspectives, large amounts of water use and COD discharge embodied in urban consumption and capital formation formed prerequisite for advancing urbanisation at an unprecedented rate (figure 3) (Zheng *et al* 2019). Given that urban areas can better manage water use and control water contamination than rural areas (figure 3), urbanisation to some extent alleviated China's water issues (Wu *et al* 2012). China's plummeted embodied water use (116–80 Bts) and embodied COD discharge in export (3.95–2.22 Mts) (figure 3), and doubled export values (11–25 trillion CNY) from China Statistical Yearbooks indicated that more high-value-added products than water-intensive low value-added products were preferred for export.

We also observed the optimised water use structures in China, that embodied water use in heavy-manufacturing sectors (except chemicals and transport equipment) dropped while that in light-manufacturing and tertiary sectors increased (figure 4). It demonstrated the improving water status under industrial transformation and upgrade within the country (Mi *et al* 2017). From international perspectives, textile was the largest water exporter. However, we found from the Chinese Input–Output Association that the total outputs for textile's domestic demand (68–212 billion CNY) increased while the same indicator for its export (873–607 billion CNY) dropped. Combined with the water data in textile (figure 4), it revealed that China's textile products, along with water use and COD discharge embodied in these products, were partly transferred from international markets to domestic markets in the new phase of globalisation, when some of its production activities have been relocated in other developing countries (Meng *et al* 2018). Yet China's dominant water exporters were still primary and secondary sectors (figure 4).

5. Conclusions

This study explores direct and embodied water quantity and quality across sectors in primary, secondary and tertiary industries by applying China's input–output tables in 2010, 2012 and 2015. Based on our analysis, some key conclusions can be drawn as follows,

(1) In the virtual water supply chain, agriculture was the most significant producer sector while food and tobacco and construction were the most vital consumer sectors. Embodied water use and COD discharge in construction skyrocketed during 2010–2015 as developing infrastructure construction and real estate enabled a boost to the national economy (Giang and Pheng 2011).

(2) China had the resolution to encourage urbanisation without jeopardising the aquatic environment. Urban consumption, as the largest embodied water users and COD dischargers, laid foundation for urbanisation, which stimulated economy and alleviated water crisis with more effective water management (Wu *et al* 2012).

(3) The changing patterns of embodied water use and COD discharge also reflected the achievements of water-saving and water pollution control under the 'new normal' phase. Embodied water and COD intensities in final demands presented downward trends. And the reduction rates of embodied water and COD intensities from 2012 to 2015 were smaller than those during 2010–2012, which was attributed to the transition from the high- to medium-high growth speed of the country (Zhang *et al* 2019). Besides, the overall trend showed that embodied water use in light-manufacturing and tertiary sectors grew, while embodied water use in heavy-manufacturing sectors (except chemicals and transport equipment) reduced dramatically (especially in metal and nonmetal products). It signified the optimisation of the water use structures and the fulfilment of industrial transformation and upgrade (Mi *et al* 2017).

(4) China has obtained high water efficiency in export while maintaining the market growth in the post financial crisis era. From 2010 to 2015, embodied water use and COD discharge in export plummeted (especially in textiles and garments), but China's export values still soared. It was because China has focused more on high value-added over low value-added markets since the global financial crisis in order to sharpen its competitive edges. In addition, some comparatively low-end sectors, such as textiles, tended to shift their embodied water use and COD discharge from international to domestic markets instead when some production activities have been transferred to other developing countries in the new phase of globalisation (Meng *et al* 2018).

Chinese government should first fully utilise market mechanism and economic leverage in water rights transaction, and offer subsidies to producer sectors in the virtual water supply chain, especially agriculture, to catalyse fairer responsibility allocation for water use and water pollution control. Second, the authorities should grasp the opportunities to reinforce sound urbanisation while improving water status in rural areas. Third, under China's current economic structure, management of water-intensive heavy-manufacturing sectors, chemicals and transport equipment, should be emphasised as their embodied water use and COD discharge still presented upward trends. Fourth, when China shifts its focus from low-end to high value-added international markets, or from international to domestic markets, the priority is to achieve higher water efficiency in its production activities. This can be achieved by establishing more capital- and technology-oriented pilot enterprises for the advancement of industries, and investing more capitals in long-term environmental gains and water sustainability.

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Data availability statements

Most of the data that support the findings of this study are openly available at Chinese Input–Output Association (http://stats.gov.cn/ztjc/tjzdgg/trccxh/zlxz/trccb/), China Water Resources Bulletins (http://mwr.gov.cn/sj/tjgb/szygb/), Annual Statistic Reports on Environment in China (http://mee.gov.cn/gzfw_13107/hjtj/hjtjnb/), and China Statistical Yearbooks (http://stats.gov.cn/tjsj/ndsj/). Parts of data at Chinese Input–Output Association and Annual Statistic Reports on Environment in China can be accessed from the corresponding authors upon reasonable request as they are not publicly available due to legal ethical reasons.

Conflict of interest

The authors have no conflict of interest to declare.

Appendix. Converted 18 IO sectors.

Converted sectors	42 IO sectors	
Agriculture	S01	Agriculture, forestry, animal husbandry and fishery
Food and tobacco	S06	Food processing and tobaccos
Textiles and garments	S07; S08	Textiles; Clothing, leather, fur, etc
Wood and paper	S09; S10	Wood processing and furnishing; paper making, printing, stationery, etc
Chemicals	S12	Chemical industry
Metal and non-metal products	S13; S14;S15	Nonmetal products; Metallurgy; Metal products
General and specialist equipment	S16; S17	General machinery; Specialist machinery
Transport equipment	S18	Transport equipment
Electrical equipment	S19	Electrical equipment
Electronic equipment	S20	Electronic equipment
Electricity and gas and water	S25; S26; S27	Electricity and hot water production and supply; Gas production and supply; Water production and supply
Other manufacturing	S02; S04; S05	Coal mining; Metal mining; Nonmetal mining;
	S03; S11	Petroleum and gas; Petroleum refining, coking, etc
	S21; S22; S23; S24	Instrument and metre; Other manufacturing; Waster and flotsam; Repair service for metal products, machinery and equipment
Construction	S28	Construction
Hotels and restaurants	S31	Hotels and restaurants
Education	S39	Education
Sanitation	S40	Sanitation and social welfare
Public management	S42	Public management and social organisation
Other service	S29; S30; S32; S33; S34; S35; S36; S37; S38; S41	Wholesale and retailing; Transport and storage; Information transfer and software; Banking; Real estate trade; Leasing and commercial services; Scientific research; Management of water conservancy, environment and public establishment; Resident services and other services; Culture, sports and entertainment

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