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Key Points:

- A multi-layer water-energy-carbon production path analysis model is developed
- Exports drive more than half of water, energy and carbon footprints in the Pearl River Delta
- In the Pearl River Delta, cities of Jiangmen and Huizhou supply the most water and energy, and Huizhou and Dongguan provide the most carbon

Supporting Information:

Supporting Information may be found in the online version of this article.

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Mapping Water, Energy and Carbon Footprints Along Urban Agglomeration Supply Chains

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Abstract China's urban population will increase by 268 million from 2010 to 2030, with the consumption of a large number of resource-intensive products. Quantitative analysis of the environmental impacts (water, energy and carbon) of urban agglomerations can make trade-offs among water conservation, energy use, climate change mitigation, and urban development. In this study, a multi-layer water-energy-carbon production path analysis (MWPPA) model is developed for identifying the key final demands, sectors and supply chain paths of the Pearl River Delta urban agglomeration (PUA). Results show that, water, energy and carbon-emission intensities respectively reduced by 27.3%, 35.6% and 27.6% in 2015, compared to the levels in 2012. More than half of the water-energy-carbon (WEC) footprints are export-driven, where Guangzhou, Shenzhen and Foshan dominate the WEC footprints of PUA. Results also disclose that Shenzhen is the main recipient of water-energy, while Jiangmen and Huizhou are the main providers of water and energy, respectively. Policy makers are suggested that each industry actively integrate into global value chains in order to leverage its comparative advantage, and Huizhou should take full advantage of its fossil base to form a complete industry chain from the R&D end to the production end around the energy industry.

Plain Language Summary Not only do urban areas consume large amounts of water and energy, they are also the specific implementation units of carbon reduction policies. The United Nations Sustainable Development goals (UN SDGs) make it clear that water conservation, energy access, climate change mitigation, and urbanization development are important parts of its agenda. As one of the most developed urban agglomerations in China, the Pearl River Delta urban agglomeration (PUA) is also the main consumer of water, energy and carbon (WEC). This study reveals that more than half of the WEC footprints are export-driven, and Guangzhou, Shenzhen and other developed economies dominate the WEC footprints of PUA. Compared to 2012, the consumption intensity of WEC was reduced in 2015. The results also find that light industry and equipment manufacture play key roles in the WEC system. Results suggest that greener production needs to be adopted not only within but also outside of urban agglomerations, while individual cities need to actively promote the integration of each industry into global supply chains.

1. Introduction

Not only do urban areas consume large amounts of water and energy, they are also the specific implementation units of carbon reduction policies (Batty, 2008; OECD, 2015; Wang et al., 2020). According to the United Nations, the world urbanization rate was 56% in 2020 and would reach 68% by 2050, with China increasing from 64% in 2020% to 80% in 2050 (United Nations, 2018; Yang et al., 2019). With the continuous expansion of urban boundaries and the massive migration of rural population to cities, cities have become high concentration areas of production and consumption activities. Urban areas consume a large amount of global fresh water and 67% of the world's energy, as well as emit 75% of global greenhouse gases (GHGs), making cities a critical region to address issues such as water conservation, energy efficiency and carbon emission (Mahlknecht et al., 2020; UN-Habitat, 2020; Zhang et al., 2016). Moreover, as urbanization continues to advance, different cities are combined together through production factors such as population, resources and technology to become massive urban agglomerations. Due to the frequent material and energy interaction process within urban agglomerations, regional environmental problems are highlighted, making the joint water–energy–carbon (WEC) management policy face an unprecedented challenge. Therefore, there is an urgent need to establish a systematic and holistic

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research framework to comprehensively consider the relationship of WEC in the urban agglomeration system from multi-region, multi-factor and multi-angle perspectives, which is also the current frontier and hot spot of related research (Bukhary et al., 2020; Elshkaki, 2019).

In recent years, several methods have been used to study the impact of urban development on the WEC system. Specifically, these methods fall into two main categories: inventory accounting and system simulation (Garcia et al., 2019; Mannan et al., 2018; Muhanji & Farid, 2020). Inventory accounting focuses on the accounting and prediction of WEC consumption, and system simulation is mainly aimed at exploring the system properties and flows of WEC, through using input-output analysis (IOA), life cycle assessment (LCA), and principal component analysis (PCA; Fang & Chen, 2017; Newell et al., 2019; Zheng et al., 2018). Among them, IOA is often used to quantify regional and sectoral WEC footprints, analyze end-user regional and sectoral responsibilities, and identify key impact factors through different supply chains (Li et al., 2019; Mi et al., 2018; Singh & Kansal, 2018; Zhao et al., 2020). For example, Yang et al. (2018) employed IOA to analyze the WEC nexus in Beijing and Shanghai, and the results indicate that environmental pressure per unit of output in Shanghai is higher than that in Beijing. Hu et al. (2020) used IOA to explore the key sector of WEC system from different perspectives in Guangdong province, China; they found agriculture, transportation and electricity supply are key sectors for WEC footprints, respectively, while light industry plays a critical role in the transmission of the water footprint. Generally, the previous studies focused on single-region supply chain issues, and rarely explored WEC footprints along urban agglomeration supply chains, especially they had difficulties in revealing the impact of urbanization on the supply chains (Artioli et al., 2017; Hanaka et al., 2021; Onat et al., 2019).

In order to further reveal the critical transmission paths and sectors in complex networks, much research has been conducted on the identification of critical supply chains using a powerful tool called structural path analysis (SPA), which not only quantifies the environmental transport in upstream production processes, but also identifies critical paths with the highest potential for environmental improvement by tracing complex chains (Kikuchi et al., 2020; Mo et al., 2011). As a result, some scholars have introduced SPA to the field of ecology to gain insight into the environmental impacts of supply chains. For instance, Feng et al. (2019) combined IOA and SPA to uncover food-energy-water supply chains in the Detroit Metropolitan Area (DMA), and the results showed that the water use in the DMA is primarily from local sources, while food and energy are mainly imported. Pomponi and Stephan (2021) used SPA to quantify the WEC footprints of the construction sector in countries such as South Africa, India, Italy and the UK; the results showed a lack of correlation between the three flows, while developed economies occupied a higher international water footprint compared to developing economies. Zhang et al. (2021) tracked China's water use and GHG emission supply chains based on SPA and showed that there is a significant water-GHG coupling in the supply chains; they suggested that synergies in water saving and emission mitigation can be achieved through regulating critical supply chain paths and sectors.

As a new product of human social development and civilizational progress, the evolution of urban agglomerations has profound harmful effects on the environment, such as excessive carbon emission, energy crisis, and water shortage (Liu et al., 2020; Meng et al., 2020; Mei et al., 2021; Peng et al., 2020; Sundar et al., 2021). As one of the most important urban agglomerations in China, the urbanization rate of PUA was 86.3% in 2019, with a GDP per capita of 136.3 thousand yuan, making it the top of the five largest urban agglomerations in China (Dong & Xu, 2019; Li & Li, 2020; Zhang et al., 2020). The PUA's tremendous economic success comes at the cost of consuming large amounts of resource-intensive inputs (e.g., cement, steel and sand) that generate large amounts of WEC footprints through its supply chains. However, only a fraction of studies have explored the resource consumption in its development processes. These studies suggest that economic development in the PUA has a significant impact on the environment, but they are limited by the lack of comprehensive and systematic investigations (Abegaz et al., 2018; Ji et al., 2020). This is due to the facts that (a) the flow of resources between cities and their dependence on resources is difficult to quantify due to the absence of multi-regional input-output (MRIO) tables in the PUA; (b) the driving role of each city on resources has not been studied; (c) key sectors and paths in the WEC supply chain network have not been identified.

In this study, MRIO tables of PUA, developed by China Emission Accounts and Datasets, are used for analyzing the dependence of cities on the WEC from the supply- and demand-based perspectives. SPA is introduced to identify the critical supply chain paths and sectors that have an important impact on WEC footprints. A multi-layer WEC production path analysis (MWPPA) model is developed to analyze the WEC flows in the PUA. MWPPA is

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not only applicable to provide insights for integrated WEC management in other urban agglomerations, but also useful for other environmental impact assessments, such as land, food and pollutants.

The rest of this study is structured as follows. The methodology and data acquisition are presented in Section 2. The results are shown in Section 3. In Section 4, the discussions and conclusions are provided.

2. Methodology

2.1. Multi-Layer Water-Energy-Carbon Production Path Analysis Model

Based on the economic MRIO table, using the direct water, energy and carbon emission inventories, the environmental extended input-output model has been successfully applied to many studies to explore the impact of urbanization on the environment (Lenten et al., 2010; Wei et al., 2021; Zheng et al., 2019). The imports have been excluded to focus on the production in the PUA. First, the input-output constant equations are expressed as:

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

$$T_w = f_w(I - A)^{-1}F \tag{2}$$

$$T_e = f_e(I - A)^{-1}F \tag{3}$$

$$T_c = f_c(I - A)^{-1}F \tag{4}$$

where I is the identity matrix; A is the direct requirement matrix, which is calculated by dividing the monetary flow of the intermediate input by the economic output of the sector; $(I - A)^{-1}$ is Leontief inverse matrix; T_w, T_e, and T_c represent demand-based water, energy, and carbon footprints in the production chain, respectively; and f_w, f_e, and f_c are water, energy, and carbon emission intensity, respectively; F is the final demand for each sector. T_w represents the water footprint used by each sector in the process of products and does not include the footprint by all types of consumers in final demand.

The quantification of WEC footprints, based on the final demand matrix, can reflect the environmental impact of consumption activities (also known as WEC footprints). Since economic activity stimulates end-user consumption of WEC products, a more comprehensive identification of key cities and sectors can be achieved by analyzing the WEC footprints from multiple perspectives through MRIO. Equations 5–7 represent supply-based water, energy and carbon footprints, respectively.

$$H_w = V(I - B)^{-1}f_w \tag{5}$$

$$H_e = V(I - B)^{-1}f_e \tag{6}$$

$$H_c = V(I - B)^{-1}f_c \tag{7}$$

where H_w, H_e, and H_c represent supply-based water, energy and carbon footprints, respectively; V is the value added; B is the direct distribution matrix, which is calculated by dividing the total output of each sector with the corresponding row elements of intermediate products; $(I - B)^{-1}$ is Ghosh inverse matrix.

Numerous interdependent economic sectors form a large and complex network. When the final demand of one sector changes, it can bring an impact on other sectors through the network, and the affected sector can then affect other sectors or feed back to the original sector (Ding et al., 2020; Liang et al., 2016; Pomponi & Stephan, 2021; Wu et al., 2021). SPA is able to find the critical paths and sectors by decomposing the network into an infinite number of paths and sorting them by the traffic of each path (Peters & Hertwich, 2006). In this study, SPA not only is used to quantify the WEC footprints generated by each production layer and analyze their relationship with final demands, but also measure how many WEC footprints are generated by specific production chains, that is, from the final demand of a certain product back to the upstream production sector, forming a chain from demand to supply, and analyze through what path the WEC footprints are transferred and what characteristics each city presents.

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SPA allows for the identification and measurement of WEC footprint paths along the value chain of urban agglomerations by organically combining demand and supply, based on the level expansion of the Leontief inverse matrix:

$$L = (I - A)^{-1} = I + A + A^2 + A^3 + \cdots \quad (8)$$

By substituting Equation 8 into the input-output constant Equation 1, a series expansion of total output can be obtained:

$$\partial = (I - A)^{-1}F = F + AF + A^2F + A^3F + \cdots \quad (9)$$

In the MWPPA model, in order to more conveniently represent the demand-to-supply path, the PUA economic system is considered as a whole with 162 sectors. The first term (F) denotes the 0th tier (tier0) of the production hierarchy (i.e., the output of each sector required to meet the final demand, which contains 162 nodes); the second term (AF), denotes the first tier (tier1) of the production hierarchy (i.e., the final demand for the production of Y, the direct demand generated by one sector for the inputs of another sector, and since there are 162 inputs in each sector, there are 162 nodes in the first tier, and similarly, there are 162 nodes in the second tier (tier2), and so on.

The number of nodes grows exponentially with the number of production layers, and the WEC footprints of each node at each layer can be calculated. The diagonal matrixes of water, energy and carbon intensity are multiplied by Equation 9. The WEC footprints can be obtained:

$$T_w = f_w IF + f_w AF + f_w A^2F + \cdots + f_w A^nF \quad (10)$$

$$T_e = f_e IF + f_e AF + f_e A^2F + \cdots + f_e A^nF \quad (11)$$

$$T_c = f_c IF + f_c AF + f_c A^2F + \cdots + f_c A^nF \quad (12)$$

where $f_w A^n F$ presents the water footprint on the n-tier in the production process. For example, $f_w IF$ and $f_w AF$ represent the water footprints on the 0-titer and 1-tier, respectively.

The first term of Equation 10 denotes the 0th tier and the second term denotes the first tier, and since the production process can be extended infinitely, the above equations have an infinite number of terms. However, this study only focuses on the first four tiers, and the remaining tiers are classified as other; this is because a number of studies have proved the first 2–4 tiers contained the vast majority of the effects (Owen et al., 2018; Zhang et al., 2018). Li et al. (2021) showed that 35.3%, 27.1% and 16.1% of China's carbon emissions in 2012 occur at Tier0, Tier1, and Tier2, respectively. Pomponi and Stephan (2021) revealed that first four tiers account for over 94% of India's total water footprint during 1995–2015. It should be noted that the lower the production layer indicates the closer to the final demand, and the higher the production layer is, the farther away from the final demand. For example, $f_w A^n F$ indicates the water footprint generated by the t+1th production layer, taking cell phone production as an example, F indicates the final demand for cell phone sector, then $f_w F$ is the direct water footprint of cell phone manufacturer in the process of cell phone production; in order to produce F units of cell phone, intermediate inputs from other sectors AF are needed, and these sectors generate $f_w AF$ water footprint in the production process; similarly, the production of the above intermediate inputs requires inputs from other sectors A^2F and generates the water footprint of $f_w A^2F$. By analogy, this goes all the way to the fourth production tier explored in this study (Hong et al., 2016; Skelton et al., 2011).

Next, the critical path measurement method of water footprint is introduced, the water footprint measurement is taken as an example, in the economic system of urban agglomerations consisting of 162 sectors, and the water footprint matrix can be expressed as:

$$T_w = f_w(I - A)^{-1}F = [f_1\ f_2 \cdots f_{162}] \begin{bmatrix} l_{1,1} & \cdots & l_{1,162} \\ \cdots & \cdots & \cdots \\ l_{162,1} & \cdots & l_{162,162} \end{bmatrix} \begin{bmatrix} F_1 \\ \cdots \\ F_{162} \end{bmatrix} \quad (13)$$

Combining the level expansion of Equation 12, the water footprint of any node p in Tier0 can be measured by Equation 14 as:

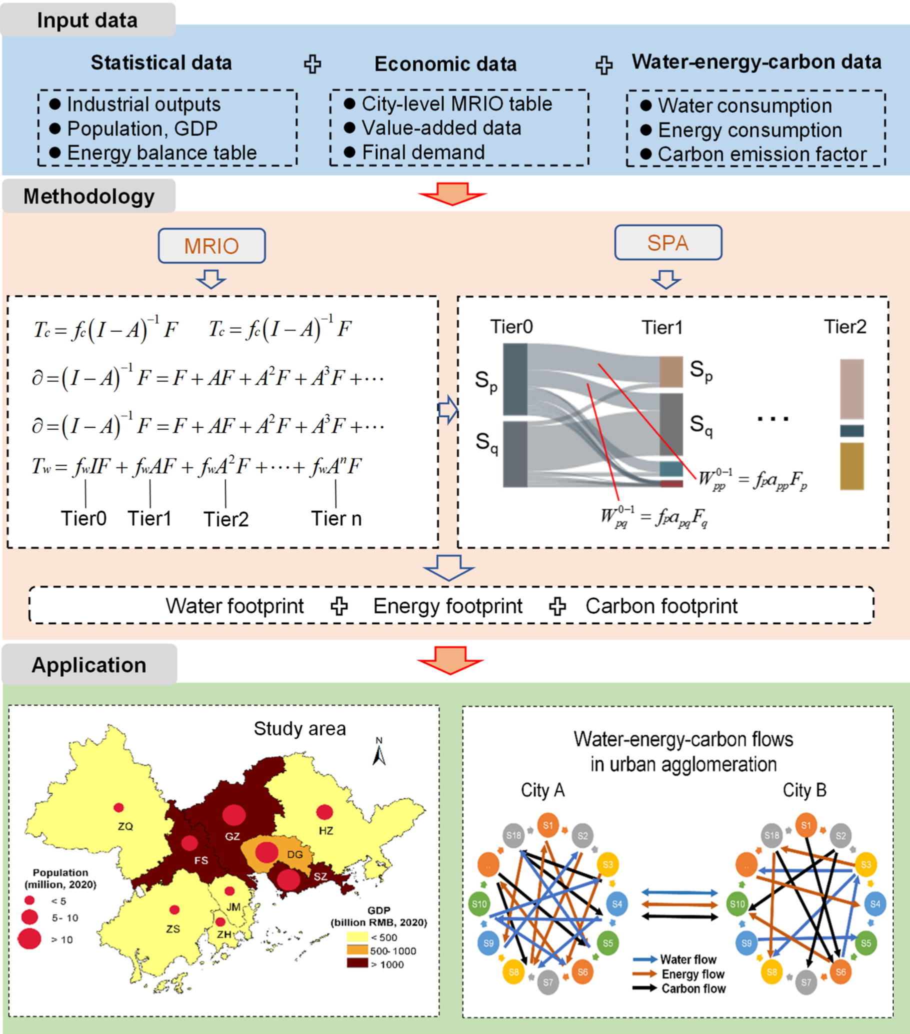

Figure 1. Framework of MWPPA model.

$$W_p = f_p F_p \tag{14}$$

Tier0 is the water footprint generated when the final demand is provided, excluding any production chain. The water footprint of any of the 162^2 nodes in Tier1 is $f_p a_{pq} F_q$, and the production path it represents is $q \rightarrow p$, which represents the water footprint of the production in sector p caused by the final demand in sector q.

$$W_{pq} = f_p a_{pq} F_q \tag{15}$$

Tier2 contains 162^3 nodes, and the water footprint measurement for any path is shown in Equation 16, which indicates that the final demand F for sector q requires intermediate goods of input $a_{iq} F_q$ from sector i. Sector i needs sector p to produce unit product $a_{pi} a_{iq} F_q$ in order to produce this intermediate input, and the water footprint generated by sector p as a result (Figure 1):

$$W_{piq} = f_p a_{pi} a_{iq} F_q \tag{16}$$

The energy and carbon footprints can be calculated accordingly. The WEC footprints in this study refer to the territorial footprint, which represents the direct and indirect WEC consumption induced by human activities within the regional boundary. The WEC footprints induced by international aviation and shipping are not included. There is complex relationship among water, energy and carbon emission. In deal, large amounts of water are required for fossil energy exploitation, processing, conversion and power generation; water production, supply and wastewater treatment consume a mass of energy; activities involving energy and water can produce a large amount of carbon (Romero-Lankao et al., 2017; Salehi et al., 2020). Therefore, carbon-related water (C-water), water-related energy (W-energy) and water-related carbon emission (W-carbon) are also calculated and analyzed. The calculation method is the same as the water footprint.

2.2. Case Study and Data Sources

The Pearl River Delta urban agglomeration (PUA) is located in central and southern part of China, including nine cities, Guangzhou, Shenzhen, Zhuhai, Foshan, Huizhou, Dongguan, Zhongshan, Jiangmen, and Zhaoqing (Figure S1 in Supporting Information S1); a combined land area of 55,000 square kilometers accounts for 0.6% of China; a total economic output of 9.0 trillion yuan in 2020 accounts for 8.9% of China; a resident population of about 78.2 million people accounts for 5.5% of the country, and an average annual population growth rate is 2.4% (Guangdong Province Statistics Bureau, 2021). As a typical export-oriented city agglomeration, international and domestic trade generates about half of the GDP, and consumes a large amount of natural resources, creating serious environmental problems for the region (Liu et al., 2020).

In this study, 42 sectors are combined into 18 sectors (Table S1 in Supporting Information S1), water consumption data are mainly obtained from the water resources bulletins of each city, the division method of water consumption in each sector refers to Liang et al. (2014) and Chen et al. (2019), water, energy and carbon inventories are presented in Tables S2–S7 in Supporting Information S1. The 2012 and 2015 multiregional input-output tables of PUA are obtained from the China Emission Accounts and Datasets (https://www.ceads.net/data/input_output_tables/), which is based on entropy construction framework and the Guangdong Statistical Bureau (Zheng et al., 2021). Since the use of SPA generates countless production tiers and paths, calculating all of them would make the task very demanding, so this study uses the "tree pruning" method commonly used in the existing literature (Lenten; Peters & Hertwich, 2006) to reduce the computational effort, and only the tiers and paths with flow rates greater than 0.1% of the total footprint are retained. The detailed steps are presented in Supporting Information S1.

3. Results

3.1. Water-Energy-Carbon Footprints and Inter-Regional Flows

The WEC footprints of PUA were 19.2 billion m^3, 146.5 million ton of coal equivalent (Mtce) and 289.1 million ton CO_2 equivalent ($MtCO_2eq$) in 2012, respectively; the WEC footprints were 18.2 billion m^3, 123.0 Mtce and 272.7 $MtCO_2eq$ in 2015, respectively (Figure 2, Figures S2 and S3 in Supporting Information S1). The WEC footprints in 2015 decreased by 5.2%, 16.0%, and 5.7%, compared with the values in 2012. This is related to the local government's measures to curb the blind development of high water consumption, high energy consumption and high emission projects, such as closing down some high water consumption and high pollution enterprises, developing renewable energy vigorously, receiving clean power from outside the region actively, and developing nuclear power efficiently (Guangdong Province Statistics Bureau, 2021). The water, energy and carbon emission intensities of PUA in 2015 were also reduced by 27.3%, 35.6%, and 27.6% respectively compared to the levels in 2012.

From the water footprint view, Guangzhou, Foshan, and Jiangmen maintained the top three cities, accounting for about 60% of the total water footprint in the PUA. This is because that, agriculture- and electricity-related sectors, which consume large quantity of water, are pillar industries in these three cities. Due to the geographical separation of resource-rich areas and economic centers, resource-rich cities transferred large amounts of WEC to developed cities by trade. Based on the difference between WEC inflow and outflow, nine cities could be divided into two categories: net importer and net exporter. Shenzhen was the largest net water importer, importing 698.2 million m^3 in 2012 and 911.7 million m^3 in 2015. The majority of imported water came from Jiangmen, Huizhou and Zhaoqing. This is due to the fact that the three cities provide a large number of agricultural products, electricity and other services to other cities, and these products are usually water-intensive products. Foshan and Zhongshan became the net importers in 2015, while they were the largest net exporters in 2012. This is because of the rapid urbanization and economic transformation of these two cities. Jiangmen became the largest net exporter

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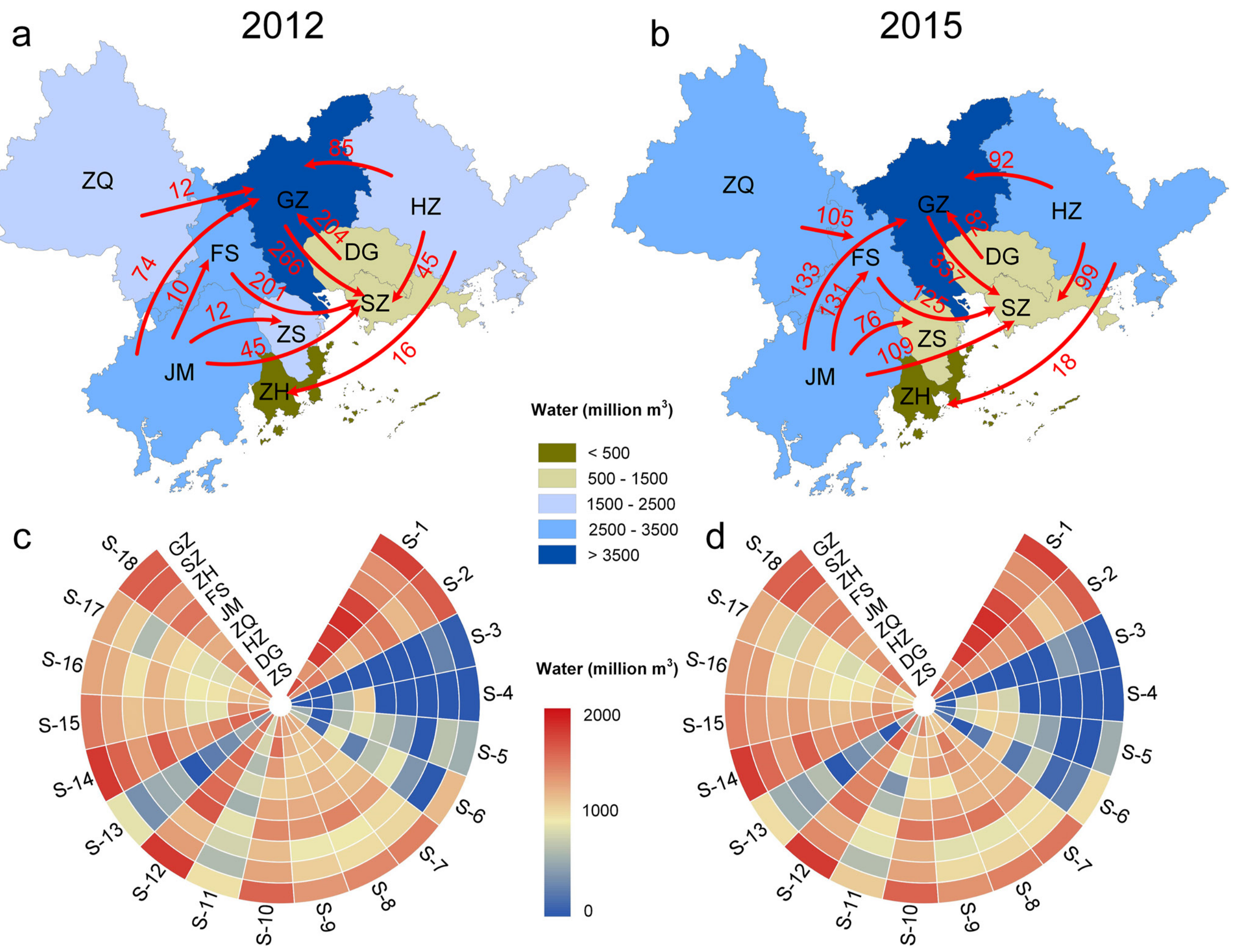

Figure 2. The water flow and sectoral consumption in the PUA, (a) and (b) represent water flow in 2012 and 2015, respectively, (c) and (d) represent water sectoral consumption in 2012 and 2015, respectively. (a) and (c): the arrows represent the main water flows. GZ: Guangzhou, SZ: Shenzhen, ZH: Zhuhai, FS: Foshan, JM: Jiangmen, ZQ: Zhaoqing, HZ: Huizhou, DG: Dongguan, ZS: Zhongshan. S-1: Agriculture, S-2: Light industry, S-3: Extraction industry, S-4: Metal mining, S-5: Nonmetal mining, S-6: Petroleum refining and coking, S-7: Chemical industry, S-8: Nonmetallic manufacture, S-9: Metal manufacture, S-10: Equipment manufacture, S-11: Other manufacture, S-12: Electricity supply, S-13: Gas supply, S-14: Water supply, S-15: Construction, S-16: Wholesale and retail trades, S-17: Transportation, S-18: Others.

in 2015, because of the agricultural products export. Due to the export of a large number of manufacturing products and services, Dongguan became a net exporter from a net importer. From the sector view, agriculture and electricity were main water consumers, accounting for more than half of the total water consumption in the PUA. Water supply industry in Guangzhou and other services (e.g., real estate, accommodation and catering) in Guangzhou and Shenzhen were also important water consumers.

From the energy footprint view, Shenzhen is still the largest net importer, while Huizhou become the largest net exporter. The reason is that Huizhou is an important chemical base in the PUA, and chemical products are both energy- and water-intensive products. This also explains why Huizhou is also a major net exporter of water. Guangzhou and Zhongshan became the net importers of energy in 2015 because of population growth and economic development. From the sector view, the distribution of energy is very different from that of water; transportation, light industry, chemical industry, and electricity occupy about 60% of the total energy footprint, mainly from fossil energy. With the continuous development of clean energy, these sectors would consume less and less fossil energy.

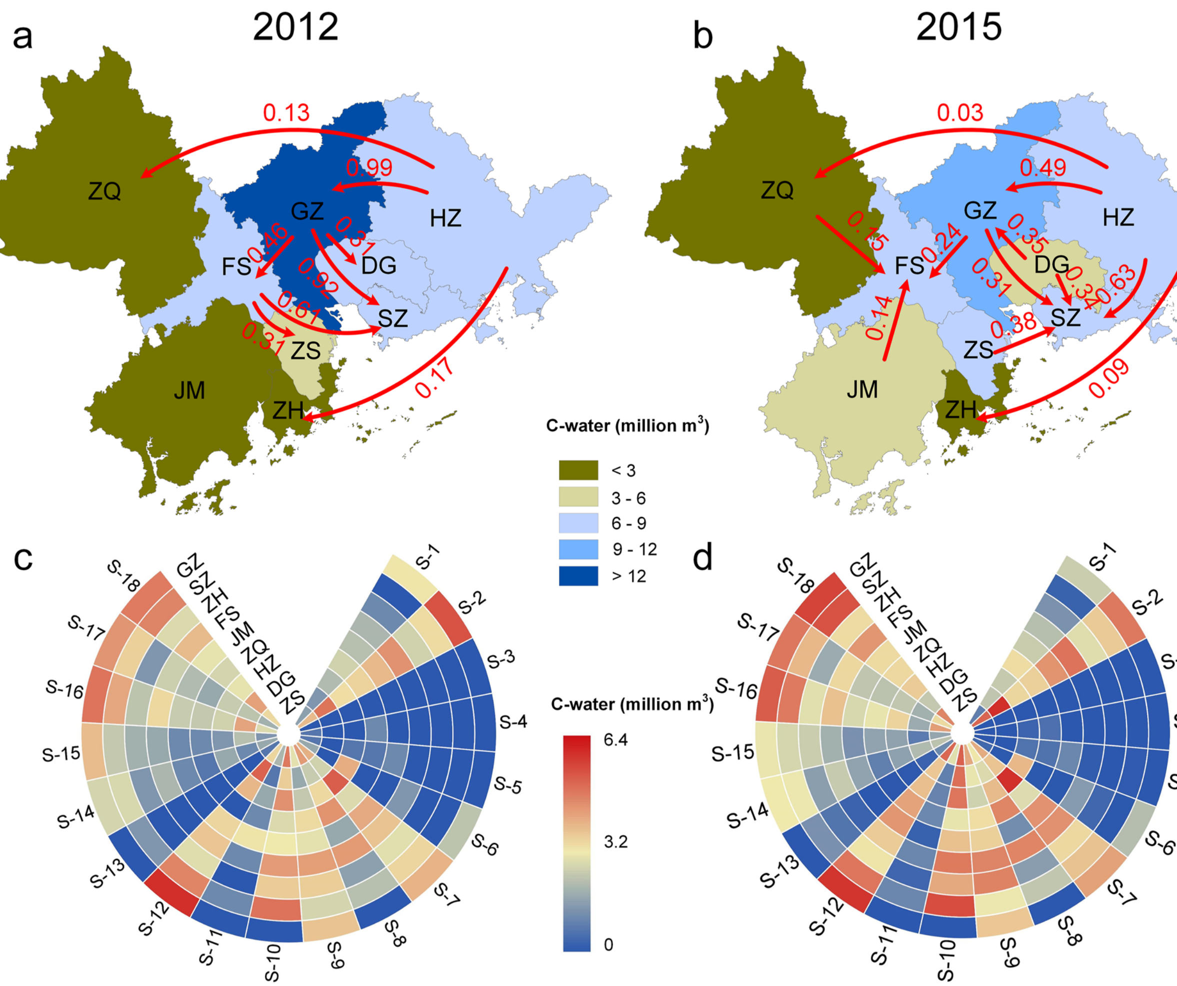

Figure 3. The C-water flow and sectoral consumption in the PUA, (a) and (b) represent C-water flow in 2012 and 2015, respectively, (c) and (d) represent C-water sectoral consumption in 2012 and 2015, respectively.

From the carbon footprint view, Shenzhen still maintains the largest net importer, mainly from Dongguan, Huizhou and Jiangmen. Huizhou was the largest net exporter in 2012, while Dongguan became the largest net exporter in 2015. The developed cities (e.g., Shenzhen, Guangzhou, and Foshan) are the main importers and rely on the resource-rich cities (e.g., Huizhou, Zhaoqing, and Jiangmen). Since carbon footprint in industrial processes was considered, the sectoral distribution of carbon footprint was slightly different from that of energy. For example, nonmetallic manufactures in Huizhou and Zhaoqing were identified as important sectors in carbon footprint. In terms of the WEC flows between cities within PUA, Shenzhen was the most dependent city on WEC resources, Huizhou was the main provider, and Zhuhai was the city with the most self-sufficiency.

3.2. Water-Energy-Carbon Nexus

The C-water, W-energy, and W-carbon of PUA were 35.3 million m^3, 1.03 Mtce and 2.2 $MtCO_2eq$ in 2012, respectively; their values were 28.7 million m^3, 1.02 Mtce and 1.9 $MtCO_2eq$ in 2015, respectively (Figure 3). In 2012, Huizhou and Guangzhou were the largest exporters, exporting 1.9 million m^3 and 0.7 million m^3 of C-water, respectively; in 2015, Huizhou and Dongguan exported the largest amounts of C-water, 1.93 million m^3 and 1.52 million m^3, respectively. Due to economic development and population increase, Guangzhou became a net importer in 2015, importing 0.72 million m^3 of C-water. As Dongguan gradually became one of the largest manufacturing bases in the world, providing a large number of intermediate products and services to developed cities such as Guangzhou and Shenzhen, Dongguan shifted from being a net importer in 2012 to a net exporter in 2015. Shenzhen is the largest net importer, mainly from Guangzhou, Foshan, and Dongguan. Foshan became a net importer of C-water in 2015, occupying the second position. This is because Shenzhen, as a mega-city, needs a lot of resources and services from other cities to meet its rapid econmoic development and population growth (e.g., especially for electricity). Foshan is caused by a large amount of basic infrastructure in its rapid urban expansion. Generally, Huizhou is the supplier of C-water in PUA, Shenzhen is most dependent on C-water transfers from other cities, and Jiangmen can basically achieve self-sufficiency of C-water.

In terms of sectoral consumption, electricity sectors in developed economies such as Guangzhou, Shenzhen, and Dongguan consume large amounts of C-water due to their large populations and developed manufacturing industries with high demands for electricity. For other cities, such as Zhaoqing, a large amount of C-water is consumed due to its well-developed non-mineral product industries. Huizhou consumes a large amount of C-water due to its high chemical fuels and chemicals.

In terms of W-energy and W-carbon, Shenzhen remains the largest net importer, relying mainly on cities such as Guangzhou, Foshan, and Huizhou; Huizhou remains the largest net exporter, mainly to developed cities such as Guangzhou, Shenzhen and Foshan (Figures S4 and S5 in Supporting Information S1). Jiangmen and Zhaoqing are net exporters because, as major food-production bases of PUA, the two cities provide a large amount of water-consuming food to other cities. A large amount of W-energy and W-carbon are consumed during the process of food production, and Jiangmen and Zhaoqing indirectly send a large amount of W-energy and W-carbon to other cities. The distribution of W-energy and W-carbon in the sector is clearly different from that of C-water. In developed cities such as Guangzhou, Shenzhen, and Dongguan, water sector occupy an important position, while agriculture dominates W-energy and W-carbon in food exporting cities such as Zhaoqing, Huizhou and Jiangmen. Although the amounts of C-water, W-energy, and W-carbon are large, they account for less than 1% of WEC footprints and have a limited impact on the overall WEC footprints, so only WEC footprints are discussed in the following sections.

3.3. Water-Energy-Carbon Footprints Driven by Sector

Top 10 sectors of the supply-based water footprint (SWF) and demand-based water footprint (DWF) for each city are presented in Figure 4. In general, the sectors with high water footprint vary by city. From a supply perspective, agriculture provides the largest water footprint in the PUA except Guangzhou, Shenzhen, and Dongguan, especially in Zhaoqing, Jiangmen, and Huizhou, where agriculture provides more than 70% of the water footprint. The reason is that these cities are important agricultural bases and provide a large amount of water-intensive agricultural products. In Guangzhou, water supply sector replaced agriculture as the sector with the largest water footprint in 2015, the reason is that water supply sector provides a large amount of water to other cities and sectors. From a city perspective, Guangzhou is the city with the largest water footprint, accounting for 26.3% and 28.7% of PUA in 2012 and 2015, respectively, followed by Jiangmen. From a temporal perspective, the water footprint of PUA has reduced from 12.7 billion m^3 to 11.5 billion m^3, with Zhongshan having the largest reduction due to the development of efficient water-saving irrigation technology, which has saved a large amount of water for agriculture.

From a demand perspective, Guangzhou remained the largest city with water footprint, accounting for 29.1% and 29.0% of PUA's total water footprint in 2012 and 2015, respectively. It is followed by Foshan. Unlike from the supply side, Foshan plays a more important role on the demand side, due to the fact that with the deep integration of the industrial chain with other cities in the PUA, Foshan has developed into the third largest city in the PUA in terms of GDP, after Guangzhou and Shenzhen. In particular, light industry and equipment manufacturing is the root of Foshan's economic and industrial development. From a sectoral perspective, agriculture, light industry and other services are the three sectors with the largest water footprint, accounting for 22.2%, 18.8%, and 15.4% respectively. Compared to the supply side, light industry and other services play a more important role and should be fully taken into account in water conservation policy development. From 2012 to 2015, the PUA water footprint decreased from 19.2 billion m^3 to 18.2 billion m^3, with less developed economies such as Dongguan and Huizhou experiencing the largest decrease in water footprint, while developed economies such as Shenzhen and Foshan experienced a slight increase in water footprint, due to the fact that developed economies attract a large number of foreign populations and inputs, increasing their demand for water resources.

Figure 4. Water footprint of top 10 sectors for each city in 2012 and 2015; SWF: supply-based water footprint, DWF: demand-based water footprint. (The values on the left and right of the axis represent water footprints in 2012 and 2015, respectively; the bars represent the water footprint of top 10 sectors as a percentage of the overall water footprint, million m^3).

Figure S6 in Supporting Information S1 shows the supply-based energy footprint (SEF), demand-based energy footprint (DEF) for each city. In the supply-based case, the energy footprints of PUA were 146.5, 122.9 Mtce during 2012–2015, respectively. The top three cities are Guangzhou, Dongguan and Huizhou, which are responsible for more than half of PUA's energy footprint. Among them, Guangzhou's transportation industry, Dongguan's light industry and Huizhou's chemical industry are the key industries. From the demand side, the PUA's energy footprints in 2012–2015 were 76.7 and 64.0 Mtce, respectively. A comparison with the energy footprint on the supply side shows that the PRD is still an energy supplying urban agglomeration, with about half of the energy footprint distributed outside the urban agglomeration. The impact of the extraterritorial regions should be fully considered, when formulating policies on environmental issues caused by resource consumption in the PUA.

The supply-based carbon footprint (SCF) and demand-based carbon footprint (DCF) of each city are presented in Figure S7 in Supporting Information S1. Guangzhou is the city with the largest carbon footprint on both the supply and demand side. The reason is that, firstly, Guangzhou has the highest energy use in the PUA, and secondly, Guangzhou has carried out a lot of infrastructure construction between 2012 and 2015, of which cement use contributes a large amount of carbon emission. In terms of sectors, Guangzhou's electricity supply sector and transportation are the two sectors with the largest carbon footprints in the PUA, and it is worth noting that the carbon emission of Guangzhou's electricity supply sector in 2015 are reduced by about half compared with 2012,

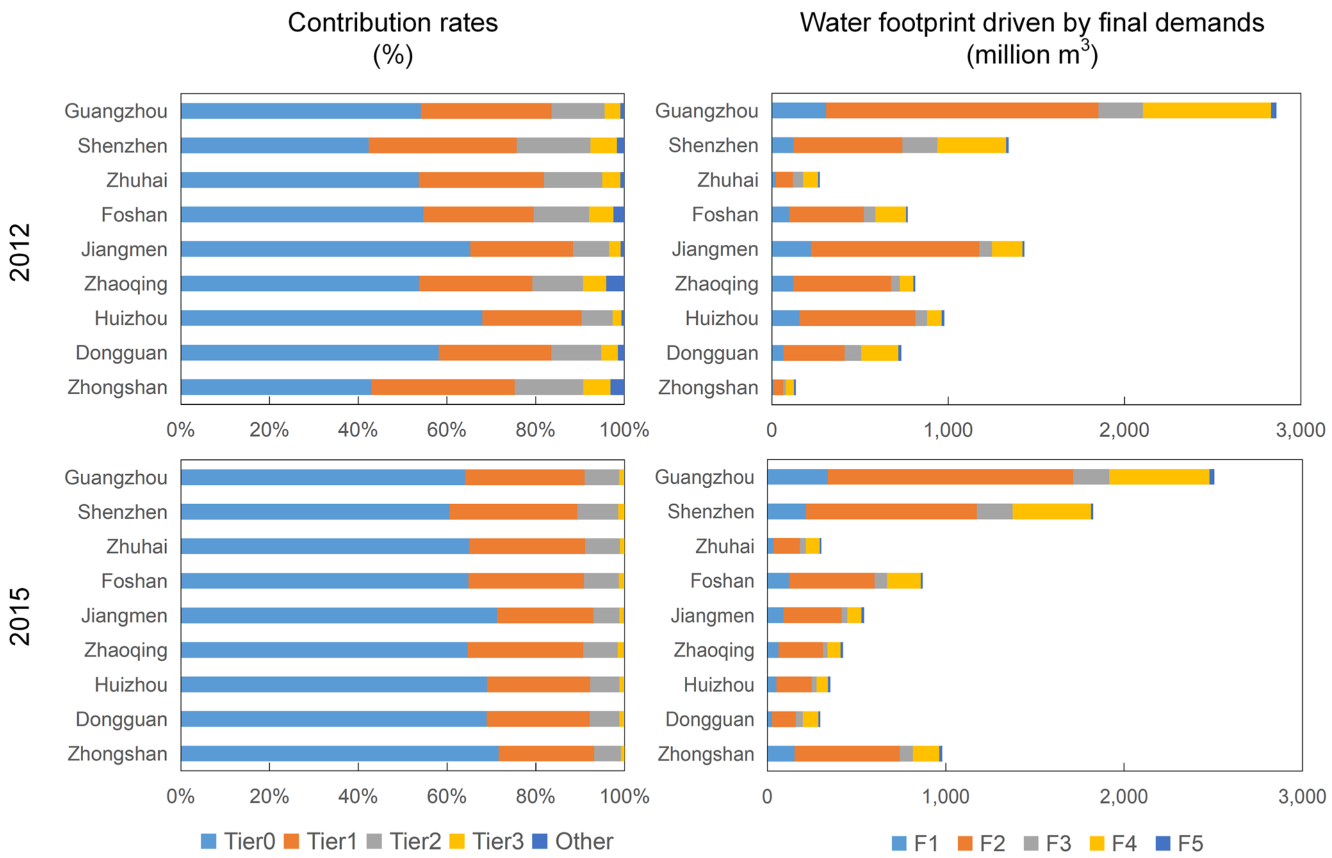

Figure 5. Water footprint driven by final demand for each city in 2012 and 2015; F1: Rural consumption, F2: Urban consumption, F3: Government consumption, F4: Fixed capital formation, F5: Inventory increase.

while the carbon reduction effect of transportation was not obvious (reduced by about 2%), which means that the decarbonization project of Guangzhou's electricity is effective, and with the gradual popularization of electric vehicles, the decarbonization results of the transportation sector will gradually appear.

3.4. Water-Energy-Carbon Footprints Driven by Each City

The water footprint occurs at Tier0, indicating that these water resources are consumed directly, while the water footprints of other tiers indicate that water resources are consumed indirectly. In 2012, more than half of the water resources in the PUA were directly consumed, reaching 60% in 2015 (Figure 5). It can be seen that, with the progress of water-saving technology, a large amount of indirect water has been saved, and reducing the consumption of water resources at the production site is the focus of the water resources policy in the PUA. From the city view, Guangzhou drives the largest water footprint, accounting 30.3% and 31.1% of the total in 2012 and 2015, respectively. From the final demands view, urban household drives the most water footprint, the reason is that the average urbanization rate of PUA has reached 83.1%, and a large number of people pour into the cities, consuming a large amount of water footprint. Although the water footprint of PUA in 2015 decreased by 13.4% compared with 2012, Zhongshan and Shenzhen increased by 657.6% and 36.9%, respectively. The urban household of the two cities contribute most of the increase.

Energy and carbon footprints driven by final demands for each city are shown in Figures S8 and S9 in Supporting Information S1. Unlike the water footprint distribution, more than 30% of the energy and carbon footprints of all cities are located at Tier1. A large amount of energy is consumed indirectly, more attention should be paid to the energy consumption and carbon emission of Tier1. From the city view, the energy footprints of all cities have been reduced, except for Zhongshan and Zhaoqing. Urban household and capital formation contribute more than 70% of the increase, especially in Zhaoqing, where capital formation contributes more than 95%. The reason is that the

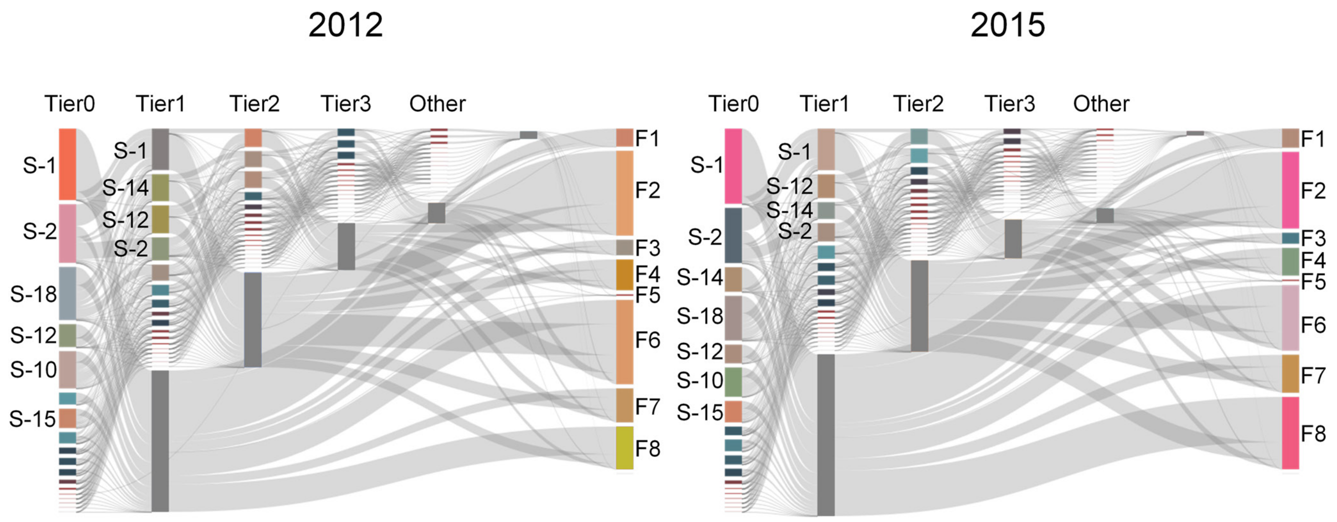

Figure 6. The main water supply chains in the PUA; S-1: Agriculture, S-2: Light industry, S-3: Extraction industry, S-4: Metal mining, S-5: Nonmetal mining, S-6: Petroleum refining and coking, S-7: Chemical industry, S-8: Nonmetallic manufacture, S-9: Metal manufacture, S-10: Equipment manufacture, S-11: Other manufacture, S-12: Electricity supply, S-13: Gas supply, S-14: Water supply, S-15: Construction, S-16: Wholesale and retail trades, S-17: Transportation, S-18: Others; F1: Rural consumption, F2: Urban consumption, F3: Government consumption, F4: Fixed capital formation, F5: Inventory increase, F6: International exports, F7: Domestic exports, F8: Provincial exports.

rapid urbanization of two cities has attracted a large number of rural population and investment in recent years. The details of water, energy and carbon driven by final demands are presented in Supporting Information S1.

3.5. Critical Water-Energy-Carbon Paths and Nodes

3.5.1. Critical Supply Chain Paths

Since WEC footprints have more than 50,000 supply chain paths, it is very difficult to show all the paths at the city-level. In order to identify the critical nodes and paths, the MRIO table is merged into a general table of PUA, then according to the WEC footprints, SPA is used to obtain the supply chain paths of all the PUA.

Since the first four tiers account for more than 98% of the total water footprint, four tiers are selected (namely Tier0, Tier1, Tier2, and Tier3), and the results of the other levels classified as "other," the results of water footprint distribution are shown in Figure 6. The width of the line represents the transfer of footprints from one sector to another, the direction is from high-tier to low-tier. In addition, the gray rectangle represents the footprints consumed at the next tier, taking the gray rectangle of the water footprint Tier1 in Figure 6 as an example, it represents the water footprint consumed by various industries in the Tier0, the total water of 8.42 billion m^3 is consumed directly in the first tier, that is, the water footprint is directly consumed, while the other water footprints are transferred along the supply chain to the next tier, the gray rectangle of Tier2 represents the consumption of 5.63 billion m^3 in various sectors of the first tier.

There are more than 50,000 supply chain paths in the water footprint, which are sorted according to the flow. Table S8 in Supporting Information S1 shows the top 20 supply chain paths of water footprint in 2012 and 2015, accounting for 45.5% and 48.5% of the total water footprint in the PUA, respectively. Specifically, in 2012, all the water footprint of the top four paths comes from agriculture, the reason is that agricultural products directly consumed or exported are water-intensive products. Therefore, from the water-saving view, the export of low value-added agricultural should be reduced. From the final demands view, most of the water footprint is transferred to exports and urban consumption, which is caused by the high urbanization rate and export-oriented economic structure of PUA. Top two paths in 2015 are the same as in 2012, and "water sector—urban consumption" becomes the third largest path, which means that with the improvement of urbanization, the water sector is under more and more pressure.

The number of energy footprint supply chain paths is also more than 50,000. Table S9 in Supporting Information S1 shows the top 20 supply chain paths in 2012 and 2015, accounting for 39.9% and 40.9% of the total energy footprint in the PUA, respectively. Unlike the water footprint, exports dominate the energy footprint. Among the top 10 paths, there is only one non-export-driven path, which is driven by fixed capital formation. In detail, international exports drive most of the energy footprint in three types of exports. From the sector view, light industry plays a more important role in energy footprint, this is because light industry provides a large number of energy-intensive products and services for various sectors.

Top 20 supply chain paths of carbon footprint are shown in Table S10 in Supporting Information S1. The presented paths account for 38.0% and 38.3% of the total in 2012 and 2015, respectively. Similar to the energy footprint, exports play a dominant role in all the final demands for driving carbon footprint. The reason is that the carbon emission in this study mainly come from energy consumption and industrial production process, in which energy consumption accounts for more than 90% of the total carbon emission. Top three paths are "electricity sector—provincial exports", "transportation—international exports" and "light industry—international exports". All three sectors are major carbon emitters and should be paid enough attention to.

3.5.2. Key Nodes

In the water system, there are six critical sectors, of which four are dominated by direct water use (agriculture, light industry, equipment manufacture and others) and two are dominated by indirect water use (electricity and water sector; Figure 6). Specifically, the water footprints of agriculture and light industry, no matter at the Tier0 or other tiers, are more prominent, while the water footprints of equipment manufacture and others at Tier0 are much larger than those of other tiers, indicating that equipment manufacture and others mainly consume direct water, and electricity sector has more prominent water footprints at other tiers, indicating that electricity mainly use indirect water. It is worth noting that the water footprint of water supply sector (S-14) at Tier0 is only 0.71 billion m^3, accounting for 18.4% of the overall water footprint of the sector. This is because S-14 is an industry that produces and supplies water to other sectors, and therefore consumes less water directly. In addition, water from the S-14 mainly goes to other service sectors (S-18) and construction (S-15), indicating that reducing the water intensity of these two sectors can effectively reduce the water consumption of the whole urban agglomeration.

From the final demands view, international exports, provincial exports and urban consumption drive most of the direct water consumption, which means reducing direct water consumption and paying more attention to the final demand in addition to improving water-saving technologies. Most of the agricultural low-tier water footprint is consumed directly, indicating that this part of the water resources is irrigation water, while the water footprint of light industry flows to the high-tier of agriculture and light industry, and more water footprints of light industry goes to the lower of agriculture, showing that the degree of agricultural mechanization in the PUA is constantly improving, and there will be more water footprints from light industry to agriculture in the future.

In the energy system, three sectors (light industry, chemical industry and transportation) are dominated by direct energy consumption, and two sectors (nonmetallic manufacture and equipment manufacture) by indirect energy consumption (Figure S10 in Supporting Information S1). Unlike the water system, the sectoral sources of direct energy consumption are more evenly distributed, except for sectors light industry, chemical industry and transportation, which consume about half of the direct energy consumption, and equipment manufacture, electricity and wholesale and retail trades also consume a significant amount of direct energy. Most of the energy footprint of the upper tiers of light industry and equipment manufacturer comes from their footprint at the lower levels, which means that these sectors can reduce their energy consumption by improving their production processes. More than 70% of the energy footprint driven by exports, especially international exports, indicates that the PUA pays a large environmental cost for the development of other regions, especially foreign ones.

In the carbon emission system, four industries (light industry, nonmetallic manufacture, electricity and transportation) are dominated by direct emissions and one industry (equipment manufacture) by indirect emissions (Figure S11 in Supporting Information S1). Since electricity sector provides electricity to the rest of the sectors and the PUA is dominated by purchased electricity, electricity sector has a significant impact on the overall carbon emission system. On the final demand side, similar to the energy system, exports still drive the bulk of carbon emission. It is noteworthy that equipment manufacture has very little carbon emission in Tier0, and its carbon footprint flows mainly to electricity sector and equipment manufacture in the upper tiers, mainly because equipment manufacture provides a large amount of electrical equipment to electricity sector.

4. Discussions and Conclusions

The successful achievement of UN SDGs requires integrated management of WEC from policy makers. Therefore, it is crucial to identify the key supply chains and major driver demands of WEC in urban agglomerations. Based on the up-to-date input-output data, a MWPPA model has been developed, which can provide multiple perspectives for regions and countries around the world to achieve the UN SDGs (especially SDGs 6, 7, 11, and 13).

The spatial and temporal differences in the WEC footprints of PUA are obvious. From the spatial scale, developed economies such as Shenzhen, Guangzhou, and Foshan drive more than half of WEC footprints; from the time scale, due to the active environmental policy, water, energy and carbon emission intensities in 2015 were, respectively, reduced by 27.3%, 35.6%, and 27.6%, compared to the levels in 2012. However, there is still a gap with the world's developed urban agglomerations, the future policy of PUA should focus on water-energy saving and emission reduction from the supply side. In the identification of critical paths and nodes, "agriculture–urban consumption," "light industry–international exports" and "electricity–provincial exports" are the critical paths of WEC footprints, respectively. The key nodes of WEC are different, where light industry and equipment manufacture play key roles; this is due to the fact that, with the development of mechanization and intelligence, the machinery industry provides a large number of basic products and services for various sectors. Results suggested that each industry should actively integrate into the global supply chain to exploit its comparative advantage.

The PUA's long-term fossil energy structure brought a large amount of carbon emission and various environmental problems. Renewable energy should be largely developed, which mainly depend on some new energy industry bases (e.g., Shenzhen, Zhongshan and Foshan) these cities can utilize clean energy sources (e.g., onshore and offshore wind, solar, biomass) as well as promote the gradual rationalization of the energy consumption structure.

Exports account for more than half of the final demand-driven WEC footprints, indicating that the PUA contributes a large amount of WEC to the development of other regions, which is unsustainable under the increasingly stringent environmental protection in recent years. Correspondingly, PUA needs to improve its own industrial competitiveness and reduce WEC intensities; specifically, the PUA has currently been in a low-end production position in equipment manufacturing, with advanced technologies heavily dependent on imports, for example, since the U.S.–China technology war, the U.S. has used China's reliance on high-end U.S. chips to crack down on Chinese high-tech companies such as Zhongxing telecom equipment and Huawei, causing both companies to suffer heavy losses, and this reliance on foreign technology and design also substantially reduces the profits flowing to Chinese companies. Therefore, the PUA (as the national technology center) is leading China's technical transformation and reforming by establishing its own intellectual property rights, promoting technological upgrading, optimizing the export structure, and increasing the value and competitiveness of industrial products.

In the context of China's "dual circulation" development pattern, the PUA should strengthen economic and environmental cooperation with neighboring countries, which can reduce the WEC footprints of PUA, and expand cooperation and exchange with regions such as Eastern Europe, the Middle East and Africa through South-South cooperation, the Belt and Road Initiative, and so on. These cross-border cooperation should be sharing advanced technologies and production capacities, rather than directly transferring highly polluting, energy-consuming and backward production capacities, so as to achieve energy conservation and emission reduction from the perspective of the global supply chain.

As the first attempt to explore the policy path of sustainable development in the PUA, this study has some limitations. First, This study focuses on CO_2 emissions from fossil fuels and industrial processes, which have a large impact on economic and industrial development, and less on GHGs emissions from agriculture and households, where non-CO_2 GHG emissions (e.g., N_2O and CH_4) from agriculture also make a significant contribution to climate change and have a larger short-term impact than CO_2, and GHG emissions from households may also increase with the increase in time spent working at home during the epidemic. Second, this study divides the PUA's exports into provincial, domestic and international exports, without considering re-importing exported products and re-exporting imported products. With increasing globalization, cross-border trade of intermediate products will become more frequent, for example, the PUA processes parts of Japanese automobiles, exports them to Japan, and the parts are assembled in Japan and re-imported to the PUA. All these issues need to be deepened in future work.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The multiregional input–output tables of PUA are derived from the city-level input–output tables for China published by China Emission Accounts and Datasets (https://www.ceads.net), which includes 313 cities in mainland China. The MRIO table for 2012 is available at https://www.ceads.net/user/index.php?id=1103&lang=en and the MRIO table for 2015 is available at https://www.ceads.net/user/index.php?id=1271&lang=en Water, energy and carbon inventories are presented in Tables S2–S7 in Supporting Information S1.

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