Energy Proceedings
Vol 29, 2022
ISSN 2004-2965

Water-carbon nexus for an urban physical-virtual water supply system-a case study of Beijing-Tianjin-Hebei region in China#

Feng Jiang[1], Saige Wang[1], Bin Chen [1*], Dan Song[2]

1 School of Environment, Beijing Normal University, Beijing 100875, China

2 Beijing Climate Change Management Center, Beijing 100086, China

ABSTRACT

The carbon mitigation for water supply system has become a hot issue concerning carbon peaking and carbon neutrality goals of cities. This study aimed to establish an integrated water-carbon nexus model to account the carbon emissions of urban water supply system. First, the physical-virtual water inventory was established covering local water intake, water transfer, and virtual water imports. Then, the water-carbon nexus model was constructed to simulate the carbon emissions of each stage along the whole water supply chain. Regarding physical water supply, the carbon emissions of pumping station and valve combinations, and water delivery routes were accounted while those from virtual water imports embodied in water-intensive products were calculated as well based on the multi-regional input-output (MRIO) analysis. Finally, taking Beijing-Tianjin-Hebei region as a case, we conducted a scenario analysis in context of regional water resource planning and carbon mitigation goals during 2020-2030. This study may provide a novel integrated water supply optimization framework for coordinating regional water resource management and carbon mitigation activities.

Keywords: water-carbon nexus, water supply system, virtual water, input-output analysis, water resource planning

NONMENCLATURE

Abbreviations	
BTH	Beijing-Tianjin-Hebei
MRIO	Multi-regional input-output analysis

1. INTRODUCTION

The urban water supply system involves multiple subsystems, and the use of electricity and other energy makes the water supply system become one of the main sources of carbon emissions in the city. The Beijing-Tianjin-Hebei (BTH) region, China's main economic center, is facing severe water shortages. 51% of the physical water resources it uses come from groundwater extraction with high emissions [1]. In addition to physical water supply, the import of water-intensive products is also an important way to relieve local water pressure [2]. In the BTH, the energy consumption related to the inter-provincial exports of virtual water accounts for nearly half of the water-related energy consumption [3]. Goods and services flow from Hebei to Beijing and Tianjin, resulting in increased local carbon emissions and water losses [4]. With the implementation of the dual carbon goals and increasing urban water demand, low-carbon management of water supply systems covering both physical and virtual water in the BTH has become increasingly important.

The water-carbon nexus is used to quantify the complex interactions between water resources and carbon emissions in supply chains [5, 6]. Energy is consumed in various processes such as water intake, water production, water conveyance, water use, and sewage treatment. The concept of water-carbon nexus is used to account for the energy consumption and carbon emissions of the physical water supply system from the perspective of the life-cycle. Studies have calculated the total carbon emissions related to energy use in China's urban water supply sector [7, 8] and water operation sector [9]. The energy consumption and carbon emissions of surface water intake, seawater desalination, non-potable water recycling [10], and inter-regional water transfer [11] have also been extensively investigated. However, in the case of urban water supply systems, the carbon emissions caused by virtual water supply are often overlooked.

Industrial transformation is an adaptive measure to deal with water pressure. Existing studies have discussed the impact of industrial transformation on regional water consumption and greenhouse gas emissions [12]. Huang et al. studied the impact of the low-carbon transition of China's power sector on future water supply constraints

This is a paper for the 14th International Conference on Applied Energy - ICAE2022, Aug. 8-11, 2022, Bochum, Germany.

with the goal of saving industrial water, Zhang et al. proposed an optimization path for Beijing's industrial structure [15]. Zhao et al. found that implementing industrial adjustment measures under water supply constraints in the Beijing-Tianjin-Hebei region could reduce the regional grey water footprint by 2.2% [16]. However, the impact of industrial transformation in the BTH region on local water resources pressure and carbon emissions in the water supply system has not been resolved. This is crucial for achieving the dual goals of water conservation and carbon reduction in the BTH region.

Given this, this paper firstly establishes a comprehensive water-carbon nexus model to calculate the carbon emissions of urban water supply system. Specifically, taking the BTH region as an example, we calculated the carbon emissions in the physical water supply process covering water abstraction, water production, and water distribution. Based on the multi-regional input-output model, the carbon emissions of the virtual water supply in the region are calculated. Then, we construct the industrial transformation scenarios in the BTH from 2020 to 2030, and analyze its impact on the local water supply system and its carbon emissions.

The rest of this paper is organized as follows. Section 2 describes the water-carbon nexus analysis method and the scenario analysis method. Section 3 presents the case study results of BTH. Section 4 gives the discussion and conclusions.

2. METHODS

2.1 System boundary

This study defines an urban water supply system as the entire process of water resources from nature to users. Water supply is divided into physical water supply and virtual water supply. The carbon emission of physical water supply comes from the energy consumption in the process of water abstraction, water production, and water delivery. Carbon emissions from virtual water supply refers to the carbon emissions embodied in the virtual water supply chain.

This study defines an urban water supply system as the entire process of water resources from nature to users. Water supply is divided into physical water supply and virtual water supply. The carbon emission of physical water supply comes from the energy consumption in the process of water abstraction, water production, and water delivery. Carbon emissions from virtual water supply refers to the carbon emissions embodied in the virtual water supply chain.

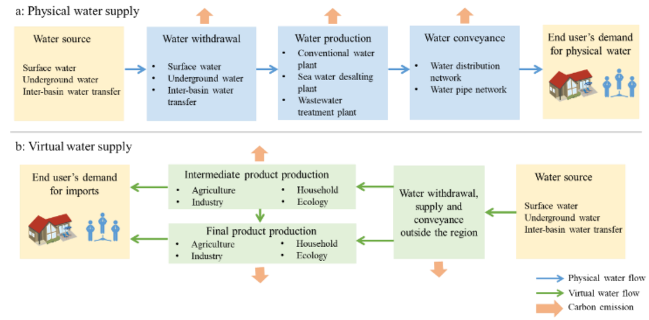

Fig. 1 System boundary

2.2 Water-carbon nexus analysis

2.2.1 Carbon emissions of physical water supply

The sources for urban physical water supply include surface water, groundwater and unconventional water sources. As the carbon emissions from the unconventional water withdrawal process mainly come from the energy consumption in water treatment plants. Therefore, its carbon emissions are included in the water production process.

(1) Surface water withdrawal

Surface water withdrawal includes water storage, water diversion, water lift and water transfer. Water diversion projects in the Beijing-Tianjin-Hebei region are generally completed with the help of gravitational potential energy. Therefore, the carbon emissions of water diversion are negligible.

Carbon emissions in the water storage process come from the operating energy consumption of infrastructure (reservoirs, storage tanks) and the loss of taps along the way. Carbon emissions from the water storage process:

$$C_{stor} = Q_{stor} W_{stor} EF_{CO_2}$$

Among them, Q_{sto} is the water supply volume from the water storage project. W_{sto} is the energy intensity of the water storage project, with a value of 0.109kWh/m^3. EF_{CO_2} is the power carbon emission coefficient, with a value of 1.246kg/kWh.

The process of water lifting is to use power equipment such as pumping stations to lift water resources from lower places to higher places to meet people's needs. According to the principle of energy conversion, the energy consumption of the lifting process of surface water can be approximately equal to the gravitational potential energy:

$$E_{lift} = \frac{\rho Q_{lift} g h_{lift}}{3.6 \times 10^6 \eta}$$

where ρ is the density of water, Q_{lif} is the volume of water lifted, and g is the acceleration of gravity. h is the lift, which is 5 meters due to the flat terrain in the Beijing-Tianjin-Hebei region. The carbon emission of water lift is

$$C_{lift} = E_{lift} EF_{CO_2}$$

The carbon emissions in the water transfer process mainly comes from the energy consumption in the operation of sluice gates.

$$C_{tran} = Q_{tran} W_{tran} EF_{CO_2}$$

Among them, Q_{tran} is the water supply volume of the water diversion project. W_{tran} is the energy intensity of water transfer project, with a value of 0.102kWh/m^3.

(2) Underground water withdrawal

In the process of taking water from groundwater, electrical energy is converted into potential energy of water. Therefore, the electrical energy consumed by groundwater withdrawal can be approximately equal to the work done by the water from the dynamic water level to the surface.

$$E_{Unde} = \frac{\rho Q_{unde} g H}{3.6 \times 10^6 \eta}$$

where Q_{unde} is the volume of underground water withdrawal. H is the total lift. The carbon emission of underground water withdrawal is

$$C_{Unde} = E_{Unde} EF_{CO_2}$$

(3) Water production

The energy consumption intensity K of conventional water plants is taken from the average of n water plants in the Beijing-Tianjin-Hebei region. E_{conv}^{i} is the energy consumption of the i-th water production plant, and W_{conv}^{i} is the annual water production of this plant.

$$K_{conv} = \frac{\sum_{i=1}^{n} E_{conv}^{i}}{\sum_{i=1}^{n} W_{conv}^{i}}$$

The carbon emission of conventional water production is

$$C_{conv} = K_{conv} Q_{conv} EF_{CO_2}$$

The calculation method of carbon emissions from unconventional water production is consistent with that of conventional water. K_{wast} are the average energy consumption of l water reuse plants in the Beijing-Tianjin-Hebei region.

$$K_{wast} = \frac{\sum_{i=1}^{l} E_{wast}^{i}}{\sum_{i=1}^{l} W_{wast}^{i}}$$

$$C_{wast} = K_{wast} Q_{wast} EF_{CO_2}$$

(4) Water conveyance

The carbon emissions of the water distribution process are

$$C_{cove} = Q_{cove} W_{cove} EF_{CO_2}$$

Among them, Q_{cove} is the water conveyance volume. W_{cove} is the energy intensity of the water conveyance project.

2.2.2 Virtual water

We track virtual water and embodied carbon emissions along the supply chain based on a multi-regional input-output model. It uses a series of equations to express the flow of goods and services between different sectors [17]. Suppose there are m regions and n departments.

$$X_i^r = \sum_{s=1}^{m} \sum_{j=1}^{n} Z_{ij}^{rs} + \sum_{s=1}^{n} Y_i^{rs}$$

X_i^r is the total input of sector i in region r, which consists of intermediate input and final input. Z_{ij}^{rs} is the intermediate input of sector i in region r to sector j in region s, and Y_i^{rs} is the final input of sector i in region r to region s.

The direct consumption coefficient a_{ij} represents the products of sector i consumed by sector j for the total output of the production unit:

$$\mathrm{A} = \left[a_{ij}^{rs}\right], \qquad a_{ij}^{rs} = Z_{ij}^{rs} / X_j^r$$

Therefore, the above formula can be expressed in the form of a matrix

$$\mathrm{X} = \mathrm{AX} + \mathrm{Y}$$

Inverse can be obtained

$$\mathrm{X} = (I - A)^{-1} \mathrm{Y}$$
$$\mathrm{L} = [l_{ij}^{rs}] = (I - A)^{-1}$$

L is a Leontief inverse matrix, and its element l_{ij}^{rs} represents the input required by sector i in region r to meet the final output of sector j in region s. Thus, the Leontief inverse matrix establishes a link between production and consumption activities.

The direct water use coefficient matrix F_W and the carbon emission intensity matrix F_C can be written as the following equations, respectively. The representative is based on the direct water consumption W, carbon emission C and economic output of each sector.

$$F_W = \left[{f_w}_i^r\right] = W / \mathrm{X}$$
$$F_C = \left[{f_c}_i^r\right] = \mathrm{C} / \mathrm{X}$$

The virtual water supply and carbon emissions triggered by final demand are calculated using the following equations

$$\mathrm{VW} = F_W \mathrm{LY}$$
$$\mathrm{EC} = F_C \mathrm{LY}$$

2.3 Industrial transition scenarios analysis

Industrial transition scenarios are designed to reduce water consumption in production activities. In this study, we set "water supply constraints" based on the water stress index for 2020-2030. 80% of the total available water is set as water supply. Referring to the “Measures for industrial structure adjustment with energy conservation” and available literature related to the water footprint at the sectoral scale we designed industrial transition scenarios [18]. In order to mitigate the adverse impacts of water shortages on human health and well-being, tertiary sectors such as Freight transport and warehousing; Hotels, food and beverage places (establishments) would not be considered as water supply constraint sectors [19]. To maintain the safe and necessary functioning of urban systems, the water supply to key sectors such as Gas and water production and supply; Social services and Wholesale and retail would not be rationed. As a consequence, the water constraints are mainly imposed upon agriculture and some secondary sectors.

3. RESULTS

3.1 Carbon emissions from physical water supply

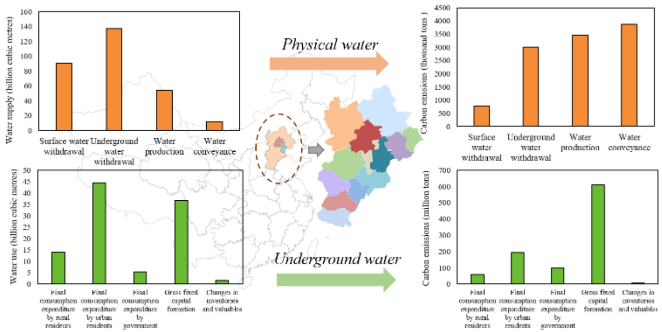

Fig. 2 Carbon emissions from physical water supply

Physical water supply in the Beijing-Tianjin-Hebei region totaled 2.948 billion tons, resulting in 11.11 million tons of carbon dioxide emissions. The region's virtual water supply reached 10.2 billion tons, one-third of physical water. But the resulting carbon emissions reached 969.19 million tons (Fig. 2). Carbon emissions from Surface water withdrawal. We could see that the total amount of surface water intake reached 9.08 billion cubic meters. 769.05 thousand tons of CO2 was discharged. Beijing's surface water intake accounts for 13.66% of the total of Beijing-Tianjin-Hebei, and its carbon emissions reached 234.13 thousand tons, accounting for 30.44% of the total. Tianjin has the largest surface water withdrawal, which was 1.9 billion cubic meters, accounting for 20.93% of the total. Carbon emissions only account for 2.83%. The Beijing-Tianjin-Hebei region has withdrawn a total of 13.72 billion cubic meters of groundwater and discharged a total of 3010.94 thousand tons of CO2. Unlike surface water, Shijiazhuang ranks first in both groundwater exploitation (22.39%) and carbon emissions (22.82%). Beijing's groundwater exploitation is second only to Shijiazhuang. Carbon emissions from physical water supply – water production: The water production process produced 3465.07 kilotons of CO2. Among them, the production process of conventional water, recycled water and desalinated water accounted for 44.30%, 39.32% and 16.38% respectively. Beijing ranks first in both conventional water carbon emissions and recycled water carbon emissions. Carbon emissions from desalinated water are concentrated in Tianjin and Cangzhou. In 2017, the total amount of water transmission and distribution in the Beijing-Tianjin-Hebei region was 1.224 billion cubic meters, generating 3870.24 thousand tons of CO2.

3.2 Carbon emissions from virtual water supply

The virtual water consumption in the final demand of the Beijing-Tianjin-Hebei region is 10.327 billion cubic meters (Fig. 3). Among the five types of final demand, the virtual water consumption is urban residents' consumption (43.33%), gross fixed capital formation (35.61%), rural household consumption (13.54%), the government consumption expenditure (5.74%) and inventories increased (1.77%).

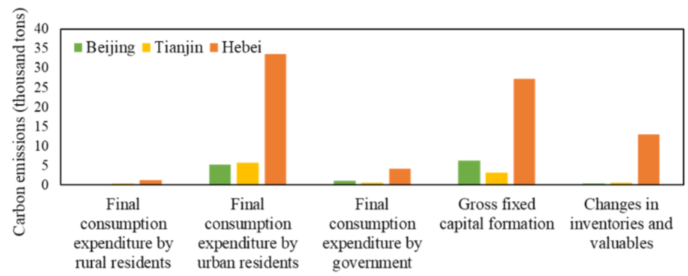

Fig. 3 Carbon emissions from virtual water supply

From the perspective of sectoral flows. The food and tobacco industry is the largest net input sector of virtual water, with a net input of 5.68 billion m³ of virtual water. Virtual water mainly comes from agricultural products; the net input of virtual water in the textile and garment industry is 3.38 billion m³. The food and tobacco industry and the textile and garment industry have a high inflow of virtual water and a large amount of intermediate input. As the end of the industrial chain, they use a large amount of virtual water from other departments in the production process.

3.3 The impact of industrial transition on water supply and carbon emissions

According to the Beijing-Tianjin-Hebei Industrial Water Saving Action Plan, we set up 16 scenarios (Table 1). Water supply constraints have been set in some sectors, excluding the livelihood sector. These impacts alter carbon emissions across the supply chain. The results show that Water supply constraints have the greatest impact on the agricultural sector. In each scenario, water supply constraints in the agriculture and metalworking industries result in the greatest water savings and emissions reductions. The additional environmental gains from water supply constraints imposed on the agricultural and food processing industries in Hebei Province are the largest (Fig. 4).

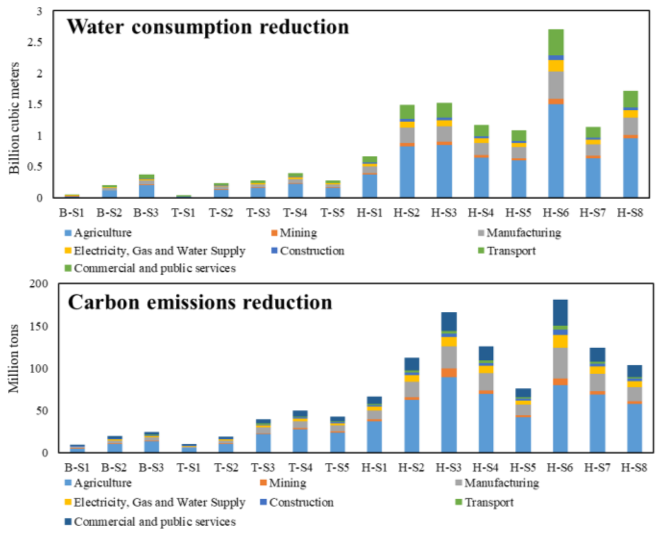

Fig. 4 Industrial transition's impact on water supply and carbon emissions

4. CONCLUSION

This paper establishes a comprehensive water-carbon nexus model to calculate the carbon emissions of urban water supply system. Specifically, taking the BTH region as an example. We construct the industrial transformation scenarios in the BTH from 2020 to 2030, and analyze its impact on the local water supply system and its carbon emissions. It may provide a novel integrated water supply optimization framework for coordinating regional water resource management and carbon mitigation activities. The research results can provide some reference and support for the setting of water saving policy. Such as Improvements in water saving efficiency, how to set up water resource constraints departments. When water is scarce, those sectors are given priority. Inevitably, there are a few potential extensions worth further exploring. The most important thing is that the setting of water resource constraint scenarios should be more abundant, and the balance of supply and demand in each region should be considered.

ACKNOWLEDGEMENT

This work was supported by the Strategic Priority Research Program of Chinese Academy of Sciences (No. XDA20100104), National Natural Science Foundation of China (Nos.72073017, 72091511, 71725005) ,Beijing Outstanding Scientist Program (BJJWZYJH01201910027031) and Beijing Natural Science Foundation (9222017).

REFERENCE

[1] Smith K, Liu S. Energy for Conventional Water Supply and Wastewater Treatment in Urban China: A Review. Global Challenges. 2017;1:1600016.

[2] Liu J, Li M, Wu M, Luan X, Wang W, Yu Z. Influences of the south–to-north water diversion project and virtual water flows on regional water resources considering both water quantity and quality. Journal of Cleaner Production. 2020;244:118920.

[3] Wang S, Chen B. Unraveling energy–water nexus paths in urban agglomeration: A case study of Beijing–Tianjin–Hebei. Applied Energy. 2021;304:117924.

[4] Zheng H, Zhang Z, Zhang Z, Li X, Shan Y, Song M, et al. Mapping Carbon and Water Networks in the North China Urban Agglomeration. One Earth. 2019;1:126-37.

[5] Chen S, Chen B, Feng K, Liu Z, Fromer N, Tan X, et al. Physical and virtual carbon metabolism of global cities. Nature Communications. 2020;11:182.

[6] Wang S, Liu Y, Chen B. Multiregional input–output and ecological network analyses for regional energy–water nexus within China. Applied Energy. 2018;227:353-64.

[7] Smith K, Liu S, Chang T. Contribution of Urban Water Supply to Greenhouse Gas Emissions in China. Journal of Industrial Ecology. 2016;20:792-802.

[8] Smith K, Liu S, Liu Y, Savic D, Olsson G, Chang T, et al. Impact of urban water supply on energy use in China: a provincial and national comparison. Mitigation and Adaptation Strategies for Global Change. 2016;21:1213-33.

[9] Zhang Q, Nakatani J, Wang T, Chai C, Moriguchi Y. Hidden greenhouse gas emissions for water utilities in China's cities. Journal of Cleaner Production. 2017;162:665-77.

[10] Mo W, Wang R, Zimmerman JB. Energy–Water Nexus Analysis of Enhanced Water Supply Scenarios: A Regional Comparison of Tampa Bay, Florida, and San Diego, California. Environmental Science & Technology. 2014;48:5883-91.

[11] Zhao Y, Zhu Y, Lin Z, Wang J, He G, Li H, et al. Energy Reduction Effect of the South-to-North Water Diversion Project in China. Scientific Reports. 2017;7:15956.

[12] Liu X, Dai H, Wada Y, Pan C, Liu X, Correspondence Y, et al. Achieving carbon neutrality enables China to attain its industrial water-use target. One Earth. 2022;5:1-13.

[13] Huang W, Ma D, Chen W. Connecting water and energy: Assessing the impacts of carbon and water constraints on China's power sector. Applied Energy. 2017;185:1497-505.

[14] Jia C, Yan P, Liu P, Li Z. Energy industrial water withdrawal under different energy development

scenarios: A multi-regional approach and a case study of China. Renewable and Sustainable Energy Reviews. 2021;135:110224.
[15] Zhang Z, Zhang X, Shi M. Urban transformation optimization model: How to evaluate industrial structure under water resource constraints? Journal of Cleaner Production. 2018;195:1497-504.
[16] Zhao D, Liu J, Sun L, Ye B, Hubacek K, Feng K, et al. Quantifying economic-social-environmental trade-offs and synergies of water-supply constraints: An application to the capital region of China. Water Research. 2021;195:116986.
[17] Miller RE, Blair PD. Input-output analysis: foundations and extensions: Cambridge university press; 2009.
[18] Zhao D, Tang Y, Liu J, Tillotson MR. Water footprint of Jing-Jin-Ji urban agglomeration in China. Journal of Cleaner Production. 2017;167:919-28.
[19] Liang Z, Tian Z, Sun L, Feng K, Zhong H, Gu T, et al. Heat wave, electricity rationing, and trade-offs between environmental gains and economic losses: The example of Shanghai. Applied Energy. 2016;184:951-9.

Table. 1 Industrial transition scenarios based on the water supply constraint.

Region	Code	The water-constrained sectors	Economic output shrinks
Beijing	B-S1	Agriculture	2.21765
	B-S2	Agriculture	2.17765
		Food and tobacco processing	5.568765
	B-S3	Agriculture	1.878765
		Electricity and heating power production	14.408765
Tianjin	T-S1	Agriculture	1.268765
	T-S2	Agriculture	1.248765
		Food and tobacco processing	6.438765
	T-S3	Agriculture	1.208765
		Chemicals	5.958765
	T-S4	Agriculture	1.198765
		Smelting and processing of metals	16.978765
	T-S5	Agriculture	1.248765
		Construction	5.7102
Hebei	H-S1	Agriculture	31.9402
	H-S2	Agriculture	31.2402
		Smelting and processing of metals	32.078765
	H-S3	Agriculture	37.178765
		Food and tobacco processing	6.078765
	H-S4	Agriculture	30.4
		Textile industry	11.978765
	H-S5	Agriculture	31.8402
		Garments, leather, furs, and related products	10.278765
	H-S6	Agriculture	31.4402
		Smelting and processing of metals	78.1402
	H-S7	Agriculture	30.5402
		Electricity and heating power production	17.378765
	H-S8	Agriculture	31.6402
		Construction	37.2402