Postprint of Virtual Water Accounting in the Beijing-Tianjin-Hebei Region Based on Multi-Regional Input-Output Analysis

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Abstract

Optimizing regional water resource allocation through trade and consumption regulation has become one of the approaches to alleviate regional water resource pressure. Inter-regional input-output analysis can provide a basis for inter-regional virtual water trade strategies. Based on the 2012 input-output tables and production water consumption data for the Beijing-Tianjin-Hebei region, a cross-regional virtual water accounting model was constructed to calculate the total volume of virtual water embedded in economic trade, as well as the direct water consumption coefficients, complete water consumption coefficients, and pull coefficients for various sectors across the three regions. The study also analyzed the virtual water import and export situation of each sector and identified key water-consuming sectors. The results indicate that the Beijing-Tianjin-Hebei region exhibits a net virtual water export status, with the main net-exporting sectors being Beijing's service and transportation industries, and Hebei's agriculture and manufacturing sectors. Agriculture, mining, and water supply industries in Beijing-Tianjin-Hebei directly consume large amounts of water during production, and should focus on improving water use efficiency and developing water-saving technologies. The average pull coefficients of manufacturing, construction, and service and transportation industries across the three regions are relatively large, indicating that other sectors' production activities are highly dependent on these sectors, and an increase in their unit output will drive more virtual water input across the entire region. Furthermore, Hebei's agriculture and manufacturing sectors deliver substantial amounts of virtual water to various sectors in Beijing-Tianjin-Hebei, providing support for production across all sectors. These are key sectors for water conservation, and their industrial structure should be adjusted with emphasis, while reducing water consumption from both direct and indirect water use perspectives. Direct and indirect water resource consumption, water consumption pull coefficients,

and inter-sectoral virtual water trade for different sectors in the Beijing-Tianjin-Hebei region were calculated, providing a foundation for inter-sectoral water resource allocation and virtual water strategy formulation in this region.

Full Text

Preamble

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Virtual Water Analysis for the Jing-Jin-Ji Region Based on Multiregional Input-Output Model

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Abstract

Optimizing regional water resource allocation through trade and consumption regulation has emerged as a key strategy for alleviating water scarcity. Multiregional input-output (MRIO) analysis provides a robust framework for examining virtual water trade patterns among regions. This study establishes a virtual water accounting model for the Jing-Jin-Ji region based on MRIO analysis, integrating the 2012 economic input-output tables with sectoral water consumption data. By calculating direct water use coefficients, total water use coefficients, final consumption of virtual water, and virtual water trade volumes, we analyzed the import and export of virtual water across different regions and sectors. The results reveal that the Jing-Jin-Ji region is a net exporter of virtual water. Key net-exporting sectors include Beijing' s service and transportation sectors, and manufacturing and agriculture in Hebei. From the perspective of driving coefficients, manufacturing, construction, services, and transportation in the Jing-Jin-Ji region exhibit high cumulative water input but low direct water input, indicating substantial reliance on indirect water inflows from other sectors for production. Moreover, agriculture and manufacturing in Hebei demonstrate high virtual water outflow, suggesting these should be priority sectors for water-saving management through reducing both direct and indirect water consumption. By investigating direct water consumption, indirect water consumption, water use coefficients, driving coefficients, and inter-sectoral virtual water trade in the Jing-Jin-Ji region, we identify key sectors and pathways for water consumption, thereby providing a solid foundation for developing virtual water trade strategies to alleviate regional water resource pressure.

Keywords: virtual water; multiregional input-output analysis; Jing-Jin-Ji region; trade and consumption

1. Introduction

Water resources are fundamental to human survival and development. In 2015, China's total water resources reached 2039.2 billion m^3. Despite this substantial aggregate volume, per capita water availability is alarmingly close to the international water scarcity threshold. More critically, water resources are unevenly distributed spatially—northern China, which supports 20% of the national population, possesses only a small fraction of the country' s total water resources. This disparity has intensified regional water crises and made addressing water scarcity in water-deficient regions an urgent priority.

Traditional approaches include large-scale water diversion projects such as the South-to-North Water Transfer. Alternative strategies involve adjusting regional industrial structures according to local water availability and implementing virtual water trade regulation. Virtual water refers to the water resources consumed during the production of goods or services. The core concept of virtual water strategy is that water-scarce regions can alleviate local water shortages by importing water-intensive products, thereby reducing domestic water consumption.

Cheng Guodong et al. first explicitly defined virtual water in 2003 and recommended implementing virtual water strategies in China' s water-deficient northwestern arid regions. The Beijing-Tianjin-Hebei region (hereinafter referred to as Jing-Jin-Ji) is located in a resource-based water-deficient area of China. With less than [MATH_0] of the national water resources, it supports approximately [MATH_1] of national grain production and [MATH_2] of industrial output. Rapid industrialization and urbanization, including the planning and construction of the Xiong' an New Area, continue to stimulate growing water demand across sectors. Water resource constraints and supply-demand contradictions are increasingly limiting sustainable development in the Jing-Jin-Ji region.

The three regions maintain close economic ties and industrial transfer relationships, forming a development pattern with Beijing and Tianjin as economic leaders and Hebei as a coordinated partner, making Jing-Jin-Ji one of China' s fastest-growing and most economically advanced regional clusters. Quantifying virtual water transfers among the three regions thus holds strategic significance. This study integrates Jing-Jin-Ji economic input-output tables with sectoral water consumption data, employing multiregional input-output analysis to calculate virtual water embodied in economic outputs and services across the three regions. By comparing direct water use coefficients, total water use coefficients, and driving coefficients across sectors, we explore inter-sectoral water resource linkages, identify key water-consuming sectors, and provide a theoretical basis for alleviating water resource pressure in the Jing-Jin-Ji region.

2. Research Methods

2.1 Construction of the Jing-Jin-Ji Multiregional Input-Output Table

The Jing-Jin-Ji multiregional input-output table used in this study is adapted from relevant research [18,29]. The original input-output table contains i rows and j columns for intermediate inputs. By aggregating input values from outside the three regions into "total external input" and combining output values to other regions with final consumption to obtain total output, while maintaining the core intermediate input-output structure unchanged, we constructed and validated the Jing-Jin-Ji interregional input-output table for 2012 based on balance principles (total input equals total output). The simplified table is presented in Table .

2.2 Jing-Jin-Ji Virtual Water Input-Output Model

Assume a system with m regions (R) and n sectors (S). The input-output model for regional production activities consists of R linear equations [30], where each sector' s total output equals the sum of intermediate use, final demand, and exports outside the system:

$$x_i^{R_a R_b} = \sum_{j=1}^{n} x_{ij}^{R_a R_b} + \sum_{R_b=1}^{m} y_i^{R_a R_b} + e_i^{R_a}$$

where $x_i^{R_a R_b}$ represents total output of sector i in region R_a; $x_{ij}^{R_a R_b}$ denotes intermediate inputs from sector i in region R_a to sector j in region R_b; $y_i^{R_a R_b}$ represents inputs to final demand in region R_b from sector i in region R_a; and $e_i^{R_a}$ is exports from sector i in region R_a outside the system.

Introducing the direct input coefficient $a_{ij}^{R_a R_b}$, which represents the direct input from sector i in region R_a required per unit output of sector j in region R_b:

$$a_{ij}^{R_a R_b} = \frac{x_{ij}^{R_a R_b}}{x_j^{R_b}}$$

In matrix form:

$$X^{R_a} = A^{R_a R_b} X^{R_a} + Y^{R_a R_b} + E^{R_a}$$

where X^{R_a}, $A^{R_a R_b}$, $Y^{R_a R_b}$, and E^{R_a} represent the total output matrix, direct consumption matrix, final demand matrix, and export matrix, respectively. Rearranging:

$$X^{R_a} = (I - A^{R_aR_b})^{-1}(Y^{R_aR_b} + E^{R_a})$$

The Leontief inverse matrix $(I - A^{R_aR_b})^{-1} = \lambda^{R_aR_b}$ contains elements $\lambda_{ij}^{R_aR_b}$ representing the input required from sector i in region R_a to produce one unit of output in sector j of region R_b.

To convert economic data to water-related data, we introduce the direct water use coefficient row vector W^{R_m}, where each element is calculated as:

$$w_i^{R_m} = \frac{q_i^{R_m}}{x_i^{R_m}}$$

where $q_i^{R_m}$ represents water consumption and $x_i^{R_m}$ represents economic output value of sector i in region R_m.

The total water use coefficient Q^R is then derived:

$$Q^R = W^R(I - A^{R_aR_b})^{-1}$$

This coefficient represents the total water resources required per unit output across all sectors in the study region, expressed in product value terms.

Virtual water trade volume in individual sector trade is calculated as:

$$\mu_{ij}^{R_aR_b} = Q_j^{R_b} \times c_{ij}^{R_b}$$

where $\mu_{ij}^{R_aR_b}$ is the virtual water trade volume imported by sector i in region R_a from sector j in region R_b, and $c_{ij}^{R_b}$ is the economic output.

The driving coefficient L, defined as the ratio of total water use coefficient Q^R to direct water use coefficient W^R, indicates the degree to which a unit increase in water consumption in one sector drives increased water consumption across the entire economic system. Some researchers refer to this as the water multiplier [31-32].

To examine virtual water flow directions among sectors in the three Jing-Jin-Ji regions, we introduce the virtual water sectoral transfer matrix TVW:

$$VW^R = W^R B$$

$$TVW = VW^R - W^R$$

where W^R is the direct water use coefficient row vector, B is the original economic input-output intermediate input matrix, and VW^R is the total water requirement matrix. The diagonal elements of TVW are zero (excluding self-transfers). Each element $tvw_{ij}^{R_aR_b}$ represents the virtual water transferred from sector i in region R_a to sector j in region R_b. The row sum represents the net virtual water transfer of sector i.

2.3 Data Sources

The Jing-Jin-Ji input-output table used in this study is based on the 2012 China Input-Output Table. Agricultural water use data for the three regions were obtained from the *China Water Resources Bulletin 2012*. Given the strong positive correlation between water consumption and economic growth in construction, water supply, and service/transportation sectors, water use data for these sectors were extrapolated based on 2012 economic growth rates from the *First Water Resources Census Bulletin* of Beijing, Tianjin, and Hebei. Manufacturing and electricity supply sector water data were sourced from the *Beijing Statistical Yearbook*, *Tianjin Statistical Yearbook*, and *Hebei Economic Yearbook*. The original 42 sectors in the input-output table were aggregated into 7 sectors as shown in Table .

Table Compilation of Sectors in the IO Table

Aggregated 7 Sectors	Original 42 Sectors in the IO Table
Agriculture (Ag)	Farming, forestry, animal husbandry, fishery products and services
Mining (Mi)	Coal mining and washing products; petroleum and natural gas extraction; metal ore mining; non-metallic mineral mining
Manufacturing (Ma)	Food and tobacco; textiles, apparel, leather, down and related products; wood processing and furniture; paper, printing and stationery; coking products and nuclear fuel; non-metallic mineral products; metal smelting and rolling; transportation equipment; electrical machinery; computers and electronics; other manufactured products; machinery repair services
Electricity and gas supply (El)	Electricity and heat production/supply; gas production/supply
Water supply (Wa)	Water production and supply
Construction (Co)	Construction

Aggregated 7 Sectors	Original 42 Sectors in the IO Table
Services and transportation (ST)	Storage and postal services; wholesale and retail; accommodation and catering; software and IT services; leasing and business services; scientific research and technical services; environmental and public facility management; repair and other services; health and social work; sports and entertainment; social security and organizations

3. Results and Discussion

3.1 Analysis of Direct, Total, and Driving Coefficients in Jing-Jin-Ji

Figure [Figure 1: see original paper] presents the total water use coefficients across different sectors in the Jing-Jin-Ji region, which represent the sum of direct and indirect water use coefficients. Agriculture in all three regions, mining and electricity supply in Hebei, and services show relatively high total water use coefficients, while construction exhibits relatively low coefficients across all regions. In terms of coefficient composition, sectors where direct water use exceeds indirect water use include agriculture in Beijing, Tianjin, and Hebei.

From a structural perspective, Beijing' s industry shows the highest total water use coefficient, followed by agriculture and services, with relatively small gaps among the three sectors, indicating that Beijing' s industrial structure emphasizes services with relatively low water consumption per unit of economic activity. Tianjin' s agriculture has the highest total water use coefficient, followed by industry and services. Hebei' s industrial average total water use coefficient reaches 580.6 m^3, far exceeding other sectors, indicating an industrial structure heavily weighted toward manufacturing. This suggests a need to enhance industrial water efficiency and upgrade water-intensive industrial sectors.

The direct water use coefficients are largest in agriculture, mining, and water supply sectors across the three regions. For sectors where indirect water use exceeds direct water use, water conservation policies must consider the entire production cycle rather than direct consumption alone, as these sectors require substantial inputs from other sectors, particularly water-intensive agricultural products. Ignoring indirect water use would overlook significant conservation opportunities.

The driving coefficient reflects how sectoral production changes affect regional water consumption. Manufacturing, construction, and services/transportation show notably higher average driving coefficients than other sectors, indicating that increased output in these sectors substantially drives water consumption in other sectors. The driving coefficients for agriculture across the three regions are similar because, while direct water consumption is high, indirect consumption is relatively low due to limited raw material inputs, resulting in small differences between direct and total water use. Variations in driving coefficients among sectors within the same region primarily stem from differences in input materials and production processes, while variations for the same sector across regions reflect relative differences in water efficiency between local and intermediate input production locations.

Table Results of Driving Coefficients at Sector Level in Jing-Jin-Ji Region

Region	Agriculture	Mining	Manufacturing	Electricity & Gas Supply	Water Supply	Construction	Services & Transport
Beijing	67.16	21.20	17.76	73.04	130.10	73.70	14.63
Tianjin	25.99	20.59	16.67	-	-	-	-
Hebei	-	-	-	-	-	-	-

3.2 Sectoral Import-Export Trade Analysis in Jing-Jin-Ji

To identify key sectors in Jing-Jin-Ji' s virtual water trade, we analyzed sectoral virtual water imports and exports. The Jing-Jin-Ji region exhibits larger virtual water exports than imports, functioning as a net virtual water exporter. While Wang et al. [33] identified Beijing as a net virtual water importer using single-region input-output analysis, our multiregional analysis confirms this result: Beijing' s net virtual water imports reached 4.03×10 m^3 in 2012, Tianjin' s net imports were 1.23×10 m^3, and Hebei' s net exports were 8.26×10 m^3—far exceeding Beijing and Tianjin' s net imports. Consequently, the Jing-Jin-Ji region as a whole is a net virtual water exporter.

Key sectors engaged in external virtual water trade include Beijing's services and transportation, Tianjin' s manufacturing, and Hebei' s agriculture and manufacturing. Net-exporting sectors are primarily Beijing's services and transportation, and Hebei' s agriculture and manufacturing, which play producer roles in the regional water consumption system. Net-importing sectors include Beijing' s agriculture and Tianjin' s manufacturing, representing important consumers in the system.

Manufacturing and services/transportation show large total trade volumes. Beijing's manufacturing is import-oriented, while Hebei's is export-oriented; Tianjin shows balanced trade. This reflects Hebei' s substantial virtual water investment in manufacturing products transferred externally, a pattern related to local industrial structure and policy orientation.

Excluding manufacturing and services/transportation (to better visualize smaller sectors), Figure [Figure 3: see original paper] shows that, aside from these omitted sectors, Tianjin exports most virtual water through construction, followed by agriculture. Hebei exports most through agriculture, followed by construction and mining. Meanwhile, Beijing' s construction and agriculture, Tianjin' s electricity supply and agriculture, and Hebei' s agriculture and electricity supply are major virtual water importers.

3.3 Inter-regional Trade Flow Analysis in Jing-Jin-Ji

Sectoral virtual water inflows and outflows reveal each sector' s role in the regional water resource system. Identifying key virtual water flow pathways is crucial for rational water allocation. Figure [Figure 5: see original paper] illustrates inter-regional virtual water flows, where colored bands represent sectors and radiating flows show outputs to other sectors (virtual water destinations).

Hebei' s agriculture sector exports substantial virtual water to support production in other sectors, primarily serving Hebei' s own manufacturing and construction sectors, while also supplying Tianjin and Beijing. Tianjin' s sectors also export virtual water to various degrees. Several sectors import significant proportions of virtual water from Hebei agriculture (exceeding 10% of total imports), including Beijing' s mining, electricity supply, and construction; Tianjin' s manufacturing and construction; and Hebei' s manufacturing and construction. This indicates strong dependence on Hebei agriculture.

Hebei' s mining exports considerable virtual water to its construction and manufacturing sectors, while Hebei manufacturing exports to Hebei construction. These sectors, where flows exceed 5% of total sectoral inflows/outflows, warrant attention in regulation.

Manufacturing, construction, and services/transportation across the three regions show high and diverse virtual water inflows, reflecting their position as downstream sectors that import numerous raw materials (intermediate inputs) from various sources. Sectors identified as active in virtual water trade (both inputs and outputs) should be prioritized in policy formulation.

Hebei inputs substantial virtual water into Beijing and Tianjin by providing energy resources, making Hebei agriculture a critical water supplier for regional economic production. Tianjin also exports significant water resources. These inter-sectoral virtual water flows provide crucial guidance for water allocation strategies.

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4. Conclusions and Recommendations

Virtual water accounting reveals water resource allocation relationships and quantities across economic sectors and regions, offering new insights for identifying water consumption reduction pathways. This study explored direct and indirect water consumption patterns and inter-sectoral virtual water flows in the Jing-Jin-Ji region.

Key findings include: 1. **Sectoral water use**: Sectors with large direct water use coefficients include agriculture, mining, and water supply. Those with large total water use coefficients are agriculture, water supply, and manufacturing. Analysis of direct versus indirect water use differences reveals sector-specific production characteristics. For example, manufacturing shows relatively small direct water consumption but large total consumption due to water-intensive raw material inputs, suggesting that indirect water reduction should be prioritized over direct water savings.

2. **Regional trade patterns**: Beijing and Tianjin are net virtual water importers, while Hebei is a net exporter, indicating that Beijing and Tianjin' s industrial structures help mitigate their water stress. However, the Jing-Jin-Ji region overall is a net exporter, with Hebei' s industrial structure exacerbating regional water pressure. Given Hebei' s large total water consumption, structural adjustments are needed to reduce water consumption and gradually transform it from a virtual water exporter to an importer.
3. **Key trade sectors**: Net virtual water imports are concentrated in Beijing' s agriculture and Tianjin' s manufacturing. Net exports are primarily from Beijing' s services/transportation and Hebei' s agriculture and manufacturing. To reduce virtual water exports, these sectors should adjust their industrial structures toward water-saving orientations.
4. **Inter-regional flows**: While inter-regional sectoral linkages exist, most virtual water flows occur within the same region across different sectors. Hebei agriculture, as a key water-consuming sector, exports substantial virtual water to support production across Jing-Jin-Ji sectors, providing critical water resource support. Transforming Hebei' s virtual water trade characteristics and improving water efficiency in its agricultural sector are key to reducing water consumption across the entire Jing-Jin-Ji region.
5. **Active trade sectors**: Sectors with large output volumes relative to local sectors and active virtual water exports include water supply, electricity supply, mining, and manufacturing. Sectors with high and diverse virtual water inputs include manufacturing, construction, and services/transportation. These sectors should be prioritized in policy formulation.

To ensure water security in the Jing-Jin-Ji region, Hebei should prioritize structural adjustments to reduce both direct and indirect water consumption. Based on differences in direct and indirect water use characteristics, manufacturing should focus on reducing indirect water consumption. The large driving coefficients in manufacturing, construction, and services/transportation mean that reducing water consumption in these sectors will significantly impact regional water stress and should be central to water conservation implementation.

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Note: Figure translations are in progress. See original paper for figures.