

Virtual Water Accounting in Northeast China Based on Multi-Regional Input-Output Analysis

Qinghua Zhang

School of Geographical Sciences, Liaoning Normal University (LNNU), Dalian, China

Email: 3100643334@qq.com

How to cite this paper: Zhang, Q.H.

(2026) Virtual Water Accounting in Northeast China Based on Multi-Regional Input-Output Analysis. *Open Journal of Applied Sciences*, 16, 4024-4038.

<https://doi.org/10.4236/ojapps.2026.1610222>

Received: September 17, 2026

Accepted: October 24, 2026

Published: October 27, 2026

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Abstract

Against the backdrop of an increasing demand for coordinated regional development and spatial optimization of water resource allocation, quantitatively evaluating virtual water flow patterns at the prefecture-level city scale across Northeast China is of critical importance for enhancing efficient allocation and collaborative management of water resources. Based on a 2017 multi-regional input-output (MRIO) model covering 36 prefecture-level cities in Northeast China, this study quantifies and examines the characteristics of inter-city and inter-sectoral virtual water flows. The results indicate that: 1) Sectoral water intensity exhibits pronounced heterogeneity. The agricultural sector has the highest direct water coefficient ($0.0513 \times 10^8 \text{ m}^3/10^8 \text{ yuan}$, *i.e.*, $513.38 \text{ m}^3/10^4 \text{ yuan}$). Conversely, the ratios of total water consumption coefficients to direct water consumption coefficients for manufacturing and construction reach 29.77 and 17.59, respectively, demonstrating a typical pattern of “low direct consumption, high indirect inducement”. 2) Total inter-city virtual water flows reach $230 \times 10^8 \text{ m}^3$, accounting for 41.1% of total actual water use. This total excludes virtual water exports outside Northeast China; the region still exhibits a notable net supply characteristic. 3) Net virtual water flows exhibit a polarized pattern. The three major hub cities—Changchun, Harbin, and Dalian—have a combined net inflow of $27.99 \times 10^8 \text{ m}^3$, accounting for 79.2% of the total positive net inflow in the region. In contrast, 26 resource- and agriculture-based cities, including Jiamusi, Jixi, and Qiqihaer, act as major net virtual water exporters. 4) The spatial network structure exhibits strong intra-provincial agglomeration, with intra-provincial flow intensity significantly exceeding inter-provincial flows, reflecting administrative boundaries’ influence on supply chain integration and water resource constraints. These findings provide a scientific foundation for balanced spatial allocation and differentiated management of water resources across Northeast China.

Keywords

Virtual Water Flow, Multi-Regional Input-Output (MRIO) Model, Northeast China

1. Introduction

Water resources are foundational and strategic for sustaining regional socio-economic development. Influenced by both natural endowments and human activities, a long-standing structural mismatch exists in China between the spatial distribution of water resources and productivity layout. As crucial commercial grain bases and traditional industrial hubs, the three provinces of Northeast China fulfill strategic responsibilities in safeguarding national food and energy security. However, they simultaneously face challenges such as heavy industrial structures, high agricultural irrigation intensities, and intensifying localized water stress. In this context, optimizing water resource allocation to reconcile regional development with resource conservation has become an urgent scientific priority.

In 1998, Allan [1] first introduced the concept of virtual water, defining it as the water embodied in products and services. Virtual water transfers implicitly through inter-regional trade. Hoekstra [2] further proposed the virtual water strategy, suggesting that water-intensive industries be exported via trade from water-abundant regions to water-scarce regions, thereby achieving optimal water resource allocation. Currently, input-output (IO) models are widely employed to quantify and assess virtual water flows [3] [4]. These models are classified into single-region input-output (SRIO) models and multi-regional input-output (MRIO) models. Compared to SRIO models, MRIO models offer a comprehensive framework for capturing trade-driven embodied water resources and their spatial transfers across sectors in different regions. Consequently, researchers globally have utilized MRIO models to investigate virtual water at various scales, primarily focusing on national [5]-[9], regional [10]-[14], and inter-provincial levels [15]-[20].

Significant heterogeneity exists among cities within Northeast China regarding resource endowments, industrial structures, and economic tiers. Examining virtual water transfers solely at the provincial scale often masks severe efficiency polarization at the prefecture-level city scale. To address this gap, this study uses an MRIO model to elucidate virtual water transfer patterns across 36 prefecture-level cities. This research deepens the understanding of implicit inter-city water allocation mechanisms in Northeast China and provides a quantitative foundation for collaborative water governance and differentiated policy-making.

2. Data Sources and Methodology

2.1. Data Sources and Processing

This study focuses on 36 prefecture-level cities in Northeast China for the year 2017,

covering Liaoning, Jilin, and Heilongjiang provinces. Input-output data were obtained from the 2017 *City-Level Multi-Regional Input-Output Table for China* published by the China Carbon Emission Accounts and Datasets (CEADs). Built upon 42 unmerged sectors, this dataset provides an MRIO framework encompassing 1512 “city-sector” units, including intermediate input matrices, final demand matrices, value-added matrices, and total output vectors, establishing the foundational data support for city-scale virtual water accounting.

To balance water data availability with analytical interpretability, and in accordance with the *Industrial Classification for National Economic Activities* (GB/T 4754-2011), the 42 sectors were aggregated into 7 major categories: Agriculture, Mining, Manufacturing, Electricity and Water Supply, Construction, Transportation, and Services (**Table 1**). The MRIO table was consolidated accordingly.

Regarding water use data, agricultural water use was obtained directly from the water resources bulletins of each region. For each city, water use data were preferentially taken from the 2017 Water Resources Bulletin of the corresponding city. For cities without a separately published prefecture-level water resources bulletin, data were derived from the 2017 Water Resources Bulletins of Liaoning, Jilin, and Heilongjiang provinces and statistical yearbooks, and disaggregated in proportion to agricultural value added, gross industrial output, or water use. The water use variable in this study follows the “water use” definition in the Water Resources Bulletin, *i.e.*, water withdrawal, including surface water, groundwater, other water sources, and self-supplied water, without deducting return flow. Therefore, the virtual water accounting in this study reflects virtual water flows under a water withdrawal perspective rather than a consumptive water use perspective; if comparison with consumptive water use is required, return flow should be further deducted.

For mining, manufacturing, electricity and water supply, construction, transportation, and services, water use was indirectly allocated using industrial water use and urban public water use, with reference to existing studies [21]. Specifically, industrial water use was allocated to mining, manufacturing, and electricity and water supply, while urban public water use was allocated to construction, transportation, and services. The allocation coefficients were determined by the proportion of intermediate inputs from the “production and supply of water” sector to the corresponding sectors in each city, and the specific formula is provided in reference [22]. If the intermediate input of a sector is zero or missing, allocation is based on the proportion of that sector’s total output or value added in the total output or value added of sectors in the same group; if allocation remains infeasible, the water use of that sector is set to zero. Agricultural water use was obtained directly from the water resources bulletins and was not involved in the above allocation. If the intermediate input of a sector is zero or missing, the allocation is based on the proportion of that sector’s total output or value added in the total output or value added of sectors in the same group; if allocation remains infeasible, the water use of that sector is set to zero.

Table 1. Sector aggregation mapping for 36 cities in Northeast China (7 merged sectors).

Aggregated Sector (7 Sectors)	Original 42 Sectors in IO Table	42-Sector Code
Agriculture	Agriculture, Forestry, Animal Husbandry, and Fishery Products and Services	01
	Coal Mining and Washing Products	02
Mining	Petroleum and Natural Gas Extraction Products	03
	Metal Ore Mining and Dressing Products	04
	Non-metallic Mineral and Other Ore Mining and Dressing Products	05
	Food and Tobacco	06
Manufacturing	Textiles	07
	Textile Garments, Shoes, Caps, Leather, Down, and Related Products	08
	Wood Processing Products and Furniture	09
	Paper Processing, Printing, and Educational and Sports Goods	10
	Petroleum, Coking, and Nuclear Fuel Processing Products	11
	Chemical Products	12
	Non-metallic Mineral Products	13
	Smelting and Pressing of Metals	14
	Metal Products	15
	General Purpose Equipment	16
	Special Purpose Equipment	17
	Transport Equipment	18
	Electrical Machinery and Equipment	19
	Communication Equipment, Computers, and Other Electronic Equipment	20
	Instrumentation	21
	Other Manufactured Products	22
	Waste and Scrap	23
	Metal Products, Machinery, and Equipment Repair Services	24
Electricity and Water Supply	Production and Supply of Electric Power and Heat	25
	Production and Supply of Gas	26
	Production and Supply of Water	27
Construction Transportation Services	Construction	28
	Transportation, Storage, and Postal Services	29
	Wholesale and Retail	30
	Accommodation and Catering	31
	Information Transmission, Software, and Information Technology Services	32
	Financial Services	33
	Real Estate	34
	Leasing and Business Services	35
	Scientific Research and Technical Services	36

Continued

Water Conservancy, Environment, and Public Facilities Management	37
Resident Services, Repair, and Other Services	38
Education	39
Healthcare and Social Work	40
Culture, Sports, and Entertainment	41
Public Administration, Social Security, and Social Organizations	42

2.2. Methodology

Multi-Regional Input-Output Model

The multi-regional input-output (MRIO) model captures economic interdependencies across sectors in different regions, serving as a key tool for accounting inter-regional virtual water flows.

Assuming an input-output system containing m cities and n sectors, the total number of sectoral units in the system is $N = m \times n$. The basic MRIO formulation is expressed as:

$$x_i^K = \sum_{S=1}^m \sum_{j=1}^n x_{ij}^{KS} + \sum_{S=1}^m Y_i^{KS} + E_i^K \quad (1)$$

where x_i^K represents total output of sector i in region K ; x_{ij}^{KS} denotes intermediate flow from sector i in region K to sector j in region S ; Y_i^{KS} is final demand in region S for goods/services from sector i in region K ; and E_i^K is exports from sector i in region K outside the economic system.

The direct input coefficient a_{ij}^{KS} measures direct input required from sector i in region K per unit of total output in sector j in region S :

$$a_{ij}^{KS} = \frac{x_{ij}^{KS}}{x_j^S} \quad (2)$$

where x_j^S represents total input (output) of sector j in region S .

Substituting Equation (2) into Equation (1) yields:

$$X_i^K = \sum_{S=1}^m \sum_{j=1}^n a_{ij}^{KS} x_j^S + \sum_{S=1}^m Y_i^{KS} + E_i^K \quad (3)$$

In matrix form:

$$X = AX + Y + E \quad (4)$$

where X , A , Y , and E represent total output matrix, direct input coefficient matrix, final demand matrix, and export coefficient matrix, respectively.

Transforming Equation (4) into demand-driven form:

$$X = (I - A)^{-1} (Y + E) = L(Y + E) \quad (5)$$

where $L = (I - A)^{-1}$ is the Leontief inverse matrix. The element l_{ij}^{KS} represents output generated in sector i of region K to satisfy one unit of final demand in sector j of region S .

Incorporating water consumption into the IO framework, direct water intensity

q_j^K is defined as:

$$q_j^K = W_j^K / X_j^K \quad (6)$$

where q_j^K is direct water intensity of sector j in region K ; W_j^K is direct water consumption of sector j in region K ; and X_j^K is total output of sector j in region K .

Total water consumption coefficient d_i^{KS} represents total (direct + indirect) water consumption induced in region K to satisfy one unit of final demand in sector i of region S :

$$d_i^{KS} = \sum_{j=1}^n q_j^K l_{ji}^{KS} \quad (7)$$

Virtual water outflow from sector i in region K to final demand in region S is calculated as:

$$t_i^{KS} = d_i^{KS} \times Y_i^{KS} \quad (8)$$

where t_i^{KS} is virtual water flow from origin K to sector i in destination S ; d_i^{KS} is total water consumption coefficient; and Y_i^{KS} is final demand satisfied by region K for region S .

Similarly, virtual water flow from origin S to sector i in destination K (virtual water inflow to city K) is:

$$t_i^{SK} = d_i^{SK} \times Y_i^{SK} \quad (9)$$

Net virtual water flow for city K (NVW^K) is:

$$NVW^K = \sum_{S=1}^m \sum_{i=1}^n t_i^{KS} - \sum_{S=1}^m \sum_{i=1}^n t_i^{SK} \quad (10)$$

where $S \neq K$. $NVW^K < 0$ denotes net virtual water outflow, while $NVW^K > 0$ represents net virtual water inflow.

This study further distinguishes “inter-city virtual water flows within Northeast China” from “virtual water exports outside Northeast China”. The total scale of bilateral inter-city virtual water flows within Northeast China is defined as:

$$TotalVW_{internal} = \sum_{K=1}^m \sum_{S=1}^m \sum_{i=1}^n t_i^{KS} \quad (11)$$

where the summation excludes $S \neq K$, and both K and S refer to the 36 prefecture-level cities in Northeast China. This indicator only accounts for virtual water embodied in inter-city trade within Northeast China and excludes exports outside the system. Virtual water exports outside Northeast China are defined as:

$$TotalVW_{export} = \sum_{K=1}^m \sum_{i=1}^n t_i^{K,out} \quad (12)$$

where $t_i^{K,out}$, out denotes the virtual water embodied in final demand exports from sector i in city K to regions outside Northeast China. This part is not included in $TotalVW_{internal}$.

Total actual regional water use is

$$W_{total} = \sum_{K=1}^m \sum_{j=1}^n W_j^K \quad (13)$$

In this study, $TotalVW_{internal}/W_{total} = 230/559.6 \approx 41.1\%$.

The total positive net inflow is defined as the sum of net inflows of all cities with $NVWK^K > 0$:

$$TotalVW_{positive} = \sum_{K: NVWK^K > 0} NVWK^K \quad (14)$$

If only inter-city trade within Northeast China is considered, the sum of net flows across all cities is zero, *i.e.*,

$$\sum_{K=1}^m NVWK^K = 0 \quad (15)$$

The total positive net inflow equals the total negative net outflow in absolute value. If exports and imports outside Northeast China are included, the regional net output should be calculated separately.

3. Results and Discussion

3.1. Sectoral Water Intensity Accounting

Direct water consumption (DWC) coefficients and total water consumption (TWC) coefficients across the 7 aggregated sectors exhibit substantial polarization (**Table 2**). Agriculture has the highest direct water coefficient ($0.051338 \times 10^8 \text{ m}^3/10^8 \text{ yuan}$), *i.e.*, $513.38 \text{ m}^3/10^4 \text{ yuan}$), approximately 24.5 and 76.8 times higher than Mining ($0.002095 \times 10^8 \text{ m}^3/10^8 \text{ yuan}$) and Manufacturing ($0.000669 \times 10^8 \text{ m}^3/10^8 \text{ yuan}$), respectively. reflecting agriculture's extreme direct dependence on water resources.

Table 2. Sectoral direct water consumption coefficients and total water consumption coefficients.

Sector	Direct Water Coefficient DWC ($10^8 \text{ m}^3/10^8 \text{ yuan}$)	Total Water Coefficient TWC ($10^8 \text{ m}^3/10^8 \text{ yuan}$)	Ratio (TWC/DWC)
Agriculture	0.051338	0.081305	1.58
Mining	0.002095	0.002906	1.39
Manufacturing	0.000669	0.019916	29.77
Electricity and Water Supply	0.006223	0.015323	2.46
Construction	0.000375	0.006597	17.59
Transportation	0.000089	0.004620	51.91
Services	0.000272	0.002841	10.44

Note: Coefficients are intensity indicators in 10^8 m^3 per 10^8 yuan , *i.e.*, water use per unit of monetary output; monetary output is in 2017 current prices; 1 unit = 10^4 m^3 per 10^4 yuan .

However, evaluated by total water consumption coefficients, ratios of TWC to DWC for Manufacturing ($0.01996 \times 10^8 \text{ m}^3/10^8 \text{ yuan}$) and Construction ($0.006597 \times$

$10^8 \text{ m}^3/10^8 \text{ yuan}$) reach 29.77 and 17.59, respectively. This highlights secondary industry's implicit water consumption profile: "low direct consumption, high upstream inducement". Through complex intermediate supply chain networks, manufacturing and construction indirectly consume vast amounts of water embedded in upstream agricultural products (e.g., raw materials for food processing) and utility inputs. Although Transportation exhibits a high ratio (51.91), its small base value primarily reflects marginal inducement driven by indirect demand for energy and agricultural goods. These results demonstrate that evaluating sectoral water consumption solely based on direct water use overlooks hidden transfer risks along middle-stream supply chains.

3.2. Spatial Patterns of Net Inter-City Virtual Water Flows

Total volume and spatial distribution of inter-city virtual water flows characterize internal coupling between economic links and resource consumption across Northeast China (**Figure 1**). In 2017, total virtual water flows among the 36 cities reached $230 \times 10^8 \text{ m}^3$, accounting for 41.1% of total actual regional water use. This scale demonstrates that nearly 40% of water consumption undergoes transboundary implicit transfer via inter-city trade in goods and services, making virtual water allocation a crucial mechanism regulating regional water cycles. This total excludes virtual water exports outside Northeast China; such exports require separate accounting. The strategic role of Northeast China as a net supplier of primary industrial and agricultural resources nationwide remains notable.

At the urban scale, net virtual water flows exhibit a distinct "core-periphery" spatial polarization. Only 10 cities act as net virtual water importers, while 26 cities are net exporters. Net inflow regions are concentrated in top-tier central cities: Changchun, Harbin, and Dalian record net inflows of $10.14 \times 10^8 \text{ m}^3$, $9.56 \times 10^8 \text{ m}^3$, and $8.33 \times 10^8 \text{ m}^3$, respectively. Combined net inflows of these three hubs total $27.99 \times 10^8 \text{ m}^3$, accounting for 79.2% of the total positive net inflow ($35.34 \times 10^8 \text{ m}^3$) in the region. The remaining seven net-importing cities, such as Shenyang and Jilin, exhibit relatively modest net inflow volumes. If only intra-Northeast China trade is considered, the sum of net flows across all cities is zero, and the total positive net inflow equals the total negative net outflow in absolute value. This concentration pattern indicates that high-tier urban centers serve as primary destination sinks for virtual water transfers, driven by large population scales, strong consumer demand, and clusters of high-value-added industries.

Conversely, the 26 net-exporting cities are widely dispersed geographically. Jiamusi ranks first in net outflow volume, reaching $10.38 \times 10^8 \text{ m}^3$; net outflows from Jixi, Qiqihaer, and Songyuan follow at $2.54 \times 10^8 \text{ m}^3$, $2.29 \times 10^8 \text{ m}^3$, and $1.86 \times 10^8 \text{ m}^3$, respectively. These cities are predominantly agricultural resource-based or resource-exhausted regions. Their substantial net virtual water exports reflect their socio-economic roles as key suppliers of primary agricultural commodities and raw materials within regional division of labor. Spatially, net virtual water inflow hubs cluster as distinct patches along key transit corridors (e.g., Harbin-Changchun and Harbin-Dalian railways), whereas net outflow regions spread across the Sanjiang

Plain, Songnen Plain, and Western Liaoning, painting a spatial landscape of “core consumption driving peripheral resource support”.

If only intra-Northeast China trade is considered, the sum of net flows across all cities is zero, and the total positive net inflow equals the total negative net outflow in absolute value.

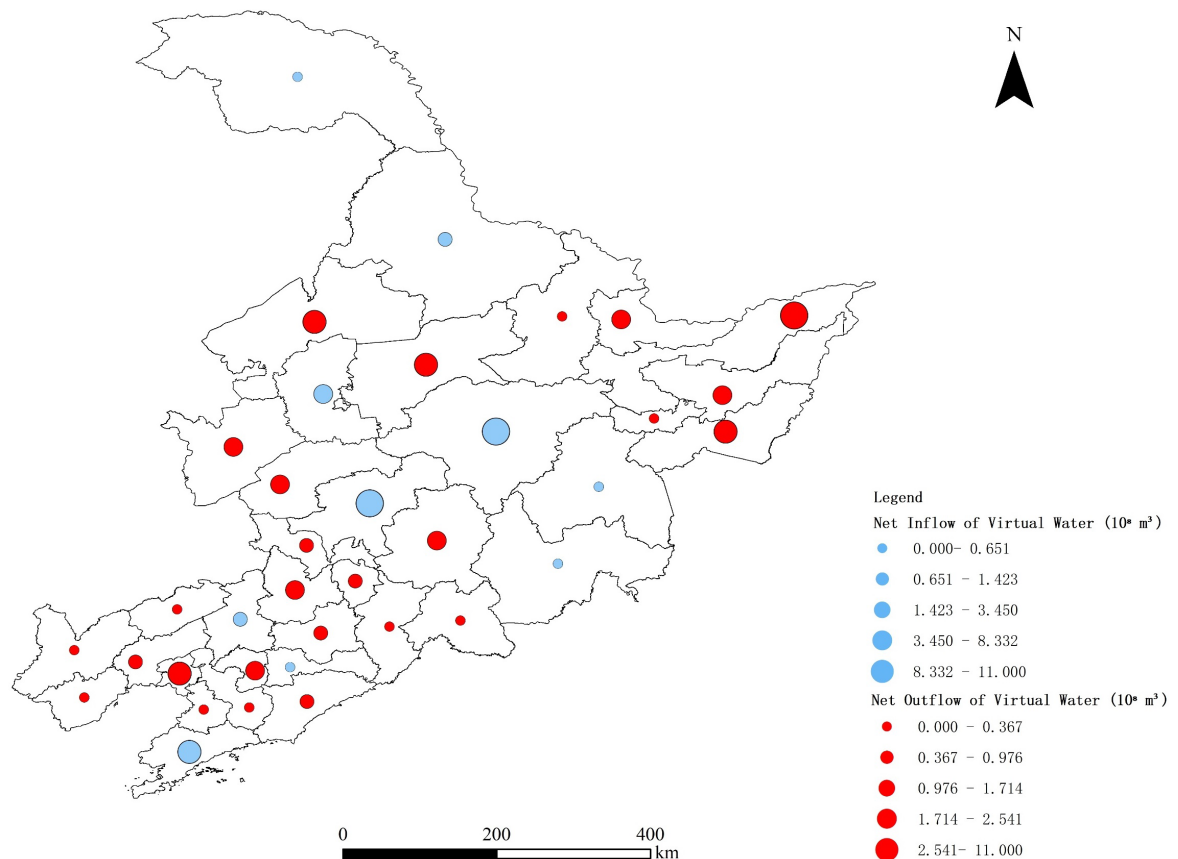


Figure 1. Net virtual water flows across Northeast China. Note: The base map is derived from the Fundamental Geographic Information Database; no alterations have been made to national administrative boundaries.

3.3. Sectoral Composition of Virtual Water Flows

Differences in virtual water inflow and outflow dynamics across cities are fundamentally shaped by sectoral trade structures. As illustrated in **Figure 2** and **Figure 3**, trade in agricultural products serves as the primary driver of virtual water outflows due to agriculture’s significantly higher direct water intensity relative to other sectors. For example, Jiamusi’s massive net outflow ($10.38 \times 10^8 \text{ m}^3$) stems mainly from agricultural exports. As a key commercial grain hub in Heilongjiang Province, Jiamusi exports water-intensive agricultural products to consumption hubs like Harbin and Changchun. Conversely, although Harbin possesses well-developed manufacturing and service sectors, agricultural virtual water continues to comprise the largest share of its net virtual water inflows. This underscores how large resident populations and high consumption levels in provincial capitals generate strong indirect resource dependence on agricultural water.

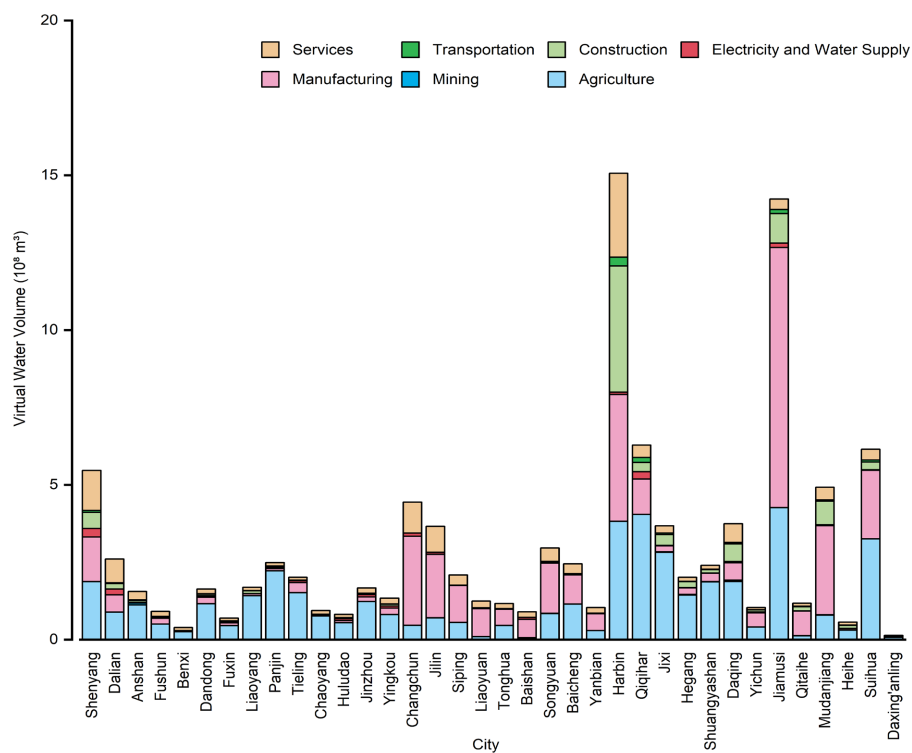


Figure 2. Inter-sectoral net virtual water outflows in Northeast China.

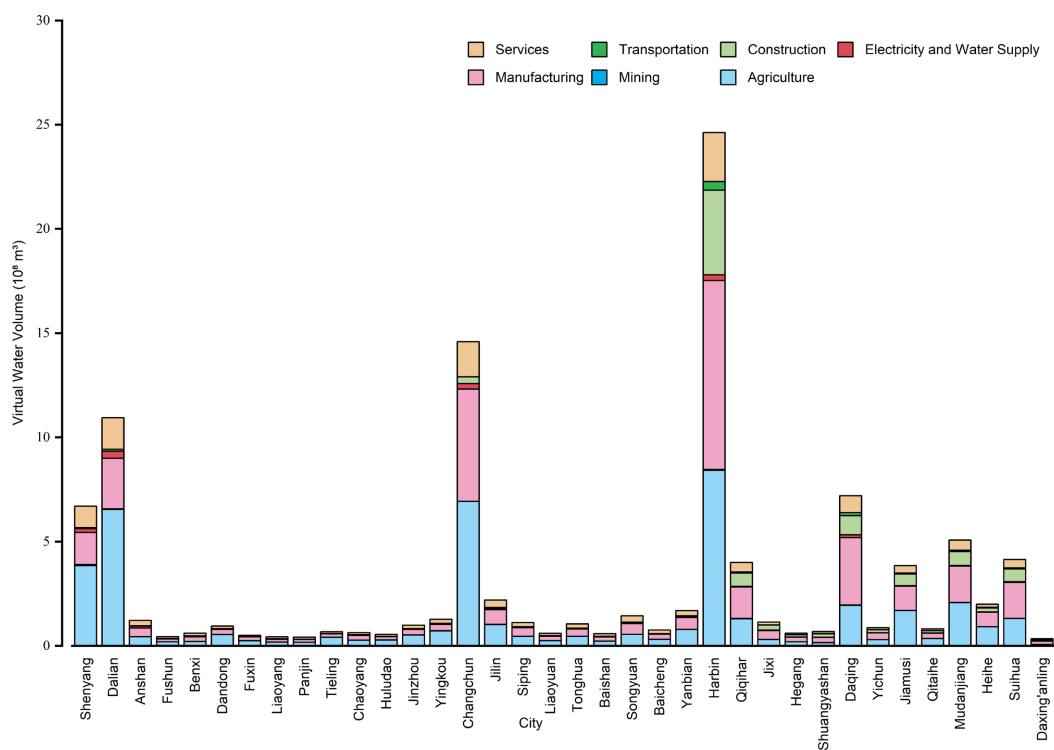


Figure 3. Sectoral composition of total virtual water inflows in Northeast China. Note: **Figure 3** shows total virtual water inflows (from all source cities), whereas the net inflows reported in Section 3.2 refer to total inflows minus total outflows. Therefore, values in **Figure 3** are larger than the net inflow values reported in Section 3.2.

Implicit water pull effects generated by manufacturing and construction are more pronounced in central cities. In Dalian, a coastal industrial center, local manufacturing water consumption primarily serves municipal output; however, through upstream supply-chain linkages, Dalian indirectly absorbs substantial virtual water embodied in mining and raw materials from surrounding cities. This demonstrates how secondary processing industries pull water resources from foundational sectors. Furthermore, manufacturing products with strong cross-regional marketability lead to dispersed virtual water destinations, primarily transferring to regions outside Northeast China and developed coastal areas. Virtual water flows associated with construction correlate strongly with fixed-asset investment and infrastructure scale, resulting in significantly higher net construction-related virtual water inflows in central cities compared to small- and medium-sized cities.

3.4. Inter-City Virtual Water Flow Networks

To isolate core backbone pathways within complex trade networks while filtering out noise from low-volume connections, the top 120 virtual water flow paths were selected to generate a chord diagram network. These 120 primary pathways account for over 85% of total inter-city virtual water flows, accurately representing the network's key topology.

Network analysis indicates (**Figure 4**) that inter-city virtual water flows in Northeast China exhibit strong intra-provincial agglomeration and are constrained by administrative boundaries. Intra-provincial flows in Heilongjiang exhibit the highest intensity, forming a unipolar network anchored by Harbin and radiating outward. Cities such as Jiamusi, Qiqihaer, Daqing, and Suihua funnel virtual water to Harbin through thick flow chords. After absorbing regional agricultural and resource-based virtual water, Harbin utilizes a portion to meet municipal consumption and exports the remainder outside the province. Jilin Province exhibits a similar unipolar clustering pattern centered on Changchun, with substantial industrial and agricultural virtual water flowing in from neighboring cities like Jilin City and Siping. Liaoning Province exhibits a dual-core driving structure led by Shenyang and Dalian: Shenyang exerts strong radiative pull over the Central-South Liaoning urban agglomeration, while Dalian absorbs diversified inter-city inputs via its coastal location. Nevertheless, intra-provincial transfers remain dominant across Liaoning.

In contrast, inter-provincial virtual water flows remain small in scale and weak in connectivity, appearing sparsely as agricultural virtual water transfers from Heilongjiang to Liaoning and intermediate manufacturing flows from Jilin to Liaoning. Total intra-provincial flows within Heilongjiang reach $36.13 \times 10^8 \text{ m}^3$, vastly outstripping cross-provincial flows. This network topology reveals underlying mechanisms governing water constraints and industrial coordination in Northeast China: bound by existing administrative divisions and localized industrial chain architectures, individual provinces prioritize completing production-con-

sumption cycles of water-intensive products internally. Consequently, spatial market-based allocation of water elements remains constrained by provincial administrative barriers.

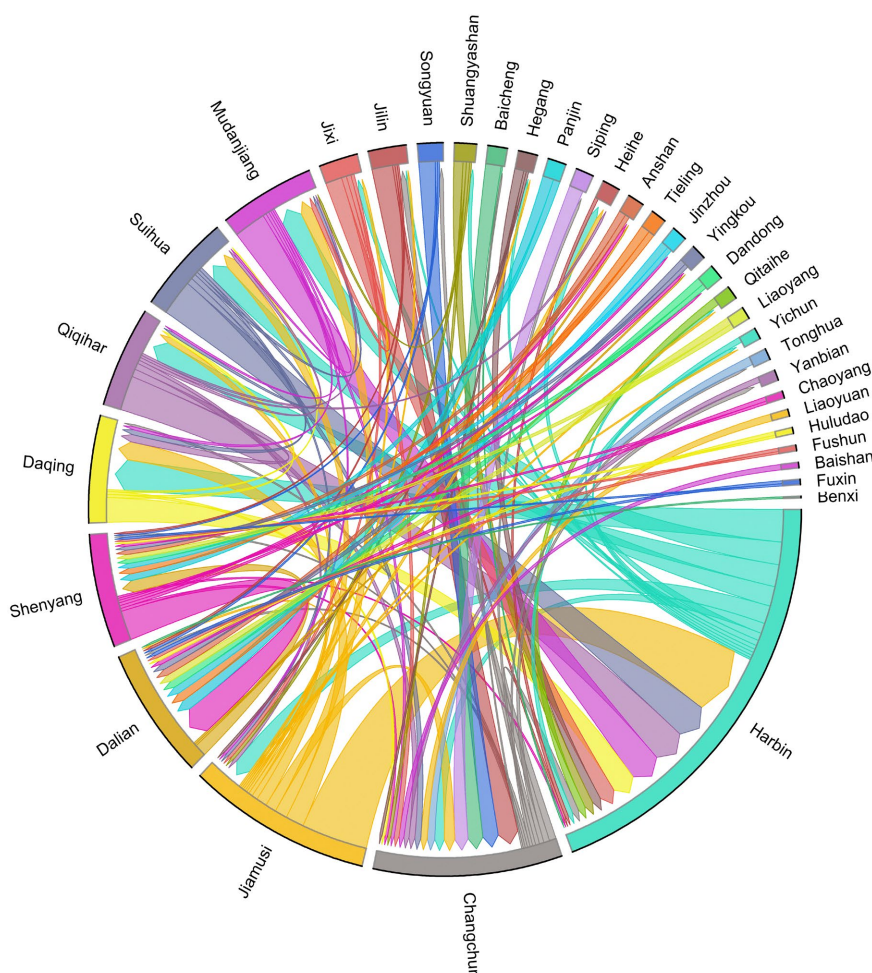


Figure 4. Chord diagram of inter-city virtual water flows in Northeast China.

4. Conclusions and Policy Implications

Based on the 2017 city-scale MRIO table for 36 prefecture-level cities in Northeast China, this study systematically quantified inter-city virtual water flow patterns. The main conclusions are as follows:

1) Heterogeneity in sectoral water intensity fundamentally drives virtual water transfers. Agriculture exhibits the highest direct water coefficient ($0.0513 \times 10^8 \text{ m}^3/10^8 \text{ yuan}$, *i.e.*, $513.38 \text{ m}^3/10^4 \text{ yuan}$), approximately 76.8 times that of manufacturing, confirming its dominant position in direct water consumption. The ratios of total to direct water coefficients for manufacturing and construction are 29.77 and 17.59, respectively, demonstrating strong upstream supply-chain water pull effects and serving as critical intermediaries for implicit virtual water flows.

2) Inter-city virtual water flows are substantial, illustrating Northeast China's clear identity as a net resource exporter. Total inter-city virtual water flows within

Northeast China reach $230 \times 10^8 \text{ m}^3$, representing 41.1% of actual regional water use. This total excludes exports outside Northeast China; such exports require separate accounting, indicating that while Northeast China secures national food and energy security, it bears substantial implicit costs associated with trans-boundary water transfers.

3) Inter-city virtual water transfers display a polarized “core-periphery” spatial pattern. The three hub cities—Changchun, Harbin, and Dalian—have combined net inflows of $27.99 \times 10^8 \text{ m}^3$, accounting for 79.2% of the total positive net inflow. Conversely, 26 agricultural and resource-based cities (e.g., Jiamusi, Jixi, Qiqihaer) serve as primary net exporters, reflecting how urban hierarchy and spatial division of labor shape virtual water directionality.

4) Virtual water flow networks exhibit marked intra-provincial self-containment and unipolar/bipolar clustering. Heilongjiang, Jilin, and Liaoning are dominated by intra-provincial flows, with inter-provincial flow intensity remaining weak. Trade in water-intensive products relies heavily on intra-provincial supply chains, creating implicit administrative barriers to regional water allocation optimization.

Based on these findings, the following policy recommendations are proposed to promote coordinated regional water development across Northeast China:

1) Implement differentiated, sector-specific water conservation strategies. Given agriculture’s high direct water reliance and industry’s high indirect inducement, traditional end-of-pipe agricultural water conservation must be integrated with green supply-chain management in manufacturing. Major agricultural cities such as Jiamusi and Qiqihaer should accelerate high-efficiency water-saving irrigation and modern irrigation infrastructure upgrades. In industrial hubs like Changchun, Harbin, and Dalian, water-saving standards should be established across full product lifecycles to reduce secondary manufacturing reliance on water-intensive upstream inputs.

2) Establish a trans-boundary virtual water ecological compensation mechanism. High virtual water demand from core cities on peripheral agricultural and resource-based regions represents structural resource support provided by peripheries to sustain core development. A “Virtual Water Ecological Compensation Fund” should be explored, funded by net virtual water importers (Changchun, Harbin, Dalian) to compensate net exporters (Jiamusi, Jixi). Through fiscal transfer payments, joint industrial development, or technical assistance, ecological and water resource pressures in resource-exporting regions can be effectively alleviated.

3) Dismantle administrative barriers to build an integrated regional water governance system. To address weak inter-provincial flows and provincial self-containment, industrial layout and water allocation across the three provinces should be holistically planned under the Comprehensive Revitalization Strategy of Northeast China. Inter-provincial supply chain integration should be encouraged to facilitate the scientific gradient transfer of water-intensive industries based on re-

gional water carrying capacities, driving a paradigm shift from “intra-provincial self-circulation” to “regionally optimal allocation”.

Acknowledgements

The author thanks the China Carbon Emission Accounts and Datasets (CEADs) for providing the city-level multi-regional input-output data, and the relevant water resources bulletins for providing water use data. In addition, the author appreciates the academic support provided by Liaoning Normal University. Special thanks are given to all individuals and institutions that contributed to data collection and processing for this study.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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