Spatiotemporal variations of water resources metabolism efficiency in the Beijing-Tianjin-Hebei region, China

Lihong Meng, Dewei Yang, Zhiyong Ding, Yuandong Wang and Weijing Ma

ABSTRACT

Intensive and extensive water consumption and its potential negative impacts are increasingly challenging regional development in the Beijing-Tianjin-Hebei region (BTH). It is necessary to enhance the metabolic efficiency of both physical and virtual water, and the latter is often neglected in research and practical fields. The material flow analysis method was employed in evaluating spatiotemporal variations of the Water Resources Metabolism Efficiency (WME) for exploring the inherent driving mechanisms in the BTH region. Results indicate that the WME increased obviously and differently in Beijing, Tianjin and Hebei, as well as in the whole BTH region from 1990 to 2015. The changes in WME depend significantly on the improvement in society and economics. Water production and water consumption are crucial for the integrated metabolic efficiency of physical and virtual water, followed by other influencing factors, i.e., freshwater recycling use ratio (R_{fw}), total retail amount of commodities of unit water use (C_w), and industrial output value per cubic metre of water resources (U_{io}). The results could provide alternative references for efficient and effective utilization of water resources within and beyond similar cities.

Key words | Beijing-Tianjin-Hebei region, material flow analysis, spatiotemporal variations, virtual water, water resources metabolism efficiency

Lihong Meng (corresponding author)
Yuandong Wang
College of Geography and Environment Project,
Gannan Normal University,
Ganzhou 341000,
China
E-mail: *mlh8158@163.com*

Dewei Yang
School of Geographical Sciences,
Southwest University,
Chongqing 400715,
China
and
Key Lab of Urban Environment and Health,
Institute of Urban Environment, Chinese Academy of Sciences,
Xiamen 361021,
China

Zhiyong Ding
State Key Laboratory of Earth Surface Processes and Resource Ecology, Faculty of Geographical Science,
Beijing Normal University,
Beijing 100875,
China

Weijing Ma
Faculty of Geography,
University of Marburg,
Marburg 35032,
Germany

INTRODUCTION

Water is essential in maintaining the sustainable development of regional societies and economies, as well as for upholding complete cycles in regional natural ecosystems (Su *et al.* 2017). However, in recent years, due to the impacts of climate change and intensive human activities, people all over the world are facing water scarcity and water pollution (Vörösmarty *et al.* 2000). Water scarcity is the lack of freshwater resources to meet water demand, which occurs in each continent and was listed as one of the largest global risks in terms of potential impact over the next decade by the World Economic Forum in 2015. According to the China Water Resources website, China is desperately short of freshwater, with a per capita volume of freshwater which is less than one quarter of the global average. Among all of the 669 cities in China, 440 cities are lacking water, and 110 are suffering from severe water shortages, especially in the Beijing-Tianjin-Hebei (BTH) region which is suffering increasingly serious water shortage problems. According to the statistics, the per capita water resource is only 286 m^3, far below the per capita water resource of 500 m^3 in China, which is internationally recognized as the 'extreme water shortage standard' (Bao & He 2017). Thus, it is imperative to efficiently utilize water resources to maintain a sustainable water supply. The enhancement of Water Resources Metabolism Efficiency (WME) could reduce water resources input and alleviate the environmental pressures. It is necessary to optimize water resource metabolism

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processes and structures and reform human production and consumption behaviors.

'Metabolism' is a concept that was first developed to describe the flows of energy and materials in biological systems (Yang *et al.* 2014a). In the wake of long-term research development, metabolic theory began to be quantitatively applied to present exchanges of materials and energy between humans and natural systems, and to quantify the scale and composition of a social metabolic system and its relationship with economic growth and environmental impacts (Huang & Hsu 2003). Earlier Wolman (1965) proposed the concept of urban metabolism, considering a city to be an ecosystem and its metabolism deemed as a process of supplying materials and energy to the urban system as inputs ('food') and producing outputs (products and wastes). The relationship between resources and wastes resulted from their consumption, highlighting the importance of metabolic processes as a tool for understanding the functions of cities. Previous research focused on the accounting and evaluation approaches for typical cities, such as American cities (Wolman 1965), Hong Kong (Warren-Rhodes & Koenig 2001), and so on. Subsequently, research into urban metabolism was conducted in China, e.g., Shenzhen (Yan *et al.* 2003), Beijing (Zhang & Yang 2007), Dalian (Liu *et al.* 2013), and Xiamen (Yang *et al.* 2014b). A city needs the inputs of materials and energy, and discharges a variety of metabolites as a metabolic system. 'Urban metabolism efficiency' can be used to measure the ratio of such inputs and metabolites (Vogtländer *et al.* 2002). Early research into urban metabolism and efficiency was carried out in western developed countries. In China, the earliest studies of urban metabolism efficiency were conducted in Hong Kong and Taipei (Warren-Rhodes & Koenig 2001), then Xiamen (Yang *et al.* 2012), and other Chinese cities. For example Liu (2010) evaluated the urban material metabolism efficiency of 34 Chinese cities based on the DEA-Malmquist method from 2005 to 2007. Song *et al.* (2013) investigated the metabolic efficiencies of 31 Chinese cities in 2010 by the Principal Component Analysis and Data Envelopment Analysis (DEA).

As one of the crucial metabolic materials, water received special attention (Tambo 2004). The concept of water metabolism was proposed to indicate the process of water supply, consumption and discharge in a region or a city in 1999 (Hermanowicz & Takashi 1999). Water resources metabolism can be regarded as a process where water resources are put into a regional socio-economic system, along with the output of by-products and pollutants. Scholars have attempted to analyze water resources metabolism. For example, Qian *et al.* (2000) analyzed the metabolic process of ground water and established the ultimate metabolic equation of ground water from the systematic point of view. Danbao (2002) indicated that the water pollution of an urban system was the consequence of urban material metabolism imbalance. Renouf *et al.* (2017) evaluated the extent to which plans are supported between land-use and water resource sectors. However, the above mentioned studies have mainly focused on physical water metabolism, and few studies have simultaneously considered the metabolic process of virtual water. Although scholars carried out various analyses, such as water consumption (Zhang *et al.* 2019), optimal allocation (Ye *et al.* 2018), and water flows (Porkka *et al.* 2012), taking physical and virtual water into consideration, studies on the spatiotemporal changes of water resources metabolism efficiency associated with physical water and virtual water have been rarely reported.

Therefore, to fill the above-mentioned gaps, this paper aims to analyze the spatiotemporal variations of the WME of the BTH region in China from 1990 to 2015, where water resources utilization which had reached or exceeded its thresholds can constrain socio-economic development. The WME reflects the holistic efficiency of physical and virtual water, including water production, consumption and decomposition efficiency from a process-oriented perspective. Our research objectives include: (1) the metabolic processes of regional physical water and virtual water are identified for integrated metabolism; (2) an integrated indicator system consisting of thirteen indicators using the Material Flow Analysis (MFA) method is constructed for linking water resource processes in the society, economy and environment; (3) an Analytic Hierarchy Process (AHP) model is employed to calculate their weights. Finally, the spatiotemporal changes of the WME are analyzed using the statistical data of the BTH region during 1990–2015 for exploring the driving mechanism in the WME. This study could provide a scientific reference for the efficient utilization of water resources in the BTH region of China, and also have the potential for application in other areas and on other scales for water resources metabolism evaluation and comparison over time.

MATERIALS AND METHODS

Case study

The BTH region is located in northern China, which includes two municipalities (Beijing, Tianjin) and one province (Hebei), as shown in Figure 1. Beijing is the capital and the center of politics, economics and culture of China, and the host city of the 2008 Olympic Games. Tianjin is the third largest city and the second largest port city following Shanghai. Hebei is an important industrial province. As a core area of economic development in China, the BTH region has a long history of industrial and urban development, covering 2.2% of the total area of China, while generating over 10% of the total national GDP in 2010 (Zhao *et al.* 2018). However, as the population has grown in recent years, the BTH region has become one of the regions with the greatest water scarcity in China. The average annual precipitation is 538 mm, and the average volume of water resources per capita is 345 m^3 in Beijing City, 279 m^3 in Tianjin City, and 307 m^3 in Hebei Province, which is less than 1/7 of the average amount in China (Gao *et al.* 2014). According to a report by the UN in 2013, an area is experiencing water stress when annual water supplies

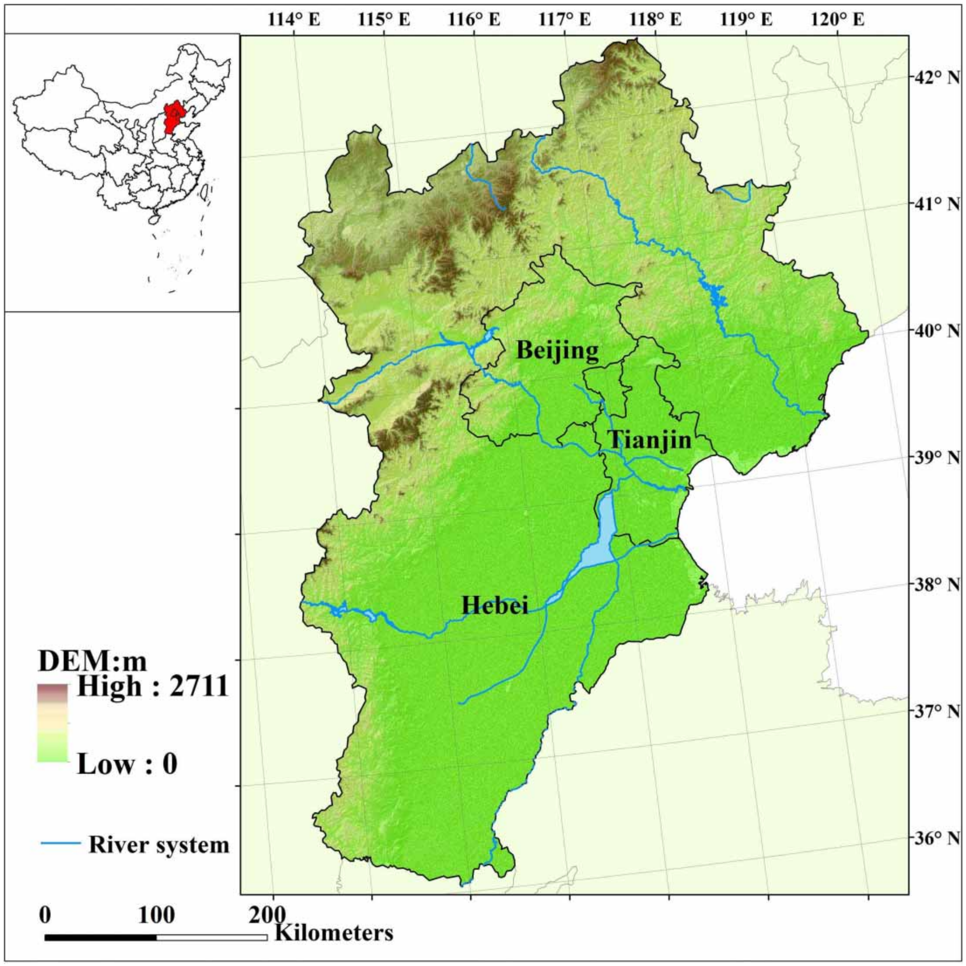

Figure 1 | Location of the Beijing-Tianjin-Hebei region, China.

drop below 1,700 m^3 per person. When annual water supplies drop below 1,000 m^3 per person, the population faces water scarcity, and below 500 cubic metres "absolute scarcity". The entire BTH region is at the absolute scarcity level. Thus, it is clear that the conflict between water supply and demand will intensify due to water scarcity and increasing socio-economic demands.

Data collection

The 468 basic data points for 13 indicators in this paper, including water process, socio-economic, and environment data, were collected from the BTH region at intervals of 5 years (1990, 1995, 2000, 2005, 2010 and 2015). The socio-economic data are all obtained from the Statistical Yearbooks of Beijing, Tianjin, Hebei province and China, respectively (NBSC 1990–2015). The water resources and environment data are obtained from the Water Resources Bulletin of Beijing, Tianjin, Hebei province and China during 1990–2015, respectively (MWRC 1990–2015). The rest of the data are from the Thematic Database for Human-earth System.

Methodology

Metabolic process of regional physical and virtual water

Water, consisting of physical and virtual water, is both an economic and natural resource. The regional water cycle is a metabolic system dominated by humans (Tambo 2004). The degree to which regional water demand can be met depends on the quantity and quality of physical and virtual water. To understand the sustainability of regional water use, it is necessary to simultaneously consider the metabolism of both physical and virtual water. Understanding the integrated metabolism of physical and virtual water is crucial for the human-environmental system. It is necessary to identify the metabolic processes of physical and virtual water to build the indicators system of the WME (Figure 2).

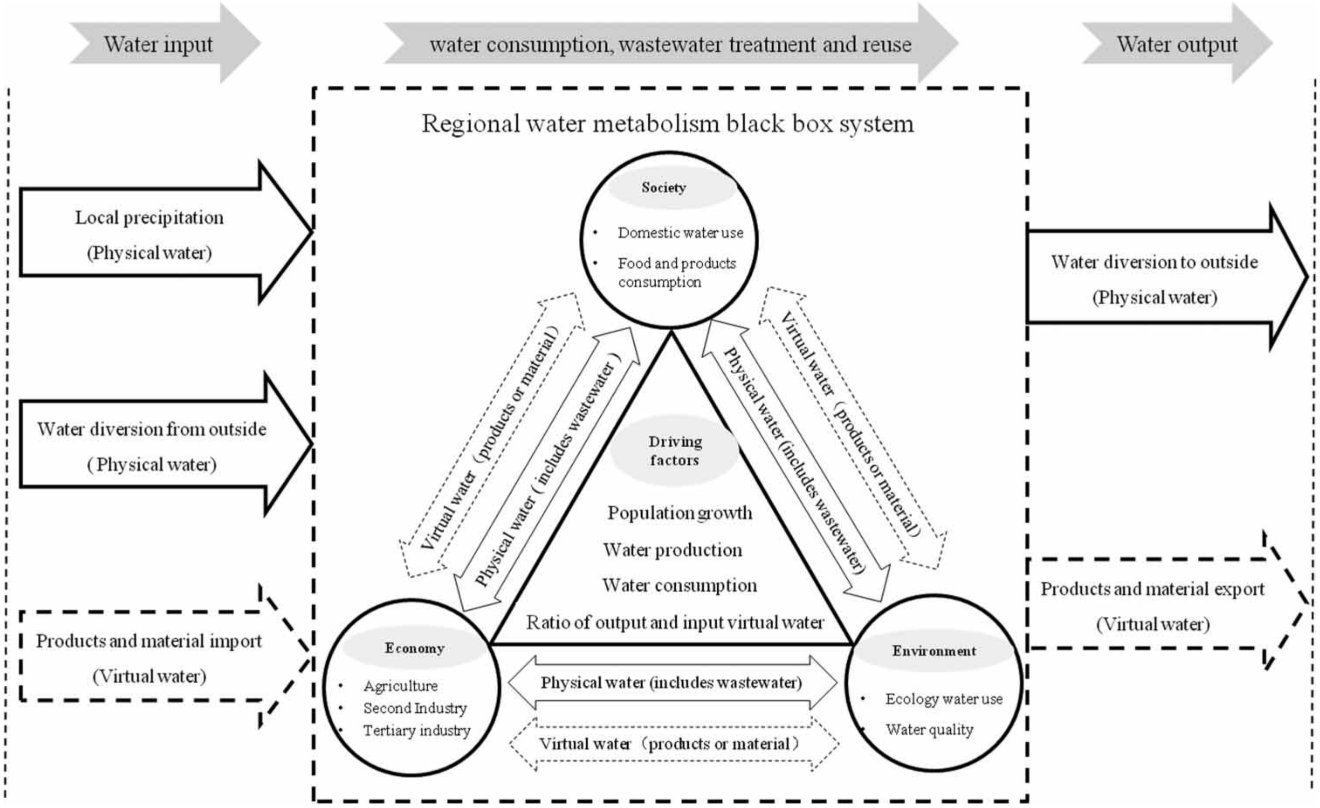

Figure 2 | Metabolic processes of regional physical and virtual water.

Indicator system of the WME

The indicator system of regional water resources metabolism should reflect the coordinated development of regional water supply and socio-economic demand. The indicator system should also provide scientific guidance for water resources management. A rational system will provide reliable evaluation results. The evaluation indicators of WME were extracted using the MFA method.

The MFA method provides a broad scope of accounting analysis in environmental-economic systems. The MFA can depict the flows and stocks of substances or materials in a system at a clearly defined point in space and time. The law of mass conservation forms the basis for conducting MFA, therefore materials balance of inputs, stocks and outputs are the main strategies of MFA, which can trace the process and pattern of water resources extraction, utilization and consumption, and can also trace the flow and distribution of virtual water resources (Gautam *et al.* 2014).

The integrated metabolism efficiency of physical and virtual water flows are reflected from water production, consumption and decomposition efficiency. In accordance with the water resources metabolism theory, the evaluation indicator system comprises four indicator clusters, i.e., water process, society, economy, and environment. The system reflects the water resources conditions, water resources supply, socio-economic development and eco-environment settings. The evaluation indicator system of regional water resources metabolism is shown in Table 1.

Evaluation of the WME

Normalization of indicator value. The influencing factors of WME were normalized to eliminate disturbance of various units (Pollescha & Dale 2016). The normalization methods are expressed as follows:

For positive indicators:

$$S_i = (x - X_{\min})/(X_{\max} - X_{\min}) \quad (1)$$

Table 1 | Indicator system and weights of regional WME

Indicators Classification	Indicators	Formulas	Unit
Water Process (0.154)	Freshwater recycling use ratio/R_{fw} (0.365, positive)	Waste water/Total fresh water	%
	Waste virtual recycling use ratio/R_{vw} (0.291, positive)	Waste virtual recycling amount/Total waste virtual water	%
	Ratio of output virtual water and input virtual water/IE_{vw} (0.078, positive)	Output virtual water/Input virtual water	%
	Industrial water ratio*/R_p (0.076, negative)	Industrial water/Total water use	%
	Ratio of ecological water use/R_e (0.190, positive)	Ecological water use/Total water resources	%
Society (0.430)	Level of population development/P (0.130, positive)	Population growth rate + Growth rate of students per million people	%
	Total retail amount of commodities of unit water use/C_w (0.641, positive)	Total retail amount of commodities/Total water consumption	Yuan/10^4 m^3
	Supported population per cubic metre water resources/P_{lw} (0.229, positive)	The population at the end of the current year/ Total domestic water use	person/m^3
Economy (0.168)	Irrigation area per cubic metre water resources/ U_{ai} (0.748, positive)	1/Agricultural water use per hm^2	m^2/m^3
	Value of industrial output per cubic metre water resources/U_{io}(0.252,positive)	1/Water use per 10,000 Yuan industry gross production	Yuan/m^3
Environment (0.248)	Forest coverage/Fc (0.126, positive)	Forest coverage/Total land area	%
	Runoff/E_p (0.220, positive)	1 – (Precipitation – total water resources)/ Precipitation	%
	Quality of water environment/Q_{we} (0.654, positive)	Wastewater discharges/Total water resources	%

Note: * A lower value means better water resources conditions. For the other indicators, a higher value implies better water resources conditions.

For negative indicators:

$$S_i = (X_{\max} - x)/(X_{\max} - X_{\min}) \tag{2}$$

where S_i is the standard value after being processed, x is the actual value of X, X_{max} is the maximum reference value, $X_{\min}$ is the minimum reference value.

Weighting factors. The Analytical Hierarchy Process (AHP) method is a multi-criteria decision-making technique, which provides a systematic approach for assessing the impact of various parameters. The AHP method allows us to combine data from various scientific fields. The AHP method provides a comprehensive framework to structure a decision-making problem, linking overall goals by a criterion, and assists decision-making where there are multiple and even competing objectives.

The AHP method is composed of three steps (Ayla 2015). The first step is to decide the hierarchical objective of the decision-making problem. The second step is to create decision tables at each hierarchical level. At the third step, the total rating of all hierarchical objectives follows the rating of each objective in accordance with the corresponding criterion. In this study, the weights of various fields, i.e., water resources conditions, water resources supply, socio-economic development and eco-environment settings, reflect their level of importance for the WME. The weights of the social field and the environmental field account for the greatest contribution to the WME, which can embody sustainable utilization of water resources in the biosphere.

Evaluation model. In order to avoid individual indicators affecting the whole function of the index system, we use a weighted summation method to evaluate WME. The method is as follows:

$$A_j = \sum_{k=1}^{4} w_k B_{kj} \tag{3}$$

$$B_{kj} = \sum_{i=1}^{n} w_{ki} s_{ij} \tag{4}$$

where A_j is the WME, w_k is the weight of the region k, B_{kj} is the indicator of the region k in the year j, w_{ki} is the weight of the index i in the region k, s_{ij} is the normalization value of the index i which belongs to the region k in the year j, n is the number of indicators in the region k.

RESULTS

Temporal changes of the contribution indicators in the BTH region

Figure 3 shows the contribution value of different indicators to the WME. As far as Beijing is concerned, the contribution of indicators, i.e., water process, economy and society, increased obviously from 1990 to 2015, with an increase of 100%, 359.7%, and 182.2%, respectively. However, except for the decrease in 2000, the contribution of environment indicators remained relatively stable (Figure 3(a)). In Tianjin city, the contribution of water process and society increased obviously from 1990 to 2015, especially the contribution of society, which increased by 311.5%. The contribution of economy and environment remained relatively stable (Figure 3(b)).

In Hebei province, the contribution of economy and society increased by a certain level from 1990 to 2015, with an increase of 165.25% and 64.7%, but apparent variations can not be observed from the contribution of water process and environment (Figure 3(c)). As for the BTH region, the contribution of water process, society and economics increased obviously, especially the value of society, with an increase of 260.22%. The contribution value of water process and economics increased by 124.02% and 57.92%, respectively. However, the contribution of environment decreased from 0.602 in 1990 to 0.460 in 2015 (Figure 3(d)). It is clear that the increase of indicators in society is far greater than the indicators in other clusters. For the whole region, the contribution of environment remained relatively stable or decreased to some extent, which indicates that the increase of the WME in economy and society is at the expense of environmental benefits. There remains a conflict between socio-economic development and environmental protection.

Spatiotemporal variations of the WME in the BTH region

As shown in Figure 4, the spatiotemporal variations of the WME were examined in the BTH region from 1990 to 2015

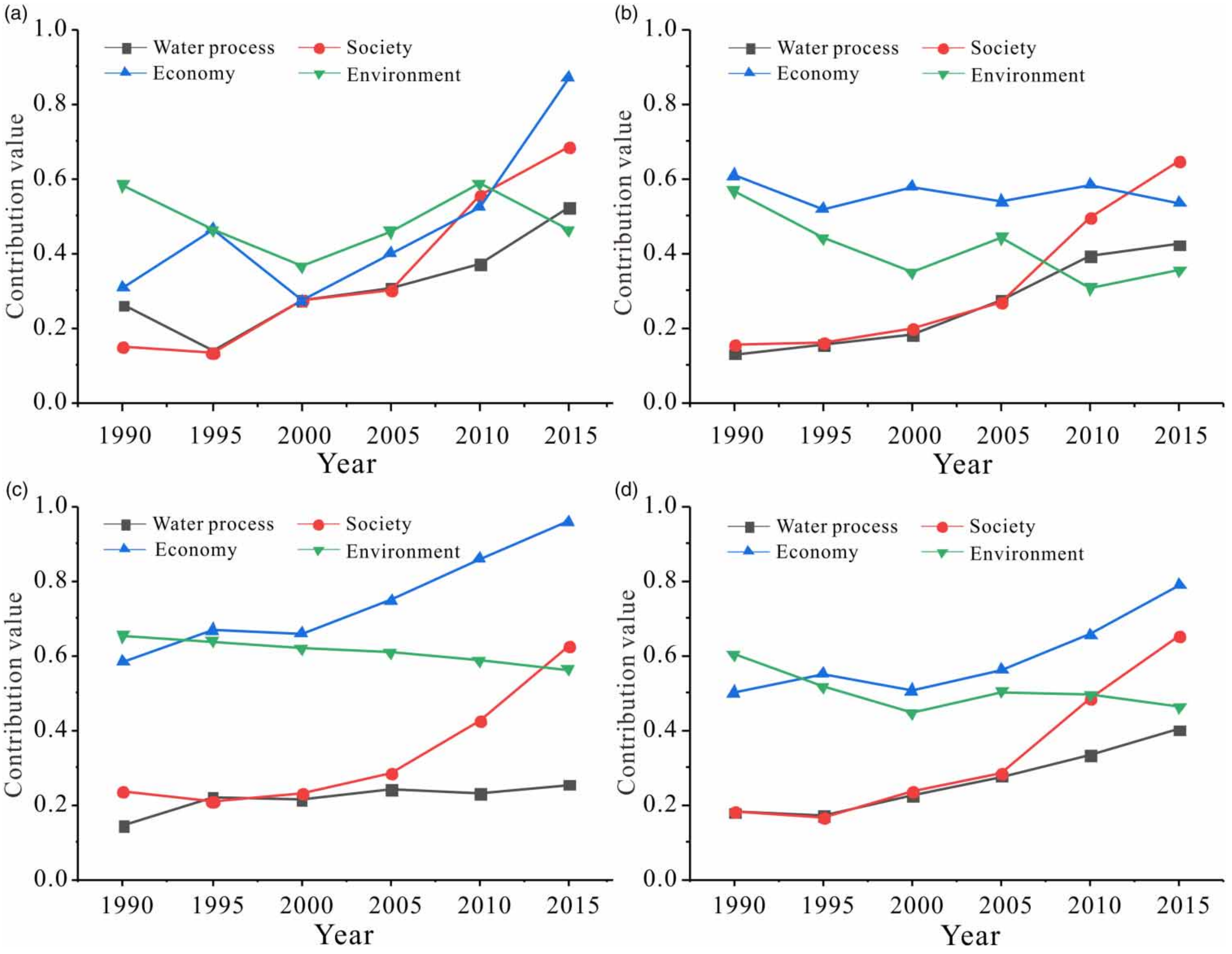

Figure 3 | Temporal variations of the contribution of specific indicators in the BTH region. (a) The contribution value of indicators in Beijing. (b) The contribution value of indicators in Tianjin. (c) The contribution value of indicators in Hebei province. (d) The contribution value of indicators in HBT.

at intervals of 5 years. At the temporal scale, the WME increased obviously in Beijing, Tianjin, Hebei and the whole BTH from 1990 to 2015. The value of Beijing city increased by 112.66% during the last 20 years, along with 57.09% in Tianjin city and 59.01% in Hebei province respectively. As for the whole BTH region, the value of water resources metabolism changed from 0.338 in 1990 to 0.589 in 2015 due to the improvement of contribution in society and economics. At the spatial scale, the spatial differences of the WME are obviously observed in the BTH region. The WME of Hebei and Tianjin is higher than that of Beijing city from 1995 to 2005. However, the WME of Beijing city and Hebei province is higher than that of Tianjin city from 2010 to 2015.

Driving factors of the WME in the BTH region

It is a challenge to understand the natural water circulation system due to its complexity, variability, uncertainty and the information available. The enhancement of WME is strongly associated with human behaviors and management rather than natural conditions during the water cycle. In addition, the increase of WME depends mainly on the improvement in society and economics in the BTH region.

The correlation between WME and all the evaluation indicators show that the most significant influencing factors are R_{fw}, C_w and U_{io}, with the correlation coefficients of 0.959, 0.979 and 0.984, respectively (Figure 5(a)).

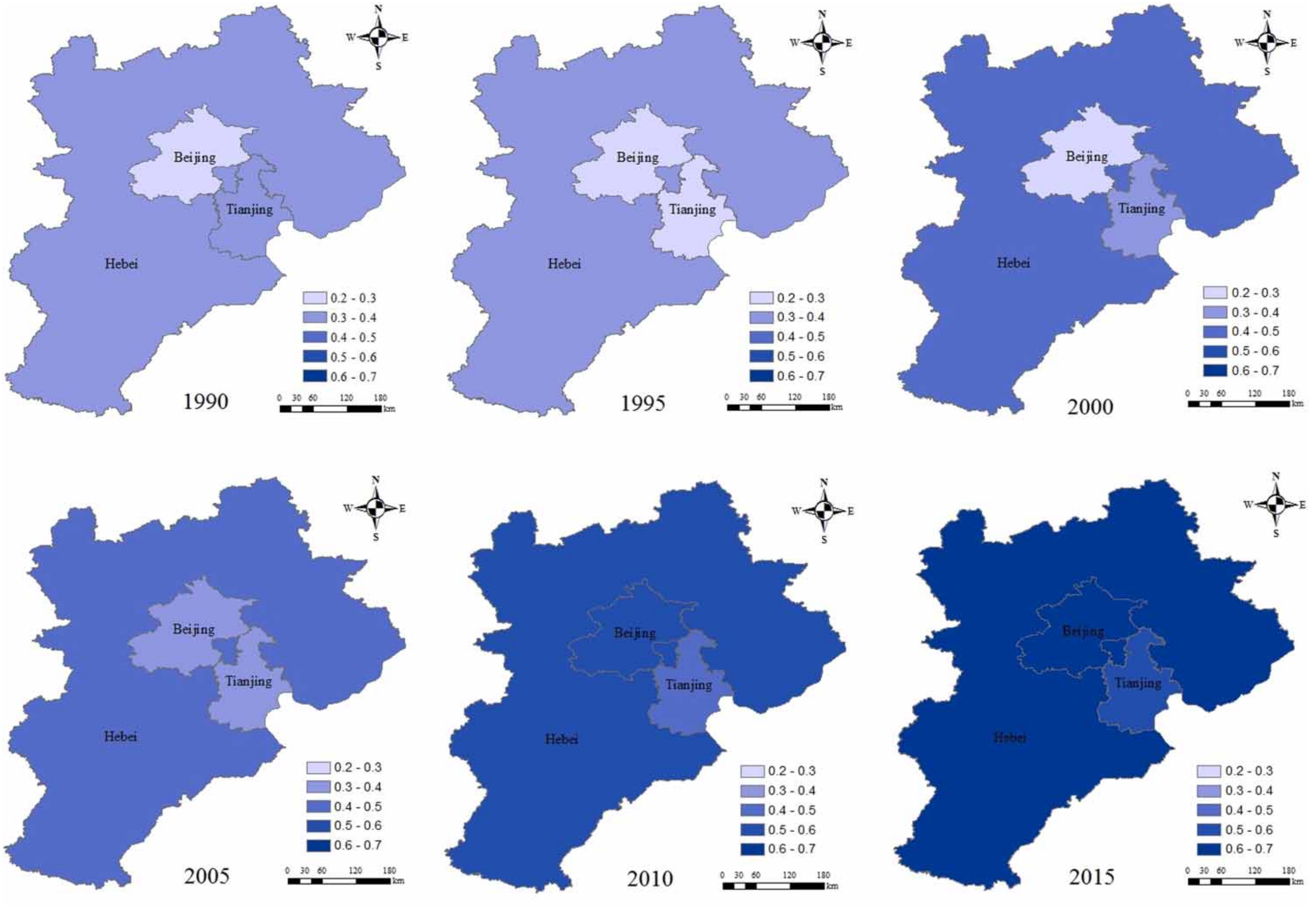

Figure 4 | Temporal and spatial variations of water metabolism efficiency in the BTH region.

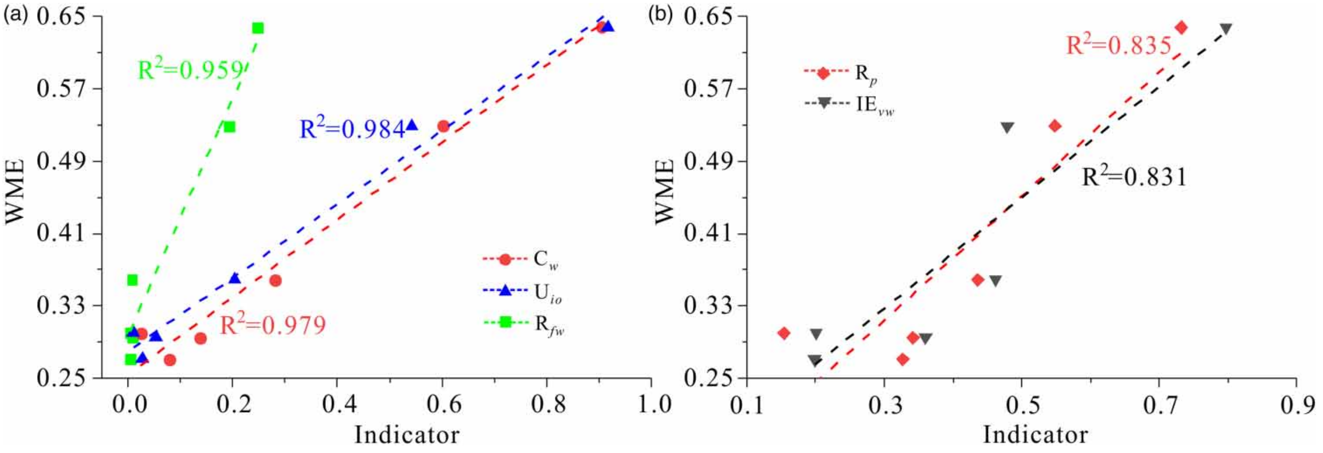

Figure 5 | Correlation between the most significant indicators and WME.

Other important indicators, such as IE_{vw} and R_p, have correlation coefficients of more than 0.8 (Figure 5(b)). Therefore, the key factors driving the coupling metabolism efficiency of virtual water and physical water are water production, water consumption and water discharge.

The supply of water resources includes the production of virtual water in domestic and industrial sectors. The structure of virtual aquatic products depends on the trade, consumption and conditions of virtual water in the study area (Feng *et al.* 2007).

Therefore, the domestic consumption, the trade volume and the structure of virtual water at home and abroad contribute significantly to the WME. The treated wastewater can recycle in the socio-economic system and enhance the self-cleaning capacity of the natural water circulation. The virtual water from treated wastewater is determined by the treatment technologies and the fate of pollutants in the wastewater.

DISCUSSION

The spatiotemporal variations of the WME are analyzed for the BTH region from 1990 to 2015. Our results reveal that the WME is associated with many factors in the BTH region, especially the improvement in society and economics. Previous studies provided valuable references in water resources metabolism (Kennedy *et al.* 2011), metabolic processes (Liang & Zhang 2012), and water metabolism communication (King *et al.* 2019), without simultaneously considering physical and virtual water resources (Zhang *et al.* 2013). This requires understanding the integrated metabolism of physical and virtual water as well as their availability. Due to the balance of both physical and virtual water, the water circulation analysis should combine them for promising results.

There are few examples available in the literature on both physical and virtual water (Miina *et al.* 2012; Ye *et al.* 2018), which allows the creation of a novel and integrated study on a time-space scale. The spatiotemporal variations of the WME and driving factors are investigated using the proposed indicator system and the AHP method in the BTH region. The correlation analysis shows the main driving factors of the WME are associated with R_{fw}, C_w, U_{io}, IE_{vw} and R_p. Thus, feasible water-saving management should conserve water from the source and encourage comprehensive socio-economic actions.

(1) Plans for population size and industrial development

In the process of rapid urbanization in the populous BTH region, scientific control of the population size is necessary according to the conditions of water resources. In terms of industrial development, Beijing and Tianjin should be encouraged to develop high value-added industries and high-end service industries, and to transfer high-water-consuming industries to the peripheral regions. For Hebei Province, which has a high proportion of agricultural water use, it is vital to adjust the scale and structure of the planting industry while vigorously developing high-efficiency water-saving agriculture.

(2) Red line policy for water resources management

The Beijing-Tianjin-Hebei region is one of the significant engines for China's economic development and one of China's major grain-producing regions. It would inevitably weaken sustainable development under the mode of extensive water use due to the lack of a stringent water management system. Therefore, the red line sector objectives of water resources use should be set for meeting the needs of economic and social development without causing the ecological environment to deteriorate.

(3) Improvement of the water circulation

In order to improve the metabolic efficiency of the water circulation system in the Beijing-Tianjin-Hebei region, it is crucial to update technologies of wastewater discharge, recycle water and reduce water use for the improvement of the WME. Furthermore, the government should encourage the development of environmentally friendly fields, e.g., cleaner production, industries which consume less water, and a low-pollution economy.

Future study of the WME should focus on: (1) Discovering the inherent metabolic links influencing water consumption; (2) Simultaneously considering the driving factors from human-environmental perspectives; (3) Optimizing processes of water production, water consumption and water discharge; (4) Providing new insights from intercity comparisons.

CONCLUSIONS

The extensive consumption of water resources are a challenge for rapid development in the BTH region. The integrated indicator system of physical and virtual water metabolism is established using the MFA method from the aspects of water process, society, economy and environment. The indicator system is employed to analyze the spatiotemporal variations and driving forces of physical and virtual WME in the BTH region in China from 1990 to 2015. Results show:

(1) During 1990–2015, the contribution of water process, society and economics increased obviously in the BTH region. However, the contribution of environment decreased from 0.602 in 1990 to 0.460 in 2015.
(2) On the time scale, the WME increased obviously in Beijing, Tianjin, Hebei and the whole BTH from 1990–2015 attributable to the improvement of society and economics.
(3) On the space scale, the variation in WME in the BTH region was obvious. The WME of Hebei and Tianjin is higher than that of Beijing city from 1995 to 2005. However, the WME of Beijing city and Hebei province is higher than that of Tianjin city from 2010 to 2015.
(4) Results also indicated that the increase of water resources metabolism efficiency mainly depended on the improvement in society and economics in the BTH region. The correlation between WME and all the indicators shows the significant influencing factors were R_{fw}, C_w, U_{io}, IE_{vw} and R_p. Therefore, the key factors that drive the coupling metabolic efficiency of virtual water and physical water are mainly water production, water consumption and water discharge.
(5) Measures for the enhancement of the WME in the BTH region are proposed, including plans for population size and industrial development, red line policy for water resources management, and the improvement of water circulation.

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