How Can City's Water Resources Pressure be Alleviated? from the Perspective of Critical Path Water Resources Management

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How Can City's Water Resources Pressure be Alleviated? from the Perspective of Critical Path Water Resources Management

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ABSTRACT

The pressure on water resources as a result of the socioeconomic system has caused more attention to be paid to the consumption of water resources and the indirect consumption of intermediate inputs; the mitigation of pressure on water resources and its key transmission sector has been less explored. This paper, which is based on water-expanded input–output data from 2002, 2007, and 2012 in Beijing, identifies the key transmission sector for water consumption and its annual dynamic changes with a Betweenness-based method and analyzes specific categories of features of industrial water resource consumption by using a method with hierarchical clustering and typology. The results show that there are significant differences in the water consumption rankings measured with the Betweenness-based method and other traditional input–output indexes. The Betweenness method provides additional information on the key transmission sectors of water use that were unobservable with traditional metrics. Furthermore, the sectors with high betweenness-based water consumption changed from traditional heavy industries, such as the mining sector and paper printing, to the modern manufacturing industries, which were dominated by the communication, automobile, electronics, and high-technology service industries and were led by commercial, research and development, and information services from 2002 to 2012. Finally, the results of hierarchical clustering and typology method showed that the sectors corresponding to Category 1 and Category 2 were the key transmission sectors for water consumption in the economic system, and they need more attention. This research suggests that water resource management policies should be formulated for the key transmission sectors in order to alleviate the pressure from water resource shortages.

Keywords:betweenness; input–output; supply chain path; water resource stress; Beijing

1 Introduction

Water is an important natural resource for sustainable economic, social, ecological development; the alleviation of the pressure on water resources has become one of the most challenging issues in the world (Oki and Kanae, 2006; Han et al. 2020; Huang et al. 2021). China is one of the thirteen water-poor countries in the world, and its per capita water resources are less than a quarter of the world's average per capita level. Beijing is the capital of China, as well as the developmental center for the economy, politics, and culture. However, its annual per capita water resources (surface water and groundwater) do not exceed 150 m^3, which is only 1/15 of the national average and far less than the international water shortage threshold (1700 m^3/per capita) (Wang et al. 2019), placing it in the severe water shortage category. At the same time, Beijing's economy has grown by 1.678 trillion yuan in the past decade, and the population has grown by 5.9 million. Hence, the economic development and expansion of the population pose a great challenge for the carrying capacity of the water resources, and the pressure on the water resources must be alleviated. The pressure on water resources comes from the contradiction between the supply of and demand for water resources. The supply side pressure comes from an insufficient and unstable supply, and the demand-side pressure is mainly caused by people's increasing demand for water resources. Meanwhile, the internal contradictions of the demand side are growing, and production, life, and ecological use of water compete with one another. The industrial sector of the economic system is the most basic element of water use and allocation, and the industrial causes of water stress stem from two aspects: on the one hand, the direct water consumption of industrial development itself, and on the other hand, water use of upstream and downstream industrial sectors—namely, indirect water consumption. As key transmission centers in the middle of the supply chain, these upstream and downstream industrial sectors play a crucial role in reducing the pressure on water resources. Water resources are an indispensable input factor for economic and social development and for the protection of the ecological environment, and excessive loads placed in these water resources will hinder the speed of economic and social development. The identification of the transmission sectors of water use and the supply chain paths in the socioeconomic system will more precisely inform water management policies or regulations in specific industrial sectors, reduce the water resource pressure in the industrial sectors and the region in response to the consumption of water resource and the intensity of the double control strategy, and promote the sustainable development of water resources.

In order to identify the sectors with the highest resource consumption and environmental pressure, the existing literature has mostly explored important sectors from the production side, the consumption side, or both based on environment-extended input–output tables (Peters 2008; Lenzen et al. 2014; Gerbens-Leenes et al. 2013), but relatively rare has the perspective of supply chain paths been used, and the transmission sectors, which are equally important in easing environmental stress, are often overlooked. Consumption-based methods generally use the environmental pressure from the supply chain upstream of the terminal product, that is, the environmental pressure from all supply chain paths starting from the sector, in order to show the importance of the sector as a direct user or consumer. Production-based methods commonly use environmental pressure from the downstream supply chain path in order to describe the importance of the final production stage of the supply chain (Freeman 1978; Gui et al. 2014). In order to solve the issue of environmental pressure in the supply chain, the economic activity at the terminal or starting point of a supply chain path is usually connected with the environmental pressure resulting from the supply chain's starting point or terminal. The definition of a supply chain path comes from the structural path analysis (SPA) model, which defines it as equal to the total environmental pressure in all sectors from the beginning to the end of the supply chain (Freeman et al. 1979; Freeman et al. 1991). Based on the idea of the supply chain path, Freeman proposed the Betweenness method in 1991. This method identifies the key sectors with respect to resource consumption by accounting for the environmental pressure from all industrial chains that pass through one sector in the supply chain path. It tries to alleviate the environmental pressure from the perspective of the key transmission sectors for resource consumption. This method further improves the calculation of the environmental pressure from resource consumption. It is based on the network analysis method, in which each industry or sector is a node in a network, and the relationships between the industries or sectors engaged in water resource consumption are the lines of the network. The nodes and lines in the network constitute the network of water resource consumption in the industrial sector (Freeman et al. 1978). The Betweenness method is usually used in conjunction with an input–output network and the SPA model. Thus, an input–output network is different from the network analysis method. The difference is that the links between industries or sectors in an input–output network contain not only the direction of environmental pressure, but also the weight, and the resource consumption of a sector or industry also has a self-flow. The Betweenness method is mainly used to analyze the pressure of resource consumption in an industry or sector. For example, some scholars used a multi-regional input–output (MRIO) model considering the production and consumption sides in order to measure the dynamic changes in water consumption in 1995–2008 in the 27 European Union countries and found that the main reasons for the differences in results were the measurement methods (Serrano & Valbuena 2017). With the deepening of research and the improvement of the methods, scholars have found that the supply chain path method is more accurate than the traditional method in measuring the environmental pressure from economic activities. For instance, Zhang et al. (2017) compared three methods for measuring environmental resource pressure—namely, the production side, consumption side, supply chain path methods—and the results showed that, when measured from the perspective of the supply chain, the green productivity of light industries was lower than that measured with the traditional methods (Zhang et al. 2017).

The Betweenness method has been widely used to identify the negative externalities of economic behaviors and human activities on the environment. Most of its applications center on the field of energy consumption and emissions. For instance, Liang et al. (2017) calculated the carbon emission pressure of 135 sectors in China in 2007 based on the Betweenness method and found that, in terms of electricity and heat, steel processing in the metal production sector had the greatest energy savings and emission reductions (Liang et al. 2017). In addition, scholars explored the carbon emissions of China from 1992 to 2007 with the structural path decomposition approach from the perspective of the supply chain, and the results showed that the supply chain of the chemical industry's exports had the greatest impact on carbon emissions. Hanaka et al. (2018) studied 35 industrial sectors in 41 countries in 2008 by using supply chain network analysis and found that China's electronic and optical equipment sector was the most critical transmission sector in terms of environmental pressure (Hanaka et al. 2017). In addition, the key transmission sector in a supply chain network is defined as a sector with a large intermediary degree, which indicates that the terminal supply products in most sectors pass through that sector. Therefore, there is great pressure on environmental resources in transmission sectors. However, it is worth noting that the Betweenness method appeared very early, but its application in the field of water resource research started late, and the complication of water-extended input–output tables is the main reason (Zhao et al. 2017; Eisenbarth 2017). That is, the availability of water data in the industrial sectors of the socioeconomic system has hindered the progress of research on the application of the Betweenness method to the mitigation of pressure on water resources. Therefore, with the shortage of water resources and the aggravation of the water crisis, the research on the alleviation of pressure the impact of water resource consumption on the environment must urgently be enriched in order to provide scientific support for the efficient allocation and management of water resources.

In view of this, the paper will first consider the betweenness values of the water consumption of various sectors in order to identify the key transmission sector in the supply chain based on an extended water input–output table for the years 2002, 2007, and 2012, which is an extension of the accounting of Beijing's water resources, by using the path analysis model (SPA). Secondly, a comparative analysis of the differences in metrics is made among the betweenness and other traditional input–output indexes, such as production-based, consumption-based, income-based, and chain analysis indexes. Finally, the water characteristics of different departments are measured based on the hierarchical clustering method and a taxonomic approach, and strategies and policies for the mitigation of water resource pressure in specific sectors are formulated accordingly. This paper makes two major contributions: on one hand, it measures the water consumption based on the traditional input–output method from the perspective of supply chain path and through the identification of the key transport sector. The water resource pressure from transmission sectors in the supply chain can be identified, which is not possible with other traditional indicators. Therefore, this can help in informing scientific decisions concerning industrial development, industrial transformation, and management and allocation of water resources from the perspective of the whole industrial chain. On the other hand, the results of the analysis of water resource pressure and the cluster analysis can facilitate the formulation of a water resource management plan for specific industrial sectors or specific industries.

MATERIALS AND METHODS

Study area

Beijing is the capital of China and is in the north of China, at the northwest edge of the North China Plain. Its basic natural, social, and economic characteristics are described in Table 1. In terms of its rapid economic development and population growth, from 2002 to 2012, the average annual GDP increased by 3.3 times, the population increased by nearly 50%, and the industrial structure gradually transformed into a service-oriented model. At the same time, the demand for water resources continued to increase, and the average annual water resources increased by 13 million cubic meters in 2002–2012. From the perspective of water supply, Beijing is in a temperate, semi-arid, and semi-humid monsoon climate zone, and there are few rivers in the urban area. Therefore, Beijing's water resources are insufficient. In addition, the capacity of the sewage treatment facilities in Beijing is insufficient, and the support capacity of the water supply facilities is low. The safety factor of the urban water supply is only 1.06. From this point of view, the contradiction between the supply of and demand for water resources is becoming increasingly serious, and Beijing is facing a serious water resource crisis.

Table 1 Characteristics of natural, social and economy in 2002,2007 and 2012

Item	2002	2007	2012

population (million)	14.23	16.76	20.69
GDP (billion yuan)	413.50	984.70	1787.9
industrial structure	3.1:35.6:61.3	1.1:27.5:71.4	0.8:22.8:76.4
water usage (billion m^3)	3.46	3.48	3.59
per water resource (m^3)	113	45	191
area (km^2)		16410	

Note: 1USD ≈ 6.5 Yuan in 2012, The data is from Beijing Statistical Yearbook and Beijing Water Resources Bulletin.

Data resources

In order to calculate the water resource consumption of various sectors with the Betweenness method, this paper uses the water-extended input and output tables from 2002, 2007, and 2012. The correlations among some sectors are so strong that water consumption is difficult to distinguish, in addition to the difficulty of matching sectors between the IO table and water usage; thus, this study classifies the 42 sectors into 28 sectors, as shown in Table 2, based on the national economic industry classification (GBT4754-2008) and previous research (National bureau of statistics 2008).The water consumption data for each sector mainly came from data on freshwater in Beijing and the Beijing Water Resources Bulletin from 2002, 2007, and 2012 (Beijing Water Authority 2002, 2007, 2012). The agricultural water consumption data that came directly from the Beijing Water Resources Bulletin, the data for the industrial and tertiary sectors that referred to Beijing's main industrial water use quota (Beijing Water Conservation Office 2001), and the direct water consumption data for two types of sectors were adjusted according to the total amount of water and the rate of reuse of industrial water. In order to smooth the price fluctuations, the annual input and output tables for the years were adjusted to the comparative price in the baseline year of 2002.

Table 2. List of 28 sectors

No	Sector	No	Sector
1	agriculture	15	communications equipment, computers and other electronic equipment
2	Mining	16	instrument and meter
3	Food processing	17	other industrial
4	Textile	18	Electric power gas production and supply.
5	Textile clothing shoes and hats leather down and its products	19	The production and supply of water
6	Wood processing and furniture	20	building
7	Papermaking and teaching sports articles	21	Transportation, warehousing and postal services.
8	Petroleum processing and coking	22	Information transmission, software and information technology services.
9	Chemical industry	23	Accommodation and catering
10	Cement glass ceramics	24	business
11	Metal smelting and products	25	Scientific research and technical services
12	General purpose equipment manufacturing industry	26	Other sectors
13	Transportation equipment	27	Residents and other services
14	Electrical machinery and equipment	28	Health and social welfare

Methods

The concept of betweenness was derived from the network analysis proposed by Freeman in 1978 (Freeman 1978). Later, it was applied to an input–output network to study the resource consumption pressure from the industrial sector. In an input–output network, an industry or sector is a node in the network, and the associations of relations with respect to water consumption among the various industries or sectors are lines in the network; the points and lines constitute an associated network of the sectors' water resource consumption. Differently from the network analysis method, the lines in an input–output network that form the connections between points have both a direction and a weight, and the water consumption of a department or industry also has its own flow. The betweenness value of the water consumption of a sector in an input–output table is measured according to the sum of the water resource pressure of all the supply chains passing through the sector. The structural path analysis (SPA) model is adopted to extract a single supply chain path, and then the water resource pressure in the supply chain is used to measure the betweenness-based water consumption, followed by a check of each department based on the Betweenness method for water consumption. The pressure from water resource consumption in the input and output model of an economic system is calculated with equation (1).

$$wui = f(I - A)^{-1} y \tag{1}$$

where wui is the water resource pressure from sector i, the $1\times n$ row vector f represents the water resource pressure strength per unit of output, the $n\times n$ matrix A is the direct consumption coefficient matrix, the element a_{ij} represents the direct consumption of sector i per unit of production of sector j, the $n\times n$ matrix L is the Leontief inverse matrix, and y represents final product demand for each sector.

Furthermore, Taylor expansion is used to decompose the Leontief inverse matrix and obtain the supply chain path (Gui et al. 2014), as shown by equation (2), where each item on the equation's right side is in the production layer.

$$wui = f(I + A + A^2 + A^3 + \cdots)y = fy + fAy + fA^2 y + \cdots \tag{2}$$

The definition of betweenness is based on previous research (Liang *et al.* 2017), which showed that the betweenness value of the water consumption of a sector is the total water pressure of all the supply chains passing through sector i, as shown in equation (3).

$$b_i = \sum_{l_1=1}^{\infty}\sum_{l_2=1}^{\infty} b_i(l_1,l_2) = \sum_{l_1=1}^{\infty}\sum_{l_2=1}^{\infty} \sum_{1\le k_1,\cdots k_{l_1}\le n} \sum_{1\le j_1,\cdots j_{l_2}\le n} (f_{k_1} a_{k_1 k_2} \cdots a_{k_{l_1} i} a_{ij_1} \cdots a_{j_{l_2-1} j_{l_2}} y_{j_{l_2}})$$
$$= \sum_{l_1=1}^{\infty}\sum_{l_2=1}^{\infty} fA^{l_1} J_i A^{l_2} y = fTJ_iTy$$

(3)

where l_1 represents the upstream of the sector and l_2 represents the downstream of the sector. J_i is a matrix with elements in the (i,i) position that are 1, and the elements in all other positions are 0; the matrix T $(T = L - I)$ represents an indirect requirement for output per unit of sector i.

The methods for finding the water consumption of the production end, consumption end, and income end are shown by equations (4)–(6):

$$p_i = fx \tag{4}$$

$$c_i = f(I - A)^{-1} y \tag{5}$$

$$i_i = v(I - B)^{-1} f' \tag{6}$$

where p_i, c_i, i_i, respectively, represent the water consumption of the production end, consumption end, and income end; the $n\times n$ matrix B represents the complete consumption coefficient matrix, and the element represents the sum of the direct and indirect consumption of the final product of the unit production of sector j and sector i.

Results and Discussion

Correlation between betweenness and other IO indexes

As the water consumption index consists of numerical variables, namely, ordered variables. This paper adopts the Kendall rank correlation coefficient in order to analyze the relationships among the betweenness and other IO indicators with respect to water consumption. The results show the low correlation coefficients between betweenness and the other IO indexes, as shown in Table 3; the values are small, and the correlation coefficients were no greater than 0.5. In addition to the unweighted index of correlation, there was a significant difference between the rankings of water consumption with the other IO indexes.

Table 3. Correlation test among the order of betweenness and other indexes in 2002,2007 and 2012

Indicator	**2002**		**2007**		**2012**	
	Coefficient	**P**	**Coefficient**	**P**	**Coefficient**	**P**

Production-based	0.4550 * * *	0.0007	0.455 * * *	0.0007	0.3862 * * *	0.0042
Consumption-based	0.4339	0.0013	0.4286 * * *	0.0015	0.4021 * * *	0.0029
Income-based	0.4550 * * *	0.0007	0.455 * * *	0.0007	0.3862 * * *	0.0042
Unweighted backward correlation	0.1587	0.2438	0.1693	0.2133	0.0952	0.4893
Unweighted forward correlation	0.2487*	0.0662	0.3386 * * *	0.0121	0.3228 * *	0.0168
Weighted backward correlation	0.4339 * * *	0.0013	0.4286 * *	0.0015	0.4021 * * *	0.0029
Weighted forward correlation	0.4550 * * *	0.0007	0.455 * * *	0.0007	0.3862 * * *	0.0042

Note: *, **, *** represents the correlation coefficient significant at 10%,5%, and 1% level.

Sectoral water consumption

As shown by **Fig.1**, the three sectors with the greatest betweenness-based water consumption were: the production and supply of electric power and thermal gas, metal smelting, and mining. The sector of the production and supply of electric power and thermal gas, with 8.335 million m^3 of water consumption in the three years, ranked first among all sectors. The metal smelting and production sector, with a betweenness-based water consumption of 0.49 billion m^3, ranked second. The mining sector ranked third in betweenness-based water consumption, as it had a value of 3.581 billion m^3. Other key transmission sectors for water consumption included business, the chemical industry, paper printing, and cultural and sports equipment. In terms of the annual changes in water consumption, the top three sectors in terms of the volumes of changes the sectors mentioned above. Compared with the year 2002, the increases in water consumption in these sectors in 2012 were 8.335, 4.926, and 3.581 billion m^3, respectively.

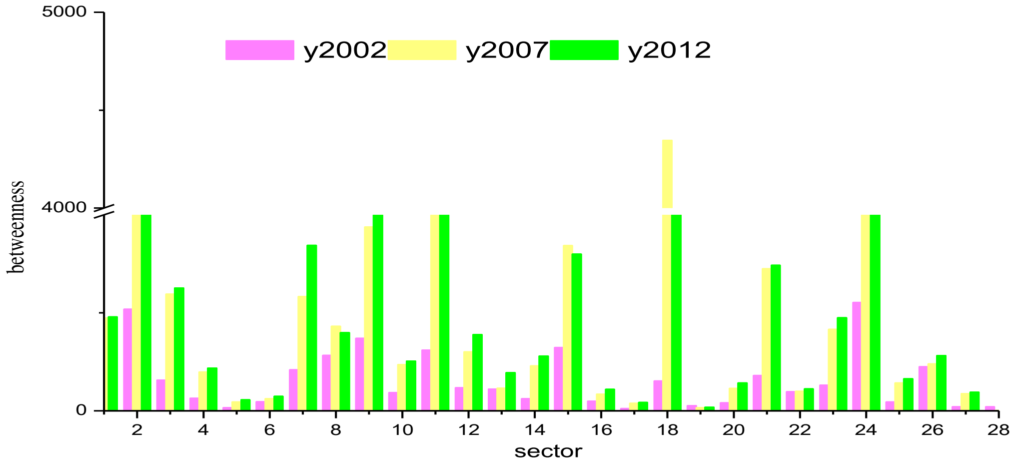

Fig. 1 Betweenness-based order of water consumption of 28 sectors from 2002 to 2012

Comparisons of the rankings of water consumption among the betweenness-based and other IO indexes for the years 2002, 2007, and 2012 are shown in **Fig.2**, **Fig.3**, and **Fig.4**; the comparisons of these results reflect the water resource consumption from three different perspectives: direct consumption, intermediate input, and initial input, respectively. Based on the determination of the key sectors with respect to pressure from water resource consumption, points in policies or strategies for the adjustment of industrial structures can be developed. It can be seen from the figures that most sectors did not fall on the diagonal line, which suggests that the betweenness-based and other water resource pressure indexes had the same rankings of water resource pressure , which was also in basic agreement with the results of the Kendall correlation test.

As shown in **Fig.2**, in 2002, the sectors of mining, communications, manufacturing of computers and other electronic equipment and paper making, printing, stationery, and sporting goods had the greatest betweenness-based water consumption, as their upstream industries used intermediate inputs with high-intensity water use. Meanwhile, the production-based water consumption was low, and the lower direct water consumption indicated that space was saved for these sectors. Consumption-based and income-based indexes reflect the water consumption of downstream sectors; the former measures a division of the upstream water resource pressure produced in the final production stage, and the latter reflects the downstream water resource pressure caused by the major inputs of a sector. As the income-based measurement of water consumption is driven by added value, this method shows the importance of starting and ending sectors of a supply chain as major suppliers. From the demand side, the water consumption of the above three sectors was small; the reason may be that the products of these departments were not final products; therefore, the final products were less used by consumers. The two other sectors were lower in their income-based water consumption. However, the betweenness-based water consumption of these sectors was larger, which means that the upstream industries of these three sectors had a greater intensity. The income-based, production-based, and consumption-based measurements of water consumption for the sectors of commerce, agriculture, and electricity, heat, and gas production and supply, and the water resources of the three sectors were more stressed.

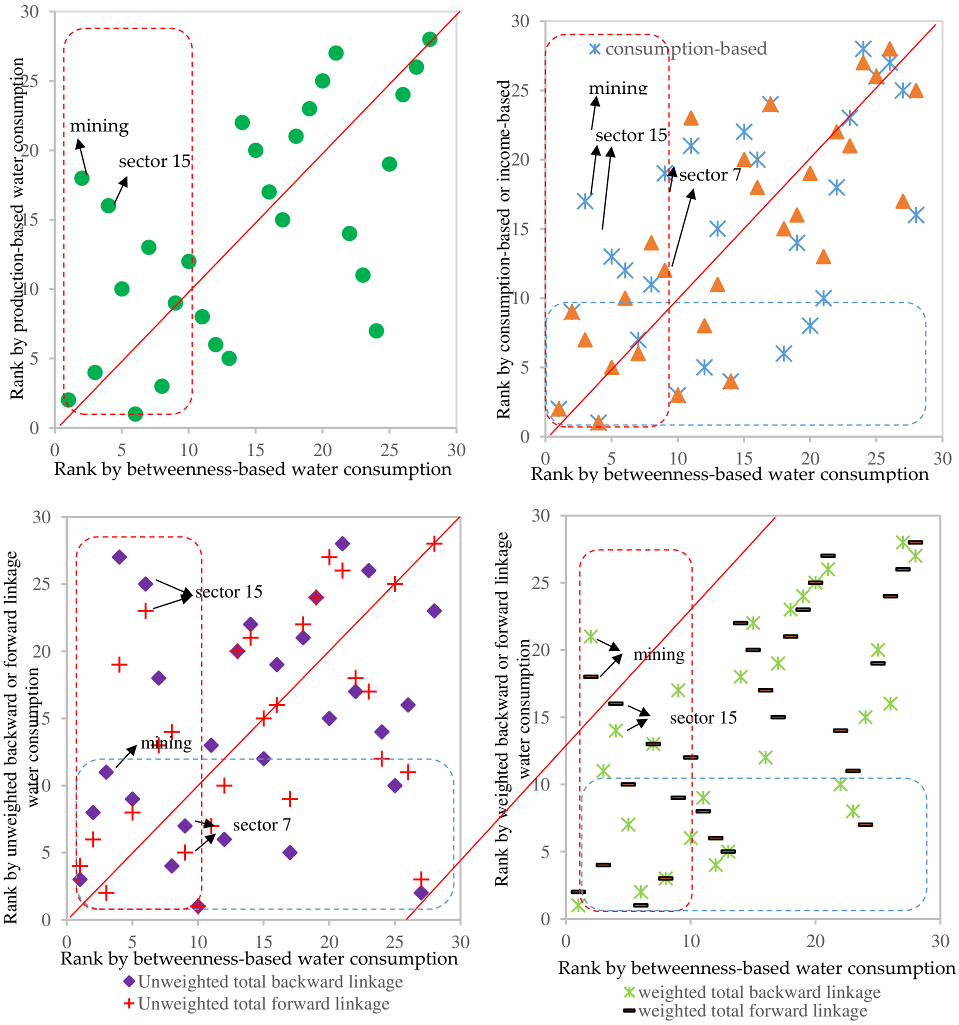

Fig. 2 Comparison of water consumption of the betweenness and other IO indexes in 2002
Note: red dotted box indicates sectors ranking top 10 by betweenness-based water consumption, and blue one indicates sectors ranking top 10 respectively by production-based, consumption-based, income-based, unweighted, and weighted water consumption.

Except for the sector of the chemical industry, the production-based and betweenness-based measurements of water consumption for 2007 were basically consistent with those for 2002, as shown in **Fig.3**. It is noteworthy that compared to 2002, the chemical industry became a new sector with a top ranking in betweenness-based water consumption, as its upstream industries intensively consumed water. In addition, the consumer-based and income-based measurements of water consumption were low because the upstream industries used water as an intermediate input with a high intensity. The upstream sectors were mainly sectors with high levels of water consumption, such as the oil, natural gas exploration and development, and electricity sectors. However, the consumption-based and income-based measurements of water consumption were low, which showed that the terminal products, such as the refining and production of oil and crude oil, were less directly used by consumers. Moreover, the end products of this sector were mostly raw materials for industrial preprocessing.

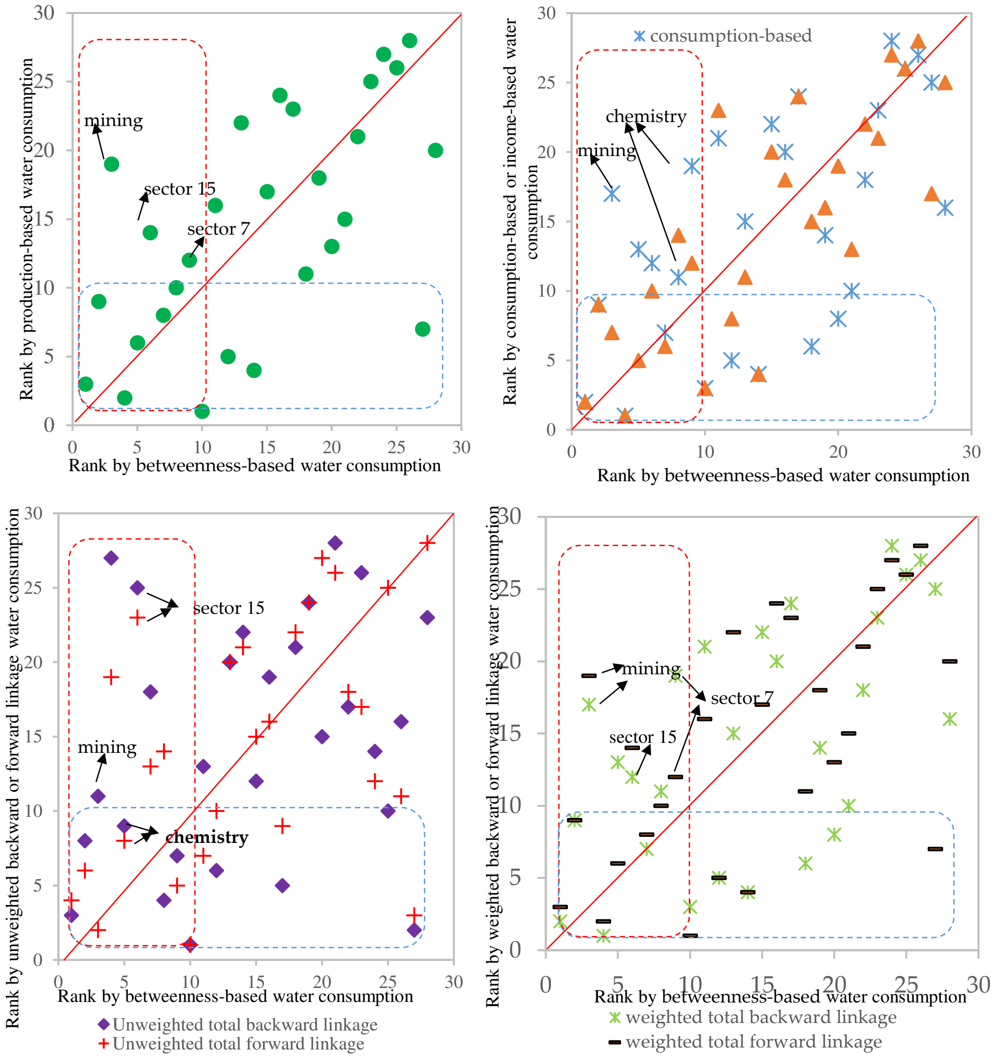

Fig. 3 Comparison of water consumption of betweenness and other IO indexes in 2007.

As shown in **Fig.4**, four sectors, mining, food processing, metal smelting and products, and communications, computers, and other electronic equipment had upstream water intensities that were the highest. The food processing sector had a high betweenness-based measurement of water consumption, which was related to its high upstream water consumption intensity as a result of agriculture, forestry, husbandry, and fishery. With economic development and the improvement of living standards, consumers also created an increased demand for food; therefore, the direct and indirect water use of the sector accordingly increased, and the water pressure also increased. At the same time, the four sectors had a low production-based measurement of water consumption with little direct water consumption, which indicates that the sector was less stressed in terms of water resources. Two sectors, communication, computers, and other electronic equipment and food processing, had low consumption-based and income-based measurements of water consumption, as the water resource pressure of the two ends of their supply chains was low.

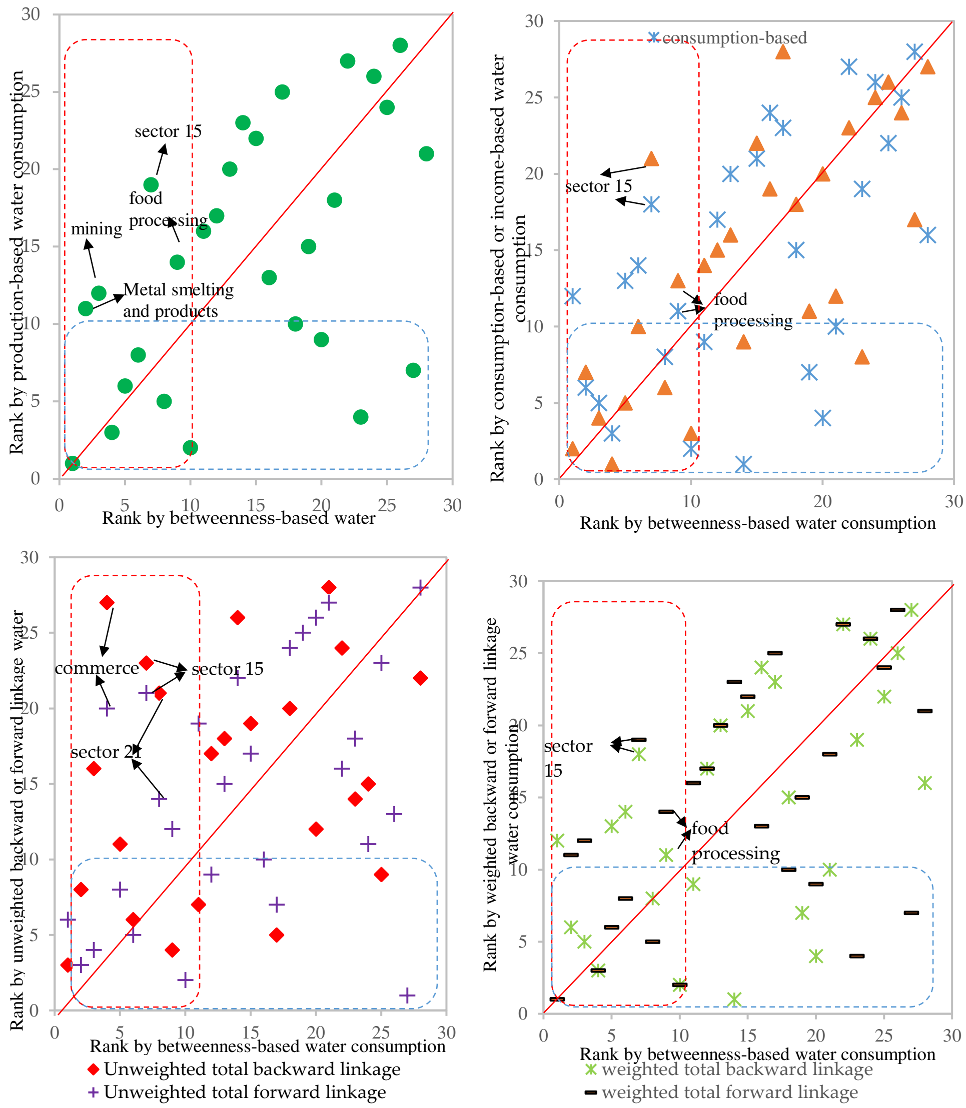

Fig. 4 Comparison of water consumption of betweenness and other IO indexes in 2012

Cluster analysis of the sectors' water consumption

The water consumption rankings of each sector were based on four indicators: betweenness-based, production-based, consumption-based, and income-based indicators. In order to facilitate a comparison and analysis, this paper divided 28 sectors into five categories by using a hierarchical clustering analysis, as shown in Table 4. The four indicators of water consumption were taken as the basis of the clustering for each sector. Every type of clustering had different characteristics, which included a reference value for exploring the industry-specific water resource pressure or the sectors' strategies and policies for mitigation.

Table 4. Sectoral water use clustering in 2002, 2010 and 2012

Year	Category	Sector	Characteristics
2002	T1	1,24,26	Four index values are higher
	T2	2,7,8,15	Betweenness is higher, and the production, consumption and income value are medium.
	T3	3,9,11,18,21 ,23	Betweenness is medium, the production, consumption and income value are higher
	T4	4,5,6,13,14, 16,17,27,28	Four index values are lower
	T5	10,12,19,20, 22,25	Betweenness is lower, production end, consumption end and income end value are medium
2007	T1	1,9,11,18,21 ,23,24,26	Four index values are higher
	T2	2,3,7,12,15,	Betweenness is higher, and the production end, consumption end and income value are medium

	T3	4,8,10,14,16,19,27,28	Betweenness and production are medium, consumption and income value are lower
	T4	5,6,17	Four index values are lower
	T5	13,20,22,25	Betweenness is lower, production and income are medium, and consumption value is higher
2012	T1	1,2,7,9,11,18,21,24	Four index values are higher
	T2	3,20,22,23,25,26	Four index values are medium
	T3	4,5,6,14,16,17,28	Four index values are lower
	T4	8,10,12,13,15	Betweenness and production end value are medium, consumption and income value are lower
	T5	19, 27	Betweenness and consumption is lower, production is higher, and income is medium

In order to analyze the characteristics of the water-use indexes of the sectors in the five categories, this study also averaged the four indicators in each category for 2002, 2007, and 2012. As shown in Figure 5, for 2002 and 2007, the parameter values in each category were similar in their characteristics; however, for 2012, the index values in each category were significantly different from those in 2002 and 2007. In 2002, in Category 1, which included the sectors of agriculture, business, and scientific research and technical services, the four types of indexes for the three sectors were high. From the perspective of the production-based, consumption-based, and income-based indicators, the sectors in Category 2, for example, mining, paper printing and stationery, sports products, oil processing and coking, and communications equipment, computers, and other electronic equipment, had a medium level of direct water consumption, but the upstream industrial sectors used highly water-intensive products as intermediate inputs. The upstream industries of the sectors in Category 3 had a medium level of water intensity, but their traditional IO indexes were higher, regardless of if they were income-based, production-based, or consumption-based. The sectors in Category 4 and Category 5 had lower index values. Category 4 consisted of eight sectors, such as textiles and apparel, wood processing and furniture, and transportation equipment. Category 5 consisted of six sectors, such as cement, glass ceramics, general-purpose equipment manufacturing, and water production and supply.

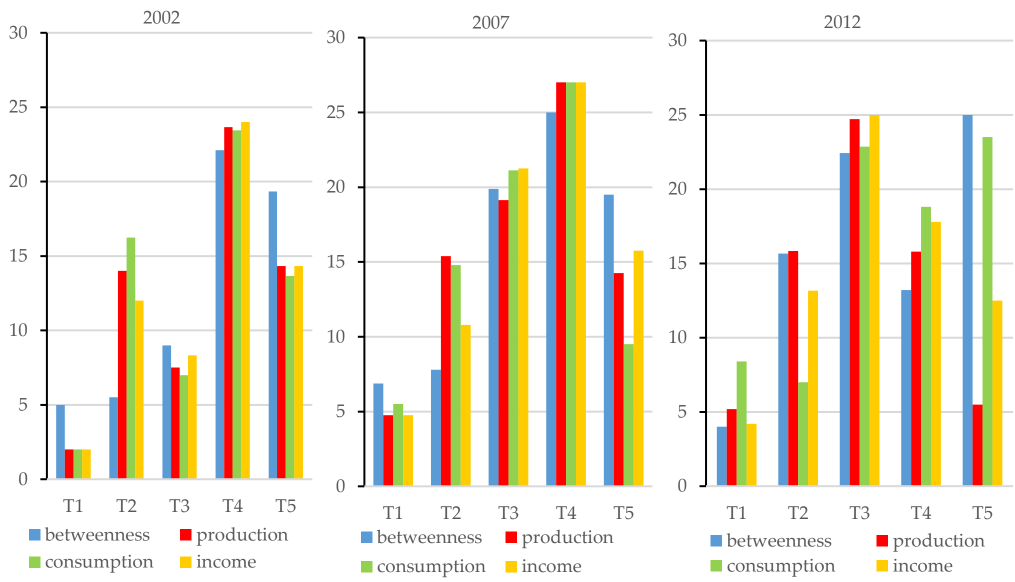

Fig. 5 Mean ranking of the five types of clustering water uses in 2002,2010 and 2012

Compared with that in 2002, the number of sectors in Category 1 increased in 2007; the added sectors included the chemical industry, metal smelting and products, electricity, heat, gas and water production and supply, transportation, warehousing and postal services, accommodation, and catering, which also suggests that the upstream portions of these sectors used highly intensive water products as intermediate inputs. At the same time, their traditional IO index values increased, which was basically consistent with the results of the inter-annual changes in the four indicators mentioned above. In 2007, Category 2 gained the two sectors of paper printing, stationery, and sporting goods and general-purpose equipment manufacturing, and it lost one sector, oil processing and coking. This change was related to the following reasons: Beijing had a strong control over the development of resource-based industries, and Beijing accelerated the pace of the relocation and adjustment of industries that did not conform to the government's functional positioning (Beijing Municipal Bureau of Statistics 2007; Beijing Municipal Bureau of Statistics 2013). According to the statistics, every year, about 30 oil and coal mining enterprises in Beijing moved outside of the fourth rings. Considering Category 3 and Category 4, in 2002, the sectors in Category 3 were basically the same as the sectors in Category 4, that is, the highly intensive intermediate inputs of the upstream sectors slightly increased from 2002 to 2007. The sectors in Category 5 had few changes; the category consisted of water production and supply, residential services, and other services. Compared with 2007, the sectors of Category 5 had a lower betweenness-based value in 2012, and the production-based and income-based measurements of water consumption were high, which shows that the water resource management on the two ends of the supply chains of these sectors should be taken more seriously.

Discussion

The assessment of the sectoral water consumption pressure of entire industrial chains with the Betweenness method is more advantageous than that with traditional methods, such as the production-based, consumption-based, and income-based methods; thus, it provides the possibility of enriching the perspectives for the mitigation of water consumption pressure. In the results of the rankings with the sectoral indicators of water consumption, it was found that most sectors did not fall on the 45-degree diagonal, which indicates that there was a significant difference between the sectoral rankings of water consumption pressure based on the Betweenness method and those based on the other water resource pressure indicators. This is basically consistent with the results of the Kendall correlation test mentioned above, that is, the correlation between the betweenness value and the values of the other IO indicators was less than 0.5, showing a weak correlation. The advantage of measuring the sectoral water consumption pressure with the Betweenness method is that sectors that are important in terms of water resource pressure relief from the perspective of the entire industrial chain can be screened out. Taking the agricultural sector as an example, from the production side, its water consumption was reduced, which may have been because the agricultural acreage in Beijing declined over the decade of 2002–2012, and the proportion of agricultural output also decreased (Beijing Municipal Bureau of Statistics 2013). However, from the perspective of the entire industrial chain, the water intensities of the intermediate inputs in the upstream industries were not significantly reduced, and the products of the sector required heavy investments in other sectors in order to obtain raw materials for production, resulting in a high betweenness-based measurement of water consumption for the sector.

Thus, the Betweenness method can provide more information than other traditional indexes in the study of sectoral water consumption pressure. Sectors with higher betweenness-based water consumption values are breakthrough points for the relief of the water consumption pressure. At the same time, sectors with higher betweenness-based values and lower values for the other traditional IO indexes cannot be ignored. The hierarchical clustering and classification results showed that the sectors corresponding to Category 1 and Category 2 were the critical transmission sectors for water consumption in the economic system. The betweenness-based values of water resource consumption of the sectors in Category 1 and Category 2 were relatively high. It is noteworthy that the sectors in Category 1, such as agriculture, commerce, transportation, warehousing, and postal services, not only consumed large amounts of water resources in their upstream industries, but also had higher values for the other traditional IO indices. Among them, the agricultural sector had a high level of direct water consumption, and the water-use characteristics of the commercial, transportation, warehousing, and postal sectors were related to the rapid development of Beijing's modern service industry. Statistics demonstrate that Beijing's modern service industry accounted for more than 50% of the GDP in 2007, and its proportion in 2012 was as high as 76% (Beijing Municipal Bureau of Statistics 2007; Beijing Municipal Bureau of Statistics 2013).

The sectors in the Category 2 had a higher betweenness-based value, while the water consumption pressure based on the production-based, consumption-based, and income-based indicators was small, which also confirmed that the Betweenness method can provide additional information for water resource management. These sectors mainly included the manufacturing of communications equipment, computers, and other electronic equipment, the paper making, printing, cultural, and sports goods industries, mining, and other sectors. The water consumption characteristics of these sectors were related to the rapid development of modern manufacturing industries through policy planning and guidance after China's reform and opening, which was suitable for the functions of the capital. In addition, the two sectors of water production and supply and residential and other services had lower betweenness-based values of water consumption and higher income-based and production-based values of water consumption, which indicated that the water resource management from the start to the end of the supply chains of such sectors cannot be ignored.

The evolution of the key transmission sectors for water consumption is basically consistent with the developmental law of industrial transformation in Beijing. According to the inter-annual evolution of the betweenness-based values, from 2002 to 2012, the sectors with higher betweenness-based values of water consumption transitioned from traditional heavy industries, dominated by mining, paper making, and printing to modern manufacturing industries and modern service industries, dominated by communications, automobiles, and electronics, as well as commerce, R&D, and information services. In addition, due to the changes in the industrial output value and layout of Beijing from 2002 to 2012, Beijing's pillar industries gradually shifted from sectors with high water consumption, such as construction, chemical industries, and the mining industry, to modern service industries and modern manufacturing industries. Specifically, statistics show that compared with 2002, the output value of Beijing's modern service industries increased by about four times in 2012, and that of its modern manufacturing industries increased by about 224%. This suggests that the evolution of the sectors in Beijing in terms of their water resource consumption is in accordance with the law of transformation and the upgrading of Beijing's industries, which are the key sectors for water resource management in the future.

CONCLUSIONS

Based on the Betweenness method and other traditional input–output indexes, this paper used water-extended input–output tables from Beijing for 2002, 2007, and 2012 in order to calculate the water resource consumption of various sectors from different perspectives, and the key transmission sectors for the alleviation of water consumption pressure in Beijing's socioeconomic system were identified. Finally, a hierarchical clustering method and classification method were used to explore the water-use characteristics of different types of sectors. The main conclusions are as follows: First, using the Betweenness method from the perspective of the entire industrial chain can provide additional information and references for policies and strategies for the reduction of water stress caused by sectors in Beijing. Secondly, in 2002, 2007, and 2012, the three sectors of electricity, heating, and gas production and supply, metal smelting and products, and mining had the highest values and the largest annual variations in their betweenness values. In addition, the agricultural sector also had a higher value of betweenness. From the perspective of the inter-annual development of the key transmission sectors for water consumption, the sectors under heavy water resource pressure in Beijing changed from heavy industries, such as mining and paper making, to modern manufacturing and service industries. Finally, the hierarchical clustering and classification results showed that the sectors corresponding to Category 1 and Category 2 were the key transmission sectors for water consumption in Beijing's economic system.

Based on the above conclusions, in order to further alleviate the water resource pressure of the sectors, the following countermeasures can be taken. Firstly, the sectors with higher betweenness values for water resource consumption should improve their water resource utilization efficiency and the utilization efficiency of intermediate inputs in the upstream industries of these sectors. Moreover, the sectors with higher betweenness values for water consumption and lower values for other traditional input–output indexes should also not be neglected. Secondly, based on the dual constraints of water quantity and intensity, it is essential to reduce the proportion of high-water-consumption industries in order to optimize the industrial structure, strengthen the matching of water resource endowments and industrial characteristics, and improve the rationality of the industrial layout. Thirdly, with the help of technology, the construction of water-saving irrigation projects can be supported, the efficiency of agricultural irrigation can be improved, and water-saving appliances can be vigorously promoted in modern service industries. In addition, the transmission equipment of the sector of power, heat, and gas production and supply should be improved in order to reduce the intermediate loss of water resources in their industrial chains. Finally, the water resource management of sub-sectors should be guided by industrial transformation and development, with a focus on water consumption in the modern service industries and the modern manufacturing industries. The introduction of water-saving technologies and the renewal of production equipment for traditional industries should be carried out in order to improve the level of informatization and intellectualization of modern manufacturing industries, and the proportion of tertiary industry that is dominated by modern service industries should continue to be increased in order to alleviate the pressure on water resources in Beijing in the future and to promote the sustainable development of these water resources.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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