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Water evaluation and planning (WEAP) model application for exploring the water deficit at catchment level in Beijing

Liu Yang[a,b], Xue Bai[b,c,*], Nina Zheng Khanna[b], Sooyeon Yi[b], Yinjie Hu[a], Jun Deng[a], Haoran Gao[a], Lanhe Tuo[a], Shijie Xiang[a], Nan Zhou[b]

[a]*College of Geoscience and Surveying Engineering, China University of Mining & Technology, Beijing, Beijing 100083, China*
[b]*Energy Technologies Area, Lawrence Berkeley National Laboratory, CA 94720, USA, email: baixue@cnis.gov.cn (X. Bai)*
[c]*China National Institute of Standardization, Beijing 100191, China*

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ABSTRACT

Water scarcity and water quality are becoming increasingly serious global issues, especially in China. Collecting accurate, scientific data about water-scarce areas is a critical first step for water resources management. Beijing is one of the cities in China that faces severe water scarcity issues, impeding economic and social development. This study assesses the water deficit in Beijing at the catchment level using the Water Evaluation and Planning (WEAP) model to provide insights for water assignment and to explore the advantages of WEAP applications in water resources management. Results show that (1) Beijing had a water shortage of 560.24 million cubic meters in 2010 with agricultural water facing the most severe shortage; (2) Catchment Yongdinghe faces the most severe water shortage challenge with demand site reliability of 45.83%, followed by Daqinghe, Jiyunhe, and Beiyunhe (64.17%–67.92%), and Chaobaihe (80.83%); and (3) the most sensitive water scarcity months are November, December, and February, characterized by the mean water demand coverage of 44.37% in all catchment areas. This study provides insights for water allocation and future research by serving as an important basis for water balance and for sustaining economic–social–environmental development in China.

Keywords: Water deficit; WEAP; Catchment; Management policy; Beijing

1. Introduction

Due, in part, to the rapid development of the world economy, many parts of the globe are facing serious water resource shortages. The water supply crisis has been named one of the top five global risks with the largest impact for the last six consecutive years, and it was ranked the number one risk in 2015 [1]. Water scarcity is particularly severe in China due to its rapid economic development and increasing population growth and urbanization. China's *per capita* water resource of 1869 m^3/person is only a quarter of the world's average and ranks 121st in the world, making China one of the 13 most water-scarce countries in the world [2]. Moreover, water shortage is widespread in China. Eleven regions in China ("Dry 11") are water scarce, including the economic powerhouse provinces of Jiangsu and Shandong and the municipalities of Beijing, Shanghai, and Tianjin. Nearly half of China's GDP comes from the Dry 11 regions [3]. These widespread water quantity and quality shortage problems have attracted attention from the Chinese central government. In its *No. 1 Document of Year 2011*, the Chinese central government addressed water problems for the first time, introducing the "3 Red Lines" water policy to (1) control water use; (2) improve water efficiency; and (3) prevent and control water pollution. China's *13th Five-Year Plan*, released in 2015, clearly put forward goals of further controlling water consumption and implementing dual control of not only the total amount of water consumed but also the intensity of water consumption. To meet this goal, in 2016 the National Development and Reform Commission and the Ministry

* Corresponding author.

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of Water Resources jointly proposed another program the "13th Five-Year Dual Control Action for the Total Amount and Intensity of Water Consumption."

Water balance and rational water resources allocation has become one of the key challenges to overcome on the road to solving the water resource shortage issue. Academically, many researchers have studied water scarcity from various aspects, such as water security [4,5], water balance [6–8], water allocation [9–11], desalination [12], water price reform [13], and the water-energy nexus [14,15] as well as by different indicators and models to find rational solutions to ease water scarcity [16,17]. Indicators applied in water scarcity studies include the water stress indicator [18,19], the water poverty index [20] and water footprint and virtual water [21–23]. Various models are used in the research, such as mathematical models [24,25], economic models [13,26], and geographic information system-based models [10,27,28]. All models attempt to evaluate the relationship between water supply and demand, assess the impact of energy and economic development on water shortage, and thus put forward optimal water assignments. However, the complexities of water resource management systems include a variety of uncertainties; there is no uniform or comprehensive methodological fit for all regions, all scales, and all situations.

Accurately evaluating the water balance of supply and demand in areas with water shortage provides a critical base of information to aid in various fields of water resources management. Integrated water resources management (IWRM), a suitable water management approach, was developed by the Global Water Partnership to promote the development of water, land, and related resources, maximizing the economic and social welfare rationally without compromising the suitability of the environment [29]. The IWRM lists many models to apply in water resource management; among them, the Water Evaluation and Planning (WEAP) model is used widely and successfully across the world [27,30–33]. Compared with its wide application in other countries, WEAP is only employed in a few studies in China. Li and Li [34], Yu [35], Li et al. [36] and Wan et al. [37] conducted their water resources studies in Zhejiang Xitiaoxi watershed, Ningxia Yellow River Basin, Tianjin Binhai New Area, and Beijing South-to-North Water Transfer area by applying the WEAP model.

Beijing is one of most water-scarce cities in China and the world, and thus, it is an important example of a water crisis city with significant conflicts between economic development and water resources conservation. Scientific and precise assessment of the gaps of water supply and demand data is an urgent and necessary first step for the Beijing government's *13th Five-Year Water Development Plan*, which follows the national plan: *Dual Control Action of 13th Five-Year Water Consumption Total Amount and Intensity*. Many Beijing water resource studies have been conducted. For example, the water demands of different Beijing sectors are predicted with the computable general equilibrium (CGE) model, with game-theoretic modeling approaches, with statistic and econometric modeling methods, and by integrating conceptual water balance model and econometric regression methods [38,39]. Other issues, such as causes of the water crisis, solutions to ease water scarcity, and explorations of the water pricing system, are also analyzed by researchers [7,40,41]. Although these studies have made contributions to Beijing's water resources issues, the research models and methods used are often not transparent for city officials, water management policy makers, or stakeholders to use in policy making and policy evaluations. In contrast, the WEAP methodology is based on a very transparent and user-friendly interface for data input and for conducting scenario analysis that is also capable of assessing the actual water resources situation and water management policy options from water and cost efficiency perspectives.

Under such a situation, this study aims not only to assess the water shortage of Beijing and put forth insights for water allocation, but also to explore the advantages of the WEAP model as a tool for policy development and management. This study serves as the basis for balancing water supply and demand to sustain economic–social–environmental development in Beijing and will provide important scientific support for the implementation of Beijing's *13th Five-Year Water Development Plan*.

2. Study area

2.1. Natural environment and socioeconomic conditions

Beijing, the capital of China, covers an area of 16,808 km^2 in the northern part of the North China Plain, between 39°28′N and 41°05′N and between 115°25′E and 117°30′E (Bureau, 2014). It is facing a critical water shortage and is among the "Dry 11" regions in China identified as water scarce [3]. The shortage of water resources has become the primary bottleneck for sustainable development of the city's economy and society [40,42]. Beijing is characterized by alluvial plains in the south and east (38% of the surface area), and by hills and mountains in the north, northwest, and west (62% of the surface area). It has an East Asian monsoon climate with four seasons, which are characterized by hot and humid summers and cold, windy, and dry winters. The average annual temperature is 12.5°C, multiyear average precipitation is 585 mm (with a recorded high of 1,406 mm in 1959 and a low of 242 mm in 1869), and multiyear evaporation is 1,842 mm [43,44].

By the end of 2014, Beijing had a total population of 13.33 million, a regional GDP of 2,133.08 billion yuan, and a *per capita* GDP of 99,995 yuan. The tertiary industry dominates the regional economic output, with the primary industry production value of 15.9 billion yuan, the second industry output value of 454.48 billion yuan, and the tertiary industry production value of 1,662.7 billion yuan [43].

There are 16 administrative districts in Beijing (Fig. 1), including the "core city districts" used in this paper: Dongcheng, Xicheng, Chaoyang, Fengtai, Shijingshan, and Haidian. The core city districts are always reported as one region for water use data in statistical yearbooks (Fig. 1). The five corresponding catchment areas of Beiyunhe, Chaobaihe, Daqinghe, Jiyunhe, and Yongdinghe are analyzed in this study.

2.2. Water resources

Except for Beiyunhe River, originating within Beijing municipality boundaries, most of the surface water flowing through Beijing comes from rivers and streams outside

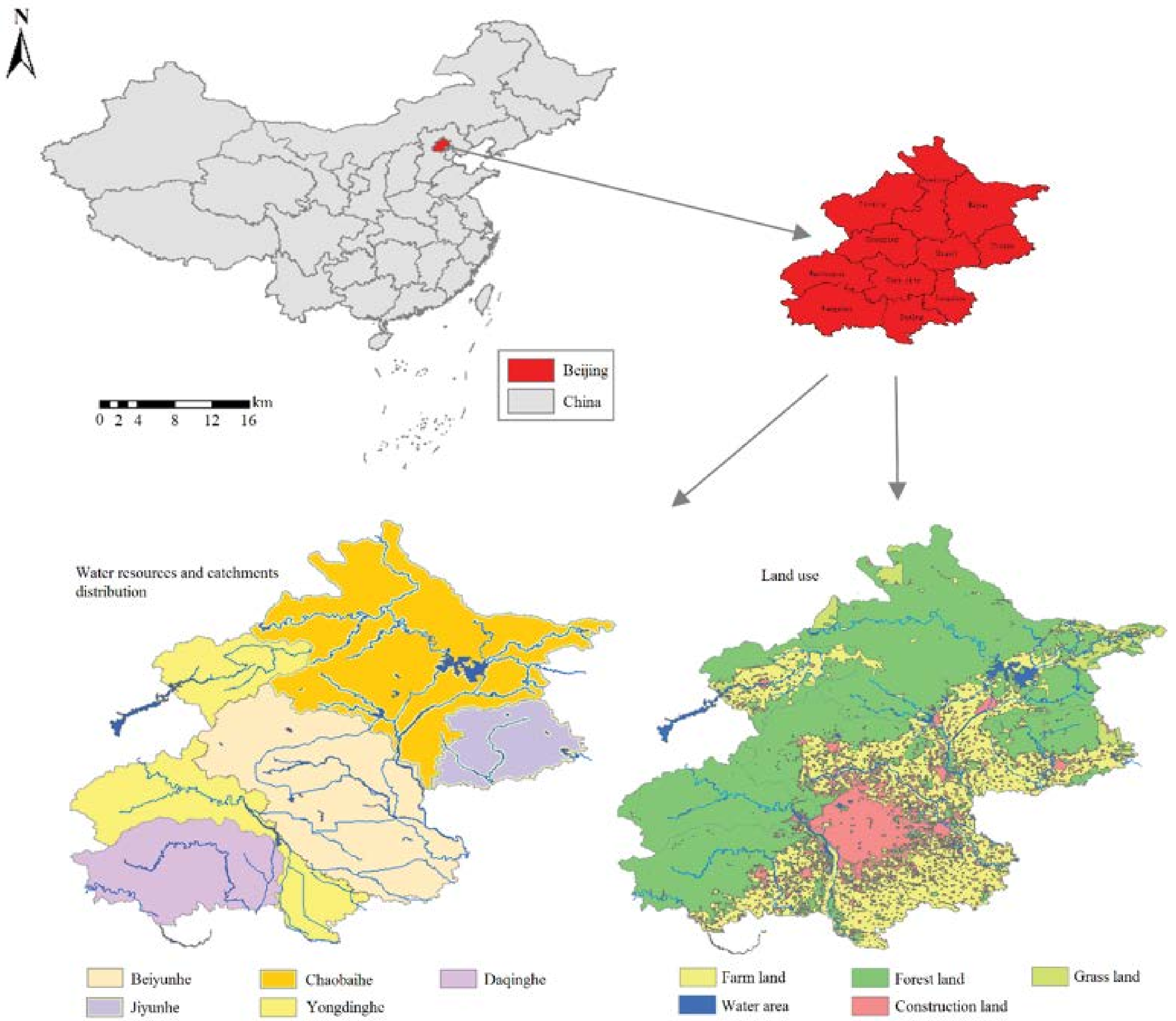

Fig. 1. The location, catchment distribution, and land use of Beijing.

the municipality in neighboring regions: Hebei Province, Shanxi Province, and Inner Mongolia [45]. They are part of the Haihe Basin, which drains into the Bohai Sea. There are five main rivers and many smaller rivers, most of them dried out, within the Beijing municipality. The five main rivers are Chaobaihe and Beiyunhe in the east, Yongdinghe and Jumahe in the west, and Jiyunhe in the northeast (Fig. 1). Beijing also has four large and medium reservoirs and several small reservoirs, including Miyun, Guanting, Baihe Fort, and Haizi. Among them, Miyun and Guanting reservoirs are the largest.

Groundwater resources are a major part of Beijing's water supply. There are 16 groundwater sources within the Beijing municipality, including 11 groundwater sources in respective administrative districts, and four emergency water sources: Huairou, Pinggu, Machikou, and Zhangfang.

Beijing's rainfall varies seasonally, annually, and between the sub-watersheds, especially in mountainous areas and the low-lying plain. Eighty-five percent of Beijing's annual precipitation falls between June and August. Beijing has recorded 27 years of drought since the 1970s according to study results from Group (2008) and statistics of Beijing Water Resource Bulletin 2009–2015, and there is a decline trend of average annual precipitation (Fig. 2). In this context, drought means below multiyear average precipitation. Between 1999 and 2015, average annual precipitation was 476 mm, 19% below the average. The amount of available surface water depends on rainfall; average annual precipitation declining resulted in declines of surface runoff and inflows to reservoirs (Fig. 3).

Beijing has seen a slow increase in total water consumption between 2003 and 2015, characterized by an increase in municipal and environmental water consumption and a decrease in industrial and agricultural water consumption, according to the statistics of Beijing Water Resource Bulletin of 2003–2015 (Fig. 4). Since 1949, the available amount of *per capita* water resources has dropped from 1,000 to 94 m^3

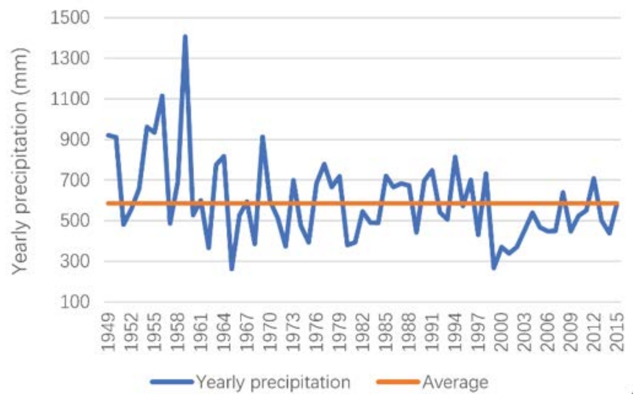

Fig. 2. Yearly precipitation of Beijing 1949–2015.

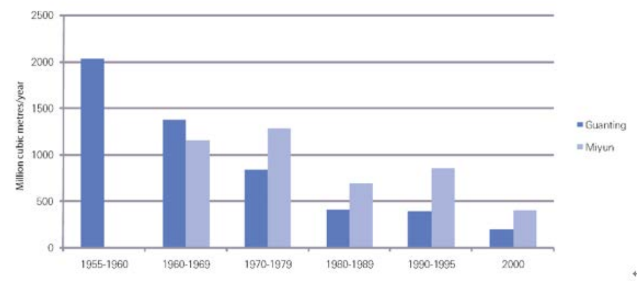

Fig. 3. Declining inflows to Guanting and Miyun reservoirs [45].

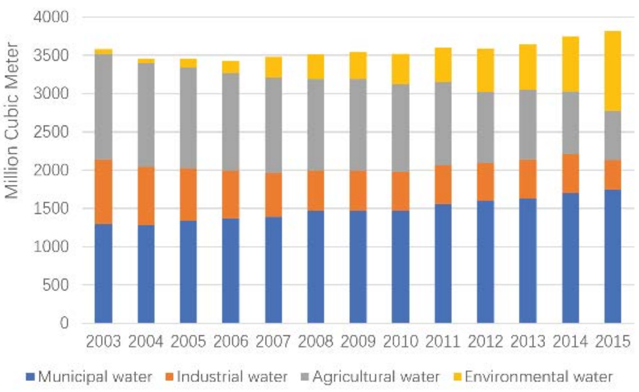

Fig. 4. Water consumption within Beijing municipality 2003–2015 [46].

in 2014 [46]. This means that *per capita* water use in Beijing in 2014 was less than 1.4% of the world average and 10% of the level of the world's seriously water-scarce areas. The imbalance of water supply and water demand has limited Beijing's social and economic development.

3. Methods and data

3.1. WEAP model description

WEAP was originally developed by Stockholm Environment Institute in Boston, USA (SEI-US) [28]. The current version of the model, WEAP21, combines an integrated modeling tool for evaluating water supply policies and suitable water resources plans in a single watershed or a complex trans-boundary river basin system [28]. It operates at a monthly step on the basic principle of water balance accounting and is considered a conceptual model for describing the hydrological processes [27]. WEAP applies a scenario approach to assess water availability and socioeconomic activities with water resources and their allocation for current and future periods [31].

WEAP model elements fall into two categories: nodes and links. Nodes are where water is demanded and supplied, and links are places that transfer water between nodes. A linear program is used at every node to calculate and evaluate the satisfaction of demand site and user-specified instream flow requirements based on a daily or monthly basis. It operates on a monthly step water balance equation, which is shown as follows:

$$Q_{\text{inflow}} = Q_{\text{outflow}} + Q_{\text{consumption}} + Q_{\text{storage}} \quad (1)$$

where Q_{inflow} is total inflows at a node and all connected inflow links; Q_{outflow} is total outflows at a node and all connected outflow links; $Q_{\text{consumption}}$ is water consumed at a node and all connected links; Q_{storage} is net of any change in storage (reservoirs and aquifers).

3.2. Data sources and processing

The data employed in this study are classified into three categories: water supply, water demand, and social–economic data. Water supply includes meteorology (temperature, rainfall, humid, wind, cloudiness, and evaporation), land use, river flow, hydrology, local reservoir, groundwater, and wastewater treatment plant data. Water demand data include municipal water, industrial water, agricultural water, and environmental water. Social–economic data include population and gross domestic output (Table 1).

Among the reservoirs in Beijing, only Miyun and Guanting have comprehensive statistical records of inflow, elevation, and volume data since they are the largest and most important. Therefore, the five rivers, and these two reservoirs, are used in the WEAP modeling work as surface water resources.

In order to explore water balance status at watershed/catchment level, the optimal unit for computation in the WEAP model, this study used recalculated statistical water demand and social–economic data based on administrative units, according to the respective area ratio of the administrative districts in different catchments.

3.3. WEAP model setup for Beijing

3.3.1. Current account

A period where all or most of the data are available is defined as current account or baseline year [31]. Absent or incomplete water supply and consumption data in China are a common problem, but great progress has been made in water resources monitoring recently. For example, Water Law of the People's Republic of China was released in 2002 to advance water resources management in China. Furthermore, Water Resources Ministry determined the national water service integration system reform in 2004, aiming at strengthening

Table 1
Data sources used in the Beijing WEAP model

	Data type	Scale	Format	Description	Source
Water supply and resources	Meteorology	Daily (1951–2015)	Excel	Precipitation; temperature; humidity; wind speed; cloudiness	National Meteorological Information Center http://data.cma.cn/
	Land use	1:250,000	Shapefile	Forest land, construction land, grassland, farm land, water area	National Administration of Surveying, Mapping and Geoinformation
	River flow	Daily (2010–2016)	Excel	Streamflow (Chaobaihe; Beiyunhe; Yongdinghe; Jumahe; Jiyunhe)	Beijing Water Authority http://www.bjwater.gov.cn/
	Reservoir	Daily (2010–2016)	Excel	Reservoir's volume, elevation, and inflow (Miyun, Guanting)	Beijing Water Authority http://www.bjwater.gov.cn/
	Hydrology	1:250,000	Shapefile	Rivers, reservoir distribution	National Administration of Surveying, Mapping and Geoinformation
	Ground water	Yearly (2010–2014)	PDF	Ground water initial storage; maximum withdrawal	Beijing Water Statistical Yearbook; Beijing Water Resource Bulletin; Ground Water Dynamic Monthly
	Wastewater treatment plant	Yearly (2010–2014)	PDF	Daily capacity; consumption	Beijing Water Statistical Yearbook
Water demand	Municipal water	Yearly (2010–2014)	PDF	Annual water use rate; consumption; reuse rate	Beijing Water Statistical Yearbook
	Industrial water	Yearly (2010–2014)	PDF	Annual water use rate; consumption; reuse rate	Beijing Water Statistical Yearbook
	Agricultural water	Yearly (2010–2014)	PDF	Annual water use rate; consumption; reuse rate	Beijing Water Statistical Yearbook
	Environmental water	Yearly (2010–2014)	PDF	Annual water use rate; consumption; reuse rate	Beijing Water Statistical Yearbook
Social-economic data	Population	Yearly (2010–2014)	PDF	Total population; population density	Beijing Water Statistical Yearbook
	GDP	Yearly (2010–2014)	PDF	Gross domestic product; Gross domestic product *per capita*	Beijing Water Statistical Yearbook

water data service ability for management [47]. Beijing is the first city to make this water service integration system effort by setting up Beijing Water Authority in 2004; relatively comprehensive water statistics data for the city have been released by the Beijing Water Bureau since 2010. Therefore, year 2010 is set as the current account for this study's Beijing WEAP model.

3.3.2. Model generalization

The Beijing WEAP generalization model is simplified and built using the 2010 basic data (Fig. 5). The water system is characterized by five catchments nodes (Chaobaihe or CBH, Beiyunhe or BYH, Yongdinghe or YDH, Daqinghe or DQH, and Jiyunhe or JYH); five rivers (Chaobaihe, Beiyunhe, Yongdinghe, Jumahe, and Jiyunhe); two reservoir nodes (Miyun and Guanting); five groundwater nodes (one for each catchment area); 20 demand site nodes (municipal water, industrial water, agricultural water, and environmental water in each catchment); five wastewater treatment plant nodes (one for each catchment area); 10 runoff/infiltration links; 25 transmission links; and 20 return flows (Fig. 5).

The nodes of demand sites, catchments, and wastewater treatment plants are linked to the respective river by transmission links and return flow links. The nodes of catchments, groundwater sites, and municipal water demand sites are connected to each other through transmission links and runoff/infiltration links in each catchment area. The demand site nodes are created in WEAP's schematic view at their relative positions. According to the historical water consumption data and actual observation, the demand priority was set as municipal and agricultural water (1) and industrial and environmental water (2). Water supply sources are then linked to the demand site nodes via transmission links.

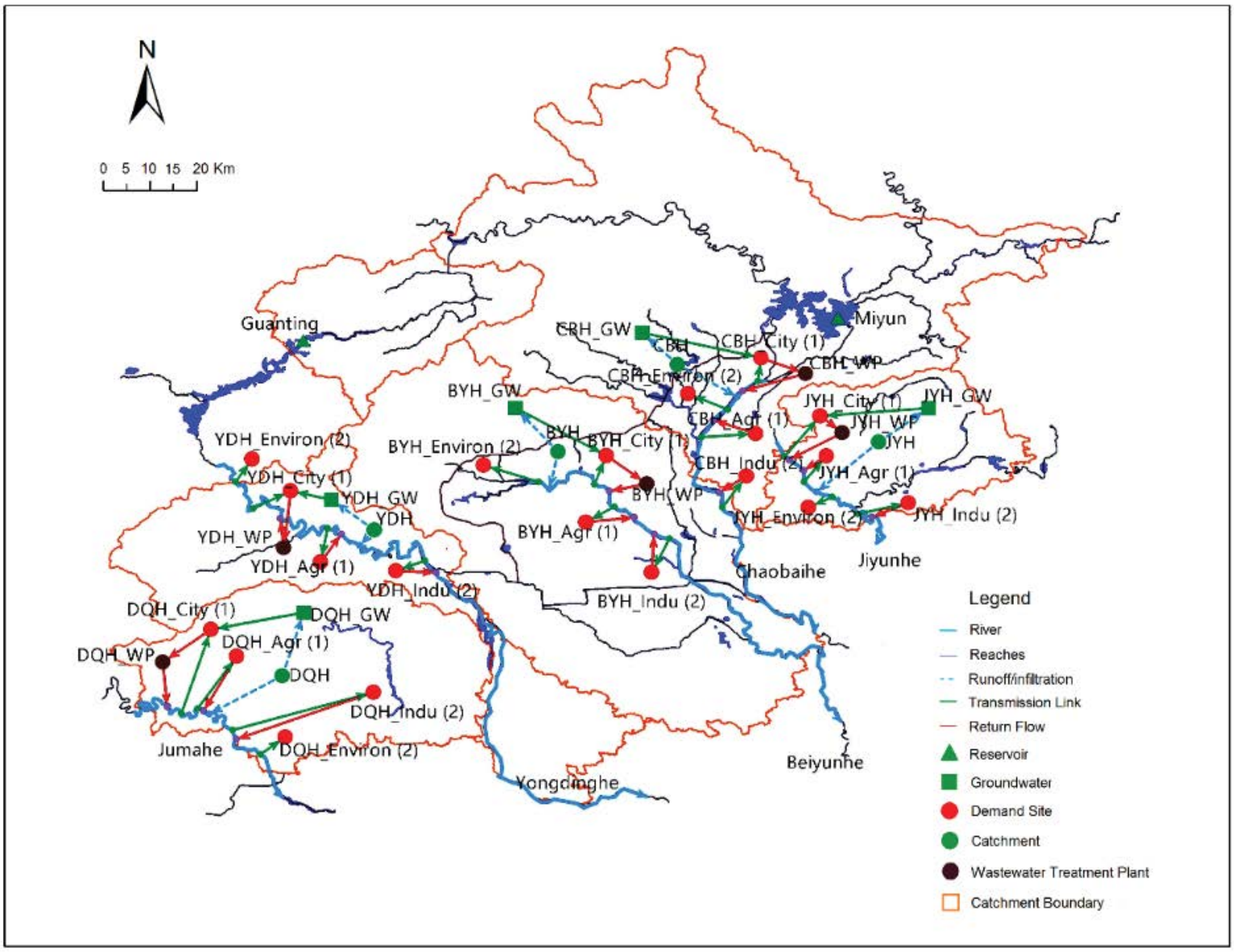

Fig. 5. The schematic model of the Beijing WEAP.

4. Results

4.1. Water balance at the city scale

Results from calculating Beijing's WEAP 2010 modeling show a total water demand of 2,417.57 million cubic meters, a water supply requirement of 1,687.09 million cubic meters, 1,126.85 million cubic meters of water delivered, and unmet water demand equaling 560.24 million cubic meters. The highest unmet demand sector is agriculture, accounting for 77% of the total – other unmet demands include environmental (13%) and industrial (10%). The municipal water demand is totally met in 2010 (Fig. 6).

There appears to be differences between months in water demand sectors, with the exception of municipal water (Fig. 7). Monthly changes in unmet demand relate to supply delivered; the unmet demands are larger during those months with less supply delivered. Agricultural demand is unmet in every month, while the industrial demand is unmet only in January, February, November, and December. Environmental demand is unmet in eight months, months excepting June through September. These results show that Beijing faces a severe water scarcity during its dry season: January, February, November, and December (Fig. 7).

4.2. Water balance at the catchment level

4.2.1. Yearly characteristics

Water demand is almost met in the BYH, CBH, DQH, and YDH catchments; water demand is best met in JYH (Fig. 8). In BYH, municipal water is the greatest demand sector, and it is completely met; environmental and agricultural water demands are in serious deficit status. In contrast, in the other four catchments, agriculture is the greatest demand sector and the largest shortage (Fig. 8).

Demand site reliability is defined as the percent of the time steps in which a demand site's demand was fully satisfied [48]. Unfortunately, all the demand sites have unsatisfied reliabilities in catchments except for municipal water with 100% reliability (Fig. 9). The municipal water reliability probably results from the first priority of water use in this Beijing WEAP model. Water reliability in CBH is greater than that in the other catchments. YDH has the least reliability,

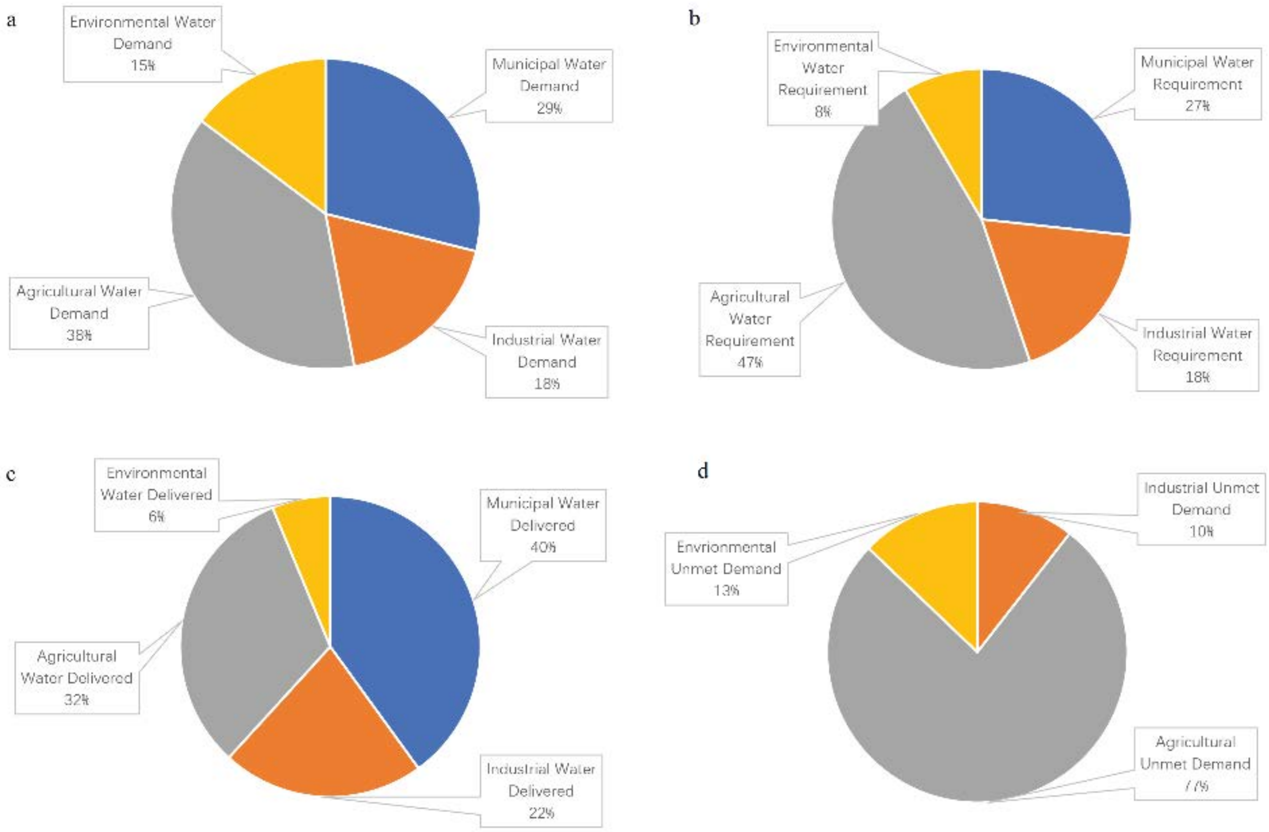

Fig. 6. Water supply and demand calculated by Beijing WEAP 2010. (a) water demands; (b) water requirements; (c) supply delivered; (d) unmet demands.

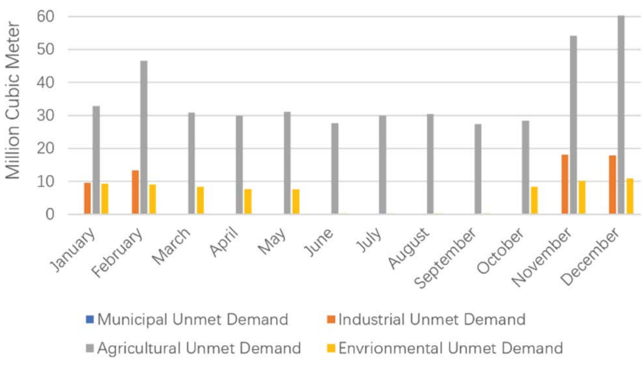

Fig. 7. Unmet demand computed by Beijing WEAP 2010 during different months.

characterized by both agricultural and environmental at 0% (Fig. 9).

4.2.2. Monthly change

Results illustrate that there is not a significant monthly change of water demand in any of the catchments (Fig. 10). However, monthly rainfall and transmission losses are different for each month, presenting an obvious monthly variability within respective catchment for unmet demand (Fig. 11).

In CBH, unmet demand data show a monthly change characterized by water shortage only appearing in February, November, and December. Furthermore, in these months, agricultural water faces the most serious water deficit. There are eight water deficit months in BYH, and most severe are January, February, November, and December. Unmet environmental water demands are extreme in January, while the most serious water deficit for agriculture is February, November, and December. Unfortunately, serious water shortage is clear in all months, with the primary water scarcity in the agricultural sector in the YDH, DQH, and JYH catchments. Results show that February, November, and December are facing the most serious water deficit challenge in all five catchments (Fig. 11).

Water demand coverage is defined as the percent of each demand site's requirement (adjusting for demand site losses, reuse, and demand-side management savings) that is met, from 0% (no water delivered) to 100% (delivered of full requirement) [48]. It gives a quick assessment of how well water demands are being met. The results demonstrate that serious water shortage is widespread in all catchments in Beijing (Fig. 12). The agricultural sector has the highest water scarcity demand and the lowest coverage, while municipal water is met 100% in all months in almost all of the catchments. Beijing's dry season, especially February, November, and December, is the worst water demand coverage period, when agricultural, environmental, and industrial sectors have the lowest

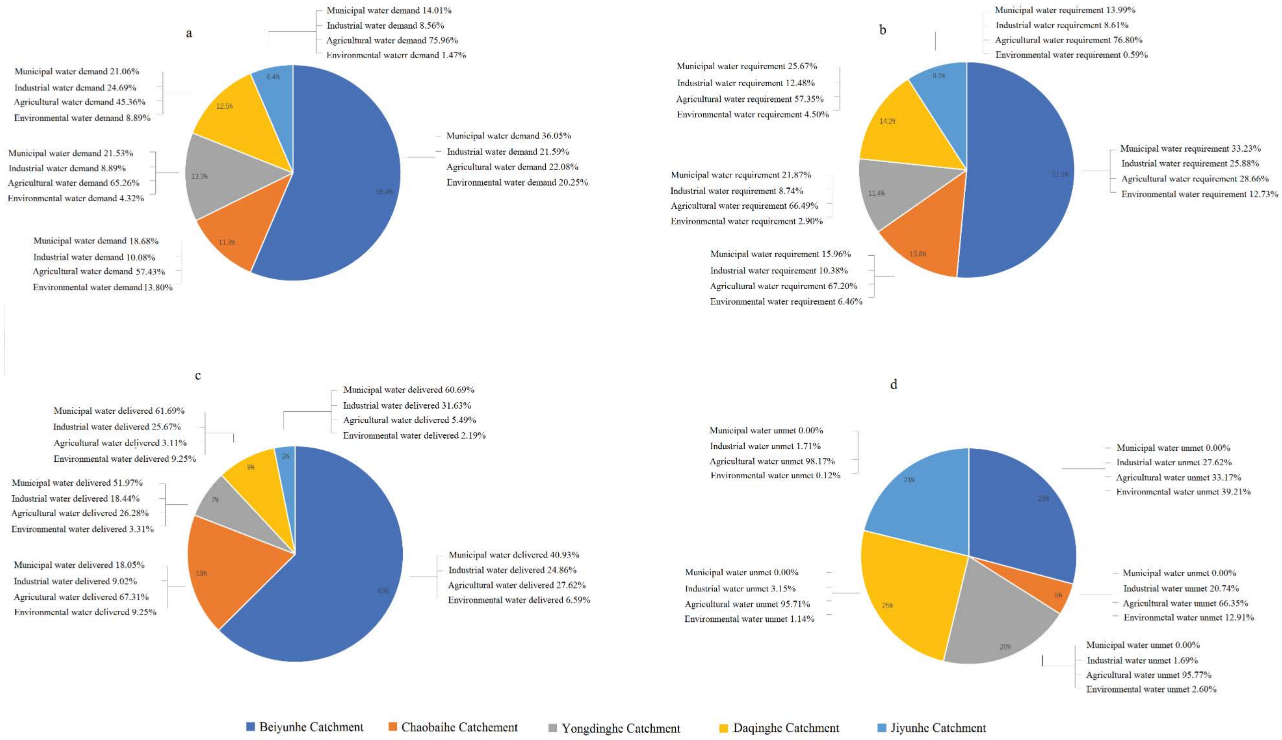

Fig. 8. Water demand computed by Beijing WEAP 2010 in different catchments: a – water demand; b – supply requirement; c – supply delivered; d – unmet demand.

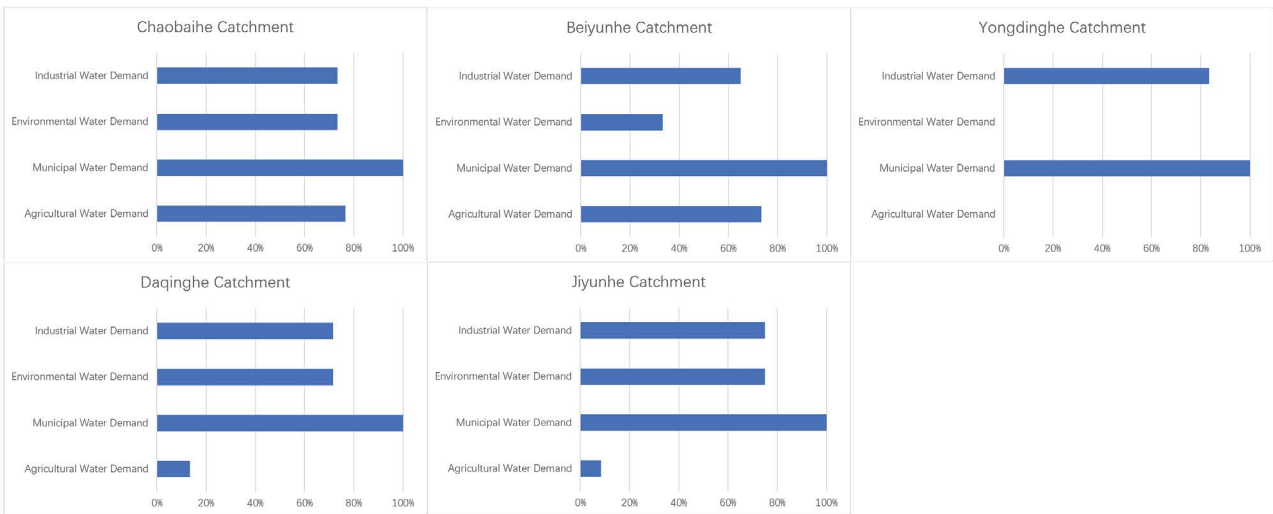

Fig. 9. Demand-site reliability in different catchments, Beijing region.

coverage (coverage as low as 0% appearing in this period) (Fig. 12). The results of demand coverage also illustrate that the catchments of JYH and DQH have the most severe water shortage problem; water demand is best met in CBH (Fig. 12).

4.3. Water assignment

One of the WEAP model's strengths is that it gives water inflows and outflows for every node, so that water assignment of each node can be calculated by empirical formulas embedded in the WEAP model. In this study, Beijing WEAP 2010 provides the results of monthly water supply inflows for different nodes (Table 2). It presents the water assignment in Beijing catchments ruled by natural rainfall and transmission losses without any policy intervention.

BYH has the greatest total inflow (1,126.24 million cubic meters), and JYH has the least inflow (267.23 million cubic meters) (Table 2). Surface runoff makes up the majority of the

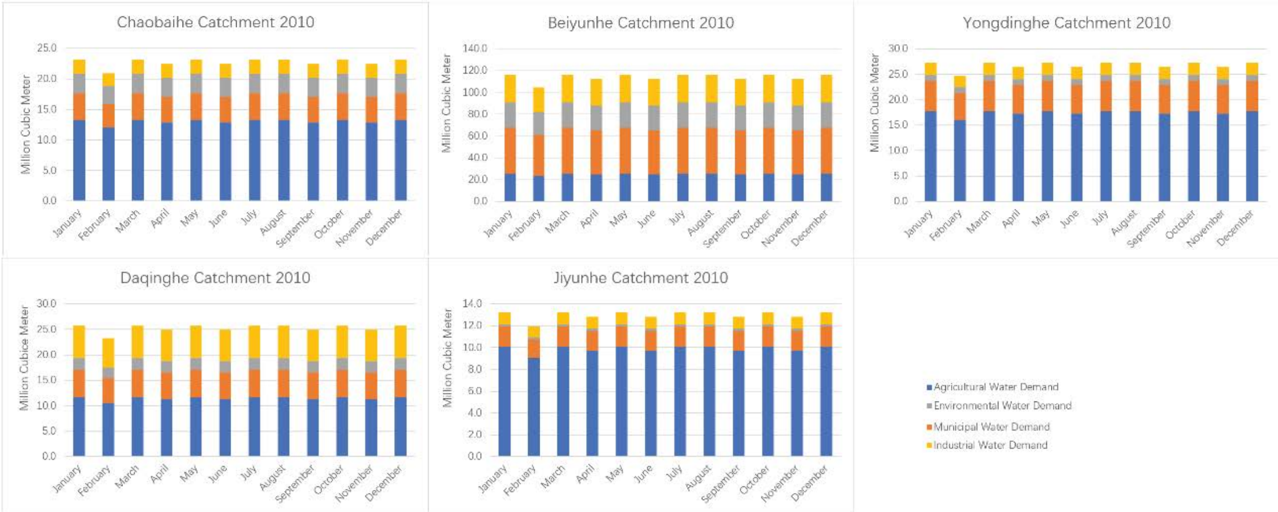

Fig. 10. Monthly water demand in different catchments, Beijing region 2010.

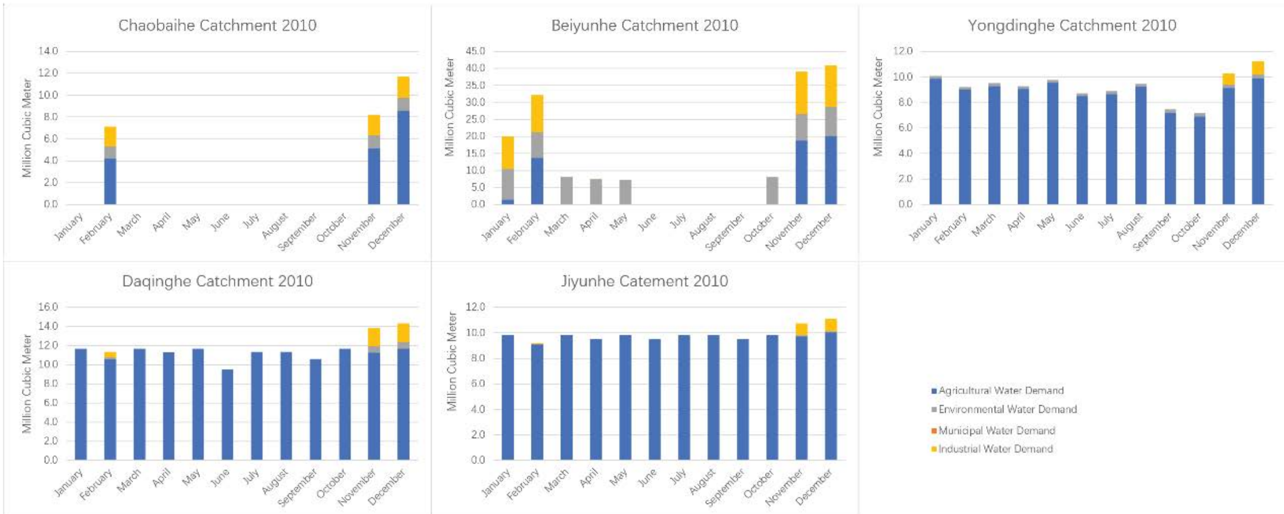

Fig. 11. Monthly unmet demand in different catchments, Beijing region 2010.

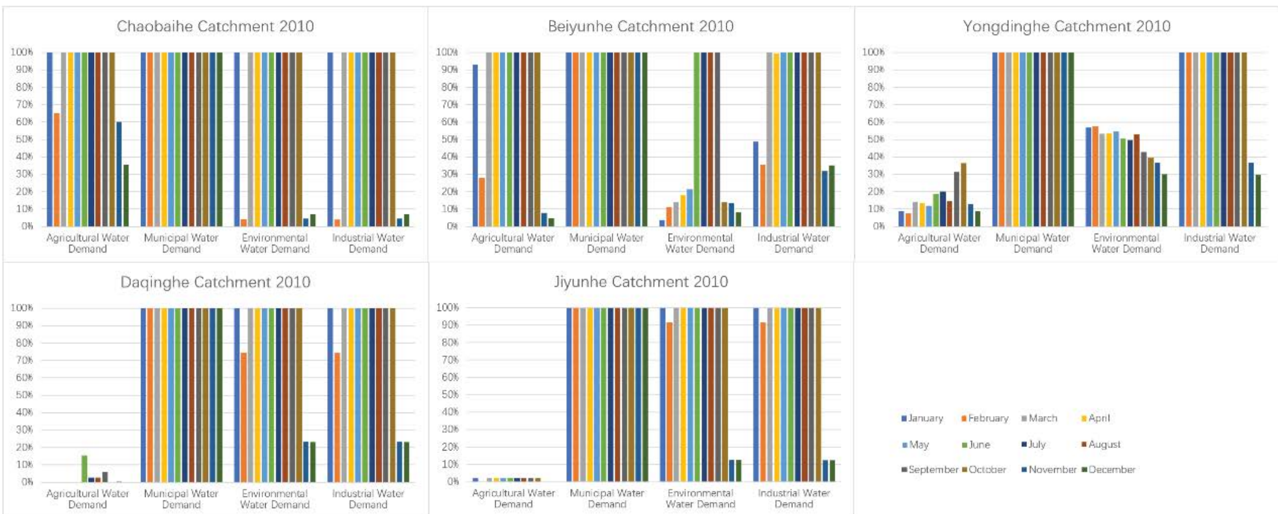

Fig. 12. Monthly water demand coverage in different catchment, Beijing region 2010.

Table 2
Water supply inflows in different nodes computed by Beijing WEAP 2010 (million cubic meter)

Inflow nodes	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Sum
Chaobaihe Catchment													
River headflow	1.09	1.14	1.67	1.59	1.40	2.85	5.04	3.38	4.22	8.32	5.11	3.13	38.94
Surface runoff	17.86	4.02	38.68	24.94	55.07	159.98	59.50	309.01	170.25	101.77	0.00	0.00	941.06
Return flow from agricultural water	4.21	2.47	4.21	4.07	4.21	4.07	4.21	4.21	4.07	4.21	2.45	1.50	43.88
Return flow from industrial water	0.34	0.01	0.34	0.33	0.34	0.33	0.34	0.34	0.33	0.34	0.01	0.02	3.09
Return flow from wastewater treatment plant	0.33	0.30	0.33	0.32	0.33	0.32	0.33	0.33	0.32	0.33	0.32	0.33	3.88
Groundwater	2.07	2.86	1.50	1.47	1.76	0.21	0.00	0.00	0.00	0.00	3.06	3.16	16.08
Sum	25.90	10.79	46.72	32.72	63.11	167.76	69.41	317.27	179.19	114.97	10.96	8.14	**1,046.94**
Beiyunhe Catchment													
River headflow	2.10	0.94	1.31	1.64	2.01	16.64	25.37	24.49	19.99	1.31	1.22	0.76	97.78
Surface runoff	12.76	3.10	27.93	21.22	38.11	126.01	46.49	241.63	111.19	76.04	0.00	0.00	704.49
Return flow from agricultural water	6.22	1.69	6.68	6.46	6.68	6.46	6.68	6.68	6.46	6.68	0.51	0.32	61.54
Return flow from industrial water	2.90	1.92	5.94	5.70	5.94	5.75	5.94	5.94	5.75	5.94	1.83	2.10	55.66
Return flow from wastewater treatment plant	5.19	4.69	5.19	5.02	5.19	5.02	5.19	5.19	5.02	5.19	5.02	5.19	61.13
Groundwater	24.51	22.14	18.62	23.72	8.43	0.00	0.00	0.00	0.00	0.00	23.72	24.51	145.64
Sum	53.68	34.48	65.67	63.77	66.37	159.89	89.67	283.94	148.42	95.17	32.30	32.88	**1,126.24**
Yongdinghe Catchment													
River headflow	0.92	0.73	1.50	1.38	1.26	1.92	2.12	1.55	3.20	3.83	1.31	0.92	20.64
Surface runoff	8.83	2.08	22.74	16.69	31.65	93.21	33.94	157.73	83.22	58.53	0.00	0.00	508.61
Return flow from agricultural water	0.30	0.24	0.49	0.45	0.41	0.62	0.69	0.50	1.04	1.24	0.42	0.30	6.70
Return flow from industrial water	0.17	0.16	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.06	0.05	1.80
Return flow from wastewater treatment plant	0.29	0.26	0.29	0.28	0.29	0.28	0.29	0.29	0.28	0.29	0.28	0.29	3.43
Groundwater	3.56	3.22	3.56	3.45	3.56	3.45	3.56	3.56	3.45	3.56	3.45	3.56	41.93
Sum	14.07	6.68	28.75	22.41	37.34	99.65	40.77	163.81	91.35	67.63	5.52	5.12	**583.12**

(Continued)

Inflow nodes	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Sum
Daqinghe Catchment													
River headflow	0.00	0.00	0.00	0.00	0.00	1.64	0.28	0.31	0.64	0.01	0.04	0.01	2.91
Surface runoff	5.48	1.41	14.73	11.31	20.56	62.88	24.29	113.51	53.17	39.22	0.00	0.00	346.56
Return flow from agricultural water	0.00	0.00	0.00	0.00	0.00	0.55	0.09	0.10	0.21	0.00	0.01	0.00	0.98
Return flow from industrial water	0.43	0.29	0.43	0.42	0.43	0.42	0.43	0.43	0.42	0.43	0.10	0.10	4.33
Return flow from wastewater treatment plant	0.69	0.63	0.69	0.67	0.69	0.67	0.69	0.69	0.67	0.69	0.67	0.69	8.17
Groundwater	4.53	4.72	4.53	4.38	4.53	4.49	4.55	4.55	4.42	4.53	5.05	5.22	55.50
Sum	11.14	7.04	20.39	16.79	26.21	70.64	30.34	119.59	59.53	44.88	5.88	6.03	**418.45**
Jiyunhe Catchment													
River headflow	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Surface runoff	4.17	0.86	8.14	6.03	13.42	41.39	15.91	86.33	40.07	25.50	0.00	0.00	241.83
Return flow from agricultural water	0.07	0.00	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.00	0.00	0.62
Return flow from industrial water	0.14	0.12	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.02	0.02	1.44
Return flow from wastewater treatment plant	0.15	0.14	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	1.77
Groundwater	1.83	1.66	1.83	1.77	1.83	1.77	1.83	1.83	1.77	1.83	1.77	1.83	21.58
Sum	6.36	2.77	10.34	8.16	15.61	43.52	18.10	88.53	42.20	27.70	1.94	2.00	**267.23**

total inflow in each catchment, followed by groundwater; the other inflow nodes contribute only a little. Inflows are higher from June to October, reaching a climax in August (Table 2).

5. Discussion

5.1. Reliability of WEAP modeling

Based on water demand statistical data and water supply field data for Beijing in 2010, water deficit – the gap between water supply and water demand – is estimated to be 560.24 million cubic meters, with a total water demand of 2,417.57 million cubic meters. When water withdrawal quantities within the municipality are considered but not water transfer from the south to the north (SNWTP) and water withdrawal from emergency water resources, the reported statistical water shortage is 543 million cubic meters [43]. This is very close to the calculated water deficit of 560.24 million cubic meters from the WEAP model results.

Estimated results for Beijing's water balance in the literature fall into unsatisfied reliability, especially for the water shortage projections for 2010 (Table 3). Comparing the statistical data released by Beijing Water Statistical Yearbook (BWSY), results in the literature show deviations of between 39.2% and 78.7% for water demand estimations and deviations of between 118.5% and 203.7% for water shortage estimations, which overestimates the actual data. The deviation of the calculated result in this paper is underestimated water demand by 31.3% and overestimated water shortage by 3.7%. It implies that the WEAP model is relatively more reliable than other methods applied in the literature.

5.2. Data scarcity impact

The WEAP model's projection capacity is impacted by the availability of input data. Due to the lack of relevant historical monitoring data (monthly and daily) for societal water consumption, results did not show a detailed exploration of the water deficit at monthly and daily levels in this study. Monthly water demand changes are calculated by assigning the annual demands into months according to the exact number of days in each month. Therefore, the monthly water deficit is estimated only on the water supply side. However, the water deficit is associated with both water supply and water demand. The more accurate the monthly water demand information available, the more valuable the monthly water shortage picture to give insights for practical water assignments.

Furthermore, there is no long-term annual historic (more than 30 years) data for water demand, so a statistical temporal–spatial variation of water balance could not be presented. However, water balance is a critical element for optimal water resources allocation. Therefore, it is important and urgent to obtain and accumulate the long-term basic data for WEAP modeling. Another basic data gap appears in the monitoring data at different water demand nodes, which could allow for more reasonable water allocation across the different water demand sectors.

5.3. Water resource assignment

An optimal water resource assignment is essential for increasing water efficiency, especially in severe water scarcity

Table 3
Water demand and water shortage estimations of 2010 for Beijing by major relevant studies and government departments (billion cubic meters)

Departments/Authors	Demand		Shortage	
	Amount	Deviation	Amount	Deviation
Beijing Institute of Urban Planning (1993)	4.90	39.2%	No data	No data
UNDP (1994)	6.29	78.7%	No data	No data
The Editorial Committee of Chinese Natural Resource Series (1995)	4.90	39.2%	No data	No data
Beijing Municipal Water Resource Bureau (1997)	5.43	54.3%	No data	No data
IWHR (1998)	5.24	48.9%	No data	No data
Beijing Municipal Government (1999)	5.27	49.7%	1.64	203.7%
Wang C. et al. (2006)	No data	No data	1.18	118.5%
Yang L. et al. (the present study)	2.42	–31.3%	0.56	3.7%
Beijing Water Statistical Yearbook (2010)	3.52		0.54[a]	

Note: [a]The statistical water data from SNWTP and emergency water resources together.

areas. Researchers have been working on both water allocation theory and practical approaches such as the "social-natural" dualistic water cycle [49–53], the social water cycle [54], rule-based water resource allocation [11], and water price impact [13]. These studies provide good ideas and methods for the optimization of water resource allocation. But there is still a lack of effective tools for water rights allocation to date. The WEAP model has advantages in the water resources optimization studies, since it can estimate water demand at all water use nodes and links. It could play a role in all stages of the natural-social dualistic water cycle (Fig. 13). Furthermore, based on the model calibration and validation, WEAP can also evaluate the implementation effects of the relevant policies and measures, so that the optimal water resources allocation scheme with economic and technological rationality could be obtained.

Results from the WEAP modeling for Beijing in 2010 show that the water assignment by natural water system rules in each catchment area is very different across water demand sectors, and it is variable by month. It indicates that water right assignment should have flexibility for different catchments, water demand sectors, and months. Because of the severe water deficit occurring in February, November, and December in Beijing, water resource allocation policy on both water supply side (desalinated water, water transfer, and virtual water) and water demand side (water use sector priority, water price, and water efficiency) should give emphasis to these severe water shortage months in order to effectively ease the imbalance of water supply and demand.

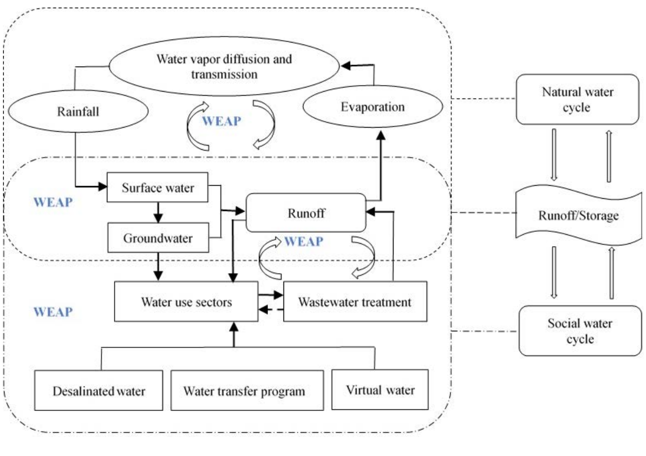

Fig. 13. The WEAP roles in natural and social water cycle (modified based on [49]).

5.4. Limitations

This study advances water shortage evaluation by applying the WEAP model, a powerful and user-friendly WEAP tool. The modeling results show the difference in water shortages in the various catchment area, the most severe water-scarce demand sectors, and the most sensitive months of water deficit in the Beijing municipality. Because the results are limited by a lack of comprehensive monthly water demand data, this study fails to highlight the WEAP model's ability to give insights on monthly water assignment strategy. Moreover, because it is outside the scope of this paper, scenario analysis performed in the present study will be presented in another paper, projecting the implementation effects of the *Beijing 13th Five-Year Plan Water Development Plan*, the water resource allocation policy, and the impact of climate change on the water deficit of Beijing via the WEAP Beijing model.

6. Conclusions

This study builds a WEAP model for evaluating both annual and monthly water deficit, water demand, and supply at city and catchment levels in Beijing, a city typical of both economic development and severe water scarcity in China. The water balance shows Beijing at a city level has a water deficit of 560.24 million cubic meters in 2010, characterized by the most water shortage in the agricultural sector. At the catchment level, YDH suffers the most severe water shortage challenge, with a demand site reliability of 45.83%, followed by DQH, JYH, and BYH (64.17%–67.92%) and CBH (80.83%). It also indicates that November, December, and February are the most severe water shortage months with a mean water demand coverage of 44.37% in all catchment areas.

The water balance results of this study provide insights on water resource assignment in water-scarce areas: (1) The reality of monthly variations in water scarcity for different demand sectors should be considered when formulating government economic development plans and policies, which seems to better meet water demand and balance economic development and water resource conservation. (2) The WEAP model could become a powerful and effective tool for government policy designers, with its user-friendly interface and excellent evaluating and scenario analysis ability. It couples with the models of water quality, groundwater, energy, and climate to help policy makers capture the detailed characteristics of water availability and socioeconomic activities with water resources and their allocation for current and future periods, which are important basis for rational policy making. (3) In order to fully employ the WEAP model advantages for water assignment strategy formulation, it is necessary to enhance the water consumption monitoring system, especially for social water cycle monitoring, and the water auditing system, which provides information for cost-effective analysis of water management policies. With the help of detailed data collected from water monitoring and auditing systems, water shortage could be accurately evaluated by the WEAP model at each demand site, and it could obviously provide valuable insights for water allocation. (4) Current water policies seldom consider the impact of energy consumption and green gas emissions though they have already aggravated the water crisis in both China and the world. The water-energy-environment nexus should be an emphasis of study to give a clear thinking for better water conservation.

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References

[1] W.E. Forum, The Global Risks Report 2017, World Economic Forum, Geneva, 2017, pp. 10–15.
[2] L. Ge, G. Xie, C. Zhang, S. Li, Y. Qi, S. Cao, An evaluation of China's water footprint, Water Resour. Manage., 25 (2011) 2633–2647.
[3] D. Tan, F. Hu, H. Thieriot, D. McGregor, Towards a Water & Energy Secure China, China Water Risk 2015.
[4] Y. Jiang, China's water security: current status, emerging challenges and future prospects, Environ. Sci. Policy, 54 (2015) 106–125.
[5] V. Kumar, D.L. Vasto-Terrientes, A. Valls, M. Schuhmacher, Adaptation strategies for water supply management in a drought prone Mediterranean river basin: application of outranking method, Sci. Total Environ., 540 (2016) 344–357.
[6] L. Boithias, V. Acuna, L. Vergonos, G. Ziv, R. Marce, S. Sabater, Assessment of the water supply: demand ratios in a Mediterranean basin under different global change scenarios and mitigation alternatives, Sci. Total Environ., 470–471 (2014) 567–577.
[7] C. Wang, C.D. Whitehead, J. Chen, X. Liu, J. Chu, Options for the future: balancing urban water supply and demand in Beijing, Water Policy, 8 (2006) 97–110.
[8] S.K. Wei, Estimating water deficit and its uncertainties in water-scarce using integrated modeling approach, Water Sci. Eng., 5 (2012) 450–463.
[9] R.F. Bangash, A. Passuello, M. Hammond, M. Schuhmacher, Water allocation assessment in low flow river under data scarce conditions: a study of hydrological simulation in Mediterranean basin, Sci. Total Environ., 440 (2012) 60–71.
[10] C. Li, Y. Wang, G.Y. Qiu, Water and energy consumption by agriculture in the Minqin oasis region, J. Integr. Agric., 12 (2013) 1330–1340.
[11] W.Z. Song, Y. Yuan, Y.Z. Jiang, X.H. Lei, D.C. Shu, Rule-based water resource allocation in the Central Guizhou Province, China, Ecol. Eng., 87 (2016) 194–202.
[12] Y. Zhou, R. Tol, Implications of desalination for water resources in China – an economic perspective, Desalination, 164 (2004) 225–240.
[13] J. Zhao, H. Ni, X. Peng, J. Li, G. Chen, J. Liu, Impact of water price reform on water conservation and economic growth in China, Econ. Anal. Policy, 51 (2016) 90–103.
[14] A. Gu, F. Teng, Y. Wang, China energy-water nexus: assessing the water-saving synergy effects of energy-saving policies during the eleventh five-year plan, Energy Convers. Manage., 85 (2014) 630–637.
[15] Y. Qin, E. Curmi, G.M. Kopec, J.M. Allwood, K.S. Richards, China's energy-water nexus – assessment of the energy sector's compliance with the "3 Red Lines" industrial water policy, Energy Policy, 82 (2015) 131–143.
[16] H. Dong, Y. Geng, T. Fujita, M. Fujii, D. Hao, X. Yu, Uncovering regional disparity of China's water footprint and inter-provincial virtual water flows, Sci. Total Environ., 500–501 (2014) 120–130.
[17] P. Wu, C. Xia, F. Liu, Y. Wu, Y. He, An integrated water strategy based on the current circumstances in China, Appl. Math. Modell., 40 (2016) 8108–8124.
[18] J. Blasco, A. Navarro-Ortega, D. Barcelo, Towards a better understanding of the links between stressors, hazard assessment and ecosystem services under water scarcity, Sci. Total Environ., 503–504 (2015) 1–2.
[19] V. Smakhtin, C. Revenga, P. Doll, Taking into Account Environmental Water Requirements in Global-scale Water Resources Assessments, Comprehensive Assessment of Water Management in Agriculture – Report 2, International Water Management Institute (IWWI), 2004, pp. 1–32.
[20] C. Sullivan, J. Meigh, A. Giacomello, The water poverty index: development and application at the community scale, Nat. Resour. Forum, 27 (2003) 189–199.
[21] M. Aldaya, P. Martinez-Santos, M. Llamas, Incorporating the water footprint and virtual water into policy: reflections from the Mancha Occidental Region, Spain, Water Resour. Manage., 24 (2010) 941–958.
[22] A. Hoekstra, A. Chapagain, Water footprint of nations: water use by people as function of their consumption pattern, Water Resour. Manage., 21 (2007) 35–48.
[23] F. Pellicer-Martinez, J.M. Martinez-Paz, The water footprint as an indicator of environmental sustainability in water use at the river basin level, Sci. Total Environ., 571 (2016) 561–574.
[24] J. Gu, G. Huang, P. Guoe, N. Shen, Interval multistage joint-probabilistic integer programming approach for water resources allocation and management, J. Environ. Manage., 128 (2013) 615–624.
[25] M. Hojjat, M. Erik, Z. Mahdi, G. Nick, A new bankruptcy method for conflict resolution in water resources allocation, J. Environ. Manage., 144 (2014) 152–159.
[26] L. Jiang, F. Wu, Y. Liu, X. Deng, Modeling the impacts of urbanization and industrial transformation on water resources in China: an integrated hydro-economic CGE analysis, Sustainability, 6 (2014) 7586–7600.
[27] A. Psomas, Y. Panagopoulos, D. Konsta, M. Mimikou, Designing water efficiency measures in a catchment in Greece using WEAP and SWAT models, Procedia Eng., 162 (2016) 269–276.
[28] D. Yates, J. Sieber, D. Purkey, A. Huber-Lee, WEAP21 – a demand-, priority-, and preference-driven water planning model, Water Int., 30 (2005) 487–500.

[29] G.W. Partnership, Integrated Water Resources Management in Mediterranean, GWP-Med and MIO-ECSDE, Athen, 2002.
[30] L.L. Dale, N. Karali, D. Millstein, M. Carnall, S. Vicuña, N. Borchers, An integrated assessment of water-energy and climate change in Sacramento, California: how strong is the nexus?, Clim. Change, 132 (2015) 223–235.
[31] M. Maliehe, D.M.M. Mulungu, Assessment of water availability for competing uses using SWAT and WEAP in South Phuthiatsana catchment, Lesotho, Phys. Chem. Earth, Parts A/B/C, (2017) 44–57.
[32] V.K. Mehta, O. Aslam, L. Dale, N. Miller, D.R. Purkey, Scenario-based water resources planning for utilities in the Lake Victoria region, Phys. Chem. Earth, Parts A/B/C, 61–62 (2013) 22–31.
[33] M.D. Omar, A.M. Moussa, Water management in Egypt for facing the future challenges, J. Adv. Res., 7 (2016) 403–412.
[34] Y. Li, H. Li, A WEAP-based model for the management of water quality and safety in Xitiaoxi watershed, Adv. Water Sci., 21 (2010) 666–673.
[35] L. Yu, Optimized Allocation of Water Resources in Ningxia Yellow River Basin on WEAP Model, Southwest University, Chongqing, 2014 (in Chinese).
[36] X. Li, Y. Zhao, C. Shi, J. Sha, Z.L. Wang, Y. Wang, Application of Water Evaluation and Planning (WEAP) model for water resources management strategy estimation in coastal Binhai New Area, China, Ocean Coastal Manage., 106 (2015) 97–109.
[37] W. Wan, J. Yin, J. Zhao, X. Lei, W. Liao, T. Qin, Sustainability evaluation of Beijing water deployment model before and after south-to-north water diversion, South-to-North Water Transfer Water Sci. Technol., 14 (2016) 62–69 (in Chinese).
[38] S.T. Li, X.Y. Xu, South-to-North Water Transfer and China Development, Economic Science Press, Beijing, 2004 (in Chinese).
[39] S. Wei, A. Lei, S.N. Islam, Modeling and simulation of industrial water demand in Beijing, Front. Environ. Sci. Eng. China, 4 (2010) 91–101.
[40] M.Y. Han, G.Q. Chen, M.T. Mustafa, T. Hayat, L. Shao, J.S. Li, Embodied water for urban economy: a three-scale input–output analysis for Beijing 2010, Ecol. Modell., 318 (2015) 19–25.
[41] P. Wu, W. Zhang, Water crisis and sustainable water resource utilization in Beijing, J. Liaoning Tech. Univ., 24 (2005) 436–439 (in Chinese).
[42] Z. Wang, K. Huang, S. Yang, Y. Yu, An input–output approach to evaluate the water footprint and virtual water trade of Beijing, China, J. Cleaner Prod., 42 (2013) 172–179.
[43] B.M.S. Bureau, Beijing Statistical Yearbook 2014, China Statistics Press, Beijing, 2014 (in Chinese).
[44] Y. Wang, L. Liu, Water: how much the shortfall in Beijing is? Beijing Stat., 6 (2002) 18–19 (in Chinese).
[45] Group PIB, Beijing's Water Crisis 1949–2008 Olympics, China Heritage Quart., 2008 (in Chinese).
[46] Authority BW, Beijing Water Resources Bulletin, Beijing, 2014 (in Chinese).
[47] S. Wu, The Research of China's Water Service Integration System – The Case of Hangzhou, Zhejiang University, 2007 (in Chinese).
[48] J. Sieber, D. Purkey, WEAP User Guide, SEI-US Center, SEI, 2015.
[49] H. Cao, X. Gu, L. Guo, Dynamic disequilibrium and restoration mechanism of Beijing's water resources in a supply-demand perspective, China Environ. Sci., 35 (2015) 1271–1280 (in Chinese).
[50] A. Falkenma, Society's interaction with the water cycle: a conceptual framework for a more holistic approach, Hydrol. Sci. J., 42 (1997) 451–466.
[51] H.L. Fu, X.J. Liu, Research on the phenomenon of Chinese Residents' spiritual contagion for the reuse of recycled water based on SC-IAT, Water, 9 (2017) 846.
[52] Z.G. Li, C. Han, T.Y. Gu, Potential of economic utilization of biomass waste for gasification purposes, Energy Sources Part B. DOI:10.1080/15567249.2017.1410593.
[53] H. Wang, Y. Jia, Theory and study methodology of dualistic water cycle in river basins under changing conditions, Shui Li Xue Bao, 47 (2016) 1219–1226 (in Chinese).
[54] Y. Lu, X. Zhang, S. Chen, L. Shao, H. Sun, Changes in water use efficiency and water footprint in grain production over the past 35 years: a case study in the North China Plain, J. Cleaner Prod., 116 (2016) 71–79.