EPiC Series in Engineering
Volume 3, 2018, Pages 2399–2407
HIC 2018. 13th International Conference on Hydroinformatics

Water Energy Nexus in Urban Water Resources Allocation: A Case Study of Jinan City

Zhaohui Yang[1], Hao Wang[1,2], Jie Du[3], Weiwei Shao[1], Guiyu Yang[1]
1 China Institute of Water Resources and Hydropower Research, Beijing 100038, China
2 State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, Beijing 100038, China
3 Beijing Forestry University, Beijing 100083, China
yzh2010@iwhr.com.com, wanghao@iwhr.com, taiyuandujie1992@163.com, shaoww@iwhr.com, guiyuy@iwhr.com

Abstract

The water energy nexus– energy used for water – has received increasing attention in a changing world. With rapidly growing population and economic growth in urban areas, the demand of energy and water resources may subsequently rise. Since supply different water resources (such as transferred water and reclaimed water) requires different amount of energy, the city should perform a quantitative assessment of water energy nexus, and work out how to allocate various water resources to reduce urban energy consumption. Taking Jinan city as an example, this paper analyzes the advantages and disadvantages of using various types of water resources, predictions of the future trends in water use, and estimates unit electricity requirements for the supply of fresh water and the treatment of wastewater, and briefly depict the water energy nexus in the urban water resources allocation, and try to find a water resource -energy balance for the urban water allocation. This work would help to explore the water energy nexus for urban water resources management, and to optimize the allocation of water resources.

1 Introduction

Each link of social water cycle, including water supply, water use, water consumption, water drainage, sewage treatment, etc., consumes energy (conversely, energy development and transportation consume water resources). The correlation between water and energy—used for energy consumption in water resources—attracts more and more attention in such a changing world. In urban water resources allocation, energy consumption is relatively low and is often ignored by the government. With the rapid growth of population and urban economy, the demands for energy and water resources are increasing. For example, 19% of the power in California is used for water related services, including water supply, sewage treatment, irrigation and other purposes (Stokes and Horvath, 2009). For the shortage of local water resources, an increasing number of cities have to supply water resources through seawater desalination and water reuse.

G. La Loggia, G. Freni, V. Puleo and M. De Marchis (eds.), HIC 2018 (EPiC Series in Engineering, vol. 3), pp. 2399–2407

Chinese energy consumption rate is far higher than the world average. The per-capita energy consumption among urban residents is 2.5 times as high as the per-capita energy consumption among rural residents. So far, Chinese urbanization has been developing very quickly. Over 1978~2015, the national population grew from 960 million to 1.37 billion, see Figure 1; permanent urban population grew from 170 million to 770 million; the urbanization rate rose by 1.35%, from 17.9% to 56.1%; the energy consumption and per-capita energy consumption increased by 9.5% and 8.5%. Today when the domestic energy demand increases rapidly, the urban energy supply-demand contradiction is increasingly apparent.

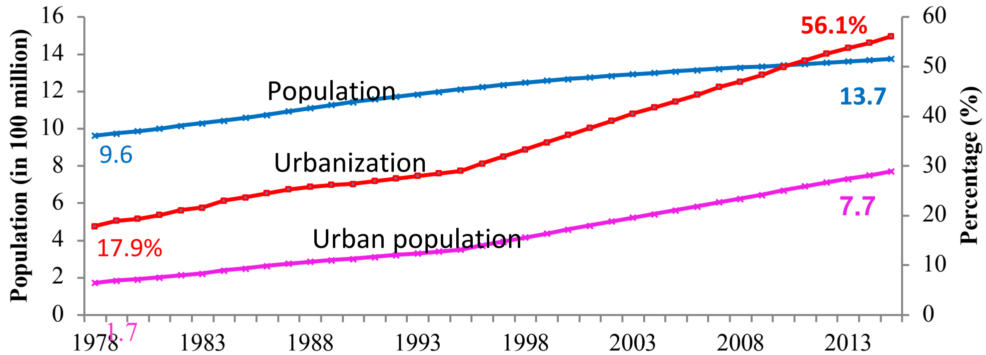

Figure 1: 1978 ~ 2015 Trend Chart of Population and Urbanization Rate

In the world, the recycled consumption and mutual restraining of water and energy have emerged gradually. In these years, the structural adjustment of urban water resources and improvement of urban water quality requirements cause that the energy consumption of urban water system increases. European and American countries have paid attention to the energy consumption in water resources utilization. In 2000, Electric Power Research Institute (EPRI) initiated a series of researches into water resources and sustainable development, containing the statistics of public water resources supply and sewage treatment power consumption per user and the prediction of water and power consumption (Goldstein R, Smith W., 2002). China's energy consumption was quantified during water resources utilization with an input-output method and put emphasis on the correlation between capital or economy and water or energy (Fritz Kahrl and David Roland-Holst,2007). And the water consumption of different kinds of power generation in each link and the power consumption during water resources utilization according to the data provided by several departments of the U.S. (Afreen Siddiqi and Laura Diaz Anadon,2011). Ashlynn et al. (2011) quantified the relationship of water resources with energy sources in Texas, especially the correlation between power generation and water resources; studied the water demand of different kinds of power generation equipment in a typical system throughout the U.S., including Texas; and discussed the energy demand of water supply and sewage treatment systems. Laurent Hardy et al. (2012) assessed the current situation of relationship between water and energy in Spain; highlighted Spain's energy consumption in water resources utilization and water consumption in energy utilization; and specially analyzed the energy consumption of agricultural water saving measures.

At present, China's research into energy consumption in water resources utilization is just at the beginning. Gao Jinjing (2012) submitted a dissertation Analysis of Correlation between China's Water Resources Utilization and Power Generation, quantifying the mutual consumption between water resources utilization and power generation and making suggestions on the sustainable development of water resources and energy sources on the basis of water-energy relationship. Wang Zhimin (2012) submitted a dissertation Study of Energy Saving Control of Urban Water Supply System, analyzing the situation that urban water supply systems are the main power consumer and highlighting that variable-frequency controllers in urban water supply systems can save 5% of electrical energy for water plants. Wen Hua et al. (2014) took the lead in carrying out "analysis of water-energy relationship in urban water resources selection: taking Qingdao for example", putting emphasis on analyzing the effects of different water resources on the water supply cost, energy consumption, and greenhouse gas emission. Generally speaking, these scholars carried out exploratory research into the energy consumption in water resources utilization and made progress to a certain extent. Now, analyzing and quantifying the power consumption in such links as supply, utilization, consumption, drainage, and treatment of social water cycle, quantifying the space-time relationship of social water cycle with energy consumption, and quantifying the threshold that energy consumption constrains the water supply capacity of different structures are difficulties in research.

2 Research Objective and Method

To think about how to choose from water supply sources, including surface water, transfer water, reclaimed water, rainwater, seawater, etc., in urban water resources allocation when facing the severe challenge of energy supply during urbanization. Water supply from different sources requires not the same energy consumption. The energy consumed for water supply by seawater desalination system is 5–10 times as much as that consumed by conventional surface water. This paper is to analyze the energy consumption of Jinan urban water supply system in 2014. The research objectives are: (1) to describe the analysis of water-energy correlation in urban water resources allocation; and (2) to reduce the energy consumption in each link of urban water resources allocation.

Social water cycle (including water supply, water consumption, water drainage, sewage treatment, and other links), mainly driven by manpower, mechanical energy, electric power or any other artificial energy, is a process of water resources dissipation. The artificial energy makes water resources run from lows to heights, from under populated places to populated places. Cities have a strong demand for water and energy resources for its dense population and developed economy. In this paper, we calculate and analyze (based on the unified unit of power consumption) the artificial energy related to 2014 Jinan water resources utilization and water supply conditions and predict the future water demand and water supply conditions. We also process and analyze the basic data of energy consumption for supply, use, consumption, drainage and treatment and calculate the minimum energy consumption to satisfy the future water demand.

In urban water resources allocation, energy is mainly consumed for 4 aspects: (1) extraction and transportation of raw water. For most water resources (including surface water, groundwater, seawater, reclaimed water and transfer water), raw water need be pumped to the water works. (2) water making. The conventional water works purify raw water through precipitation, filtration and disinfection of water logging. Energy is mainly consumed by pump station and for water treatment process. About
90% of the power is consumed by the secondary pumping room. The rest 10% is consumed for backwash and sewage drainage. (3) water transportation and distribution. A tap water distribution system uses a pump station to distribute tap water to users. Energy is mainly consumed by the pump station. (4) sewage collection, treatment and drainage. Energy is mainly consumed by the pump station, fan, and for biological treatment. Water quality and amount influence the unit energy consumption.

Energy consumption varies much with the water supply infrastructure. Due to the limited data acquisition, we consider the consumption in water taking and making only. That is to say, we consider the extraction, transportation and treatment of water sources only in the study of water-energy correlation in urban water sources allocation.

2.1 Water demand prediction of study area

Jinan City is located in the middle of Shandong Province in china, known as the large number of springs, including Urban area, Zhangqiu district, Pingyin district, Jiyang district, and Shanghe district. Location of Jinan City is shown in Fig. 2. Taking Jinan City for example, its situation of power consumption is especially severe, and many large-scale power brownout occurred in recent years. Its biggest power gap in 2008 summer is 900,000~1000,000 kW, which goes beyond the load limit of Jinan power grid. According to calculation, that power brownout influences an industrial added value loss of about RMB 90.4 billion, which makes up 8.4% of Jinan industrial added value in that year. The total water demands of the city are shown in table1, and the total available water supply of the city are shown in table2.

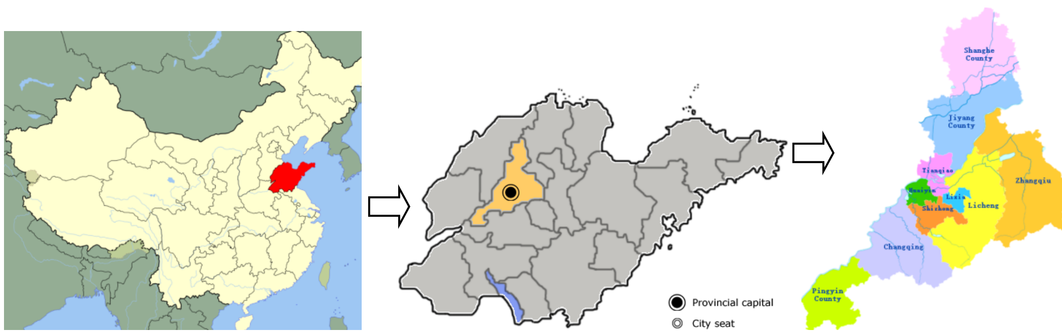

Figure 2: Location of Jinan City

Administrative division	2014 Water consumption					2020 Water demand	2030 Water demand
	Local surface water	Ground water	Unconventional water resources	Transferred water	Total	Total	Total
Urban area	1.3	1.7	0.5	3.1	6.6	7.9	9.6
Changqing	0.4	0.8	0.0	0.0	1.2	1.6	1.8
Zhangqiu	0.4	2.1	0.1	0.5	3.1	3.5	3.8
Pingyin	0.3	0.7	0.0	0.2	1.2	1.3	1.3
Jiyang	0.2	1.0	0.0	1.7	2.9	3.2	3.5
SHANGHE	1.1	0.3	0.1	0.5	1.9	2.2	2.4
Total	3.6	6.6	0.8	6.0	16.9	19.5	22.4

Table1: Water supply and future water demand in the study area unit : billion m^3

2.2 Analysis of energy consumption for water taking and making of different water sources

(1) Power consumption intensity for surface water taking

Generally, surface water sources are in a certain distance to water works. Surface water taking needs a water pump at the site of source and canals for long-distance transportation. Suppose the loss of water head in long-distance water transportation to be the energy required by the pump station, namely energy consumption for long-distance water transportation.

Administrative division	year	Local surface water	Ground water	Transferred water	Unconventional water resources	Total
Urban area	2020	1.95	1.66	3.17	1.38	8.16
	2030	1.95	1.66	3.64	2.32	9.57
Changqing	2020	0.67	0.75	0.03	0.13	1.58
	2030	0.67	0.75	0.13	0.27	1.83
Zhangqiu	2020	0.79	2.08	0.82	0.28	3.97
	2030	0.79	2.08	1.05	0.49	4.41
Pingyin	2020	0.37	0.80	0.25	0.07	1.49
	2030	0.37	0.80	0.25	0.12	1.54
Jiyang	2020	0.22	0.95	1.69	0.10	2.97
	2030	0.22	0.95	1.89	0.18	3.24
SHANGHE	2020	0.27	1.07	0.72	0.09	2.16
	2030	0.27	1.07	0.72	0.17	2.24
Total	2020	4.28	7.31	6.68	2.06	20.33
	2030	4.28	7.31	7.68	3.56	22.82

**Transferred water including water from the Yangtze river and the Yellow river*

Table2. The available water supply in the study area unit : billion m^3

(2) Power consumption intensity in transfer water taking

Transfer water taking also needs a water pump at the site of source and canals for long-distance transportation. For transfer water, we select the lift pump efficiency of 75%.

(3) Power consumption intensity in groundwater lifting

Groundwater taking needs deep wells underground and a pump station. The energy consumption for groundwater mining mainly depends on the efficiency of pump station.

(4) Power consumption intensity in reclaimed water production

A reclaimed water works may consume energy in secondary sewage collection, reclaimed water transportation, and sludge treatment besides in treatment process. Generally, sewage gathers under the influence of gravity. But sometimes, sewage need be lifted from lows to heights due to terrain restrictions. Based on the existing research results [13], use ultrafiltration as the typical membrane separation technology and the water produced from secondary sewage treatment plant as the reclaimed water.

(5) Power consumption intensity in desalination of seawater or brackish water

At present, people usually desalinate the brackish water through RO (reverse osmosis) and ED (electrodialysis) and desalinate the seawater through distillation and RO. For the desalination of both brackish water and seawater, RO occupies an absolute share for its low cost and low energy consumption. It is a future development emphasis of desalination technology.

(6) Power consumption intensity for urban water supply, treatment, transportation and distribution

In urban water supply, water works varies in terms of scale, specific treatment method, and energy consumption. In feed water treatment, the power consumption for water transportation takes up 80%–90% of the power consumption of waterworks. Feed water treatment consumes only a little energy.

2.3 Energy consumption evaluation function

Combined with Jinan's energy conservation objective, water demand prediction and analysis of available water quantity, we build the energy consumption evaluation function and seek the water sources allocation solution with minimum energy consumption. Suppose v (i) to be the power consumption coefficient in water taking and making, and this coefficient expresses the power consumption required to supply unit water. The varying value of v (i) reflects the energy consumption of different water sources. The total power consumption for Jinan water supply E can be approximately expressed as follows:

$$E = \sum_{i=1}^{n} v(i)Q(i)$$

Where, n is the number of water sources; v (i) is the power consumption coefficient in water taking and making, in kWh/m^3; Q(i) is the water supply from the ith water source, in m^3.

Constraint: In a unit of time, the sum of water supply from all water sources is the urban water used. The water supply from any water source is smaller than the available water supply. It is possible to calculate the water supply amount from each water source corresponding to the minimum power consumption.

$$Q_0 = \sum_{i=1}^{n} Q(i), Q_{MIN}(i) \le Q(i) \le Q_{MAX}(i), i = 1,2,\cdots,n$$

3 Result and Discussion

Through calculation and analysis, status statistics and future projections show that the unit of reclaimed water consumes the most energy, see Figure 3. In areas where energy is scarcer and freshwater resources are in greater demand, make choices after considering the energy costs associated with regenerating water production and the energy costs associated with other sources of new water availability. More distant water diversion, reclaimed water production and seawater desalination power consumption depends on water distance.

According to the forecast of water demand and the total available water supply, using unconventional water resources and transferred water to solve the problem of increasing demand on water resources is feasible consider water conservation. The total water supply in Jinan City add 0.6 billion m3, however the energy consumption by water supply in 2030 will be twice as that in 2014, see Figure 4. This result shows that under present technical conditions, using unconventional water resources and transferred water to solve water resource problems is to pass the pressure of expanded water shortage to energy production. To reduce the pressure caused by usage of water resources, energy consumption (especially electric consumption) should be taken into full consideration in the selection of water saving technology and the solution to water shortage.

According to the cost of electricity consumption, Jinan city should give priority to the utilization of local water resources, followed by yellow river and groundwater, the utilization of Yangtze River water and Brackish Water is currently relatively high electricity consumption. The energy consumption by water supply in 2030 will be just 1.5 times as that in 2014, see Figure 5.

Status statistics show that the water supply and water conveyance accounts for about 40% of the energy consumption of water supply, so reducing the water demand will greatly contribute to reducing the electricity consumption of water supply. The application of water saving technology is the fundamental way to reduce the demand for water resources. Jinan local surface water and groundwater, far below the water demand in Jinan City, and there must be through water diversion, reclaimed water and other water sources to solve the contradiction between water resources, under the conditions of current technology, the use of reuse water to solve the problem of water resources is the shortage of water resources pressure enlarged and passed on to power production. We should to maximize the local surface and groundwater available water resources, and water diversion from the yellow river.

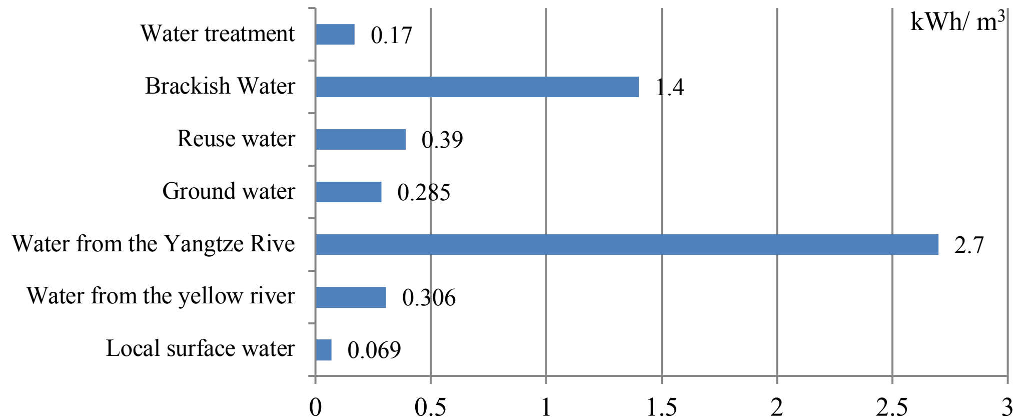

Figure 3: Electricity consumption in the process of water resource utilization in Jinan

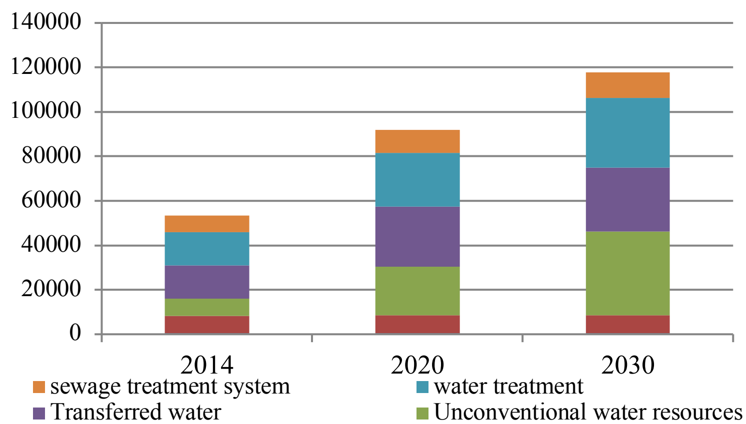

Figure 4: Energy consumption of water supply (1)

4 Conclusion

In this paper, the future demand of water resources in Jinan and the available water supply of various water sources were predicted, and the energy intensity of various types of water supply was quantitatively evaluated. Taking Jinan City as an example, the advantages and disadvantages of using various water resources were analyzed, and the future water use trend was predicted, and the power demand of fresh water supply unit and wastewater treatment unit was estimated, and the relationship between water and energy was briefly described.

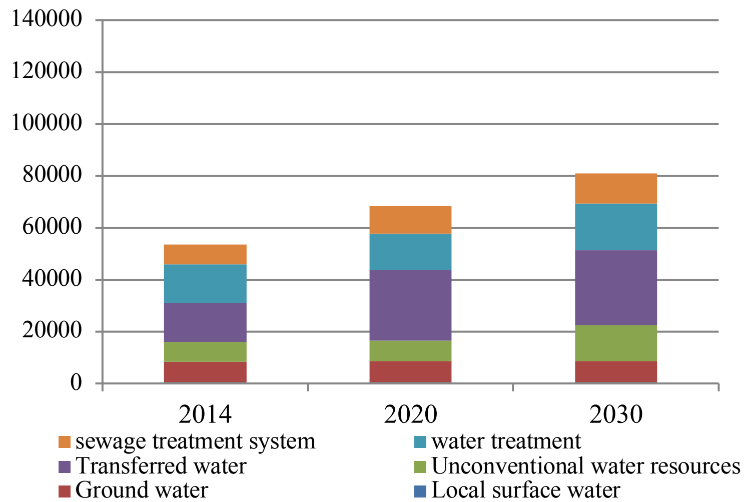

Figure 5: Energy consumption of water supply (2)

References

Gao Jinjing. *Analysis of the Correlation between Water Resources Utilization and Electric Power Production in China* [D]. Tianjin: Tianjin University, 2012.

Wen Hui, Wang Dawei. *New-Style Urbanization Promoting the Green Energy Consumption*[J] China Economic Herald. 2012, 11: 43–45

China Energy News. *Prediction of Mid-Long-Term Development Trend of Coal Industry: Consumption to Increase*[N]. China Energy News, Sept. 06, 2012.

Goldstein R, Smith W. *Water & Sustainability: U.S. Electricity Consumption for Water Supply & Treatment-the Next Half Century*[M]. California: EPRI, 2002.

Fritz Kahrl , David Roland-Holst. *Energy and Exports in China*[R]. August,2007

Afreen Siddiqi,Laura Diaz Anadon.*The water-energy nexus in Middle East and North Africa s*[J].Energy Policy ,2011(39):4529-4540

Ashlynn S, Carey W, *Michael E. The energy-water nexus in Texas*[J]. Ecology and Society, 2011, 16(1): 2-4.

Laurent H, Alberto G, Luis J. *Evaluation of Spain's water-energy nexus*[J]. International Journal of Water Resources Development, 2012, 28(1): 151-170.

Wang Zhimin. *Study of Energy Saving Control of the Urban Water Supply System* [D]. Heilongjiang: Harbin Institute of Technology, 2012.

Wen Hua, Zhong Lijin, et al. *Analysis of Water-Energy Correlation in Urban Water Sources: Taking Qingdao for Example*[R]. Beijing: World Resources Institute, 2014.

Odum H．T．*Environmental Accounting：Emergy and Environmental Decision Making*[M]．New York：John Wiley&Sons，1 996

Yang Lingbo, Zeng Siyu, Ju Yuping. *Statistical Analysis and Quantitative Recognition of Chinese Energy Consumption Rules of Urban Sewage Treatment Plants* [J]. Water & Wastewater Engineering, 2008, 34(10): 42-45.

Shi Liuqing. *Application of Ultrafiltration in Drinking Water Purification and Urban Sewage Advanced Treatment* [D]. Beijing: Tsinghua University, 2011