Energy Proceedings
Vol 29, 2022
ISSN 2004-2965

Multi-objective Optimization for Energy -Water Nexus of Urban Water Cycle Based on NSGA-II Model-a Case Study of Beijing

Jiaxiang Zou[1], Saige Wang [1], Bin Chen [1*]

1 State Key Joint Laboratory of Environmental Simulation and Pollution Control, School of Environment, Beijing Normal University, Beijing 100875, P.R. China (* Corresponding Author, Email: chenb@bnu.edu.cn)

ABSTRACT

Energy and water are intertwined in the urban water cycle and need to be coordinated for an integrated resource utilization and more resilient structure. This paper presented a multi-objective optimization model for the energy-water nexus in urban water cycle targeting less energy consumption and more water sustainability with a case study of Beijing. The findings show that the total energy consumption of the social water cycle is 389.831 billion kWh, the maximum of energy consumption in water use processes is water use process. The least energy consumption is the water supply process. Based on the ecological network analysis method, a social water cycle network with 19 flow paths of 7 nodes is constructed. Based on the non-dominated sorting genetic algorithm II (NSGA-II), a multi-objective optimization of energy-water nexus in the urban water cycle was performed to achieve the coordinated goal of water sustainability and energy consumption. The findings may help promote the urban water system management and improve its sustainability.

Keywords: water cycle system, energy-water nexus, multi-objective optimization, ecological network analysis, energy consumption

1. INTRODUCTION

With the strengthening of human activities, human's demand for water has changed from a single state of natural water cycle to a state of water cycle with artificial intervention to meet their own needs, which is called the urban social water cycle process. Urban water cycle includes the process of water intake, water supply, water conveyance, water use, drainage and sewage reuse[1]. Energy and water are highly interdependent. The process of urban social water cycle takes water resources as the carrier and energy as the driving force. Studies have shown that urban social water cycle consumes 2-3% of global total energy consumption, and it is estimated that by 2050, with the increase of social water cycle flux, the demand for energy will increase by 33%[2]. With the development of urbanization, global water consumption has increased sixfold over the past 100 years and will grow steadily at an annual rate of 1%[3]. Therefore, it is of great significance to analyze energy-water nexus in every process of urban social water cycle.

As two basic resources of social and economic development, energy and water resources are interdependent and mutually restricted. At present, there has been many studies on the energy -water nexus [4]. The sustainable development of urban social water cycle system is restricted by the energy - water nexus[5]. Following that work, more scholars had conducted more detailed studies on the energy and water resource consumption in each process from a certain aspect of the social water cycle, such as water intake, water supply, water production, sewage treatment, etc[6].

Ecological network analysis has been widely used in water resources system by quantitatively exploring the relationship between the components of the system and revealing the integrity and complexity of the system. These studies contribute to the construction of urban social water cycle network process and the understanding of network structure and relationship.

In view of the contradiction between supply and demand of water resources system, it is necessary to reasonably optimize the allocation of different water sources and water departments of water resources system[7]. Therefore, the multi-objective optimization model is widely used in the optimal allocation of water resources[8]. The non-dominated sorting genetic algorithm II (NSGA-II) is one of the most widely used multi-objective genetic algorithms. This method introduces the elite strategy, expands the sampling space, and has good convergence[9].

However, the current research is lack of detailed research on the various processes of urban social water cycle, and lack of consideration of the energy-water nexus in each process. Based on this, this paper quantified the energy- water nexus in each process of

This is a paper for the 14th International Conference on Applied Energy - ICAE2022, Aug. 8-11, 2022, Bochum, Germany.

urban water cycle. Based on NSGA-II model, considering the energy consumption and the sustainability of water cycle network, the water resources of each process of urban water cycle were optimized, hoping to realize the resilience and sustainable development of urban social water cycle.

2. MATERIALS AND METHODS

2.1 Calculation of energy consumption in social water cycle

2.1.1 Water intake process

2.1.1.1 Surface water intake

The energy consumption calculation formula of water storage project is：

$$w_1 = \frac{mgh_f}{3.6 \times 10^6} \quad (2.1)$$

$$h_f = i \times L \quad (2.2)$$

$$i = 10.294 \times n^2 \times Q^2 \div d^{5.333} \quad (2.3)$$

w_1 is the energy consumption of water storage, kWh; h_f is the head loss along the route, m; m: water quality, kg; g: the acceleration of gravity, N/kg; i: head loss per unit pipe length, m/m; L: length of pipe section, m; n: the roughness factor; Q: pipeline flow, m3/s; d: bore of pipe, m;

The calculation formula of water extraction project is：

$$w_2 = \frac{mgh}{3.6 \times 10^6 \times \varepsilon} \quad (2.4)$$

w_2 is the energy consumption of water extraction project, kWh; ε: pumping station efficiency

The energy consumption calculation of inter-basin water transfer is publicized as (2.1), but the head loss along the river is publicized as:

$$h_f = L \times Q^2 \times n^2 \times \frac{\left(b + 2h\sqrt{1 + m^2}\right)^{\frac{4}{3}}}{\left[(b + mh) \times h\right]^{\frac{10}{3}}} \quad (2.5)$$

L is the length of water conveyance, m; b is the bottom width, m; h is the height of the water surface, m; m is slope coefficient;

2.1.1.2 Groundwater intake

Groundwater is mainly used for farmland irrigation, residents drinking and industrial utilization. Among them, residents drinking and industrial use need to consider the head loss of the water pipeline β.

$$w_3 = \frac{mgh}{3.6 \times 10^6 \times \varepsilon \times (1 - \beta)} \quad (2.6)$$

w_3 : the energy consumption for groundwater intake, kWh; h is groundwater depth, m; β Losses along the way;

2.1.2 Water supply process

2.1.2.1 Conventional water plants

$$w_4 = \sum_{i=1}^{n} E_i \quad (2.7)$$

w_4: the energy consumption for conventional water plants, kWh; E_1、E_2、E_n: annual power consumption of waterworks, kWh;

2.1.2.2 Wastewater reclamation plants

The calculation formula of the energy consumption for wastewater reclamation plants is as formula (2.7).

2.1.3 Water conveyance

$$w_6 = \sum_{i=1}^{n} (k_i \times Q_i) \quad (2.8)$$

w_6: the energy consumption for water conveyance, kWh; k_i: energy intensity of water conveyance in each waterworks, kWh/m³; Q_i: total water conveyance in each waterworks, m³.

2.1.4 Water use

The calculation formula of the energy consumption for water use is as formula (2.8).

2.1.5 Drainage and sewage reuse

2.1.5.1 Sewage collection:

$$H = L \times \mu \quad (2.9)$$

H is the pump head, m; L is the straight-line distance before and after sewage lifting, m; μ is the average slope of the sewage pipe network, %.

$$w_8 = \frac{H \times M}{\omega} \quad (2.10)$$

w_8: sewage collection energy consumption, kWh; M is the amount of sewage raised by the pump, m³; ω is the average pump efficiency, %.

2.1.5.2 Sewage treatment and reuse of reclaimed water

The calculation formula of the energy consumption for sewage treatment and reuse of reclaimed water is as formula (2.8).

2.2 ecological network analysis of the urban water cycle

2.2.1 ecological network model of the urban water cycle

The ecological network analysis is represented by nodes in circles, and the path of species and energy transfer between nodes is represented by arrows. The f_{ij} between each path represents the runoff from node j to node i, and the arrow from j to i. The input path from the environment in the system is represented by z_i, and the arrow points to the component.

2.2.2 through flow and utility analysis

The network structure efficiency is measured by the network indicator Ascendency (A).

$$A = \sum_{i=1}^{n+2} \sum_{j=0}^{n} T_{ij} \log_2 \frac{T_{ij} T_{..}}{T_{i.} T_{.j}} \quad (2.11)$$

In view of the system development capability, the network structure resilience is defined as measured by the reserve capacity index (∅).

$$\emptyset = -\sum_{i=1}^{n+2} \sum_{j=0}^{n} T_{ij} \log_2 \frac{{T_{ij}}^2}{T_{i.} T_{.j}} \quad (2.12)$$

The mutual supplements of A and ∅ represent the long-term sustainability of the system, and there is a relationship between network development capacity C and the above indicators:

$$C = A + \emptyset \quad (2.13)$$

2.3 multi-objective optimization for energy-water nexus

The form of objective function can be expressed as:

$$Z = max\{f_1(X), f_2(X) \cdots f_n(X)\} \quad (2.14)$$

X is a decision variable, composed of different quantity, quality and form of water resources. $f_1(X), f_2(X) \cdots f_n(X)$: optimization function.

3. RESULTS AND DISCUSSIONS

3.1 Energy consumption

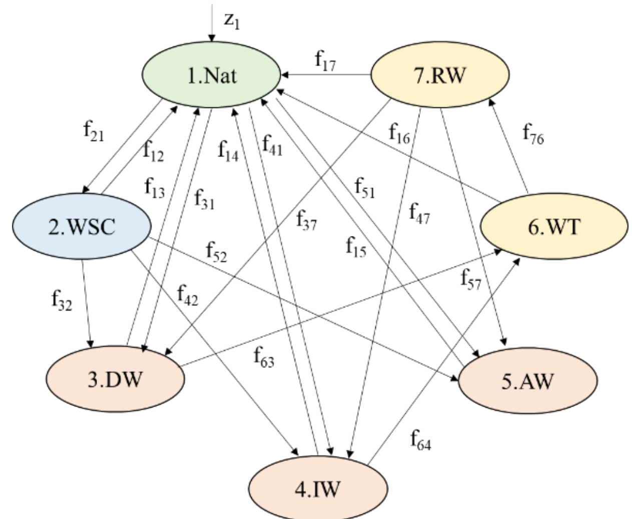
The total energy consumption of the social water cycle in Beijing is 389.831 billion kWh, of which the energy consumption of water use process is 363.02 billion kWh, of which the energy consumption of domestic water is the most, accounting for 66.72%. The energy consumption of water supply is the lowest, only 0.757 billion kWh.

Tab.1 The energy consumption of social water cycle process

Num	Process	Sub-process	Energy intensity (kWh/m³)	Water resources (10⁸m³)	Energy consumption (10⁸kWh)
1	Intake	Surface	0.029	9.08	0.165
2		Ground	0.157	4.83	0.757
3	Supply		0.028	11.83	0.329
4	Conveyance		0.626	22.59	14.14
5	Water use	Domestic	28.9	9	260.1
6		Service	11.6	5.99	69.48
7		Industrial	11	3.04	33.44
8	Drainage and sewage reuse		0.6	19.04	11.42

3.2 Ecological network analysis

According to the system boundary studied, different sectors of the ecological network model of social water cycle are represented by nodes, and the flow of water at the above nodes is represented by directional lines, obtain the metabolic ecological network model of water resources in the process of social water cycle. A total of 7 compartments, 19 flow paths.



1.Nat	Nature environment
2.WSC	Water supply and conveyance
3.DW	Domestic water
4.IW	Industrial water
5.AW	Agricultural water
6.WT	Wastewater treatment
7.RW	Reuse water

Fig.1 Ecological network analysis of social water cycle process

ACKNOWLEDGEMENT

This work was supported by the Strategic Priority Research Program of Chinese Academy of Sciences (No. XDA20100104), Beijing Outstanding Scientist Program (BJJWZYJH01201910027031), National Natural Science Foundation of China (Nos.72091511, 71725005) and Beijing Natural Science Foundation (9222017).

REFERENCES

[1] Zhang Y, Yang R, Fath R D. Ecological network analysis of an urban water metabolic system: Model development, and a case study for Beijing[J]. Science of the Total Environment, 2010, 408(20):4702-4711.

[2] Duan C, Chen B. Driving factors of water-energy nexus in China[J]. Applied Energy, 2020, 257:113984.

[3] Khalkhali M, Dilkina B, Mo W. The role of climate change and decentralization in urban water services: A dynamic energy-water nexus analysis[J]. Water Research, 2021, 207:117830-.
[4] Zhang Y, Fu Z, Xie Y, et al. Dynamic metabolism network simulation for energy-water nexus analysis: A case study of Liaoning Province, China[J]. Science of The Total Environment, 2021, 779(7):146440.
[5] Xu W, Zhang X, Cui Y, et al. Study on Comprehensive Evaluation of Urban Water Resource Vulnerability[J]. Sustainability, 2022, 14.
[6] Yan Y, Zhu A, Tsydypova A. RESILIENCE EMERGENCY STRATEGIES FOR URBAN WATER SUPPLY SYSTEM UNDER EMERGENT WATER POLLUTION EVENTS[J]. Environmental Engineering and Management Journal, 2021, 20(2):185-194.
[7] Feng J. Optimal allocation of regional water resources based on multi-objective dynamic equilibrium strategy[J]. Applied Mathematical Modelling, 2021, 90:1183-1203.
[8] Piscopo A N, Weaver C P, Detenbeck N E. Using Multiobjective Optimization to Inform Green Infrastructure Decisions as Part of Robust Integrated Water Resources Management Plans[J]. Journal of the Water Resources and Planning and Management Division, 2021, 147(6).
[9] Li J, Zhang W, Yeh W G. A Proposed Multi-Objective, Multi-Stage Stochastic Programming with Recourse Model for Reservoir Management and Operation[J]. Water Resources Research, 2021, 57.
[10] Yongxia Zhu. Research on energy consumption evaluation method of whole process of social water cycle [D]. China institute of water resources and hydropower research, 2017.