Water Quality Restoration with Ecological Water Demand Allocation Regulation

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Abstract: Ecological water replenishment is the main means of ecological restoration in urbanized rivers. The control targets of utilizing water resources, allocating water and restoring the water quality have become the research hotspot. In this study, the Chengnan River Basin in Jiangbei New District of Nanjing was taken as the object, and the ecological water demand threshold in the Chengnan River Basin was evaluated by using the calculation result of the ecological water demand obtained by the improved Tennant method. According to the ecological water replenishment configuration plan, a water quality and quantity coupling model was constructed to simulate and analyze the water quality improvement effects at the control section of the Chengnan River Basin under different guarantee conditions. The results show that the monthly water demand allocation scheme based on the improved Tennant method can be used as the basis for water replenishment of river ecological restoration, and it can effectively improve the water quality of the Chengnan River. The use of 40,000 t/d water replenishment for 11 days can make the Longwangmiao section meet the water quality target control requirements.

1. Introduction
The development of urbanization is accelerating. Problems in urbanized watersheds usually include insufficient ecological flow of rivers, substandard water quality sections, damage or even degradation of river and lake ecosystems. How to improve river ecological environment and repair river ecosystems has become a research hotspot[1]. According to relevant research, ecological water replenishment regulation is one of the important measures to effectively improve river water quality [2]. Ecological water supplement increases the river water volume and dilutes the sewage while increasing the flow velocity.

In order to rationally allocate water resources and formulate ecological water supplement schemes for river courses, ecological water demand calculation should be taken as an important basis. At present, the main calculation methods include habitat quota, overall analysis, hydraulics and hydrology [3]. The habitat quota method refers to the application of ecological hydraulics to determine the appropriate water demand for aquatic organisms. Wang Xiuying[4] once used the habitat simulation method to calculate the ecological water demand for the ecological protection goals of the Nanxi River, however the habitat quota method requires long-term field surveys and involves a large amount of biological data that are not easily obtained, its application is restricted [3,5]. Based on the integrity of the ecosystem, the overall analysis method involves multiple disciplines such as landscape, ecology, hydrology, geography, and is not easy to promote in application. Hydraulic methods, such as
the wet-period method and the R2-Cross method, refer to the method of determining the water demand through the hydraulic parameters of the river section. Gu Binjie [6] used the wet-period method and the hydraulic radius method to calculate the ecological water demand of the Yongding River, but the hydraulics methods cannot be applied to river systems lacking cross-section data. The hydrological method refers to inferring river ecological flow based on historical data, thereby establishing an adaptive relationship between the flow and the river ecosystem. This method to calculate ecological water demand requires the least data and is universal and the easiest. Among the hydrological methods, the Tennant method has the widest scope of application, and is not limited to whether rivers are equipped with hydrological stations [7]. Nikghalb [8] used the Tennant method to calculate the ecological environmental water demand of a river in a semi-mediterranean region. The above studies have considered the calculation of the river's ecological water demand, but little is involved in regulating the river's ecological water demand. In view of this, this article takes the Chengnan River Basin as an example, and adopts the idea of "determining supply based on demand" for river ecological restoration [9]. That is to determine a reasonable river ecological water demand control scheme on the basis of ensuring the river's ecological water demand, with a view to promote the benign water circulate and improve the water quality of urban river sections, and provide references and guidance for the ecological restoration of urbanized rivers.

2. Overview of the study area

2.1. Scope of study area
Chengnan River (30°51′N~32°15′N, 118°21′E~118°46′E) is an important river in the Jiangbei New District of Nanjing, with a total length of 11.4km. Chengnan River Basin is a typical urbanization basin with a catchment area of 62.8km². In recent years, due to the dual influence of natural evolution and human development and utilization, there are many problems in the Chengnan River, such as the change of natural inflow, poor fluidity and deterioration of water quality pollution. The Longwangmiao section, which is the regulation section of the Chengnan River entering the Yangtze river, has a serious water quality deterioration problem. Therefore, this article selected the Longwangmiao section as the research object, and explored the ecological water replenishment scheme under the guarantee of ecological water demand configuration.

2.2. Hydrology, water quality monitoring and analysis
Table 1 was based on the rainfall data from Jiangpu Rainfall Station located in the Chengnan River Basin from 2010 to 2016, and calculated by referring to the surface runoff coefficient of Nanjing City [10].

| site name | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Jiangpu   | 0.32| 0.60| 0.60| 0.79| 1.09| 2.17| 2.22| 1.43| 1.21| 0.81| 0.72| 0.30|

Three water quality monitoring sections named the Rubber dam section, Pubin Road Bridge section and Longwangmiao section were set along the Chengnan River. The actual monitoring data showed that the main pollution factor of the Chengnan River is NH3-N. The water quality status of each monitoring section from November 19 to 26, 2018 is shown in figure 1. As a key assessment section of the Chengnan River, the water quality of the Longwangmiao section did not meet the Class V control standard (NH3-N≤2mg/l) during the monitoring period.
3. Evaluation and analysis of ecological water demand

Based on the research of Guo Lidan[11] and others, the monthly minimum (maximum) ecological runoff method is used to calculate the minimum (maximum) ecological runoff of the river channel (Method 1). In other words, this method is to select the minimum (maximum) value of each month's runoff series as the minimum (maximum) ecological runoff of that month. The specific calculation results are shown in figure 2.

Tennant method refers to the method of determining the ecological water demand according to the percentage of the ecological water demand in different river runoff [12]. However, this method is relatively simple, and standard values are not set according to the actual situation of the river, appropriate correction should be made in the actual application process. According to relevant documents[12-14], the annual precipitation in Chengnan River Basin was divided into low flow period (October-April of the following year) and high flow period (May-September), and 10% of the annual average monthly runoff in low flow period and 15% in high flow period were selected as the minimum ecological water demand. 60% and 150% of the annual average runoff were selected as the optimum and the maximum ecological water demand respectively, and the calculation results are shown in table 2 below. Monthly comparison of the minimum(maximum) ecological water requirements of Jiangpu Station calculated by the two methods is shown in figure 2 below.

Table 2. The improved Tennant method to calculate the ecological water demand in the Chengnan River basin.

| Month | Minimum ecological runoff | Optimum ecological runoff | Maximum ecological runoff |
|-------|---------------------------|---------------------------|--------------------------|
|       | Q (m³/s) | Rₖ (10⁶m³) | Q (m³/s) | Rₖ (10⁶m³) | Q (m³/s) | Rₖ (10⁶m³) |
| 1     | 0.03    | 8.28      | 0.19    | 49.68      | 0.48    | 124.20      |
| 2     | 0.06    | 15.50     | 0.36    | 93.01      | 0.90    | 232.53      |
| 3     | 0.06    | 15.57     | 0.36    | 93.42      | 0.90    | 233.55      |
| 4     | 0.08    | 20.59     | 0.48    | 123.57     | 1.19    | 308.92      |
| 5     | 0.16    | 42.43     | 0.65    | 169.71     | 1.64    | 424.27      |
| 6     | 0.33    | 84.51     | 1.30    | 338.04     | 3.26    | 845.10      |
| 7     | 0.33    | 86.15     | 1.33    | 344.59     | 3.32    | 861.47      |
| 8     | 0.21    | 55.50     | 0.86    | 221.99     | 2.14    | 554.97      |
| 9     | 0.18    | 47.20     | 0.73    | 188.80     | 1.82    | 472.00      |
| 10    | 0.08    | 20.94     | 0.48    | 125.61     | 1.21    | 314.03      |
| 11    | 0.07    | 18.64     | 0.43    | 111.81     | 1.08    | 279.53      |
| 12    | 0.03    | 7.68      | 0.18    | 46.08      | 0.44    | 115.20      |
| Total | 1.63    | 422.98    | 7.35    | 1906.31    | 18.39   | 4765.78     |
The comparative analysis of the monthly ecological water requirement of the Chengnan River in figure 2 showed that the monthly average ecological water demand calculated by method 1 was slightly larger than that of method 2, with the largest difference in July. The minimum values of ecological water demand calculated by method 1 and 2 are $1387.91 \times 10^4 m^3$ and $422.98 \times 10^4 m^3$ respectively, the maximum values are $6017.28 \times 10^4 m^3$ and $4765.78 \times 10^4 m^3$ respectively. The minimum (maximum) ecological water requirement can be determined by use of both method 1 and method 2. However, method 2 not only determines the minimum (maximum) value of the ecological water demand of the river, but also determines the optimum ecological water demand of the river[12], the calculation results of the improved Tennant method (method 2) are used this time. That is, the minimum, optimum and maximum ecological water demand of the Chengnan River is $422.98 \times 10^4 m^3$, $1906.31 \times 10^4 m^3$, $4765.78 \times 10^4 m^3$ respectively.

4. Water quality control analysis

According to table 1 and 2, the average monthly runoff of Chengnan River is greater than the optimum ecological runoff, and the river is ecologically safe and will not dry up [15]. However, the water quality monitoring data of Longwangmiao section from 2018 to 2019 showed that the water quality of this section was not up to the standard. To improve the water quality of Longwangmiao section and Chengnan River, ecological water replenishment control should be considered. According to Table 2, the annual average maximum ecological runoff of the Chengnan River is 1.5 m$^3$/s, and the annual average runoff of the Chengnan River is 1.01 m$^3$/s. If the river runoff was greater than the maximum one, flood and waterlogging disasters may occur[15]. Therefore, taking the maximum ecological runoff as the threshold, the upper limit of the ecological water replenishment volume for the Chengnan River is about 0.5 m$^3$/s or 43000 t/d.

In order to explore the effect of ecological water replenishment on improving section water quality, this study used water quality and quantity coupling model to simulate the water quality change process of Longwangmiao section under different water replenishment flows.

4.1. Model construction and calibration

Based on the relevant hydrological characteristics and water environment characteristics of the study area, MIKE11 model was selected to conduct water quality and quantity coupling simulation analysis[16]. The boundary conditions were the monitored discharge on the rubber dam and the Yangtze River water level data from March 2 to April 2, 2019. The upstream discharge of the rubber dam and the downstream water level of the Yangtze River were the open boundaries. The main pollution factor considered in the water quality model was NH$_3$-N, and the convection diffusion process of substances in water could be simulated by using the convection diffusion equation. The boundary conditions of the water quality model adopted daily monitoring data of NH$_3$-N concentration, and the initial degradation coefficient was calculated by using upstream and downstream synchronous water quality monitoring data.
The hydrodynamic model was verified using the measured water level data from the Longwangmiao section from March 2 to April 2, 2019. The simulated water level of the Longwangmiao section was basically consistent with the measured water level, and the established hydrodynamic model has a good effect. The water quality model was verified based on the calibrated hydrodynamic model. Generally speaking, the change trend of the NH$_3$-N simulation results for the Longwangmiao section is the same as the measured data, and the overall effect is within the acceptable range.

4.2. Setting of water replenishment point

According to the water replenishment plan of the Jiangbei New District in Nanjing, two water replenishment points were set in the Chengnan River, namely Xiangshan Reservoir and Jiangpu Waterworks. However, the upstream Xiangshan Reservoir had a capacity of 88×10$^4$m$^3$, which was too small to meet the long-term water supply demand of Chengnan River. Therefore, this time only Jiangpu Waterworks was considered as the replenishment point, which draws water from Yangtze River, with the replenishment water quality of Class II.

4.3. Effect analysis of section water supplement under different water supplement schemes

Considering the upper limit of ecological water replenishment for the Chengnan River, four water replenishment schemes (Q = 10000 t/d, Q = 20000 t/d, Q = 30000 t/d, Q = 40000 t/d) were set up for comparative analysis in the simulation test. The simulation duration of the model was 30 days, while the control group selected the typical substandard process of Longwangmiao section on November 23, 2018. Under different water supplement flow conditions, the ecological water replenishment effect of Longwangmiao is shown in figure 3 below. The time required for NH$_3$-N concentration in Longwangmiao section to return to the water quality target is different under different water replenishment conditions. When the water replenishment flow rate is higher, the pollutant concentration decreases faster. In spite of different water replenishment schemes, it takes more than 10 days for the Longwangmiao section to gradually reach the water quality control target.

The time required for the water quality of Longwangmiao section to reach the standard under the four water replenishment conditions and the NH$_3$-N reduction rate after 30 days of water replenishment are shown in Table 3. When the daily water supply is 40000 t, the pollutant reduction rate is the highest, and when replenishing water for 10-15 days, the water quality improvement effect is the best, but the water supply effect is weakened after the water supply exceeds 15 days.

| Replenishment conditions | concentration of NH$_3$-N (mg/l) | Reduction rate of NH$_3$-N (%) | Time for water quality to reach Class V(d) |
|--------------------------|----------------------------------|-------------------------------|------------------------------------------|
| Control group            | 2.63                             | -                             | -                                        |
| 10000 t/d                | 1.39                             | 47.1                          | 13                                       |
| 20000 t/d                | 0.73                             | 72.4                          | 13                                       |
| 30000 t/d                | 0.65                             | 75.1                          | 12                                       |
| 40000 t/d                | 0.49                             | 81.0                          | 11                                       |
5. Conclusions
1. The improved Tennant method is used to calculate the ecological water demand of the Chengnan River, the minimum, optimum and maximum ecological water requirements are respectively \(422.98 \times 10^4 \text{m}^3\), \(1906.31 \times 10^4 \text{m}^3\), \(4765.78 \times 10^4 \text{m}^3\), which can be used as the allocation threshold of ecological water supplement scheme and can be used as the design condition for the water quality control to reach the standard.

2. Reasonable regulation of ecological water replenishment can effectively improve river water quality, and has a significant reduction effect on \(\text{NH}_3\text{-N}\). The higher the makeup water flow rate is, the faster the \(\text{NH}_3\text{-N}\) concentration decreases, and the highest \(\text{NH}_3\text{-N}\) reduction rate is 81% when the makeup water reaches 40000 t on the same day. When the 40000 t/d flow is used to make up water for 10-15 days, the water quality improvement effect of Longwangmiao section is the best.

3. If there was no non-point source pollution output of extreme rainstorm, the current uniform water replenishment greater than 10000 t/d could meet the water quality target control requirements of Longwangmiao section.

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References
[1] Li, L.(2020) Study on ecological restoration of urban river water environment. Environment and Development, 32: 177-178.
[2] Jing, S.W., Zhang,J.(2018) Can Xin'anjiang river basin horizontal ecological compensation reduce the intensity of water pollution? .China Population, Resources and Environment, 28: 152-159.
[3] Zhang, H.(2014) Review of Theoretical Researches on River Ecological Water Demand and Relevant Progress. Tianjin Science&Technology, 41: 86-88+92.
[4] Wang, X.Y., BaiYin, B.L.G., Xu, F.R.(2016)Aquatic ecosystem protection objective-based study on eco-water demand of river channel. Water Resources and Hydropower Engineering, 47: 63-68,72.
[5] Guo, L.D., Xia, Z.Q., Li, J., et al.(2008) Improvement of calculation methods for instream ecological runoff. Journal of Hohai University (Natural Science),4: 456-461.
[6] Gu, B.J., Wang, F.S., Song, L., et al.(2017)Calculation and configuration of ecological water requirements for Yongding river Guanting Gorge. Beijing Water, 2: 12-18.
[7] Du, L.F., Hou.Z.L., Li, Y.B., et al.(2020) Study on Calculation Method of Ecological Water Demand of Urban River. Yellow River, 2: 1-5.
[8] Nikghalb, S., Shokoohi,. A., Singh, V.P., et al.(2016)Ecological Regime versus Minimum Environmental Flow: Comparison of Results for a River in a Semi Mediterranean Regio. Water Resources Management,30: 4969-4984.

[9] Wei, J., Pan, X.Y., Kong, G., et al.(2020)Study on ecological restoration of water-deficient rivers based on ecological water supplement method. Journal of Water Resources and Water Engineering, 31: 64-69+76.

[10] Zhang, Y.Q., Miao, Q.L., He, Y.Y., et al.(2001) Calculation and Prediction of Regional Water Resources. Scientia Geographica Sinica, 5: 457-462.

[11] Guo, L.D., Xia, Z.Q., Li, J.(2008)Comparison of common calculation methods for river ecological runoff. Yellow River, 30: 28-30.

[12] Li, J.Y., Bao, S.P.(2019) Study on ecological water demand and adjustable water intake of water intake section in river. Yellow River, 41: 36-42+92.

[13] Bai, J., Wang, H., Shang, X.B.(2016) Research on Fuyang City Ecological Water Demand Guarantee. Zhihuai,1: 18-19.

[14] Zheng, F., Cheng, H.F., Yang, Y.(2018) Analysis of ecological water demand and multi-source ecological water replenishment in urban rivers: Taking Shenzhen as an example. Water Resources Development Research, 18: 27-31.

[15] Liu, C.M.(2002) About the Concept and Importance of Ecological Water Demand. Impact of Science On Society, 2: 25-29.

[16] Lv, J.(2017) Study of Nanhu Lake ring water system with water quality-quantity coupling model based on MIKE. Guangxi Water Resources & Hydropower Engineering, 1:11-15.