Water Quality Improvement Effective Analysis for Artificial Groundwater Recharge in Urban River Network System

Wang Xiao¹, Wei Jun² *, Cheng Kaiyu³, Zhao Mingzhi²

1 Lecturer, Ningbo University, China
2 Professor level senior engineer, Huadong engineering corporation limited, China
3 Professor level senior engineer, Huadong engineering corporation limited, China
4 Senior engineer, Huadong engineering corporation limited, China
E-mail: wangxiaol@nbu.com

Abstract. With increase of population and urbanization, the persistent deterioration of urban rivers has become the most intractable problem for environment management agency. After the boom of pollution control projects implementing such as sewage system and sewage treatment plants building to decrease the pollution load, there is a growing interest on increasing ground water discharge with artificial groundwater recharge work and improving load capacity of target river. Under this background, it is important to study the exact effect of water artificial groundwater recharge work on water quality improvement, especially in the river network area, to give support on exact designment. In this study, the river network in Hanjiang district featured with complex river network has been selected as study area. Based on water quality monitoring result and current load statistical result, a one-dimensional mathematic model of target river network has been set up and the water quality has been simulated with different water artificial groundwater recharge schemes, which considering both river supplementary discharge and water quality factors. Then the simulation results under different effects have been analysed and the optimal scheme has been selected to meet the goals. The analysis results indicate that qualified option is recharging 2 m³/s fresh water of level III, under which, the water quality of study area can achieve the basic standard of Level V as qualified scenic water.

1. Introduction

According to the investigation of the current situation, the main problems affecting the water quality improvement of urban river courses are as follows: (1) both economy development and population growth in urban area have bring in large amount of urban residential pollution, industry pollutions and runoff pollution, which means more pollution will discharged into rivers than before. (2) most of urban streams are in small scale, both the river discharge and the load capacity of urban rivers is really limited. That means only small amount of pollutants will bring in the water deterioration in urban rivers [1-3]. To deal with these two key problems, both pollution control projects and ecological water artificial groundwater recharge projects should be comprehensively implemented to help urban river water environment restoration.

In recent years, many cities have made great efforts on water quality improvement and river water artificial groundwater recharge work has become one of the most important measures. The Cheonggyecheon Restoration work [4], an ambitious initiative to restore a 5.8-kilometer stream in central Seoul, is the most famous and typical urban river restoration work in the world. Artificial groundwater recharge projects, as one of massive civil engineering projects in Cheonggyecheon Restoration Project, was designed and built to deliver 120,000m³/s clean water from other basin to
Cheonggyecheon stream, which help to develop the water quality and launch the broader regeneration of Seoul’s inner areas.
According to the experience of water artificial groundwater recharge projects, the main benefits of river artificial groundwater recharge are as follows: (1) the water artificial groundwater recharge work will enhance the load capacity of rivers dramatically and develop the load degradation ability, which could improve the water quality of urban rivers; (2) it will maintain the ecological baseflow of urban streams and help rehabilitate rivers ecosystem. Attribute to these benefits, the recharge project has been introduced into more and more urban rivers restoration projects. Since 1982, paul has studied the organic water quality changes during groundwater recharge in palo alto baylands[5]. In 2007, Reija E. Kolehmainen has studied and evaluated the removal of natural organic matter (NOM) and structural changes in the microbial community during infiltration of humic lake water at three artificial groundwater recharge (AGR) sites in Finland[6]. Under this background, it is important to study the exact effect of water artificial groundwater recharge work on water quality improvement, to give support on exact artificial recharge system design and management.

2. Background and basic data

2.1. Study area
Hanjiang District, located in the eastern coast of Putian City, Fujian Province, is one of the central urban area with rapid development of industry and economy. The total area is 752 km² and the population is over 440 thousand. Hanjiang district is featured by high density of river network. The main rivers include Xikou River, Wuzi River, Wangjiang River, Tangtou River, and Haicen River. Among them, Xikou River, Wuzi River and Tangtou River are the main drainage channels, and Haicen River is the important drainage channel for Dongzhen Reservoir, an important water storage project in Putian City. All rivers converge at low-lying areas downstream and form crisscross river network. The river network in Hanjiang district is shown in Figure 1.
Attribute to the high speed of urbanization and industrial development in downtown area, large number of sewage and pollutants go into the rivers directly and the amount has exceeded the capacity dramatically. According to the monitoring results of water quality in 2017, the waters in Tangtou River, Wangjiang River, Wuzi River and Gongkou River in study area should all be graded into moderate black and odorous water according to the grading standard, and the most obvious indicators are ammonia nitrogen and total phosphorus. That means it is far from the water quality standard for water environment management in Hanjing district.
Since 2018, with sewage system of whole Hanjiang district developing, the pollution load has been dramatically controlled. However, due to the limited load capacity, lots of urban rivers still failed to reach the expected standard of grade V, which is the lowest level for urban scenic water. Then the water artificial groundwater recharge project was proposed to expand the load capacity and help water environment restoration.
In order to study the exact effect of water artificial groundwater recharge on water quality improvement in river network and identify the most reasonable recharge scheme in Hanjiang central district, the water quality under different artificial groundwater recharge conditions will be simulated by using the constructed regional river network model.

2.2. Pollution load statistics
The pollution in Hanjiang central area can be mainly divided into point source pollution and non-point source pollution according to the different way of sewage discharge. The point source pollution mainly includes the residential pollution and industrial pollution discharging directly in the scope of the study area. The non-point source pollution is mainly including the urban runoff pollution and a small amount of scattered living and farming pollution.
According to the investigation and statistical results, the ammonia and TP emissions in the study area in 2017 were 231.9t/a and 32.92t/a respectively. Details of result are shown in Table 1, and the proportion of various pollution sources is shown in Figure 2.
It can be investigated that the domestic pollution source contributes the most to the regional pollution load, accounting for 57-70% of the total load, followed by the industrial direct pollution source, accounting for 21-33% of the total. The pollution load from the nonpoint sources, including living, farming and urban runoff sources contribute the least, accounting for only 1-7% respectively.
Therefore, it can be concluded from the analysis that the pollution control targeting on the residential and farming pollution sources should be pay more attention to ensure the improvement of water quality in study region.

According to the water protection planning in Hanjiang district, the sewage system will be developed to collect more industry pollution, urban residential pollution and runoff pollution for pollution control at the beginning of pollutants migration. Cooperated with planning, the river dredging work and eco-restoration projects have also been planned to control pollution load at the end step of pollutants migration. According to the planned scale of different projects, the amount of pollution control estimated was shown as below in Table 2. Combined the current pollution load with estimated pollution control amount, the exact pollutants discharged in the river was 49.25 NH$_3$, 8.76 TP.

| pollutants | sewage system | restoration projects | river dredging work |
|------------|---------------|----------------------|---------------------|
| NH$_3$-N   | 162           | 12                   | 8.7                 |
| TP         | 23            | -                    | 1.2                 |

2.3. Pollution load statistics

Based on the investigation and field survey of the river system, the mathematical model could be built to quantify the effects of water quality improvement. Considering the hydrodynamic and pollutants transportation characteristics of the river network in study area, one-dimensional river network modelling was built using MIKE11 software. Saint-Venant Equation was the calculation formula for hydrodynamic calculation as followed:

\[
\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = q 
\]

(Formula 2.3-1)

\[
\frac{\partial Q}{\partial t} + \frac{\partial (Q^2)}{\partial x} g + gA \frac{\partial h}{\partial x} + \frac{gn^2Q|Q|}{AR^3} = q 
\]

(Formula 2.3-2)

where A, R denote the cross-section area and hydraulic radius of target cross section; x and t denote the distance in downstream direction (m) and time (s); Q and q are the discharge (m$^3$/s) of main stream and lateral inflow (m$^2$/s); g is the gravity acceleration; α is the momentum correction coefficient.

On that base, the advection and dispersion of pollutants along rivers can be simulated combing the hydrodynamic simulation results using the formula as followed:

\[
\frac{\partial c}{\partial t} + \mu \frac{\partial c}{\partial x} = \frac{\partial}{\partial x} (E_x \frac{\partial c}{\partial x}) - Kc 
\]

(Formula 2.3-3)

where c denotes the pollution concentration; u denotes the average velocity; $E_x$ is convection diffusion coefficient; K is comprehensive degradation coefficient.

This modelled system includes 24 river segments, covering all important rivers in study area as shown in Figure 3, the river section spacing varies from 200 to 1000 meters and he total number of computational grids is about 196.

The basic parameters of the model were calibrated using the water quality monitoring data measured in 2016. It is determined that the roughness coefficient of the river bed is 0.025-0.038 and Manning number is 28-40. Besides, the water quality parameters of degradation coefficient are 0.06-0.13 D-1 for ammonia nitrogen-N, 0.03-0.09 D-1 for total phosphorus. It can be seen from the comparison results of water quality calculation results and measured values that both are in good agreement. Therefore, the river network model of this project can accurately simulate the water quality situation of Hanjiang project area.
3. Simulation and results

The “water function zoning plan of Putian city” required the water quality of the urban rivers in study area achieving grade V. According to water quality analysis result, the key factors are NH$_3$-N and TP. Therefore, ammonia nitrogen and total phosphorus were considered as the pollution control indicators in this study.

In order to study the exact effects of water artificial groundwater recharge work on water quality improvement and identify the most reasonable recharge scheme, the water quality under different recharge conditions will be simulated by using the constructed regional river network model. Based on the water resource survey in the Hanjiang district, the recharge path and scale could be designed. The cleaning water could be recharged from the upstream of Diluxi and the maximum available recharge flow is 4 m$^3$/s. So different boundary conditions for prediction could be seen in Table 3 for details. And the simulation results of different scheme could be detailly shown in below.

Table 3. Details of designed water artificial groundwater recharge schemes

| Schemes | Discharge (m$^3$/s) | Water quality | Contaminate concentration (mg/L) |
|---------|---------------------|---------------|-------------------------------|
| A       | 0                   | -             | NH$_3$-N| TP |
| B       | 2                   | Level IV      | 1.5  | 0.3 |
| C       | 4                   | Level IV      | 1.5  | 0.3 |
| D       | 4                   | Level III     | 1    | 0.2 |

Scheme A: without any clean water recharged, the water quality of main streams is mostly in the grade V- and east part of river network has been polluted more seriously; the key pollutant indicator is ammonia nitrogen and concentration for average ammonia nitrogen in east part is as high as 5.2mg/l, which is tribble times larger than the standard.

Scheme B: after implementation of water artificial groundwater recharge work for the scale of 2m$^3$/s with water quality in Level IV, the water quality of whole river network is significantly improved. The concentration for ammonia nitrogen in east part is 4.2mg/l and for TP is 0.52mg/l.

Scheme C: after improving the recharge scale to 4m$^3$/s, the water quality of whole river network is significantly improved. The average concentration in east part for ammonia nitrogen is 3.2mg/l and for TP is 0.48mg/l. The pollutants concentration for TP could reach the requirements standard.

Scheme D: after strengthening the water artificial groundwater recharge work via improving the water quality of recharged water into level III, the concentration of main streams could be improved in the range of 1.5- 2.2mg/l for ammonia nitrogen and 0.41 for TP. Both the concentration of ammonia
nitrogen and TP could reach the requirements of class V standard. That means the rivers can basically reach the scenic water under that water artificial groundwater recharge scheme. Based on the comparison results, the scheme D is the only option which could meet the water quality requirements. That means both the recharge work and the water quality maintaining work of upstream should be implemented.

Figure 4. Water quality simulation results of river network for NH$_3$
4. Discussion

According to the simulation results of different schemes, the water quality of whole river network has been improved dramatically attributing to the water recharge work, especially in the east part, the most polluted area. Taking ammonia nitrogen as key pollution factor, the detailed water quality variation trend for main streams in river network could be analysed as below:

Wangjiang river, as the most polluted river, is chosen to implemented recharge work directly for pumping in 1.5-3 m³/s fresh water at the upstream. As Figure 5-(a) shown, in scheme A, the concentration at cross section of 500m length is as large as 7.35mg/L, then it continuously decreases to 5.93 mg/L as the blue line dropping. That means before the recharge work, the water quality of wangjiang river is affected heavily by the seriously polluted inflow than the locally discharged pollutants. In scheme B, C and D, the heads of concentration lines have dropped in different degrees attributing to water recharge works at the upstream of Wangjiang river. Then the concentration lines go in different trends as the length changing. Especially in the scheme D, with the recharge work of the highest level, the concentration of inflow has archived the requirements of 2mg/L, then the concentration line increases slightly, which means under this scheme the polluted inflow made less contribution on water quality of Wangjiang river and more pollution control projects should be implemented to control the local load and fit the load capacity of Wangjiang river.

In Figure 5-(b), the heads of all the lines is in the range of 2.12-2.85mg/L, that means for Tangtou river, the inflow water quality is in a relevant satisfied state. As the length growing, there is an obvious rise at the cross section of 2500m of Tangtou river. That was because the Wangjiang river and tangtou river flow converge here, the water quality of Tangtou river has been influenced by the polluted water from Wangjiang river. However, from the comparison of different scheme lines of A, B, C and D, it could be clearly seen that, as the water quality of Wangjiang river continually improving, the concentration of whole Tangtou river will reach the requirement. That means before the recharge work, the water quality of Tangtou river was affected more by the seriously polluted inflow of Wangjiang than the locally discharged pollutants.

Wuzi river was another stream recharged clean water from the upstream. Similar to Wangjiang river, the heads of concentration lines in figure5-(c) have dropped dramatically attribute to different water recharge works. And with the cleanest water recharged, the concentration of inflow has archived the requirements of 2mg/L, also the slightly rising concentration line illustrated more pollution load should be controlled to fit the load capacity.

Gongkou river was the stream in the downstream connecting the other main rivers, that means the water quality has been affected by the Tangtou river and Wuzi river directly. As the figure 5-(d) shown, the variation amount of concentration lines was in a quite small range and the concentration of NH₃ has been in scale of level V steadily.
5. Conclusion
In this study, a quantified method based on mathematical simulation has been proposed to research the exact effect of river artificial groundwater recharge on water quality improvement. Applying the 1-D mathematic model of river network in Hanjiang district, the water quality of whole river network has been simulated considering different artificial groundwater recharge conditions. Relevantly, the different effects on water quality improvement have been analysed and the best scheme which can help the water quality achieving standard has been chosen. Under that background, the effective artificial groundwater recharge system and relevant projects can be then designed to make contribution for the whole water restoration projects.

The goal of ecological water artificial groundwater recharge work in Hanjiang district is to improve the water quality and help recovering the healthy status of whole water environment. After the water artificial groundwater recharge system being built, the load capacity of urban rivers will be expanded to achieve the effect of improving water quality effectively.

6. References
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