Study on Multi-objective Combination Model Based on Pollutants Control of Groundwater Allocation System

Shen Dong\(^1\), Zebin Sheng\(^2\) and Yilin Wang\(^1\)

\(^1\)Institute of Environmental and Municipal Engineering, Qing Dao University of Technology, Qingdao, China
\(^2\)United Design Group Co. Ltd., Shanghai Qingdao Branch, Qingdao, China

*Corresponding author email: dongshen@qtech.edu.cn

Abstract. Groundwater resources are abundant on the middle and lower reaches of the Yellow River. However, due to the flat terrain and slow underground runoff, the water quality of groundwater intake wells is gradually deteriorating as a result of the deposition of pollutants, conventional allocation methods can’t meet the groundwater intake demand. In response to this problem, firstly, based on the investigation and study of groundwater intake rules and water quality characteristics on both sides of the Yellow River mainstream, the micro-hydraulic simulation model of the groundwater intake and allocation system is established. Secondly, Fourier Curve is used to fit and predict the characteristic pollutants for each well, then the water quality model of the groundwater allocation system is established combined with the dynamic equation. Finally, the combination model based on pollutants control of groundwater allocation system is constructed with three objectives, which are water quality optimization, safety optimization and energy consumption optimization. The model is solved by APGA algorithm and the corresponding calculation program is compiled with Visual Studio 2019. Through the application in a city on the middle and lower reaches of the Yellow River, the advantages of the model in pollutants control and energy consumption reduction are verified, meanwhile, a scientific and practical optimization technology for groundwater intake and allocation system is provided.

Keywords: Groundwater intake; Multi-objective combination model; Optimal allocation; Fourier fitting; Pollutants control.

1. Introduction

In recent years, due to the accelerated development of cities, the water consumption in most cities and towns in China has continued to increase, and many cities are actively developing various types of water resources to ensure urban water supply\(^[1]\), and the scientific management of water resources research has also received attention. For the first time, Professor Shiqian H\(^[2]\) comprehensively considered the rational allocation of water and the comprehensive utilization of water resources in Beijing. Nanxiang C\(^[3]\) and others applied a genetic algorithm to the solution of water resources optimal allocation model, and proposed solutions for the optimization of the complex raw water system. At present, scholars at home and abroad mostly focus on raw water quality issues and the operation of water supply and distribution network system alone, with the goal of sustainable use of water resources or the lowest energy consumption in system operation, and the optimization or control of water quality is not effectively integrated with the raw water distribution system. However, in the middle and lower reaches of the Yellow River, the terrain is relatively flat and the underground runoff is slow, which is conducive to the continuous deposition of specific pollutants\(^[4]\), but for the cities
along the Yellow River that use a large amount of groundwater, especially those whose groundwater system is more seriously polluted by toxic substances, the conventional allocation technology has been unable to meet the optimal operation of the whole system in terms of water quality, energy consumption and other aspects. So far, many countries have reported that groundwater pollutants harm human health[5]. Therefore, according to the pollutants characteristic and the combined intake law of deep and shallow wells in the groundwater system, the water quality feature and allocation rule are analyzed through experiments and field data on the middle and lower reaches of the Yellow River. Then an optimization technology for groundwater intake and allocation system is proposed further, which integrates pollutants control, water security and energy saving into the optimization objectives. The implementation process is shown in Figure 1.

Figure 1. Optimization process for multi-objective combination model.

2. Analysis on the Variation Law of Characteristic Pollutants on the Middle and Lower Reaches of the Yellow River

2.1. Water Quality Characteristic Analysis in Study Area

The submerged aquifer and weakly confined aquifer groundwater in the region are mainly supplied by the side seepage of the Yellow River, atmospheric precipitation infiltration and irrigation water recharge. Due to the influence of aquifer group pollutant deposition, aquifer burial conditions and hydrogeological conditions, the groundwater in the region has formed more unique water quality characteristics. Through the continuous aquifer soil samples and water samples detection and analysis, the content of iron, manganese, arsenic and other elements in the groundwater in the region is close to or even more than the class III groundwater limit value, which increases the difficulty of water treatment to a certain extent. It also increases the cost of water treatment, poses a certain threat to the safety and stability of factory water. In this paper, total arsenic ($\sum$As) which exceed the standard is selected as the research object to carry out related water quality control research. According to water quality testing and analysis, the highest concentration of $\sum$As in groundwater in the region's shallow wells is 0.0025mg/l, and the highest concentration of $\sum$As in groundwater in deep wells is 0.075mg/l, which even exceeds GB/T 14848-2017 IV groundwater standards.

By monitoring and analyzing the water quality of 32 groundwater sampling wells for two consecutive years, it was found that the specific pollutants in the region showed a certain cyclical pattern. From April to October each year, the aquifer recharge process is obvious, groundwater intake is high, and the content of specific pollutant is low; from November to March each year, groundwater recharge is small, the content of specific pollutant in groundwater is high, even exceeds the standard phenomenon from time to time.
2.2. Fourier Fitting and Prediction

The sampling and monitoring values of $\sum$As in groundwater wells are expressed as a time series: \{ $C_i(t), C_2(t), \ldots, C_{35}(t)$ \}, and the $\sum$As content of 32 groundwater wells was fitted with Fourier Curve, and simplified as $C_i(t) = a_0 + \sum_{k=1}^{n} (a_k \cdot \cos(k \cdot t \cdot w_i) + b_k \cdot \sin(k \cdot t \cdot w_i))$.

Where: $a_0$, $a_k$, $b_k$, $w_i$ are parameters that need to be fitted.

The Fourier fitting curve and residual error of the shallow well SW3 are shown in Figure 2, with the fit determination coefficient R-square value of 0.82; while the Fourier fitting curve and residual error of the deep well DP1 are shown in Figure 3, with the fit determination coefficient R-square value of 0.88.

![Figure 2. Fourier fitting curve and residual diagram of shallow well SW3.](image)

![Figure 3. Fourier fitting curve and residual diagram of shallow well DP1.](image)

| Well number | a0   | a1     | b1     | a2   | b2   | a3   | b3   | a4   | b4   | w    |
|-------------|------|--------|--------|------|------|------|------|------|------|------|
| SW3         | 18.88| 1.163  | -2.119 | 6.031| -1.005| -1.101| 0.254| 1.295| -1.017| 0.249|
| DP1         | 31.11| 1.357  | -1.124 | 6.951| 3.342 | 1.572 | -3.922| -0.138| 1.818 | 0.272|

3. Multi-objective Combination Model of Groundwater Allocation System

3.1. Target Functions

Generally, the purpose of water resource optimization allocation is to adjust the operation plan to minimize the total operating cost of the system as much as possible under the premise of meeting the water volume and pressure requirements\[^6\]. However, for cities along the Yellow River that intake groundwater, the quality of groundwater will have a great impact on the treatment costs of the water plants and the safety of urban drinking water. Therefore, when allocating groundwater resources, the water quality of the groundwater extraction wells should be in full consideration. It can help us make a scientific, safe and reasonable configuration, maximize the reduction of characteristic pollutant content in the water distribution system. At the same time, it ensures the rational development and utilization of water resources and establishes an optimal allocation model for the combination of water quality, water quantity and energy consumption for complex groundwater wells.

3.1.1. The Goal of Pollutants Control $P_i(t)$

The water quality status of the system in each allocation period(t) is mainly dependent on the water intake, pollutant concentration and pollutant excess of the water intake wells in various places, which is obtained by combining the Fourier fit of specific pollutants at each well with the first-order kinetic equation.

$$P_i(t) = f\left(g_1(q_{1i}, c_{1i}), g_2(q_{2i}, c_{2i}), \ldots, g_n(q_{ni}, c_{ni}), Q_i\right)$$

where: $q_{ni}$ is the amount of water withdrawn from each underground intake well (n) during the allocation cycle; $c_{ni}$ is the concentration of the specific contaminant in each intake well (n) during the
allocation cycle; \( Q_t \) is the total amount of water withdrawn from the groundwater during the allocation cycle.

### 3.1.2. The Goal of Energy Consumption Optimization and Allocation \( p_z(t) \)

Consider two parts of energy consumption during the groundwater extraction and distribution cycle: one is the energy consumption of pumping water from local wells, and the other is the increase in the cost of producing water from water plants caused by pollutants exceeding the standard.

\[
Pt(t) = \sum_{n=1}^{N} E \left( q_{nt} \cdot h_{nt} / \eta_{nt} \right) + ZS(t)
\]

(2)

where: \( N \) is the total number of groundwater intake wells; \( E \) is the power consumption factor; \( h_{nt} \) is the water supply pressure at each groundwater intake well \( n \) during the allocation cycle; \( \eta_{nt} \) is the water supply efficiency at each groundwater intake well \( n \) during the allocation cycle; \( ZS(t) \) is the conversion consumption for the increase in water production costs of the water plant due to pollutants exceeding the standard during the allocation cycle.

### 3.1.3. The Goal of Optimal Water Allocation \( p_z(t) \)

During each allocation cycle, the total amount of water from each groundwater intake well should be equal to the total water demand of the system, and the maximum intake of each well should be considered.

\[
Pt(t) = \sum_{n=1}^{N} q_{nt} - Q_t / \lambda_{nt}
\]

\[
\lambda_{nt} = \begin{cases} 
(L_{n0} - L_{nt}) / L_{n0} & \text{if } L_{nt} < L_{n0} \\
1 & \text{if } L_{nt} > L_{n0}
\end{cases}
\]

(3)

Where: \( L_{nt} \) and \( L_{n0} \) are the dynamic water level and the minimum alert level for each groundwater intake well \( n \) during the allocation cycle.

### 3.2. Model Optimization Solutions

The overall structure of the model is complex and difficult to solve. For the optimization problem of the multi-objective nonlinear mixed discrete function, the objective functions are interrelated but relatively contradictory, which is solved by the improved adaptive parallel genetic algorithm APGA. Compared with the traditional genetic algorithm, this algorithm uses adaptive crossover and mutation operators to discriminate the relationship between the individual adaptation degree and the average adaptation degree of the population, and dynamically adjust the key genetic operators, which can effectively avoid the precocity phenomenon during the iterative process of the algorithm\(^7\). In order to avoid the optimization process falling into local optimum, the multi-attribute decision-making method is used to find the satisfying optimal solution for decision-maker after the optimal solution set of each sub group is obtained. Through the Visual Studio 2019 platform, the fitness function code and the improved parallel genetic algorithm solution code are compiled, and the optimal decision solution is obtained finally.

### 4. Project Examples

To meet the needs of urban development, a city on the middle and lower reaches of the Yellow River has accelerated the construction of water plants and renovation of the pipeline network. The groundwater source that mainly composed of diving water and weak confused water is a large centralized source, which plays an extremely important role in the whole urban water supply system. 69 groundwater extraction wells and water transmission pipelines constitute the city’s groundwater intake and allocation system, which is decentralized and complex. The research area is extensive, with a distribution route of 40 kilometres and a designed daily water supply capacity of 200,000 ton. In this paper, 32 independent water intake wells are selected for technical study.
4.1. Topological Structure of Groundwater Intake and Allocation System

To analyze and calculate the hydraulic and water quality of the groundwater intake and allocation system in this area, EPANET, developed by the National Risk Management Institute of the U.S. Environmental Protection Agency, is used to establish the allocation network topology, as shown in Figure 4.

**Figure 4.** Allocation network topology in study area.

Where: SW1-SW22 are shallow wells, DP1-DP10 are deep wells, and EN is water plant entrance node.

4.2. Calculation and Validity Analysis of the Optimal Allocation

According to the analysis, the change of water quality and daily water consumption in the study area is not obvious within one month, and the characteristic pollutant concentration of each well and the total intake quantity show obvious seasonal variation. Therefore, it is most reasonable to study the optimal allocation of groundwater system on a monthly basis. The hydraulic and water quality simulation model of the study area and the Fourier fitting curves of the wells are embedded into the optimal combination model, in which the combined allocation scheme, water intake quantity and water intake duration of each well are taken as the optimal variables. Then the combination model is solved with an intelligent optimization program which is realized by Visual Studio 2019. The optimized allocation calculation was carried out based on the monthly average water consumption from January 2018 to December 2019. Some results are shown in Table 2.

**Table 2.** The optimal allocation scheme in study area.

| Month | water consumption (m³/h) | Optimal allocation scheme (in operation) |
|-------|--------------------------|----------------------------------------|
| 1     | 2335                     | SW1,SW3,SW6,SW10,SW18,SW21,SW22,DP1,DP4,DP5,DP8 |
| 3     | 2471                     | SW1,SW4,SW6,SW10,SW15,SW18,SW21,SW22,DP1,DP4,DP5,DP8 |
| 5     | 2627                     | SW1,SW4,SW6,SW15,SW16,SW18,SW21,SW22,DP1,DP2,DP4,DP5,DP8 |
| 7     | 3012                     | SW1,SW2,SW4,SW6,SW15,SW16,SW18,SW21,SW22,DP1,DP2,DP4,DP5,DP8 |
| 9     | 3168                     | SW1,SW2,SW3,SW6,SW12,SW15,SW18,SW21,SW22,SW23,DP1,DP2,DP4,DP5,DP8 |
| 11    | 2710                     | SW2,SW3,SW6,SW12,SW15,SW16,SW21,SW22,SW23,DP1,DP2,DP4,DP5,DP8 |
| 13    | 2473                     | SW2,SW3,SW5,SW12,SW15,SW16,SW21,SW22,SW23,DP1,DP2,DP4,DP5,DP8 |
| 15    | 2521                     | SW2,SW3,SW5,SW12,SW15,SW16,SW21,SW22,SW23,DP1,DP3,DP5,DP8 |
| 17    | 2649                     | SW2,SW3,SW5,SW12,SW15,SW16,SW20,SW22,SW23,DP2,DP3,DP5,DP7 |
| 19    | 2947                     | SW1,SW2,SW3,SW5,SW6,SW12,SW15,SW16,SW20,SW23,DP2,DP3,DP5,DP7 |
| 21    | 3043                     | SW1,SW2,SW3,SW5,SW6,SW8,SW12,SW13,SW15,SW20,SW23,DP2,DP3,DP5,DP7 |
| 23    | 2556                     | SW2,SW3,SW5,SW6,SW8,SW12,SW13,SW20,SW23,DP2,DP3,DP5,DP7 |

The $\sum As$ concentration at the entry and comprehensive converted energy consumption between the optimal allocation scheme and the actual operation scheme from January 2018 to December 2019 are compared and analyzed. The results show that through optimization, the reduction value of $\sum As$ concentration at the entry is up to 5.2 $\mu$g/l, with an average reduction concentration of 2.8 $\mu$g/l, and the $\sum As$ concentration at the entry can be effectively controlled within 20 $\mu$g/l after optimal allocation. Besides, the water quality at the entry can be guaranteed to meet the Class IV groundwater standard. The converted energy consumption is reduced by $1.15 \times 10^4$ kWh per month and $28.31 \times 10^4$ kWh in 24 months. The comparison of water quality and energy consumption between the optimal allocation scheme and the actual operation scheme is shown in Figure 5. It can be seen that on the basis of
meeting the water intake and consumption, compared with the traditional allocation mode, the multi-objective combination model of groundwater system has obvious advantages in controlling the $\Sigma$As concentration at the entry and reducing the energy consumption of the system.

![Figure 5. Comparative analysis of $\Sigma$As concentration and energy consumption at the entry point of two schemes.](image)

5. Conclusion
In order to realize the optimal allocation of groundwater intake system in the middle and lower reaches of the Yellow River, considering the exceeding phenomenon and the periodic change law of groundwater characteristic pollutants in the study area, the $\Sigma$As concentration of each well is fitted and predicted by Fourier curve. In order to meet the requirements of groundwater intake and consumption, control the concentration of characteristic pollutants at the entry, and reduce the system energy consumption as well as water treatment costs, taking the combined allocation scheme, water intake quantity and water intake duration of each well as optimal variables, the multi-objective combination model based on pollutants control is established and solved by an improved adaptive parallel genetic algorithm APGA. Through compiling the optimization program with VS 2019, the intelligent and optimal allocation of the groundwater system is realized, which verifies the effectiveness and practicality of the allocation model in controlling the $\Sigma$As concentration and reducing energy consumption compared the traditional operation methods. At the same time, the model can be further extended and applied to the comprehensive control and optimal allocation of multi-factor specific pollutants in the groundwater system.

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