Numerical simulation and regulation analysis of subsurface flow for an underground reservoir in Weihai

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Abstract: With the development of social economy, the contradiction between water supply and water demand is increasing. In order to alleviate this contradiction, an underground dam is proposed to be constructed in the downstream of one river for intercepting subsurface flow and increasing conjunctive utilization of surface water and groundwater. According to the hydrogeological condition of the downstream of one river, a groundwater flow numerical model through Visual Modflow was built to analyze the regulation and storage of groundwater for underground reservoir. The conclusions are as follows: the underground reservoir of a River has great potential for exploitation; the water regulation by storage of wet, normal, dry and special dry years is 23.928 million m³, 20.565 million m³, 17.43 million m³ and 10.128 million m³, respectively, and after the construction of underground reservoir, river has a great potential for development; the extraction scheme of 36 wells with a flow rate of 0.015 m³/s for the whole year is a more suitable scheme plan.

1. Introduction
After extended droughts occurred in 1980s in Shandong Peninsula, groundwater was overexploited, leading to seawater intrusion in some coastal areas[1]. An area of 1,000 km² is still affected by seawater intrusion[2]. To address water shortage in coastal plain areas and prevent seawater intrusion, eight underground reservoirs have been built in Shandong Peninsula. Compared with conventional dam, underground dams have the advantage of not overwhelm the land, offer particularly low evaporation losses and preserve the environment[3].

2. Study area
Weihai City is located at the eastern of the Shandong Peninsula, at 36°41′~37°35′ north latitude and 121°11′~122°42′ east longitude. It borders the Yellow Sea in the north, east and south, and borders Yantai City to the west. The water resources in Weihai City are characterized by large inter-annual variability, uneven distribution during the year, difficult to pump, low utilization rate and low per capita water resources. The per capita water resources in Weihai City is 858 m³, which is only 32% of the national average per capita, and it is an area with severe water resources shortage. In recent years, with the development of economy and society, water consumption has increased sharply, and the contradiction between water supply and demand has become increasingly serious. The research and development of new water supply projects can increase the water supply capacity of Weihai City and alleviate water shortages.

The underground reservoir project is divided into upper-level reservoir and lower-level reservoir.
The main buildings include underground cut-off walls and rubber dams. The storage capacity and water level parameters of underground reservoirs are shown in Table 1.

Table 1. Underground reservoir parameters.

| Reservoir     | Static storage volume/10^4 m³ | Regulated storage capacity/10^4 m³ | Total storage capacity/10^4 m³ | Water level/m | Static water level/m |
|---------------|------------------------------|-----------------------------------|--------------------------------|---------------|----------------------|
| Upper-level   | 205                          | 635                               | 840                            | 9             | 5                    |
| Lower-level   | 314                          | 1046                              | 1360                           | 6             | 1                    |
| Total         | 519                          | 1681                              | 2200                           |               |                      |

3. Hydrogeological conceptual model

3.1. The simulation area
Considering the influence of temporal and spatial distribution of rainfall evaporation on the reservoir area, the watershed of the underground reservoir is taken as the boundary to simulate the whole confluence area of the reservoir to make the simulation results more in line with the actual situation[4].

3.2. Generalization of aquifer structure
According to groundwater burial conditions, the aquifer structure is generalized into two layers from top to bottom. The ground surface and underlying soil in the study area are mostly medium-coarse sand with similar permeability, which is generalized as the upper layer with strong permeability, and it is the main water-rich layer of underground reservoirs. The bottom layer is weakly weathered granite with low water permeability, which is generally impervious.

3.3. Generalization of the boundary conditions
The boundary conditions are generalized as follows: (1) Bottom boundary: The base rock of the reservoir area is metamorphic rock, with weak water permeability and good water resistance, which is generalized as a zero flux boundary. (2) Upper boundary: The upper boundary is the phreatic surface, and the lithology is mainly medium and coarse sand with rich water and strong permeability, which is the variable flux boundary. (3) Eastern and Western boundaries: The eastern and western boundaries are divided according to the watershed of the river basin, which are all impervious boundaries. (4) The upstream boundary of the basin: the east of the upstream boundary reservoir is a watershed, which is set as an impervious boundary. (5) The downstream boundary of the basin: the lower downstream is the main drainage channel of the underground reservoir, and it is set as a free drainage boundary condition.

3.4. Hydrogeological parameters and zoning
The model is divided into two parameter areas. Figure 1 is a three-dimensional map of the active unit of a groundwater reservoir. The dark areas with higher terrain are hilly areas, and the light areas with low terrain are plain areas. According to the floor elevation detected by the actual boreholes and the influence of the cut-off wall, the maximum return water area of the underground reservoir is determined to be the area enclosed by the black line in the figure, and the orange line is the location of the cut-off wall.
Figure 1. 3D model partition map.

The initial value of the parameter is given according to the partition of the parameter, and the partition value of each parameter is obtained through parameter calibration. The initial value of the parameter partition is mainly based on the field pumping test combined with the regional experience value, see Table 2 for details.

Table 2. Initial value of main partition parameters.

| Parameter | Hilly area | Plain area |
|-----------|------------|------------|
| K (m/d)   | 0.133      | 39         |
| Sx        | 0.07       | 0.22       |
| Eff.Por   | 0.007      | 0.33       |

3.5 Terms of source and sink

The source and sink items of the groundwater system mainly include recharge items and excretion items. The recharge items mainly include rainfall infiltration replenishment, river lateral infiltration replenishment and mountain frontal infiltration replenishment. The excretion items mainly include groundwater exploitation, diving evaporation and downstream excretion.

4. Numerical model of groundwater

4.1 Modeling

When the water storage capacity of impervious aquifers is not considered, the mathematical model of shallow phreatic water and groundwater movement in confined water systems is generalized into a three-dimensional unstable flow system[5]. The mathematical model is as follows:

\[
\begin{aligned}
\frac{\partial}{\partial x} \left( k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial H}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial H}{\partial z} \right) - W &= s_1 \frac{\partial H}{\partial t} \\
H(x, y, z, t) \big|_{z=0} &= H_0(x, y, z) \quad (x, y, z) \in D \\
K \frac{\partial H}{\partial n} \big|_{z_2} &= q_1(x, y, z) \quad (x, y, z) \in s_1 \\
K \frac{\partial H}{\partial n} \big|_{z_1} &= q_2(x, y, z) \quad (x, y, z) \in s_2
\end{aligned}
\]

In the above formula: \(K\)—permeability coefficient, m/d; \(S_x\)—specific storage coefficient of the aquifer; \(S_1, S_2\)—the first and second types of boundary of the simulated area; \(H_0\)—initial water head of the aquifer, m; \(q\)—Supply flow per unit area of the second type boundary of the aquifer, m²/d;
4.2 Meshing
In this simulation, a rectangular grid is used to discretize the seepage area, and the complicated seepage problem is treated as a simple seepage problem that conforms to the rules in the split unit\[6\].

4.3 Parameter discretization
According to the collected groundwater system data in the study area, the simulation period of this numerical model is from January 1979 to December 1979. The entire simulation period is divided into 12 stress periods, each stress period is a natural month, and the time step is ten days. In each stress period, the strength of all external sources and sinks remains unchanged. Interpolate the seepage field of the phreatic aquifer was interpolate by basing on the monitoring data of the previous observation hole as the initial flow field of the study area.

4.4 Parameter calibration and verification
The parameters were calibrated using the measured values of daily groundwater level data in 2016 and the simulated values of the model. The results show that the measured values and simulated values have a good fit, with correlation coefficients greater than 95\% (Figure 2). Using the pest to iteratively adjust the parameters, the adjusted coarse sand permeability coefficient K value in the plain area is 38.5 m/d, and the permeability coefficient K value of the metamorphic rock in the hilly area is 0.012 m/d. The specific yield of coarse sand in the plain area is 0.21, and the specific yield of metamorphic rock in the hilly area is 0.058. The adjusted parameters are input into the model for calculation, and the output result is verified with the actual measured groundwater level data in 2017. The correlation coefficient between the simulated value and the measured value is 98.7\% (Figure 3), indicating that the model can better reflect the actual situation.

Figure 2. Model calibration.
5 Underground reservoir storage and exploitation

5.1 Analysis of Regulation and Storage of Groundwater Reservoir

The comparison shows that the simulation results of the model differ slightly from the results of the typical year. The results of wet years, normal years, and dry years are all within 10%, and the results of extreme dry years differ by 12.13%.

5.2 Groundwater exploitation plan

In order to rationally pump groundwater, 12 kinds of mining schemes are preliminarily drawn up after analysis, as shown in Table 3.

| Plan | Wells | Flow(m$^3$/s) | Pumping volume | Drain wells | Feasibility |
|------|-------|---------------|----------------|-------------|-------------|
| 1    | 27    | 0.01          | 209.95         | 0           | feasible    |
| 2    | 27    | 0.01          | 559.87         | 0           | feasible    |
| 3    | 27    | 0.01          | 839.81         | 0           | feasible    |
| 4    | 55    | 0.01          | 427.68         | 0           | feasible    |
| 5    | 55    | 0.01          | 1140.48        | 0           | feasible    |
| 6    | 55    | 0.01          | 1710.72        | 0           | feasible    |
| 7    | 27    | 0.015         | 314.93         | 0           | feasible    |
| 8    | 27    | 0.015         | 839.81         | 0           | feasible    |
| 9    | 27    | 0.015         | 1259.71        | 0           | feasible    |
| 10   | 55    | 0.015         | 641.52         | 0           | feasible    |
| 11   | 55    | 0.015         | 1710.72        | 2           | Not feasible|
| 12   | 55    | 0.015         | 2566.08        | 6           | Not feasible|

Analyzing the changes in the water level of each scheme, from the perspective of the stability of
the model, the scheme with a flow rate of 0.01 m³/s is more stable than the scheme with 0.015 m³/s. However, in terms of the total production volume, only 55 wells out of the six scenarios under the condition of 0.01 m³/s flow rate are close to the maximum water storage capacity, and the production plan with a flow rate of 0.015 m³/s can obtain a larger amount under the same conditions. From the engineering economic analysis, the 55 wells have a large amount of engineering and high cost, while the 27 wells are difficult to meet the pumping demand. Therefore, 36 pumping wells with a flow rate of 0.015 m³/s and a full-year mining plan have been determined to meet the engineering requirements and the demand for pumping volume.

6. Conclusion
Through analysis and calculation, the conclusions can be drawn:
(1) The correlation coefficient between the measured value and the simulated value is greater than 95%. When the model is verified, the correlation coefficient between the simulated value and the measured value is 98.7%, indicating that the model can better reflect the actual situation.
(2) The regulation and storage of underground reservoirs were analyzed through the built model, and the results showed that the maximum regulated storage capacity in wet years, normal water years, dry years and special dry years were 23.928 million m³, 20.565 million m³, 17.433 million m³ and 10.128 million m³ respectively. If the underground reservoir will be completed, there will be greater development potential, and the phreatic aquifer will have greater adjustable storage space.
(3) After many calculations and adjustments, it was found that 36 wells with a flow rate of 0.015 m³/s and a full-year pumping plan can meet the engineering requirements and the demand for pumping volume at the same time, which is a more suitable pumping plan.

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