Evaluation of Groundwater Resources and Exploitation Potential: A Case from Weifang City of Shandong Province in China

Xingyue Qu, Longqing Shi,* Xingwei Qu, Mei Qiu, Weifu Gao, and Jing Wang

ABSTRACT: With the rapid growth of population and economy, the demand for groundwater resources is also increasing, leading to the exploitation of groundwater in some areas far greater than the recharge, which easily causes a series of environmental geological problems such as groundwater drawdown, water quality deterioration, surface subsidence, and so on. Taking Shouguang water resource in Weifang City, Shandong Province, China, as an example, the water-bearing formation in the study area can be divided into three types: pore water-bearing formation of unconsolidated sediments, karst fissure water-bearing formation of carbonate rock, and bedrock fissure water-bearing formation. According to the pumping test results, the groundwater-richness zones in the study area were delineated first. On this basis, by analyzing the dynamic changes of groundwater, the study area was divided into 40 blocks, and the natural recharge of groundwater in each block was calculated by the analog method of the infiltration coefficient of precipitation. Then, combined with the actual situation of the study area, the allowable withdrawal of groundwater resources, mainly including pore water-bearing formation of unconsolidated sediments, karst fissure water-bearing formation of carbonate rock, and bedrock fissure water-bearing formation, was calculated using the safe yield modulus method, the improved method of the uniform arrangement of wells, and temporary storage capacity, respectively. Through the calculation, it can be concluded that the total allowable withdrawal of shallow groundwater resources in Shouguang city is \(6292.5783 \times 10^4\) m\(^3\)/a, that of middle and deep layer groundwater resources is \(2574.92 \times 10^4\) m\(^3\)/a, that of karst fissure water in carbonate rock is \(1767.92 \times 10^4\) m\(^3\)/a, and that of bedrock fissure water is \(307.89 \times 10^4\) m\(^3\)/a. The results show that within the study area, karst fissure water in carbonate rock and bedrock fissure water have immense exploitation potential.

1. INTRODUCTION

Compared with surface water resources, groundwater shows the characteristics of stable water quality and wide distribution. At present, about 2 billion population in the world uses groundwater as the main drinking water.\(^1\)\(^−\)\(^3\) In China, groundwater plays an irreplaceable role in the supply of water resources, especially in the northern region, where there is a shortage of surface water, both urban life and industry rely on groundwater. Thus, groundwater plays an important role in ensuring the domestic water for both urban and rural residents, promoting socioeconomic development and keeping ecological balance.\(^4\)\(^−\)\(^5\) However, With the rapid growth of population and economy, the demand for groundwater resources is also increasing, leading to the exploitation of groundwater in some areas far greater than the recharge, which easily causes a series of environmental geological problems such as groundwater drawdown, water quality deterioration, surface subsidence, and so on. So if we want to avoid these problems, it is necessary for us to accurately evaluate groundwater resources,\(^6\)\(^−\)\(^12\) in which the calculation of allowable withdrawal of groundwater is the key issue.\(^13\)\(^−\)\(^16\)

In the early 1980s, due to the overexploitation of groundwater, a cone of depression appeared in the Shouguang water resource. However, with the continuous development of China’s national economy and GNP, the quantity of groundwater intake has not been effectively controlled, causing great changes in hydrogeological conditions, reduction in the number of original shallow water resources, and a sharp decline in the shallow groundwater level.\(^17\)\(^−\)\(^19\) Furthermore, in the axis of the Mi alluvial–proluvial fan, the water-rich zones with shallow pore water outflow from a single well greater than 5000 m\(^3\)/day have completely disappeared, which further expands the area of the shallow groundwater depression cone and intensifies the trend of water quality deterioration in this area. But the mining yield of groundwater for agriculture and industry is still extending unceasingly in the study area, and as a result, the middle and deep layer groundwater in the north of the water resource has become the main resource for...
exploitation and utilization, and the mining yield for freshwater and brackish water enhances ceaselessly. With our continuous exploitation of middle and deep layer pore water, the groundwater level has begun to decline year by year, and a new middle and deep layer pore water cone of depression has appeared. Therefore, for the Shouguang water resource, it is of great practical significance for the sustainable exploitation of groundwater and water environment protection to find out the current hydrogeological conditions, redefine the groundwater-richness zones, recheck the allowable withdrawal of groundwater, and evaluate the exploitation potential.

2. STUDY AREA

The Shouguang water resource is located in the east of Shouguang City, Weifang City, Shandong Province, China (Figure 1A,B), situated in the Mi alluvial–proluvial fan. The axis and fringe of Mi alluvial–proluvial fan are areas where shallow pore water is enriched, and it is the main available groundwater development zone for industrial, agricultural, and domestic use in Shouguang City. There are mainly three water works (Figure 3).

The Shouguang water resource is located in the transition zone between the depression zone and the uplifted zone, and the study area is covered by Quaternary strata. Pore water in unconsolidated sediments is the major groundwater type, which mainly exists in the Quaternary sandy gravel layer, together with mudstone and clayey soil, as relative water-resisting layers, forming a multiter water-bearing structure (Figure 2). From south to north, the thickness changes from thin to thick, and the particles from coarse to fine. Magmatic rock, clastic rock, and carbonate rock are mainly distributed in the southern uplifted zone, where groundwater chiefly accepts the atmosphere precipitation supply and exists in weathering fissures and karst fissures as the karstic fissure water and bedrock fissure water (Figure 1C).

3. DYNAMIC CHANGE LAW OF GROUNDWATER

3.1. Shallow Pore Water. In the study area, 23 monitor points for shallow pore water were set up (Figure 3). Taking the unified mark points fastened to wellheads of observation wells as measure points, the GPS-RTK method was used to measure the buried depth and elevation of the static water level (Figure 4). The contour map of the shallow pore water level for the wet and dry seasons in the Shouguang water resource is obtained, as shown in Figure 5. The annual dynamic change curve of the groundwater level is obtained, as shown in Figure 6.

As shown in Figure 5, the motion direction of shallow groundwater in the Shouguang water resource is generally consistent with that of the gradient, slowly from south to

Figure 1. (A) Location map of Shandong Province. (B) Location map of the study area in Shandong Province. (C) Vertical cross section of water-bearing formations in the study area (modified from Li et al.18).
north. But there is a sharp decline of the shallow groundwater level in some areas, which indicates that the groundwater in these areas has been overexploited and forms a small-scale groundwater depression cone, driving groundwater to change its original motion direction and converge toward the center of the cone of depression.

As shown in Figure 6, precipitation has little effect on the change in the shallow groundwater level in the Shouguang water resource. Therefore, it can be inferred that with the groundwater overdraft, the shallow water-bearing sandy layers are drained. At present, shallow wells supply groundwater mainly through aquifers with a buried depth greater than 20 m, and in the case of a very limited recharge amount of atmospheric precipitation and no other recharge sources, mining yield is the main controlling factor for the shallow groundwater level, with a dynamic type of precipitation infiltration and exploitation.

3.2. Middle and Deep Layer Pore Water. In the study area, 15 monitor points for the middle and deep layer pore water were set up (Figure 3). The same method of measurement as shallow pore water is used. The contour map of the middle and deep layer pore water level for the wet and dry seasons in the Shouguang water resource is obtained, as shown in Figure 7. The annual dynamic change curve of the groundwater level is obtained, as shown in Figure 8.

As shown in Figure 7, the motion direction of middle and deep layer groundwater in the Shouguang water resource is generally consistent with that of the gradient, and the runoff is slow from Southwest to Northeast. Combined with the Multiyear dynamic change curve of the groundwater level, it can be seen that the curve shows the characteristics of the water level rising again for the wet season and the water level declining precipitously for the dry season, but it reveals a general trend that the middle and deep layer pore water level continues to decline. From 2016 to 2019, the middle and deep layer pore water level continues to decline by about 12 m. Moreover, the contour map of the middle and deep layer pore water level for the wet season is basically consistent with that for the dry season. It can be concluded that the hydraulic connection between middle and deep layer pore water and other aquifer systems is not close, and the middle and deep layer groundwater system is relatively closed, which cannot directly receive rainfall recharge. The supply still cannot keep up the pace, and its exploitation intensity continues to increase, with a dynamic type of groundwater consumption. It is estimated that if the mining yield continues to increase, the groundwater level will be more and more deep; meanwhile, it will cause the regional cone depression of middle and deep layer groundwater in large areas, and the areas enclosed by the water table contour with the same elevation will enlarge gradually.

To determine the recharging sources for middle and deep layer groundwater in the Shouguang water resource, 12 groups of water samples, including pore water, bedrock fissure water,
and karst fissure water, were collected (Figures 9 and 10), and the water quality was analyzed based on AqQA software. The results are shown in Figure 11. It can be seen from Figure 11 that the water samples of bedrock fissure water, including JD01 and HL940, are in the No. 2 zone of the rhombic region, with the content of alkali metals (Na\(^+\) and K\(^+\)) greater than that of alkaline-earth metals (Ca\(^{2+}\) and Mg\(^{2+}\)), and their water quality types are Cl\(\cdot\)HCO\(_3\)−Na\(^+\)K. For the water samples of karst fissure water, including HL839 and HL1126, and the water samples of pore water, including HL836, HL837, QS02, QS03, QS04, and QS08, both are in the No. 1 zone of the rhombic region, with the content of alkaline-earth metals (Ca\(^{2+}\) and Mg\(^{2+}\)) greater than that of alkali metals (Na\(^+\) and K\(^+\)), and their water quality types are HCO\(_3\)−Cl−Ca−Mg. These results indicate that middle and deep layer groundwater in the Shouguang water resource is recharged by karst fissure water.

3.3. Karst Fissure Water in Carbonate Rock and Bedrock Fissure Water. Carbonate rocks and bedrocks are exposed at higher elevations, and they are directly recharged by atmospheric precipitation in a large area. The annual variation amplitude of the karstic fissure water level is 5–8 m, and the annual variation amplitude of the bedrock fissure water level is 4–5 m. The recharge is mainly affected by

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Legend

Fine water quality  Better water quality  Poor water quality  Terrible water quality

Monitor point and number of deep pore water  Monitor point and number of shallow pore water

Monitor point and number of Bedrock fissure water  Sewage outfalls and number

Over-exploited funnel of shallow groundwater  Over-exploited funnel of middle and deep layer groundwater

Boundary line of saltwater intrusion  Collapse  Surface collapse  Boundary line of water quality

Boundary line of TDS  Water resource

Figure 3. Monitor points of groundwater and pumping test results of monitoring wells.
topographic features and fracture development. The motion direction of groundwater is basically consistent with the tilt direction of the rock stratum, and the karst fissure water flows from Southwest to Northeast for the recharge of northern middle and deep layer pore water. Manual exploitation is almost the only way of discharge, while the average gross drainage is relatively small.

4. DATABASE AND METHODS

4.1. Calculation of Natural Recharge of Groundwater. The natural recharge of groundwater in the Shouguang water resource is calculated by the analogy method of the infiltration coefficient of precipitation as follows:

\[ Q = \alpha \cdot P \cdot F \]
where $\alpha$ is the infiltration coefficient of precipitation. $P$ is the precipitation (mm/a). $F$ is the recharge area of aquifers (km$^2$). Among them, the infiltration coefficient of precipitation is mainly affected by topographic features, rock characters, structural fissures, and the depth to the water table, so the infiltration coefficient of precipitation in different blocks is also different. In this paper, the round block technique was used to carry on the permeability test in the rock strata with different lithologies, and the osmotic coefficients of the rock strata in the aeration zone were calculated, as shown in Table 2.

According to total dissolved solids (TDS), the water resource is divided into three areas: the freshwater zone (TDS $\leq$ 1 g/L), the brackish water zone (1 < TDS $\leq$ 3 g/L), and the salt water zone (TDS > 3 g/L) (Figure 12). Then, according to the lithology in the aeration zone, the water resource is divided into eight subregions (Figure 12). Finally, according to the depth to the water table and precipitation, the water resource is further divided into 40 blocks, and the area of each block is calculated by MAPGIS (Table 2). Based on the annual average precipitation from 1959 to 2019, the contour map of precipitation in the Shouguang water resource was drawn, and the average value of precipitation in each calculation block was obtained by the interpolation method (Table 2).

### 4.2. Calculation of the Allowable Withdrawal of Groundwater

The allowable withdrawal of groundwater, mainly in the water-rich area of pore water-bearing formation of unconsolidated sediments, karst fissure water-bearing formation of carbonate rock, and bedrock fissure water-bearing formation, was calculated using the safe yield modulus method, the improved method of the uniform arrangement of wells, and temporary storage capacity, respectively. In total, 23 wells for shallow pore water, 15 wells for middle and deep layer pore water, 5 wells for karst fissure water, and 11 wells for bedrock fissure water were set up in the study area, and pumping tests were conducted (Figure 13) to evaluate the water richness of each water-bearing formation. The pumping test results are shown in Figure 3, and the distribution of

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**Figure 6.** Annual dynamic change curve of the groundwater level.

**Figure 7.** Water level contour map of the middle and deep layer pore water (modified from Li et al.18).
groundwater-rich sections in the Shouguang water resource is obtained (Figure 14).

4.2.1. Safe Yield Modulus Method. Within a unit area, there is an internal balance between the mining yield of well groups and the total recharge of groundwater.

\[ Q_{\text{recharge}} - Q_{\text{mining yield}} = \Delta W \]

where \( Q_{\text{recharge}} \) is the total recharge of groundwater within the unit area (10^4 m^3/a). \( Q_{\text{mining yield}} \) is the mining yield of well groups within the unit area (10^4 m^3/a). \( \Delta W \) is the balance difference between the annual recharge and the annual mining yield (10^4 m^3/a).

If \( Q_{\text{recharge}} > Q_{\text{mining yield}} \) and \( \Delta W > 0 \), it shows that the high water level of the same groundwater level period in the exploration area is on the rise.

If \( Q_{\text{recharge}} < Q_{\text{mining yield}} \) and \( \Delta W < 0 \), it shows that the high water level of the same groundwater level period in the exploration area is on the drop.
If $Q_{\text{recharge}} \approx Q_{\text{mining yield}}$ and $\Delta W \approx 0$, it shows that the high water level of the same groundwater level period in the exploration area is relatively stable.

Supposing that the variation extent of the water level ($\Delta h$) is used to express the rise and fall of the water level of the same groundwater level period in the exploration area, the following formula is true.

$$\Delta h = H_{\text{next year}} - H_{\text{this year}}$$

If $\Delta h > 0$, the exploitation intensity of groundwater is less than that of recharge, indicating that groundwater owns itself the possibility for extending exploitation, that is, $M_{\text{allowable}} = M_{\text{exploitable}} + M_{\text{surplus}}$.

If $\Delta h < 0$, the exploitation intensity of groundwater is greater than that of recharge, indicating that groundwater has been overexploited, and the water table was noted to be declining with increasing groundwater use, that is, $M_{\text{allowable}} = M_{\text{exploitable}} + M_{\text{loss}}$.

If $\Delta h \approx 0$, the exploitation intensity of groundwater is basically consistent with that of recharge, indicating that groundwater is in dynamic equilibrium, that is, $M_{\text{allowable}} = M_{\text{exploitable}}$.

Here, $M_{\text{allowable}}$ is the groundwater allowable exploitation modulus ($10^4$ m$^3$/km$^2$·a). $M_{\text{exploitable}}$ is the groundwater exploitation modulus ($10^4$ m$^3$/km$^2$·a). $M_{\text{surplus}}$ is the groundwater surplus modulus ($10^4$ m$^3$/km$^2$·a). $M_{\text{loss}}$ is the ground-
water loss modulus \((10^4 \text{ m}^3/\text{km}^2 \cdot \text{a})\). Among them, \(M_{\text{exploitable}} = \frac{Q_{\text{mining yield}}}{f}\) where \(f\) is the calculation area for the exploitation area \((\text{km}^2)\).

The water level variation extent for shallow groundwater in the same groundwater level period is shown in Figure 15. The surplus modulus and loss modulus were calculated by MAPGIS as follows

\[
M_{\text{surplus}}(M_{\text{loss}}) = M_{\text{exploitable}} \sum \Delta h
\]

where \(\sum \Delta h\) is the annual range of the water level \((\text{m})\). The annual range of the shallow groundwater level in the Shouguang water resource is shown in Figure 16.

According to regional distribution, the shallow groundwater in the Shouguang water resource is divided into four areas: exploration area of water resource, alluvial–pluvial fan area of Mi river, salt water area of shallow groundwater, and other areas of shallow groundwater. Then, according to TDS, the shallow groundwater in the Shouguang water resource is divided into five subregions. Finally, according to the safe yield modulus, the shallow groundwater in the Shouguang water resource is further divided into 164 blocks, and the area of each block is calculated by MAPGIS (Table 3).

4.2.2. Improved Method of the Uniform Arrangement of Wells.

\[
Q'_{\text{mining yield}} = Q_{\text{outflow}} \cdot n \cdot T
\]

\[
n = \frac{F}{4R^2}
\]

where \(Q'_{\text{mining yield}}\) is the mining yield of middle and deep layer groundwater \((\text{m}^3/\text{a})\). \(Q_{\text{outflow}}\) is the water outflow from a single well when the drawdown is 15 m and the well diameter is 219 mm \((\text{m}^3/\text{a})\). \(n\) is the number of wells. \(F\) is the calculation area for planning wells \((\text{m}^2)\). \(R\) is the influence radius \((\text{m})\). \(T\) is the annual average pumping time \((\text{day/}\text{a})\). In the Shouguang water resource, we establish uniform definitions for pumping time as \(T = 60 \text{ day/}\text{a}\).

According to the water outflow from a single well and TDS, the middle and deep layer groundwater in the Shouguang water resource is divided into four areas, and each area is calculated by MAPGIS (Figure 17).

According to the buried depth of the limestone roof, the karst fissure water in carbonate rock in the Shouguang water resource is divided into two areas, and each area is calculated by MAPGIS (Figure 18).

4.2.3. Temporary Storage Capacity.
\[ Q_{\text{Tem}} = \mu \cdot \Delta H \cdot F \]

where \( \mu \) is the specific yield of the basalt aquifer within the range of the water level (%), \( \Delta H \) is the variable amplitude of the groundwater level (m), and \( F \) is the calculation area for the basalt aquifer (m²).

### 4.2.4. Potential Index Method.

\[ P = \frac{Q_{\text{allowable}}}{Q_{\text{mining yield}}} \]

where \( Q_{\text{allowable}} \) is the allowable withdrawal of groundwater (10⁴ m³/a), \( Q_{\text{mining yield}} \) is the groundwater resources amount already exploited (10⁴ m³/a). According to the classification standard of exploitation potential shown in Table 1, the exploitation potential of groundwater in the Shouguang water resource is evaluated.
5. RESULTS AND DISCUSSION

5.1. Natural Recharge of Groundwater. According to the analogy method of the infiltration coefficient of precipitation, the natural recharge of groundwater for the 40 blocks is calculated. The results are shown in Figure 19 and Table 2.

As shown in Table 2, the recharge amount of rainfall infiltration in the Shouguang water resource is $1.354188 \times 10^8$ m$^3$/a, of which the recharge for freshwater (TDS $\leq 1$ g/L) is $1.299105 \times 10^8$ m$^3$/a, accounting for 95.93%, the recharge for brackish water ($1 < $ TDS $\leq 3$ g/L) is $5.300 \times 10^7$ m$^3$/a, accounting for 3.91%, and the recharge for salt water (TDS $> 3$ g/L) is $2.083 \times 10^7$ m$^3$/a, accounting for 0.16%. Thus, it can be seen that most of the precipitation in the Shouguang water resource seeped into underground rocks to supply freshwater.
5.2. Allowable Withdrawal of Groundwater.

5.2.1. Shallow Pore Water. According to the safe yield modulus method, the allowable withdrawal of shallow pore water in water-rich sections for the four areas (164 blocks) is calculated, and the results are shown in Table 3.

5.2.2. Middle and Deep Layer Pore Water. According to the improved method of uniform arrangement of wells, the allowable withdrawal of middle and deep layer pore water in water-rich sections for the four areas is calculated, and the results are shown in Table 4.

5.2.3. Karst Fissure Water in Carbonate Rock. According to the improved method of uniform arrangement of wells, the allowable withdrawal of karst fissure water in carbonate rock is calculated, and the results are shown in Table 5.

Table 1. Classification Standard of Exploitation Potential

| potential index ($P$) | $P > 1.2$ | $0.8 < P \leq 1.2$ | $0.6 < P \leq 0.8$ | $P \leq 0.6$ |
|-----------------------|-----------|---------------------|--------------------|-------------|
| exploitation potential| with exploitation potential | dynamic equilibrium | overexploitation | serious overexploitation |

Figure 17. Zone map for the calculation of the allowable withdrawal of middle and deep layer groundwater.

Figure 18. Zone map for the calculation of the allowable withdrawal of karst fissure water in carbonate rock.

Figure 19. Zone map of modulus of natural groundwater recharge.
rock in water-rich sections for the two areas is calculated, and the results are shown in Table 5.

5.2.4. Bedrock Fissure Water. According to the temporary storage capacity, the allowable withdrawal of bedrock fissure water in water-rich sections in the Shouguang water resource is calculated, and the results are shown in Table 6.

5.3. Evaluation of Groundwater Exploitation Potentiality. The potential index method was used to, respectively, evaluate the exploitation potential of pore water in unconsolidated sediments, karst fissure water in carbonate rock, and bedrock fissure water in the Shouguang water resource. The evaluation results are shown in Table 7. As shown in Table 7, the middle and deep layer groundwater, karst fissure water in carbonate rock, and bedrock fissure water in the Shouguang water resource are

Table 2. Results of Natural Groundwater Recharge

| TDS          | block partition | rock characters of the aeration zone | depth to the water table (m) | precipitation (mm/a) | area F (km²) | coefficient of rainfall infiltration α | rainfall P (mm/a) | Q (10⁶ m³/a) | total Q (10⁶ m³/a) |
|--------------|-----------------|--------------------------------------|-----------------------------|----------------------|-------------|---------------------------------------|----------------|--------------|--------------------|
| I freshwater area |                  | I₁andesite and basalt                | 450--500                    | 68.42                | 0.12        | 487                                  | 3.9985         | 148.596      |
|               |                  | I₂limestone                          | 450--500                    | 149.24               | 0.25        | 487                                  | 18.1699        |
|               |                  | I₃diluvium                           | 450--500                    | 117.94               | 0.33        | 487                                  | 18.9541        |
|               |                  | I₄sandy soil and clayey soil interbedding | 500--550                 | 34.72                | 0.29        | 509                                  | 5.1250         |
|               |                  |                                      | >20                         | 12.24                | 0.14        | 489                                  | 0.8380         |
|               |                  |                                      | >20                         | 2.12                 | 0.14        | 509                                  | 0.1511         |
|               |                  |                                      | >20                         | 4.93                 | 0.14        | 487                                  | 0.3361         |
|               |                  |                                      | >20                         | 13.71                | 0.26        | 458                                  | 1.6326         |
|               |                  |                                      | >20                         | 5.72                 | 0.26        | 487                                  | 0.7243         |
|               |                  |                                      | >20                         | 31.33                | 0.26        | 507                                  | 4.1299         |
|               |                  |                                      | >20                         | 81.14                | 0.26        | 529                                  | 11.1599        |
|               |                  | I₅clayey soil                        | 10--20                      | 72.03                | 0.16        | 487                                  | 5.6126         |
|               |                  |                                      | 10--20                      | 11.15                | 0.16        | 489                                  | 0.8724         |
|               |                  |                                      | 10--20                      | 31.44                | 0.16        | 458                                  | 2.3039         |
|               |                  |                                      | 10--20                      | 32.63                | 0.16        | 458                                  | 2.3911         |
|               |                  |                                      | 10--20                      | 21.79                | 0.16        | 489                                  | 1.7048         |
|               |                  |                                      | 10--20                      | 23.10                | 0.16        | 507                                  | 1.8739         |
|               |                  |                                      | 10--20                      | 56.49                | 0.16        | 529                                  | 4.7813         |
|               |                  |                                      | 10--20                      | 62.78                | 0.16        | 512                                  | 5.1429         |
|               |                  |                                      | 10--20                      | 49.07                | 0.16        | 512                                  | 4.0198         |
|               |                  |                                      | >20                         | 400--450             | 119.88      | 0.11        | 407                                  | 5.3670         |
|               |                  |                                      | >20                         | 191.57               | 0.11        | 492                                  | 10.3678        |
|               |                  |                                      | >20                         | 25.44                | 0.11        | 489                                  | 1.3684         |
|               |                  |                                      | >20                         | 89.93                | 0.11        | 484                                  | 4.7878         |
|               |                  |                                      | >20                         | 32.21                | 0.11        | 489                                  | 1.7326         |
|               |                  |                                      | >20                         | 145                  | 0.11        | 512                                  | 8.1664         |
|               |                  |                                      | >20                         | 89.77                | 0.11        | 509                                  | 5.2620         |
|               |                  |                                      | >20                         | 0.45                 | 0.11        | 509                                  | 0.0252         |
|               |                  |                                      | >20                         | 14.79                | 0.11        | 512                                  | 0.8329         |
|               |                  |                                      | >20                         | 38.09                | 0.11        | 507                                  | 2.1242         |
|               |                  |                                      | >20                         | 3.44                 | 0.11        | 515                                  | 0.1948         |
|               |                  | IIbrackish water area                | >20                         | 450--500             | 14.26       | 0.11        | 489                                  | 0.7671         | 5.23         |
|               |                  |                                      | >20                         | 49.71                | 0.16        | 484                                  | 3.8495         |
|               |                  | III salt water area                 | >20                         | 11.55                | 0.11        | 484                                  | 0.6149         |
|               |                  |                                      | >20                         | 2.69                 | 0.16        | 484                                  | 0.2083         | 0.2083       |

Table 3. Calculation of Shallow Groundwater Allowable Exploitation

| regions               | subregions | F (km²) | Qallowable (10⁶ m³/a) |
|-----------------------|------------|---------|----------------------|
| exploration area of water resource | TDS < 1 g/L | 239.72 | 1295.35              |
| Mi river alluvial–pluvial fan area | TDS < 1 g/L | 562.39 | 2108.96              |
| salt water area of shallow groundwater | TDS > 3 g/L | 2.69 | 0.2083               |
| other areas of shallow groundwater | TDS < 1 g/L | 744.17 | 2651.09              |
|                          | 1 ≤ TDS< 3 g/L | 75.52   | 236.97               |
with the large exploitation potentiality. But from the analysis of Section 3, it is known that the recharge, runoff, and drainage of middle and deep layer pore water (static reserves) are poor, and the water level drops continuously. Therefore, this paper delineates karst fissure water and bedrock fissure water as prospective water sources.

According to the water level contour map of the Shouguang water source area, it is assumed that the recharge, runoff, and discharge in the Shouguang water source area are basically unchanged. The simulation time of the forecasting model for the groundwater flow field is selected from June 2019 to June 2039 and defined a month as a stress period, 20 years in all, that is, 240 stress periods. Under the condition that the exploitation amount in the Shouguang water source area remains unchanged, the final flow field of the current model is defined as the initial flow field of the forecasting model, and the pattern of the groundwater flow field for the next 20-year exploitation in the simulation area is simulated, as shown in Figure 20.

### 6. CONCLUSIONS

(1) Allowable withdrawal of shallow groundwater in the Shouguang water resource is $6292.5783 \times 10^4 \text{ m}^3/\text{a}$, that of middle and deep layer groundwater is $2574.92 \times 10^4 \text{ m}^3/\text{a}$, that of karst fissure water in carbonate rock is $1767.92 \times 10^4 \text{ m}^3/\text{a}$, and that of bedrock fissure water is $307.89 \times 10^4 \text{ m}^3/\text{a}$.

(2) Exploitation potential of shallow groundwater in the Shouguang water resource is in a state of dynamic balance between exploitation and supply. For shallow groundwater, its uneven exploitation leads to the

### Table 4. Calculation of Middle and Deep Layer Groundwater Allowable Exploitation

| sections | water outflow from a single well (m³/day) | TDS (g/L) | F (km²) | Q_{single} (m³/day) | n | T (day) | R (m) | Q_{allowable} (10⁴ m³/a) |
|----------|------------------------------------------|-----------|--------|----------------------|---|--------|------|--------------------------|
| I 500–1000 | I₁: <1 217.54 954.12 62.61 60 932 358.42 | I₂: <1 22.96 712.60 7.14 60 932 30.57 | I₃: 1–3 9.55 800.56 2.74 60 896 13.20 |
| II 1000–3000 | II: <1 618.45 1268.72 285.42 60 736 2172.73 |

### Table 5. Calculation of Karst Fissure Water Allowable Exploitation

| sections | areas | buried depth of the limestone roof (m) | calculating area (km²) | depth to the water table (m) | allowable drawdown (m) | Q_{single} (m³/day) | Q_{allowable} (10⁴ m³/a) |
|----------|-------|----------------------------------------|------------------------|-----------------------------|-----------------------|---------------------|--------------------------|
| I the bulge in the middle north region of Shouguang city | 150–450 | 80.5 | 40.5 | 120 | 800 | 30.5 | 700 | 1453.68 |
| II the eastern part of Changle county | <100 | 68.74 | 20.65 | 26.50 | 413.31 | 14.52 | 1000 | 314.24 |

### Table 6. Calculation of Bedrock Fissure Water Allowable Exploitation

| sections | μ (%) | ΔH (m) | F (m²) | Q_{allowable} (10⁴ m³/a) |
|----------|-------|--------|--------|--------------------------|
| basalt area | 1.0 | 4.5 | $68.42 \times 10^6$ | 307.89 |

### Table 7. Evaluation Results of Groundwater Exploitation Potentiality in the Shouguang Water Resource

| Shouguang water resource | water-bearing formation | exploitation amount (10⁴ m³/a) | allowable withdrawal of groundwater (10⁴ m³/a) | potential index | potential division |
|--------------------------|-------------------------|-------------------------------|---------------------------------------------|----------------|-------------------|
| shallow groundwater | | 6666.935 | 6292.5783 | 0.94 | dynamic equilibrium |
| middle and deep layer groundwater | | 1350 | 2574.92 | 1.91 | with large exploitation potentiality |
| karst fissure water in carbonate rock | | small exploitation amount | 1767.92 | with large exploitation potentiality |
| bedrock fissure water | | 15.48 | 307.89 | 19.89 | with large exploitation potentiality |

Model boundary
Forecasting water level

Figure 20. Simulated diagram for the groundwater flow field.

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formation of the overexploited funnel of groundwater in some regions of the water source area. For middle and deep layer groundwater, it owns large allowable exploitable resources, but it belongs to static reserves, unsuitable for long-term water supply source because of its poor recharge, runoff, and drainage. Therefore, this paper delineates karst fissure water and bedrock fissure water as prospective water sources.

### AUTHOR INFORMATION

**Corresponding Author**

Longqing Shi — College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China; Email: 15266249375@163.com

**Authors**

Xingyue Qu — College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China; orcid.org/0000-0001-7509-293X

Xingwei Qu — College of Safety and Environmental Engineering, Shandong University of Science and Technology, Qingdao 266590, China

Mei Qu — College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China

Weifu Gao — Department of Resource and Civil Engineering, Shandong University of Science and Technology, Taian 271019, China

Jing Wang — No. 6 Institute of Geology and Mineral Resources Exploration of Shandong Province, Weihai 264200, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c06056

**Notes**

The authors declare no competing financial interest.

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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