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Research Paper

Effective groundwater level recovery from mining reduction: Case study of Baoding and Shijiazhuang Plain area

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Abstract: The effective recovery of water level is a crucial measure of the success of comprehensive groundwater over-exploitation management actions in North China. However, traditional evaluation method do not directly capture the relationship between mining and other equilibrium elements. This study presents an innovative evaluation method to assess the water level recovery resulting from mining reduction based on the relationship between variation in exploitation and recharge. Firstly, the recharge variability of source and sink terms for both the base year and evaluation year is calculated and the coefficient of recharge variation β is introduced, which is then used to calculate the effective mining reduction and solve the water level recovery value caused by the effective mining reduction, and finally the water level recovery contribution by mining reduction is calculated by combining with the actual volume of mining reduction in the evaluation area. This research focuses on Baoding and Shijiazhuang Plain area, which share similar hydrogeological conditions but vary in groundwater exploitation and utilization. As the effect of groundwater level recovery with mining reduction was evaluated in these two areas as case study. In 2018, the results showed an effective water level recovery of 0.17 m and 0.13 m in the shallow groundwater of Shijiazhuang and Baoding Plain areas, respectively. The contributions of recovery from mining reduction were 76% and 57.98% for these two areas, respectively. It was notable that the water level recovery was most prominent in the foothill plain regions. From the evaluation results, it is evident that water level recovery depends not only on the intensity of groundwater mining reduction, but also on its effectiveness. The value of water level recovery alone cannot accurately indicate the intensity of mining reduction, as recharge variation significantly influences water level changes. Therefore, in practice, it is crucial to comprehensively assess the impact of mining reduction on water level recovery by combining the coefficient of recharge variation with the contribution of water level recovery from mining reduction. This integrated approach provide a more reasonable and scientifically supported basis, offering essential data support for groundwater management and conservation. To improve the accuracy and reliability of evaluation results, future work will focus on the standardizing and normalizing raw data processing.

Keywords: Water level recovery; Water balance; Effective mining reduction; Coefficient of recharge variation; Water level recovery contribution

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Introduction

Groundwater is an essential part of water resources, particularly in the North China Plain. It constituted about 69.5% of the total water supply in the region (Ma, 2016; Li et al. 2019). However, due to continuous and large-scale over-exploitation of groundwater over a long period, there was currently a cumulative deficit of 180 billion m^3 of groundwater reserves in North China compared to 1980. The over-exploited groundwater area covers 181 000 km^2, with a ratio of over-exploited area in deep and shallow aquifers at about 2/1, and an over-exploited groundwater volume of approximately 5.51 billion m^3 (Ding et al. 2020). The over-exploitation of groundwater had led to increasingly severe ecological and geological environmental problems in the North China Plain. In response, the government initiated a pilot project for comprehensive management of groundwater over-exploitation in Hebei Province from 2014 to 2016, in collaboration with multiple departments (Chen et al. 2016). Additionally, the first phase of the South-to-North Water Diversion East and Middle Route Project, which began operations in 2013 and 2014, aimed to transform the water supply in the North China Plain and reduce groundwater mining in this area (Shao, 2013; Hu et al. 2016; Cao et al. 2020).

The state placed significant emphasis on managing the over-exploitation of groundwater and underscores the needed to strengthen groundwater management and protection. A series of documents and plans had been issued to strictly regulate and preserve groundwater to achieve a balance between mining and replenishment. As part of these efforts, various departments carried out pilot projects for comprehensive groundwater over-exploitation management in Hebei Province between 2014 and 2016, and implemented measures to regulate groundwater mining, resulting in a reduction of approximately 20 billion m^3 in over mining (Jia et al. 2016).

Therefore, given the regulations on over-mining in the North China Plain and the implementation of the South-to-North Water Diversion Project, it becomed crucial to assess the impact of groundwater level recovery in the region after reducing groundwater mining (Ashaolu et al. 2015). Currently, various methods are employed to calculate and predict groundwater level changes (Ji et al. 2021; Liu et al. 2022; Nan and Cao, 2023). Traditional approaches often directly use Darcy's law to calculate changes caused by mining reduction (Liu et al. 2015; Ma, 2019). However, this direct application of Darcy's equation may not comprehensively reflect the influences of natural factors such as rainfall, lateral recharge, evaporation, and leakage. Numerical simulation is another significant method used to analyze the relationship between water level and water resources (Wang et al. 2008; Zhang, 2018; Lunzer, 2019; Chi, 2021). For instance, Lai et al. used the MIKE SHE model to analyze water resource utilization in the North China Plain, and predicte the impacts of the South-to-North Water Diversion Project on groundwater level recovery (Lai et al. 2018). Jing et al. employed a three-dimensional numerical model on groundwater flow to simulate the relationship between groundwater mining reduction and storage in North China, and analyzed the connection between South-to-North Water Diversion recharge and groundwater level restoration (Jing et al. 2018). Wakode et al. calculated the groundwater balance of the city of Hyderabad using remote sensing and geographic information system (GIS) technology by employing the water balance approach (Wakode et al. 2018). Hua Shan-shan and Zheng Chun-miao used the GLDAS global land surface process model to simulate the trend of China's terrestrial water storage in urbanization and climate change scenarios, exploring the meteorological and anthropogenic factors affecting the distribution of terrestrial water storage (Hua and Zheng, 2018). Xu et al. analysed changes in groundwater storage in the North China Plain by employing the GRACE satellite (Xu et al. 2021). Although numerical simulation methods could simulate regional water level changes caused by mining changes in various scenario models, the modeling process was usually time-consuming, and the simulation accuracy depended on the completeness and accuracy of the distributed hydrogeological parameters and source and sink terms data (Kitanidis, 2015; Li et al. 2021; Liang, 2022). To enhance the timeliness and relevance of evaluating the effect of groundwater mining reduction, this study introduced the concept and method of assessing the impact of water level recovery from mining reduction based on the principle of water balance. The proposed method efficiently calculates the effective reduction of mining volume that leads to water level recovery, the resulting water level recovery value, and the contribution of actual mining reduction in restoration, facilitating an efficient evaluation of drawdown recovery in the target area.

1 Study area

Baoding and Shijiazhuang are important cities supporting the development of Beijing-Tianjin-Hebei region, and serve as crucial recharge areas for groundwater resources in the region. These areas have been targeted for early groundwater mining reduction, and the plain regions of both cities share similar hydrogeological characteristics, with detailed basic information available. However, they differ in the extent of groundwater exploitation and utilization. As a result, this paper focuses on the plain area of Baoding and Shijiazhuang to conduct an evaluation, comparison, and analysis of the effect of groundwater level recovery after implementing the reduction in mining. The geographical scope of the study area is depicted in Fig. 1.

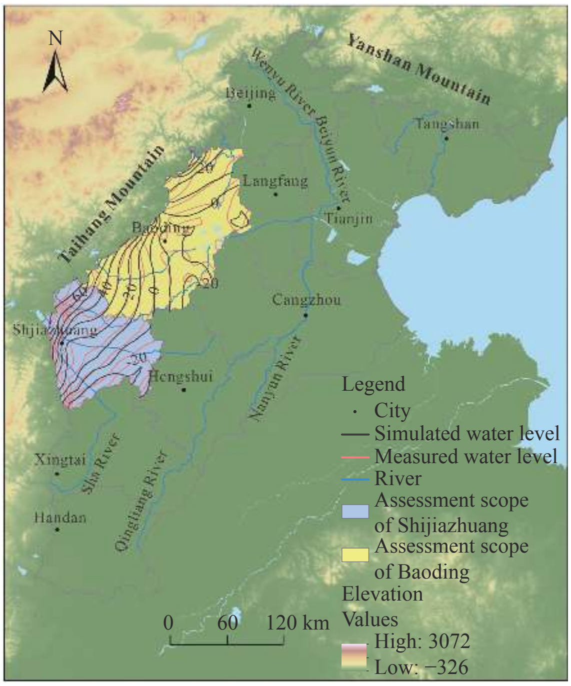

Fig. 1 Location of the study area

Baoding Plain is located in the central part of Hebei Province, west of Taihang Mountains, and it connects Langfang City and Cangzhou City to the east. It is bordered by Shijiazhuang City and Hengshui City to the south, and shares its northern boundary with Beijing, encompassing an area of approximately 11 000 km^2 (including Xiong'an New Area). The region primarily comprises alluvial fans (clusters) formed by the Dasha River, Tang River, and Juma River, and all the rivers within the area are part of the Daqing River System in the Haihe River Basin. The river network is fan-shaped, and has three branches: South, center and north, all flowing into Baiyangdian. The average annual precipitation in the study area is approximately 543.5 mm, and the average annual evaporation is 1 728 mm. The thickness of the shallow aquifer, which is part of the Quaternary System, typically ranges from 80 m to 200 m from west to east, while bottom of the deep aquifer is generally found at depths of around 300 m to 550 m. Groundwater dynamics in the region are mainly influenced by rainfall and exploitation. Of the extensive groundwater extraction over the years has led to the formation of three cones of depression, namely, the Baoding downtown area cone, the Yimuquan cone and the Gaoliqing cone.

Shijiazhuang Plain is situated in the hinterland of the North China Plain, bordered by the Daxing Mountains to the west, Baoding City to the north, Hengshui City to the east, and Xingtai City to the south, covering an area of about 7 000 km^2. The region primarily comprises an alluvial plain formed by the Hutuo River, and the rivers within the jurisdiction are part of both the Daqing River System and the Ziya River System within the Haihe River Basin. The total annual precipitation in Shijiazhuang typically ranges from 401.1 mm to 752.0 mm. The aquifer structure in the area is similar to that of the Baoding Plain. Groundwater dynamics are mainly influenced by rainfall and exploitation. Unfortunately due to years of overexploitation, the groundwater level has been steadily declining, resulting in the formation of several cones of depression.

2 Materials and methods

Water balance method is a fundamental and widely used approach in groundwater science, where the law of conservation of mass is applied to study and analyze the quantitative relationships among the elements involved in the water cycle (Wang, 1986). Based on this method, the authors of this study initially determine the evaluation year and the base year for assessing the restoration effect of mining reduction. Next the amount of groundwater inflow and outflow in the balance area is calculated and input into the balance equation. The coefficient of recharge variation β is calculated by comparing the recharge terms in the evaluation year and the base year. This β value is subsequently used to calculate the effective reduction of mining volume (Q_e) in the evaluation year. Next, the contribution of water level restoration (ΔH_e) resulting from the reduction of mining is determined by combining the hydrogeological parameters and the measurement of the balance area, and the actual reduction volume and the effective reduction volume are compared to solve the contribution of water level restoration. The technical route for this evaluation process is illustrated in Fig. 2.

2.1 Methods for evaluating the effect of water level restoration from mining reduction

2.1.1 Water balance equation

For phreatic water, considering the groundwater

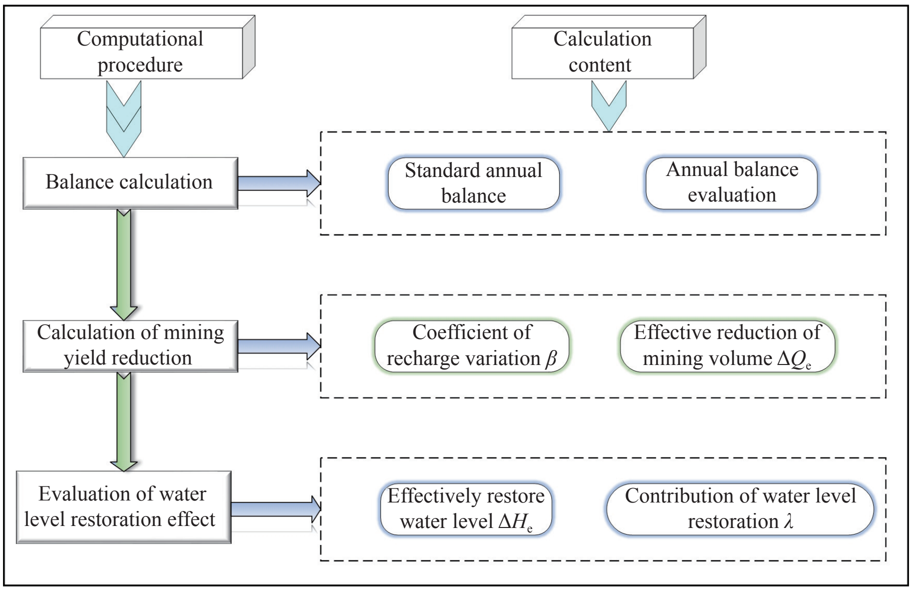

Fig. 2 Research framework employed in this study

recharge and discharge conditions in the study area, the water balance equation for one year can be formulated as follows:

$$\mu\Delta hA=(X_t+Y_t+L_{ti}+Q_{li})-(Z_u+Q_{lo}+L_{to}+Q_e) \quad (1)$$

Where: μ is the specific yield of the phreatic aquifer in the study area; Δh is the phreatic water level change value/L; A is study area/L^2; X_t is precipitation infiltration recharge/L^3; Y_t is surface water infiltration recharge/L^3; L_{ti} is lateral recharge/L^3; Q_{li} is leaky recharge to phreatic aquifer from underlying confined aquifer/L^3; Z_u is evaporation/L^3; Q_{lo} is leaky discharge from phreatic water to confined water/L^3 ; L_{to} is lateral discharge/L^3 ; Q_e is artificial exploitation from phreatic aquifer/L^3.

For confined aquifer, the equilibrium calculation equation is:

$$S_s\Delta h'A=(Q_{lo}+DL_{ti})-(Q_{li}+DL_{to}+DQ_e) \quad (2)$$

Where: S_s is the storage coefficient of the confined aquifer; $\Delta h'$ is the change of hydraulic head of confined aquifer/L; A is study area/L^2; Q_{lo} is the amount of leaky recharge from phreatic to confined water/L^3; DL_{ti} is lateral recharge/L^3; Q_{li} is leaky recharge from confined water to phreatic water/L^3; DL_{to} is lateral discharge/L^3; DQ_e is artificial exploitation of confined aquifer/L^3.

Generally, in North China, the recharge of the confined aquifer is primarily from the leaky recharge originating from the upper phreatic aquifer and lateral recharge from some adjacent areas while discharge mainly occurs through artificial exploitation, with a very small proportion through lateral discharge and leakage to the upper layer.

For the purposes of illustrating the argumentation in this paper, the collected data focuses on the phreatic aquifer. However, since the method is based on the water balance equation, it is theoretically not limited to phreatic water. In areas with comprehensive and detailed information, Equation (2) for confined aquifer can be applied as well.

2.1.2 Effective reduction of mining and coefficient of recharge variation

The concepts of coefficient of recharge variation and effective reduction of mining are introduced on the basis of the water balance equation.

The derivation is illustrated using phreatic aquifer as an example. The balance equations for the base year are as follows:

$$\mu\Delta HA=Q_{\rm r}-Q_{\rm e} \quad (3)$$

The parameters in the equation have the same physical meaning as in Equation (1). By decomposing and transforming the equations, with $Q_{\rm be}$ representing the base year phreatic mining volume and other volumes denoted by $Q_{\rm br}$, we have:

$$-\mu\Delta H_{\rm b}A=Q_{\rm be}-Q_{\rm br} \quad (4)$$

Similarly, the evaluation year balance equation can be written as:

$$-\mu\Delta H_{\rm e}A=Q_{\rm le}-Q_{\rm lr} \quad (5)$$

The coefficient of recharge variation is β= $Q_{\rm br}/Q_{\rm lr}$; the effective reduction in mining is defined as:

$$Q_{\rm er}=Q_{\rm be}-\beta Q_{\rm le} \quad (6)$$

A transformation of Equation (5) yields:

$$Q_{\rm er}=\mu A(\beta\Delta H_{\rm l}-\Delta H_{\rm b}) \quad (7)$$

The effective reduction in mining is determined by the completeness of the water balance equation.

It represents the amount of change in mining that accounts for the difference in recharge between the evaluation year and the base year.

2.1.3 Water level recovery from effective reduction in mining

The water level rebound resulting from the effective reduction in mining (ΔH_{er}) can be obtained using the following equation:

$$\Delta H_{er} = Q_{er}/\mu A \quad (8)$$

2.1.4 Calculation of the contribution of water level recovery from mining reduction

The contribution of water level restoration from mining reduction is defined as the ratio of water level restoration caused by the actual mining reduction volume to the water level restoration caused by the effective reduction of mining.

Since the evaluation area shares the same hydrogeological parameters, the contribution of water level restoration can also be simplified as the ratio of the actual mining reduction volume to the effective reduction mining volume, represented by λ:

$$\lambda = \Delta H_1/\Delta H_{er}100\% = Q_{ar}/Q_{er}100\% \quad (9)$$

In Equation (9), a larger value of λ indicates that the water level variation caused by the actual mining reduction volume contributes more significantly to the overall water level elevation.

It is important to note that when the effective reduction volume is less than or equal to the actual mining reduction volume, it means that all the mining reduction contributing to water level recovery comes from the actual mining reduction volume, resulting in a 100% contribution of water level recovery from mining reduction is 100% in this scenario.

2.1.5 Discussion on the coefficient of recharge variation *β*

The coefficient of recharge variation, β, is a key component of the methodology, and its value depends on changes in water balance, which is discussed here.

When β=1, the recharge in the evaluation year and the base year are the same, and the effective mining reduction is equal to the actual mining reduction. In this scenario, the water level can be restored if the effective mining reduction is above zero. However, if the effective mining reduction is zero or negative, it indicates that the mining reduction volume cannot cause the water level to rise under this balance condition.

When $\beta > 1$, the recharge in the evaluation year is less than recharge in the base year, resulting in the effective reduction being less than the actual mining reduction. The effective water level restoration reflects the variation brought about by the actual mining reduction after compensating for the difference in recharge.

When $0 < \beta < 1$, the recharge in the evaluation year is greater than recharge in the base year, leading to the effective mining reduction being greater than the actual mining reduction. In this case, the effective water level recovery reflects the water level elevation caused by the actual mining reduction along with other recharge and discharge terms.

2.2 Driving force evaluation method

Groundwater level changes are influenced by various elements, including meteorological conditions, topographic characteristics, aquifer hydraulic properties, and groundwater mining. In this study, to assess the impact of mining reduction, a data-driven random forest model was employed. This model comprehensively analyze the influence of each element on the trend of groundwater level change in the study area.

2.2.1 Random forest model

Random forest is a widely used supervising model commonly used in data analysis, particularly for exploring correlations between data. It falls under the category of ensemble models in machine learning (Breiman, 2001). The random forest model can comprehensively analyze decision trees with various branch types, leading to improved fitting accuracy (Fig. 3). In addition, this model exhibits better generalization ability due to its algorithmic advantages, making it suitable for research in the field of hydrogeology (Wang et al. 2018; Koch et al. 2019).

In this study, the groundwater level is categorized as rising (labelled as 1) or not rising (labelled as 0). A Random Forest model is constructed to establish the relationship between the groundwater level and eight specific indicators belonging to four classes, namely meteorological factors, anthropogenic factors, topographical factors, and aquifer hydraulic properties. The feature variable dataset is presented in Table 1.

2.2.2 Feature importance method

After fitting the random forest model, the feature importance, combined with the contribution of water level restoration from mining reduction, was utilized to synthesize and analyze the elements influencing the development trend of water level change. Feature importance is used to assess the relative influence of different feature variables on

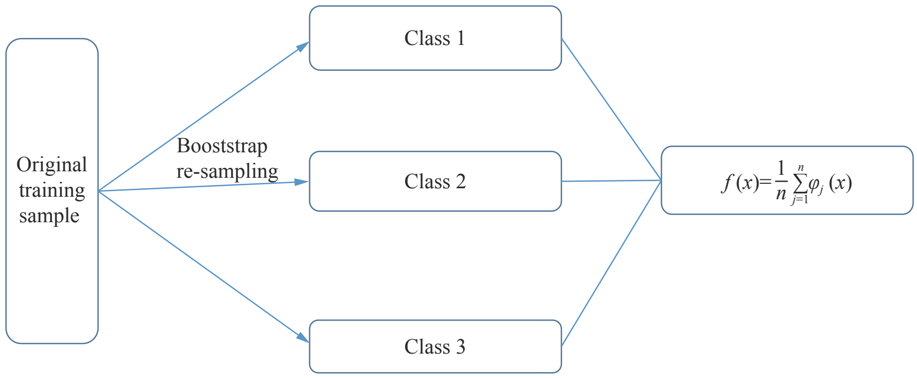

Fig. 3 Schematic diagram of random forest

Table 1 List of the feature variable dataset

Cone of depression feature variable data set			
Class	**Indicator**	**Source**	**characteristic**
Meteorological factors	Precipitation	Statistical data	Accumulative
	Evaporation	Statistical data	Accumulative
Topographical factors	Terrain slope	Remotesensing data	Distributive
	Surface elevation	Remotesensing data	Distributive
Anthropogenic factors	Riverrecharge	Statistical data	Accumulative
	Mining volume	Statistical data	Accumulative
Aquifer hydraulic properties	Permeabilitycoefficient	Empiricalparameter	Distributive
	Specific yield	Empiricalparameter	Distributive
Labeled data			
Content		**Classification type**	
Water level: Rise or not		Yes (1)	
		No (0)	

water level change, typically using the Gini impurity reduction method for statistical evaluation. By performing these statistics, it becomes possible to rank the contribution of each type of elements affecting the water level change. Combining this information with the hydrogeological characteristics of the study area allows for an analysis of the reasons behind the trend of water level change.

3 Results and discussion

3.1 Sources of parameters

The research focuses on the impact of changes in shallow groundwater mining on water level. To achieve this, the water equilibrium equation for the shallow aquifer was formulated based on data from various sources, including the water resources bulletin of the Shijiazhuang and Baoding authorities, monitoring data, remote sensing data, previous research results and geological investigations (Ministry of Water Resources of Baoding City, 2016–2018; Ministry of Water Resources of Shijiazhuang City, 2016–2018). Data and information specific to Baoding Plain were integrated, encompassing key elements such as the actual calculated area of the administrative region, the specific yield, the baseline recharge volume in the evaluation year, the mining volume, and the average water level. The actual calculated area was obtained from the water resources bulletin. An empirical coefficient was used as the specific yield of the study area. The baseline recharge volume in the evaluation year is calculated as the difference between the sum of the recharge terms and the non-exploited discharge terms. Lastly, the evaluation year mining volume refers to the actual amount of groundwater extracted, as reported in the statistics.

After collating the data, we obtained the parameter table for calculating and evaluating the recovery effect of water level from mining reduction in each administrative unit in Baoding Plain from 2015 to 2018 (Table 2). The base year for these calculations was 2015.

Similarly, the corresponding calculation parameters for the evaluation year of Shijiazhuang Plain were obtained, listed in Table 3.

Table 2 List of parameters for calculating and evaluating the effect of water level recovery from mining reduction in Baoding Plain

Evaluation area	Area / km^2	Specific yield	2015 baseline recharge volume / 10^4 m^3	2015 mining volume / 10^4 m^3	2016 mining volume / 10^4 m^3	2017 mining volume / 10^4 m^3	2018 mining volume / 10^4 m^3
Plain area in Laishui County	263	0.20	18 423.13	7 495.30	7 042.9	6 806.9	5 968.3
Plain area in Yi County	190	0.18	34 126.67	11 551.00	1 0651	10 265	4 613
Zhuozhou	742	0.05	10 204.25	17 700.00	16 900	16 307	15 337
Dingxing County	707	0.08	8 875.71	17 218.00	16 756	16 462	15 688
Gaobeidian	672	0.08	10 058.09	12 034.00	11 644	11 276	10 714
Tang County	252	0.08	16 833.70	7 835.00	7 228	6 850	6 460
Shunping County	236	0.07	10 608.58	12 646.50	11 750	11 150	10 430
Mancheng district	294	0.10	10 681.52	8 700.00	8 100	7 690	7 011
Xushui district	727	0.08	8 991.97	13 628.00	12 535	12 640	10 320.2
Rongcheng County	316	0.10	3 546.99	7 950.00	7 502	7 306	/
Baoding Downtown Area	315	0.15	3 407.75	5 845.85	4 325	4 684	4 631.8
Qingyuan district	863	0.14	11 139.53	20 510.00	19 339.43	18 232	17 055
Anxin County	726	0.10	9 459.80	8 186.00	7 711.01	7 613.03	/
Quyang County	427	0.10	17 272.07	3 965.00	3 630	3 520	3 300
Wangdu County	374	0.08	6 055.51	10 144.45	9 422.38	8 792	8 178
Anguo	486	0.10	5 915.52	13 920.00	13 025	12 364	11 138.3
Boye County	340	0.08	3 994.77	8 522.00	7 840	7 393	6 953
Li County	644	0.10	8 759.29	9 100.00	8 420	7 900	7 242
Gaoyang County	487	0.08	5 634.43	8 100.00	7 550	7 003	6 620
Xiong County	524	0.05	6 244.85	8 578.00	7 986	7 901	/
Whole city	9 585	0.10	210 234.11	213 629.10	199 357.72	192 154.93	151 659.6

Table 3 List of parameters for calculating and evaluating the effect of water level recovery from mining reduction in Shijiazhuang Plain

Evaluation area	Area/km^2	Specific yield	2015 baseline recharge volume/10^4 m^3	2015 mining volume / 10^4 m^3	2016 mining volume / 10^4 m^3	2017 mining volume / 10^4 m^3	2018 mining volume / 10^4 m^3
Downtown Area	429.4	0.12	8 132.224519	11 356	11 271	12 147	9 005
Xingtang	422.0	0.1	10 656.92124	6 889.25	6 940.25	7 693	7 831
Lingshou	128.3	0.12	3 236.08211	2 900.2	2 890	340	324
Luquan	267.7	0.12	5 032.648822	7 650	7 130.65	5 431	5 435
Yuanshi	315.5	0.1	6 102.918782	8 262.85	5 343.1	4 259	3 810
Gaoyi	222.0	0.1	3 609.209271	6 196.5	5 776.6	6 035	5 830
Zhao County	675.0	0.1	11 427.86402	19 523.65	19 050.2	19 190	18 679
Luancheng	354.0	0.1	6 742.877 551	8 667.45	7 642.35	8 992	8 381
Gaocheng	813.0	0.07	13 344.11308	26 599.05	20 242.75	0	19 915
Jinzhou	619.0	0.1	6 196.16712	16 195.9	15 310.2	17 718	13 361
Shenze	301.0	0.1	6 173.60483	6 836.55	6 813.6	4 298	4 216
Wuji	500.0	0.18	8 697.156923	11 475	11 475	12 500	12 175
Zhengding	468.0	0.1	8 096.255698	16 260.5	15 130	9 663	7 268
Xinle	525.0	0.1	10 188.89672	14 477.2	14 108.3	15 853	14 395
Whole city	6 990.9	0.1	106 807.0573	170 759.05	155 622.25	124 119	130 625

3.2 Methodological validity

Based on Equations (5) to (8), the effective mining reduction and coefficient of recharge variation were calculated (Table 4). Subsequently, using these results, the effective water level restoration caused by reduction of mining and the contribution of water level recovery (Table 5) were determined for each administrative unit of the Baoding Plain for the evaluation years. The calculation results for the Baoding Plain are shown in Tables 6 and 7.

Table 4 Effective mining reduction and coefficients of recharge variation in the Baoding Plain from 2016 to 2018

Evaluation Area	2016 effective recovery of water level/ m	λ/ %	2017effective recovery of water level/ m	λ/ %	2018 effective recovery of water level/ m	λ/ %
Plain area in Laishui County	0.20	1.13	0.00	100.00	0.18	89.77
Plain area in Yi County	0.55	0.74	0.00	100.00	1.68	14.87
Zhuozhou	0.84	14.35	0.00	0.00	0.00	100.00
Dingxing County	0.23	0.00	0.20	15.45	0.00	100.00
Gaobeidian	0.11	59.61	0.00	100.00	0.00	100.00
Tang County	0.00	0.00	0.31	18.40	0.14	35.68
Shunping County	0.00	0.00	0.93	0.00	0.45	0.00
Mancheng district	0.22	31.27	0.06	100.00	0.11	100.00
Xushui district	0.36	0.00	0.21	0.00	0.33	0.00
Rongcheng County	0.40	0.00	0.29	28.24	0.00	0.00
Baoding Downtown Area	0.84	13.56	0.00	0.00	NA	NA
Qingyuan district	0.03	0.00	0.25	10.63	0.00	100.00
Anxin County	0.00	0.00	0.13	21.89	NA	NA
Quyang County	0.09	0.00	0.00	100.00	0.15	95.06
Wangdu County	0.00	0.00	0.41	0.00	0.00	100.00
Anguo	0.15	26.38	0.02	100.00	0.00	100.00
Boye County	0.00	0.00	0.78	0.95	0.00	100.00
Li County	0.00	0.00	0.38	12.42	0.00	0.00
Gaoyang County	0.00	0.00	0.40	8.93	0.00	NA
Xiong County	0.42	0.00	0.00	100.00	NA	100.00
Whole city	0.17	8.98	0.18	16.19	0.13	57.98

Table 5 Effective mining reduction and coefficient of recharge variation in the Shijiazhuang Plain from 2016 to 2018

Evaluation area	2016 Effective mining reduction/ 10^4 m^3	β	2017 Effective mining reduction/ 10^4 m^3	β	2018 Effective mining reduction/ 10^4 m^3	β
Downtown Area	2 377.515 849	0.80	0.00	1.26	2 930.48	1.02
Xingtang	0	1.10	0	1.14	0	1.07
Lingshou	584.491 5118	0.80	2 398.682988	1.45	0	1.06
Luquan	2 780.984848	0.68	0	1.39	0	1.07
Yuanshi	4 801.894876	0.65	0	1.45	236.0331701	1.06
Gaoyi	2 257.20428	0.68	0	1.25	0	1.06
Zhao County	5 059.534095	0.76	0.00	1.18	0.00	1.07
Luancheng	3 135.757728	0.72	0.00	1.37	124.85	1.06
Gaocheng	12 671.69238	0.69	2 0242.75	1.08	0.00	1.22
Jinzhou	4 853.347933	0.74	0.00	1.05	4 224.15	1.01
Shenze	0	1.14	3 033.84	0.88	0.00	1.06
Wuji	2 612.186442	0.77	0.00	1.17	0.00	1.06
Zhengding	4 040.841819	0.81	4 669.576455	1.08	2 136.717389	1.04
Xinle	2 493.067936	0.85	0.00	1.22	698.00	1.05
Whole city	47 668.52	0.78	30 344.85	1.17	10 350.24	1.07

Table 6 Effective water level restoration by reduction of mining and effective recovery of water level in Shijiazhuang Plain from 2016 to 2018

Evaluation area	2016 effective restoration of water level/ m	λ/ %	2017 effective restoration of water level/ m	λ/ %	2018 effective restoration of water level/ m	λ/ %
Downtown Area	0.46	0.00	0.00	0.00	0.57	100.00
Xingtang	0.00	0.00	0.00	0.00	0.00	0.00
Lingshou	0.38	22.10	1.56	36.00	0.00	100.00
Luquan	0.87	0.00	0.00	100.00	0.00	0.00
Yuanshi	1.52	0.00	0.00	100.00	0.07	0.00
Gaoyi	1.02	0.00	0.00	0.00	0.00	100.00
Zhao County	0.75	0.00	0.00	0.00	0.00	100.00
Luancheng	0.89	21.47	0.00	0.00	0.04	0.00
Gaocheng	2.23	0.00	3.56	17.00	0.00	0.00
Jinzhou	0.78	0.00	0.00	0.00	0.68	42.00
Shenze	0.00	0.00	1.01	0.00	0.00	100.00
Wuji	0.29	0.00	0.00	0.00	0.00	100.00
Zhengding	0.86	0.00	1.00	0.00	0.46	71.00
Xinle	0.47	5.42	0.00	0.00	0.13	117.00
Whole city	0.79	1.97	0.50	22.00	0.17	76.00

Notably, data for the year 2018 for the plain area of Rongcheng, Anxin, and Xiongxian counties could not be obtained due to their incorporation into the Xiong'an New Area (denoted by NA) in 2018.

Similarly, the values of effective mining reduction, coefficient of recharge variation, effective water level recovery and contribution of water level restoration by mining reduction in Shijiazhuang Plain area in the evaluation year can be calculated. However, it should be noted that some areas may not have the necessary data available, and in such cases, they are marked as NA in the table. Furthermore, the effective mining reduction is considered meaningful only when the value is positive. Therefore, if the calculated value is negative, it indicates that no effective mining reduction is generated, and it is recorded as zero. This approach ensures that negative values do not skew the analysis.

To compare and validate the method, this study compares the results of the numerical model simulations conducted at the two sites (Fig. 4).

Using the water balance conditions for the year 2015 and 2016 in the study area, the model was employed to calculate the average effective restoration levels for each county and city within the Baoding Plain, as presented in Table 8. Results for areas with negative water level changes are recorded as 0.

As can be seen from Table 8, the simulation results for the overall water level restoration in the Baoding Plain were generally consistent with the

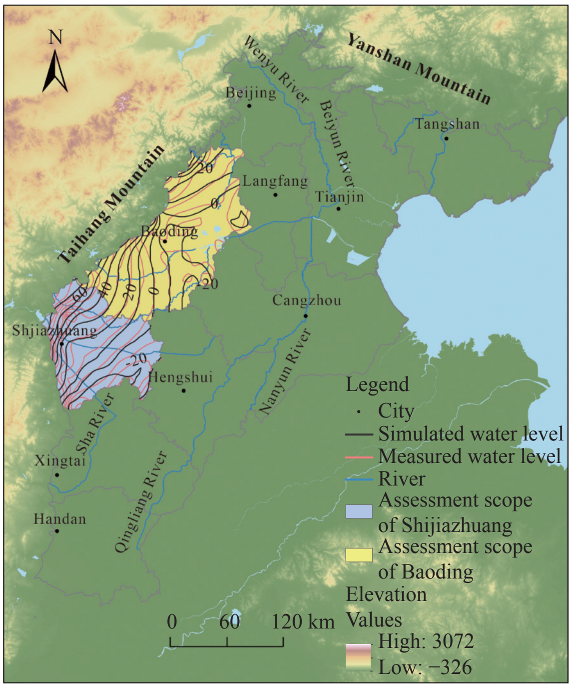

Fig. 4 Fitting effect of groundwater flow field in Baoding and Shijiazhuang Plain

calculation results obtained through the method proposed in this study. However, in certain counties and cities, larger deviation were observed, primarily concentrated in the foothill section. These discrepancies can be attributed to errors in the model itself and the influence of lateral recharge in the mountainous areas, leading to inaccuracies in calculating the lateral recharge volume and, consequently, the simulation errors.

Table 7 Comparison of 2016 water level restoration calculation results and simulation results in Baoding Plain

Evaluation area	2016 effective water level restoration/ m	2016 restoration calculated by model/ m
Plain area in Laishui County	0.20	0.070
Plain area in Yi County	0.55	0.100
Zhuozhou	0.84	0.660
Dingxing County	0.23	0.170
Gaobeidian	0.11	0.180
Tang County	0.00	0.070
Shunping County	0.00	0.050
Mancheng district	0.22	0.180
Xushui district	0.36	0.290
Rongcheng County	0.40	0.330
Baoding Downtown Area	0.84	0.650
Qingyuan district	0.03	0.020
Anxin County	0.00	0.002
Quyang County	0.09	0.001
Wangdu County	0.00	0.001
Anguo	0.15	0.000
Boye County	0.00	0.000
Li County	0.00	0.000
Gaoyang County	0.00	0.000
Xiong County	0.42	0.390
Whole city	0.17	0.150

Overall, the methodology proposed in this paper can reasonably reflect the true level of water level restoration in the study area.

3.3 Changes in the effect of groundwater mining reduction

3.3.1 Changes in the effect of groundwater mining reduction in the Baoding Plain

According to the calculation results of effective mining reduction (Fig. 5(a)), in 2016, most areas within the Baoding Plain achieved effective mining reduction, with reductions generally within the range of 20 million m^3, and the highest reduction was observed in the Zhuozhou Plain area, exceeding 30 million m^3. In 2017, the effective mining reduction in the study area was comparable to that of 2016, but the specific areas experiencing effective mining reduction changed. However, by 2018, the overall effective mining reduction in the evaluation area decreased to 106.22 million m^3, with most areas failing to reach effective mining reduction.

Analyzing the development of the coefficient of recharge variation β (Fig. 5(c)), it can be observed that in 2016, β was less than 1 in most areas, indicating that the effective reduction of mining was greater than the actual mining reduction, and the water level recovery was a result of a combination of mining reduction and other source and sink terms. A similar situation was observed in 2017, with the coefficient of recharge variation greater than 1 in most areas. By 2018, the volume of the actual mining reduction partially offset the equilibrium variance, resulting in a smaller effective reduction volume. The relative decrease was about 60 million m^3, and the water level changes were mainly attributed to reduced mining. Fig. 5(e) indicates that in 2016 and 2017, the water level in most areas of the Baoding Plain recovered between 0.2 m to 0.8 m. However, in 2018, the water level recovery was lower at 0.13 m, as water level recovery in many areas was only provided by mining reduction.

The average recovered water level caused by effective mining reduction (Fig. 5(e)) indicateed that the value of water level recovery in the plain area north of Dingxing County, Baoding, is small, less than 0.1 m. In contrast, the water level recovery in the southeastern plain area was more significant, with an average recovery of more than 0.2 m, and in Xiongxian County, it exceeded 0.7 m. Most of the remaining plain area had a recovery

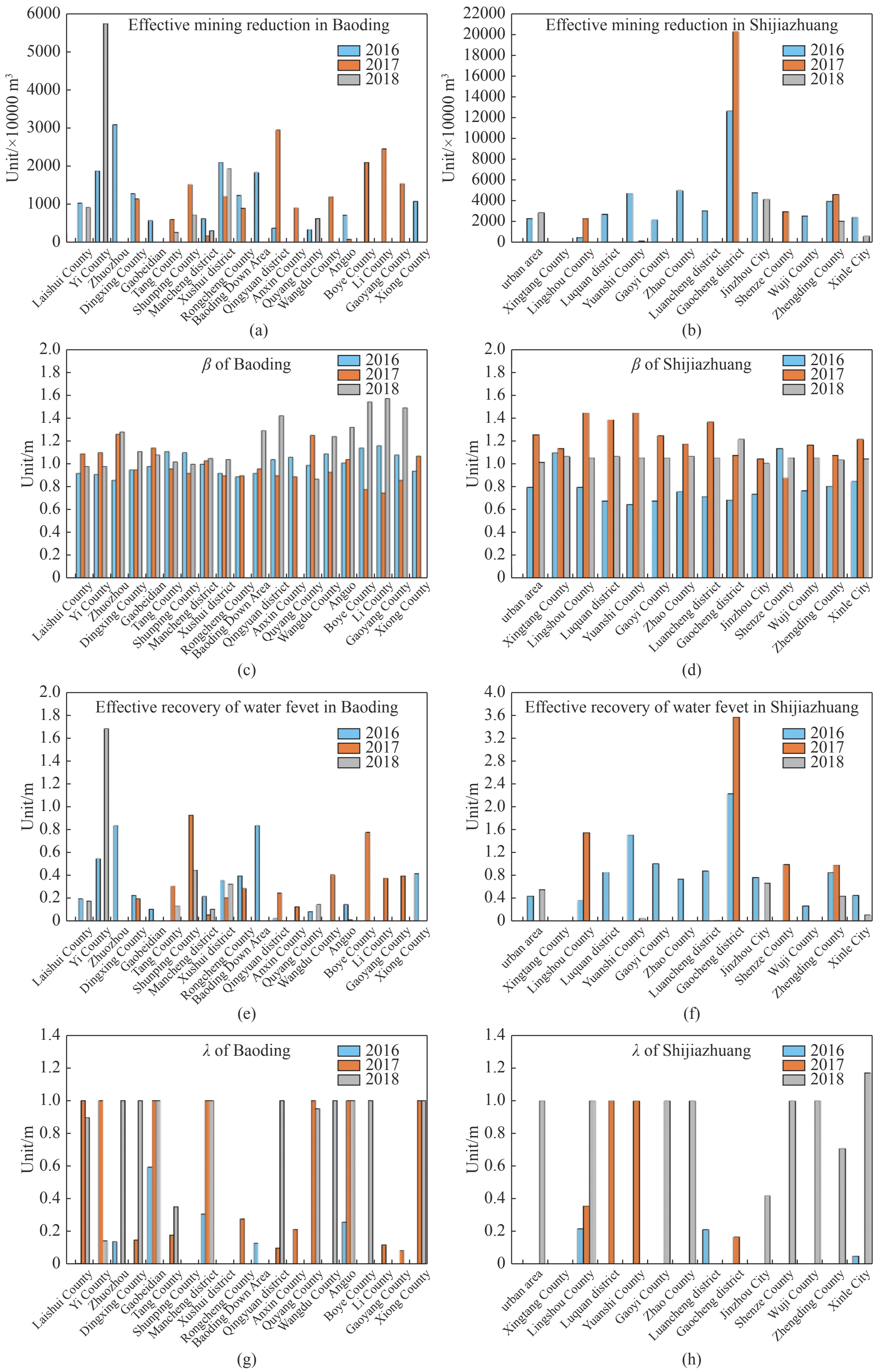

Fig. 5 Comparison of change in annual effective mining reduction and coefficient of recharge variation (β), effective recovery of water level and contribution of water level recovery by reduction of mining (λ) in Baoding and Shijiazhuang Plains

ranging from 0.1 m to 0.2 m.

Considering the calculation of the actual mining reduction volume, the contribution of water level recovery from mining reduction in each county and city in the plain can be calculated (Fig. 5(g)). In 2016, with better recharge conditions, the overall water level recovery was greater, and almost all areas with water level recovery had contributions aside from reduction in mining, resulting in relatively low contribution of mining reduction, typically within 60%. In 2017, the overall water level recovery was also higher, and the source of the water causing the recovery in each area varied greatly. In the seven evaluation areas, such as Laishui, Yi County and Gaobeidian plains areas, the reduction of mining volume dominated the water level recovery, while in other areas, the contribution of mining reduction was relatively small, ranging from 10% to 30%.

3.3.2 Changes in the effect of groundwater mining reduction in the Shijiazhuang Plain

The changes in effective mining reduction in Shijiazhuang Plain (Fig. 5(b)) revealed that in 2016, most areas achieved effective mining reduction, with reduction volume generally below 50 million m^3. Among all areas, Gaocheng Plain area had the largest reduction, with a reduction volume of 126.72 million m^3. In 2017, there was a significant change compared to 2016, with many areas failing to achieve effective mining reduction. Only the plain areas of Lingshou, Gaocheng, Shenze and Zhengding County effectively reduced mining, and the mining reduction in the Gaocheng Plain area expanded more significantly than in 2016, exceeding 200 million m^3. In 2018, the effective mining reduction in Shijiazhuang Plain was even smaller, with the total volume only at around 100 million m^3. Only the plain areas in Downtown, Yuanshi, Luancheng, Jinzhou, and Zhengding saw effective mining reduction.

According to the temporal and spatial variation of the coefficient of recharge variation β in the Shijiazhuang Plain (Fig. 5(d)), it can be observed that in 2016, most of the area, except for the plain areas of Xingtang and Shenze, had β values less than 1. This indicated that the effective reduction of mining was greater than the actual reduction. The water level restoration was provided by the combination of the reduction in mining and the other source-sink terms. By 2017, the β value in most areas of the study area had exceeded 1, and the effective reduced mining was smaller than the actual reduction of mining. As a result, the actual reduction was mostly used to balance the recharge discrepancy, resulting in an overall decline in the effective reduced mining, with a relative reduction of more than 170 million m^3. This phenomenon continued in 2018, leading to a further decline in the effective reduction of mining, which was only about 100 million m^3. Water level variations in 2017 and 2018 were mainly caused by reduced mining.

The average recovery of water level caused by effective mining reduction (Fig. 5(f)) indicated that in 2016, the groundwater recharge volume in the Shijiazhuang Plain was relatively abundant, contributing to an elevation of around 1 m in water level. The water level in the Gaocheng Plain area recovered up to 2.23 m. However, in 2017, apart from a significant water level rised of more than 3 m in the Gaocheng Plain area, only LingShou, Xinle and Zhengding Plain areas witnessed some noticeable water level rebound of around 1 m. By 2018, water level rebound could not be observed in most of the area, and the water level rise in the rebound areas was small, generally within 0.5 m.

Combined with the calculation of the actual volume of mining reduction in each county and city, the contribution of water level restoration can be obtained (Fig. 5(h)). It can be seen that in 2016, groundwater recharge in the Shijiazhuang Plain was abundant, and the overall water level experienced a rebound. In the rebound area, in addition to the reduction in mining, other sources also provided significant recharge, resulting in the reduction's relatively low contribution to the overall recharge at about 20%. In 2017, some parts of the area experienced a significant reduction in recharge, where mining reduction was the main source of water level restoration, and its proportion was relatively high. In 2018, due to the lack of recharge in most of the area, the water level rise was almost entirely from the volume contributed by the reduction in mining.

3.3.3 Comparison of trends in the effective recovery of water level in Shijiazhuang and Baoding Plains

(1) Comparison of calculations in 2018

When comparing the calculation results of 2018 (Fig. 6), it can be seen that the effective reduction of mining in Shijiazhuang Plain was relatively small, at about 103.5 million m^3. However, the effective water level restoration was greater, at about 0.17 m. This difference can be attributed to the varying scope of the evaluation area. The evaluation area in the Shijiazhuang Plain was smaller, which means that when the difference in specific yield was small, the overall water level rise caused by the same effective reduction in mining would be relatively higher. As a result, the

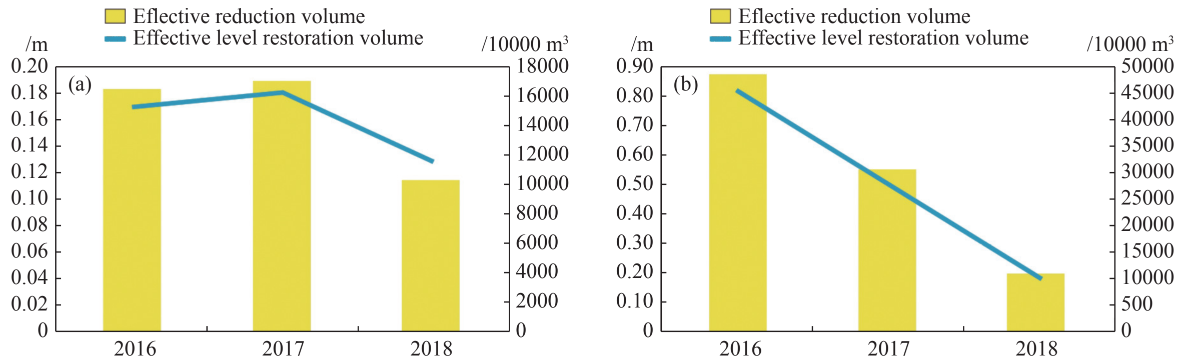

Fig. 6 Trends in effects of mining reduction in Baoding and Shijiazhuang Plains (a. Baoding; b. Shijiazhuang)

Shijiazhuang Plain showed higher efficiency in terms of water level rise.

(2) Comparison of development trends

When comparing the development trend of the effect of mining reduction in the plain area of Baoding and Shijiazhuang (Figs. 6-7), it was noticeable that the shallow groundwater level in Baoding Plain area initially increased but later declined. the contribution of mining reduction to water level restoration increased from around 10% to around 60% over time, indicating an intensified focus on mining reduction efforts. However, in 2018, the effective reduction of mining decreased due to variations in recharge, resulting in a slower water level rebound.

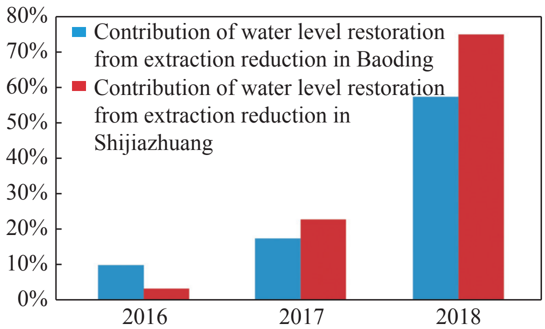

Fig. 7 Trends in the contribution of water level restoration from mining reduction in Baoding and Shijiazhuang Plains

The effective recovery of water level by reduced mining in Shijiazhuang Plain showed a decreasing trend over the years, with the effective water level recovery decreasing from 0.79 m to 0.17 m. Similar to Baoding Plain, the contribution of water level recovery from mining reduction in Shijiazhuang Plain also increased year by year, reaching over 70% in 2018. This indicated that the water level recovery in Shijiazhuang Plain heavily relied on the volume of mining reduction due to insufficient recharge resources.

Overall, the water level recovery was mainly driven by the effective mining reduction. The effectiveness of reduction is closely related to the coefficient of recharge variation; the closer the coefficient β is to 1, the greater the contribution of mining reduction to the water level recovery. When β is greater than 1, it becomes less likely to achieve effective reduction. On the other hand, when β is less than 1, the water level recovery is influenced by various water sources, and the proportion of recovery caused by mining reduction becomes smaller. In essence, water level recovery did not solely depend on mining reduction, and the mining reduction itself did not solely determine the overall water level recovery in the evaluation area.

(3) Analysis of factors influencing the trends

The feature importance ranking of each element in the Baoding and Shijiazhuang plain area from 2016 to 2018 obtained using the feature importance method of random forest model is shown in Fig. 8.

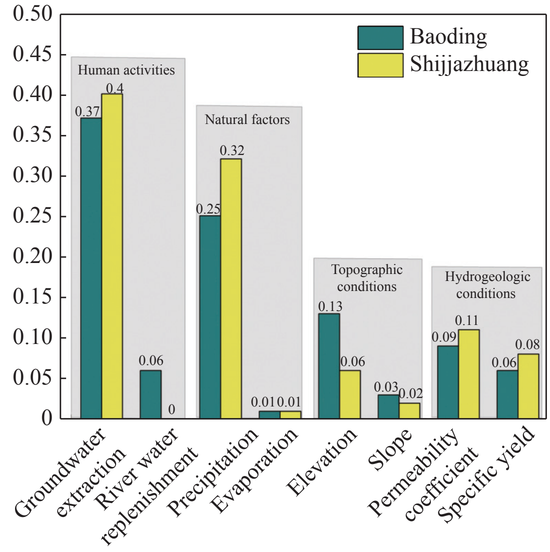

Fig. 8 Comparison of the contribution of feature elements to water level changes in Baoding and Shijiazhuang Plain Area

As observed in Fig. 8, the primary factor influencing water level changed in both Baoding and Shijiazhuang Plains was artificial groundwater mining, contributing to 37% and 40% of the impact of water level changes in the two cities, respectively. Additionally, the Shijiazhuang Plain was significantly influenced by precipitation, accounting for 32% of the impact. On the other hand, the Baoding Plain received recharge from rivers, resulting in a higher proportion of recharge compared to the Shijiazhuang Plain. Moreover, due to its narrower width, the Baoding Plain benefited from a larger amount of lateral recharge from the mountainous areas. The relative permeability coefficient variation in the Baoding Plain was also less compared to the Shijiazhuang Plain. As both cities are located on the foothill plains, groundwater levels were less affected by evaporation.

Generally, from 2016 to 2018, human activities accounted for 43% of the impact on groundwater level in Baoding Plain, which was slightly larger than that in Shijiazhuang Plain. Topographical features had a 16% impact in Baoding Plain, twice as much as in Shijiazhuang Plain. However, in Shijiazhuang Plain, aquifer hydraulic properties and meteorological factors had a greater impact on groundwater levels compared to Baoding Plain.

Specifically, the availability of multiple recharge sources in Baoding Plain allowed for more effective mining reduction through reduced extractions. The plain received not only precipitation infiltration but also lateral recharge from the mountainous areas, as well as some recharge from rivers and lakes. As a result, although effective mining reduction did not change much during the study period, water level changes were observed every year, while the overall water level recovery through mining reduction was lower than that in the Shijiazhuang Plain. On the other hand, groundwater recharge in Shijiazhuang Plain primarily relied on precipitation. In addition, water level changes in the Shijiazhuang Plain were significantly influenced by the hydraulic properties of the aquifer. When recharge was insufficient, large-scale mining reduction measures were implemented, but the actual reduced volume was used to compensate for the lack of recharge, leading to a continuous decline in the volume of effective mining reduction during the study period. At the same time, due to the limited recharge sources, mining reduction played a crucial role in causing the water level rebound in the Shijiazhuang plain, especially from 2017 to 2018.

4 Conclusions

(1) The evaluation method proposed in this paper, based on the principle of water balance, was applied to assess the restoration effect of mining reduction on water levels in Baoding and Shijiazhuang Plains. The results indicated that from 2016 to 2018, a significant portion of Baoding Plain and some parts of Shijiazhuang Plain achieved effective mining reduction. In Baoding Plain, both the effective mining reduction and water level recovery initially increased and then decreased, while the contribution of mining reduction showed an upward trend over the years. When water level recharge conditions were favorable, water level recovery was mainly from the water sources outside of mining reduction; however, with continuous reduction, the contribution of mining reduction gradually increased. In contrast, for Shijiazhuang Plain, both effective mining reduction and water level recovery decreased over the years, while the contribution of water level recovery from mining reduction increased. This method reasonably and effectively assessed the water level recovery situation in the areas of mining reduction.

(2) The calculation demonstrated that water level recovery depended on the presence of effective mining reduction in the study area rather than the specific reduction volume. The magnitude of water level recovery did not solely indicate the intensity of reduction. It was influenced not only by the volume of mining reduction, but also by changes in recharge. With an increase in effective mining reduction, water level recovery primarily resulted from the volume of groundwater mining reduction.

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