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Prediction of the dynamic changes of water table based on the quantitative theory type I in the Piedmont Plain of the Taihang Mountains

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Statistical analysis was conducted on groundwater table data in the Ji Yuan Basin from 2006 to 2018, revealing a continuous downward trend in the groundwater table with imminent depletion of shallow groundwater resources. To ensure the sustainable development of groundwater resources in the area, a quantitative model of groundwater table was successfully constructed using the principles of the Quantitative Theory Type I. This model included seven benchmark variables: rainfall, evaporation, exploitation, hydraulic conductivity, specific yield, lithology of the vadose zone, and land-use type. These factors are key contributors to the decline in groundwater levels in the study area. The model yielded an average residual value of 0.35 m and an adjusted R^2 of 0.789, indicating that it can explain 78.9% of the benchmark variables with acceptable accuracy. Additionally, the model successfully simulated four types of groundwater dynamics, with the best results obtained for the rainfall infiltration-exploitation-evaporation type. This study's findings suggest that the model can be utilized to predict the dynamic characteristics of the groundwater table and guide groundwater extraction activities.

Groundwater constitutes the most abundant freshwater resource globally[1,2], with 35% of worldwide water usage sourced from it[3,4]. The primary water consumers are agricultural, domestic, and industrial sectors, among which agricultural irrigation alone utilizes over 65% of the total freshwater consumption[5]. Groundwater plays a pivotal role in ensuring global food security and meeting the drinking water requirements of over 2 billion individuals effectively[6]. With the rapid urbanization taking place, significant volumes of groundwater are being extracted from urban regions globally[7,8]. This has led to considerable stress on groundwater reservoirs[9], resulting in declining water levels, land subsidence[10,11], and posing a threat to the sustainable development of aquifers[12].

The Ji Yuan Basin, situated in the North China Plain[13,14], has experienced a decline in groundwater levels, degradation of water quality[15], and intermittent issues with drying up of the river due to factors such as climate change, coal mining[16–18], and industrial and agricultural activities in the region over the past few decades[19]. Water scarcity poses a significant barrier to the economic advancement of the research area[20], primarily reliant on groundwater extraction for drinking and agricultural purposes[14,21], leading to an escalating struggle between water supply and demand[22]. The primary sources replenishing the groundwater system in the Ji Yuan Basin include vertical percolation of precipitation and irrigation water, and lateral runoff from the western Taihang Mountains[23]. Groundwater discharge is predominantly due to human extraction, surface runoff, and evaporation[24].

With the swift advancement of urban industrialization in the research area, the land-use patterns have shifted, resulting in a decrease in natural land area[25,26]. This transformation has also brought significant alterations to the vegetation cover. Consequently, the precipitation and leakage from agricultural irrigation have diminished[27], thereby significantly impacting the runoff characteristics of the study region[28]. Moreover, the groundwater has been over-explored for a long period of time due to the economic development in the study area[29]. These factors

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have led to an imbalance between the inflow and outflow of groundwater resources, resulting in an ongoing decline in the groundwater table and the groundwater storage depletion of shallow groundwater reservoirs in the study area[22]. Due to the inclusion of qualitative factors among the influencing factors of groundwater dynamics in the study area, which are difficult to quantify, this poses certain challenges for the simulation research of groundwater dynamics in the region.

Based on previous studies, it has been found that the quantification theory proposed is well-suited to address such issues[30,31]. The quantification theory can be classified into four categories, namely Quantification Theory Type I, II, III, and IV, depending on the research objectives[31]. Quantification Theory Type I primarily focuses on studying the relationships between things. Through this method, qualitative variables can be converted into quantitative data according to certain principles, enabling research based on quantitative data[32–36].

This study integrates the Quantitative Theory Type I, comprehensively evaluates the impact of quantitative and qualitative factors on the water table, establishes a dynamic change model for water table characteristics in Ji Yuan Basin, utilizes complex correlation coefficient (R) and average residual for model accuracy assessment. Subsequently, the model is applied to simulate and validate groundwater tables for the four groundwater dynamic types, ensuring the model's practicality.

Data and methods
Study area
The Ji Yuan Basin is situated at the southern base of the Taihang Mountains in China (Fig. 1), spanning between 112°01′~112°45′E and 34° 53′ ~ 35°16′ N, encompassing an area of approximately 350 km^2. It is enclosed by mountains on three sides, creating a basin shape with a higher elevation in the west and lower in the east. The ground elevation varies from 130 m to 450 m, resulting in significant elevation differences. The terrain comprises mountains, hills, and plains. The geological composition of the strata falls within the North China stratigraphic region, excluding the Silurian and Cretaceous systems. The study area experiences a warm temperate continental monsoon climate, characterized by distinct seasonal fluctuations in groundwater levels. With an average annual precipitation of 618.26 mm, rainfall diminishes from north to south, primarily concentrated between May and September.

The thickness of the Quaternary unconsolidated sedimentary layer in the area generally ranges from 50 to 200 m, and it is in angular unconformity contact with the underlying Neogene and earlier strata of different ages. There is only local hydraulic connection between these two layers.

The aquifer system in this region extends from northwest to southeast, featuring fine-grained lithology and interlayer structure weakening. While the western and northern areas consist of gravel layers, the eastern and southern areas transition from gravel to clayey sand. The focus of this analysis is on the quaternary aquifer as a target for studying water table dynamics. Groundwater flow in the study area is consistent with the northwest-southeast topography, and the permeability of the phreatic aquifer decreases in the northwest to southeast direction (Fig. 2).

The dynamic changes in the groundwater level within the region can be generally categorized into four types based on their recharge–discharge conditions.
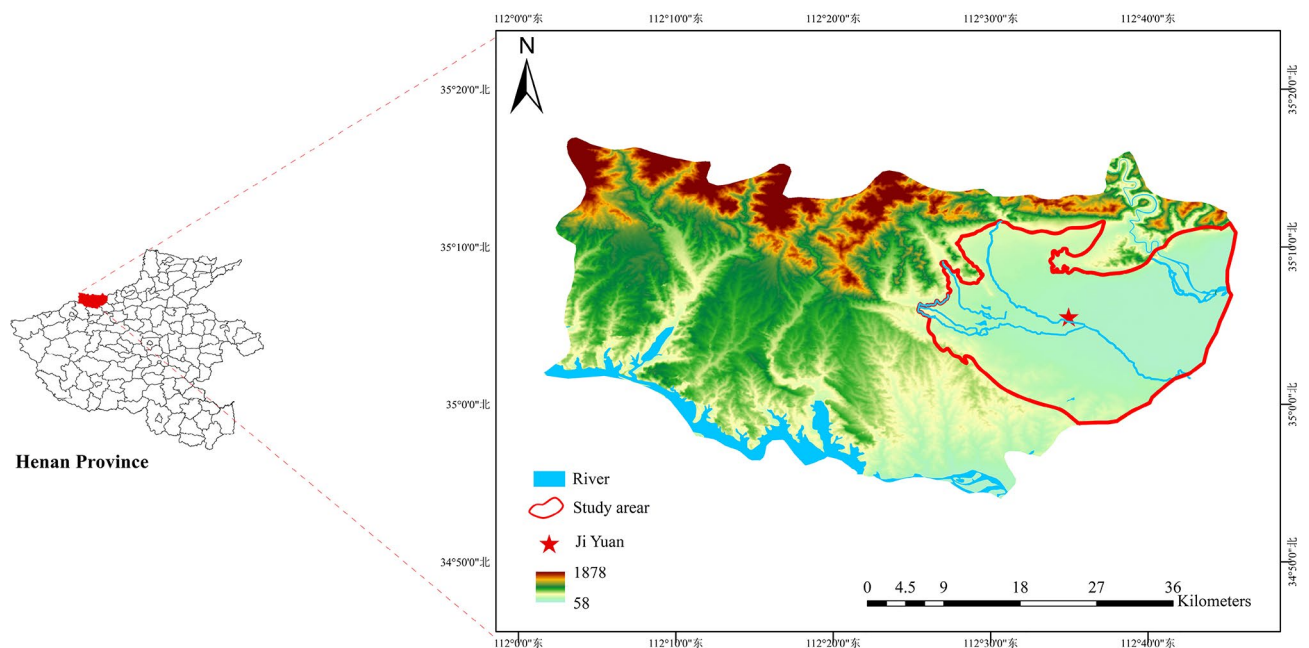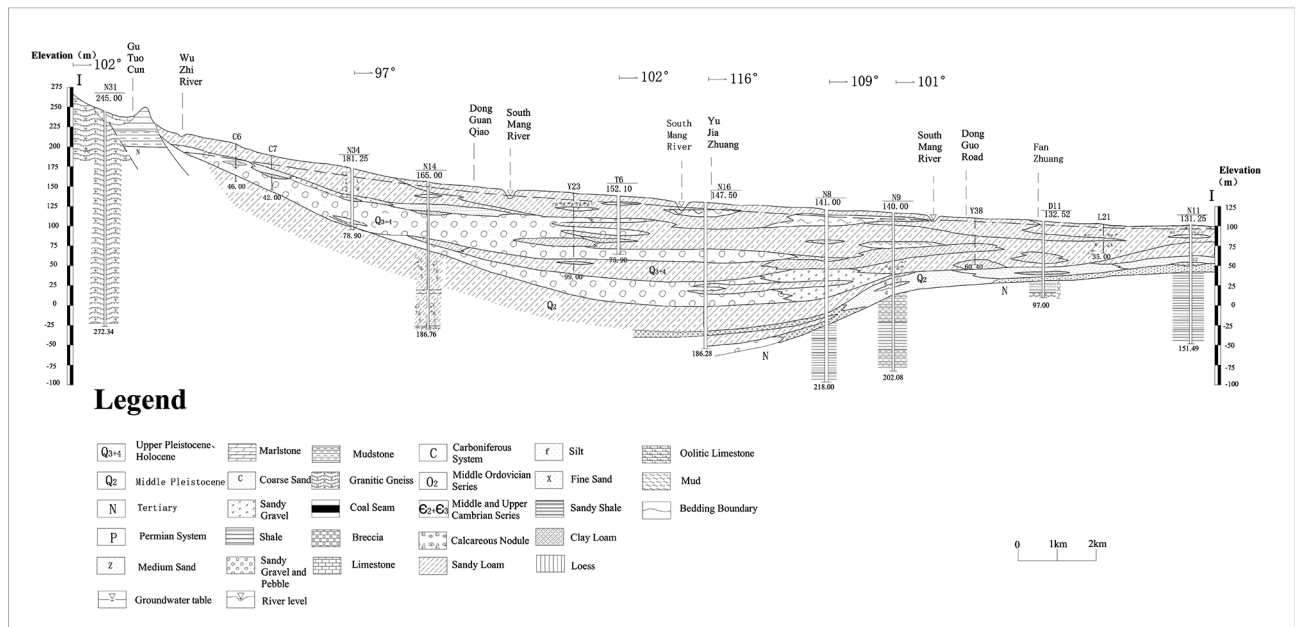

Fig. 1. Location of Ji Yuan Basin.

Fig. 2. East-West hydrogeological section map of Jiyuan Basin.

Rainfall infiltration–evaporation type
This type of groundwater is distributed in the alluvial-proluvial inclined plain area of Mang River, characterized by a relatively shallow groundwater depth, generally less than 4 m. Rainwater serves as the primary recharge source, and evaporation is the main discharge mechanism. Due to the high content of fine-grained materials, the porosity and permeability are relatively poor, leading to a relatively small groundwater storage capacity. Although atmospheric precipitation is the primary recharge source for this type of groundwater, the slow recharge rate in fine-grained lithology areas results in a minimal impact on the groundwater level.

Rainfall infiltration–extraction type
The primary recharge source for this type of groundwater is rainfall infiltration, which is primarily influenced by farmland irrigation during spring and winter seasons. The primary discharge mechanism is seasonal artificial extraction. The aquifer lithology in this region comprises clayey sand, sandy gravel, and coarse-grained materials, resulting in high permeability and significant recharge capacity from rainfall infiltration. Consequently, the rise in water level induced by precipitation infiltration is pronounced.

Rainfall infiltration-runoff type
This type of groundwater is mainly distributed in river valley terraces, alluvial fans, and inclined plain areas. The groundwater depth in this region exceeds 15 m, and the lithology is dominated by breccia and gravel. The runoff conditions are favorable, with rainwater infiltration serving as the primary recharge source. The groundwater discharges primarily through runoff.

Rainfall infiltration–extraction–evaporation type
This type of groundwater is predominantly distributed in the shallow groundwater areas of the northern plain region of Jiyuan Basin and some parts of the first-order terraces of river valleys. The groundwater is recharged by atmospheric precipitation and infiltration from surface water irrigation, and it discharges through evaporation and extraction. The aquifer lithology is primarily composed of silty clay with gravel, characterized by fine-grained particles and poor permeability. Consequently, the fluctuations of groundwater levels do not exhibit significant correlation with changes in precipitation.

Data sources
The groundwater observation network in Ji Yuan City comprises 52 long-term monitoring wells and 77 wells for integrated water resources allocation. Based on the water table data from groundwater monitoring wells between 2006 and 2018 provided by the Ji Yuan Water Conservation Office, this study focuses on 20 long-term shallow groundwater observation wells. The distribution of monitoring wells is illustrated in Fig. 3. Rainfall and evaporation data are gathered from the Jiyuan City Meteorological Bureau, while information on groundwater extraction and water supply comes from geological records of the Ji Yuan Basin. Hydraulic conductivity is computed using pumping test results from each monitoring well. Land use data is acquired by analyzing remote sensing images of the study area and classifying land use patterns using the Environment for Visualizing Images (ENVI) software.
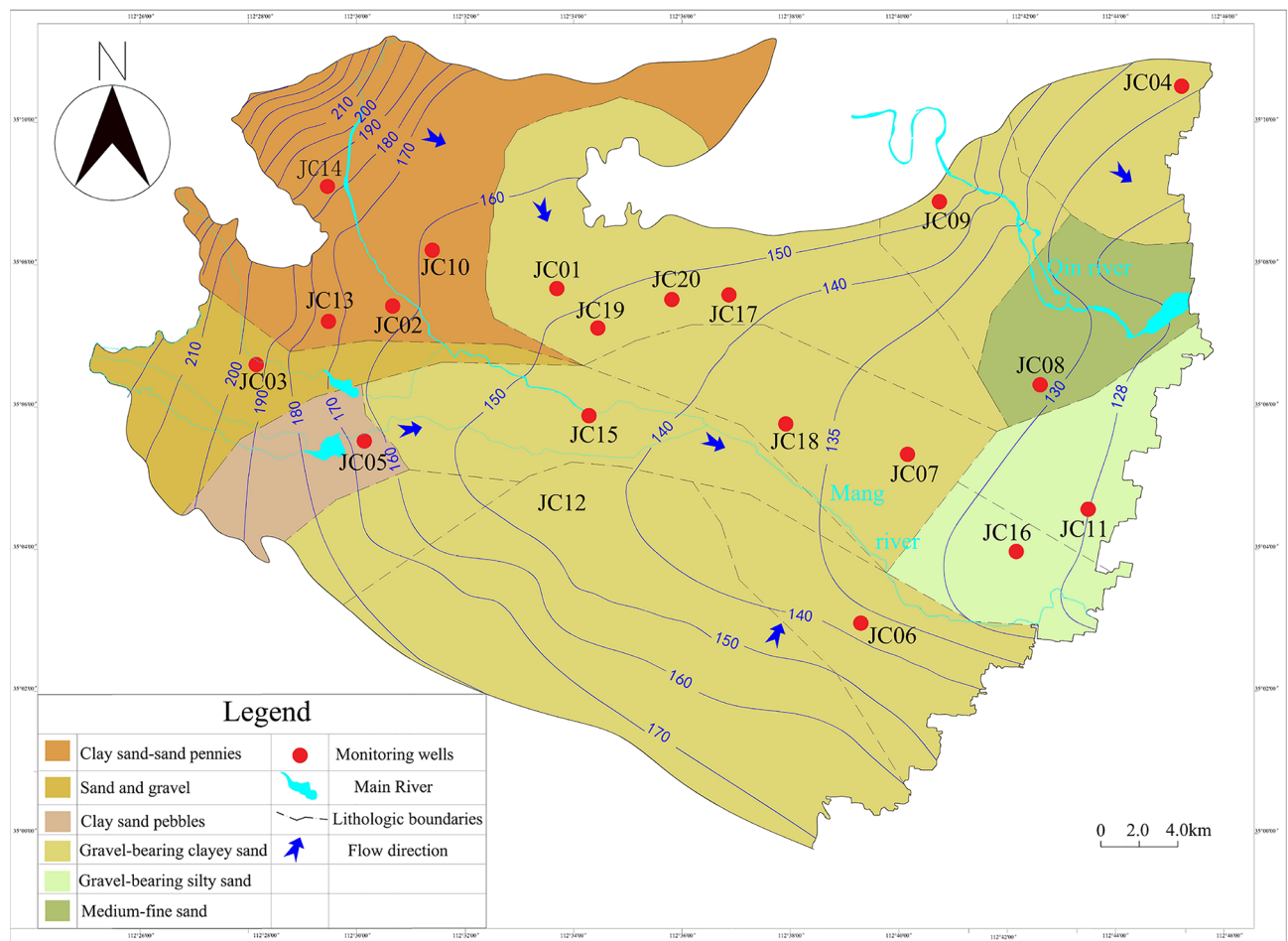
Fig. 3. Locations of monitoring wells and the Lithology of the vadose zone.

Research method

In this study, statistical tests such as Mann-Kendall trend test and Mann-Kendall mutation analysis were used to process the data on the dynamic changes in groundwater level from 20 monitoring wells in the area from 2006 to 2018 to determine the dynamic changes in groundwater in the study area.

The effects of seven major factors on the dynamic changes of groundwater level were investigated using single factor analysis. Then the data were processed using multiple linear regression analysis, on the basis of which the model was constructed using quantitative theory I principles. After that, the accuracy of the model was verified using goodness-of-fit analysis and residual test.

Figure 4 elucidates the methodological framework adopted in this research, encompassing data gathering, Mann-Kendall trend test, M-K mutation test, Pearson correlation analysis, model development, and model validation procedures. Ultimately, the model's capability to steer the scientific and rational utilization of groundwater is confirmed.

Result and discussion
Dynamic characteristics of water table

As depicted in Fig. 5a, taking the significance level as 0.01, the critical value is 2.58 by consulting the normal distribution table. According to the trend test principle, if the Z value is greater than 0, the water level is an upward trend, and less than 0 is a downtrend. The Z-value results of the statistics were plotted as histograms, and the results showed that except for the two monitoring wells JC04 and JC09, the water level changes of the remaining 18 monitoring wells showed a downward trend. This is consistent with the analysis of data from the Gravity Recovery and Climate Experiment (GRACE)[6,37,38].

In the M-K mutation test analysis, the UB curve and the UF curve represent the trend statistics of the positive and negative sequences, respectively. When their intersection is located within the confidence interval and passes the significance test, the intersection is a real mutation point. As shown in Fig. 5b, the intersection of the UF curve and the UB curve is located in the end of 2012, and it is within the confidence interval with a significance level of 0.95. Therefore, the time when the water level in the Jiyuan Basin started to change suddenly is the end of 2012. The reason for the sudden change of water level is complicated: in 2011, the annual precipitation in the study area increased abnormally, reaching 869 mm, far exceeding the multi-year average precipitation of
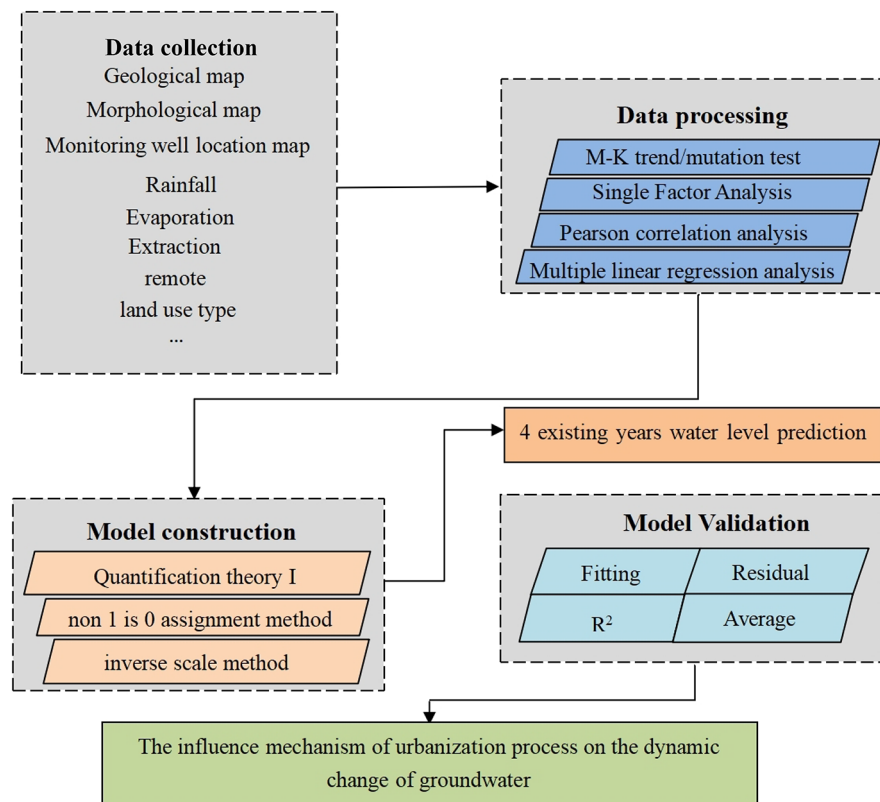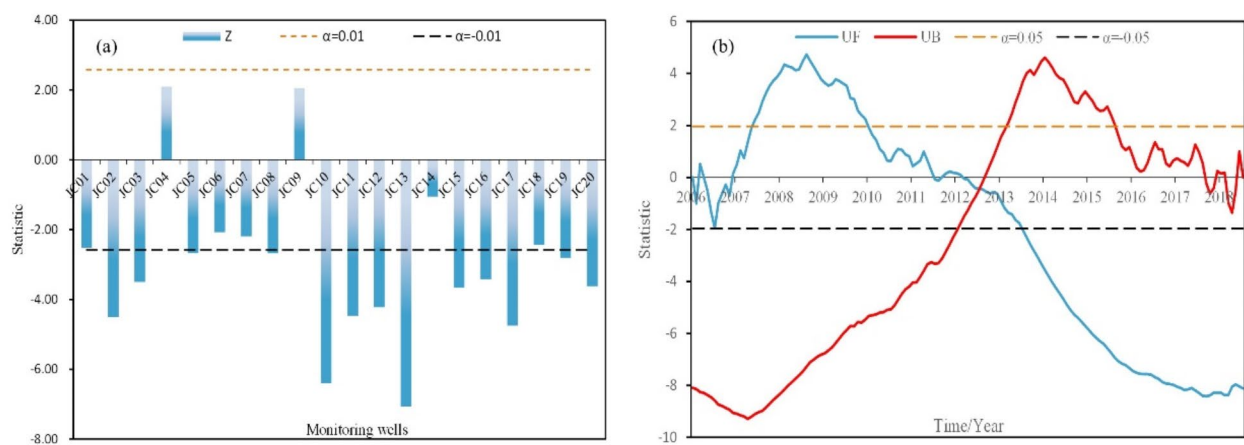
Fig. 4. Research method process diagram.

Fig. 5. M-K trend test chart: (**a**) Statistics *Z* value distribution diagram; (**b**) mutation analysis diagram.

618 mm, and due to the lag effect of precipitation, it is inferred that the sudden change of water level in 2012 is related to the sudden increase of precipitation in the previous year.

Influencing factors of water table
Quantitative factors
Precipitation within the research area peaks from June to September, with notable seasonal variability in rainfall infiltration recharge. Analysis of groundwater table dynamics from 2006 to 2018 indicates an annual water table increase starting in July, driven by concentrated atmospheric rainfall recharge. Subsequently, a decline in water table levels occurs from April to June due to limited rainfall infiltration recharge. Statistical examination of
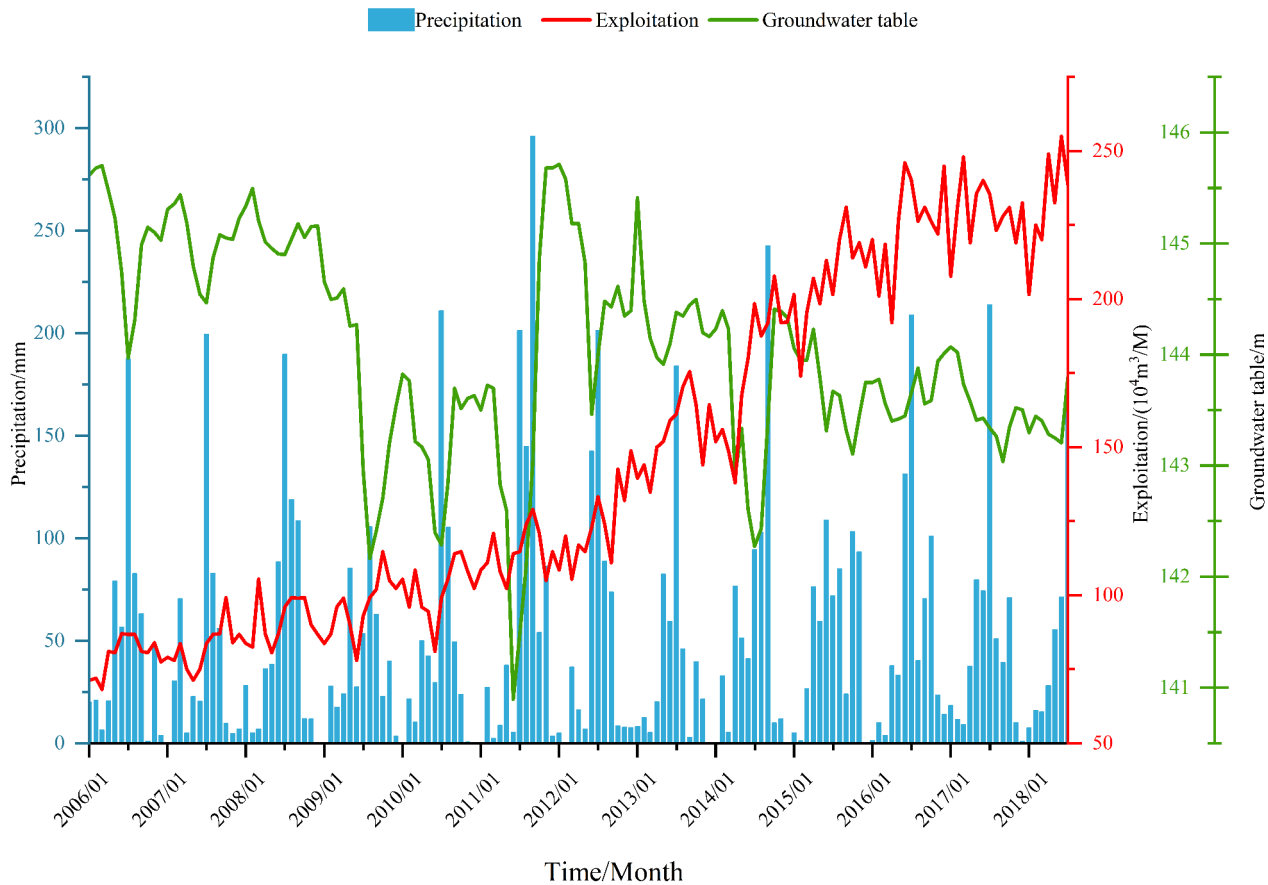
Fig. 6. Changes of water table with rainfall and groundwater exploitation from 2006 to 2018 (JC06).

Monitoring wells	JC07	JC18	JC09	JC11	JC16	JC17	JC19	JC20
Pearson correlation coefficient	− 0.268**	− 0.086	− 0.213**	− 0.207**	− 0.168*	− 0.282**	− 0.275**	− 0.108*

Table 1. Calculation results of correlation coefficient between water table and evaporation. *Indicates that the significance test of 95% confidence is passed. **Indicates that the significance test of 95% confidence is passed.

groundwater levels, water extraction, and evaporation data in the research area reveals a correlation between water table fluctuations and precipitation patterns, albeit with a time lag. This delay is attributed to the time required for precipitation to permeate through the aquifer medium, influencing water table variations subsequently. The delayed response of the water table to precipitation dynamics elucidates the abrupt changes observed in 2011–2012.

Based on the data obtained from the research, visualize the monthly groundwater extraction in the research region from 2006 to 2018 (Fig. 6). It is evident that there has been a consistent increase in groundwater extraction over the 13-year period, nearly tripling during this time frame. The analysis indicates a significant rise in groundwater extraction specifically between 2011 and 2015. Investigation reveals that this surge coincides with the twelfth five-year plan for the national economic and social development of Ji Yuan City, during which extensive efforts were made to diversify agriculture. This suggests a strong correlation between increased groundwater extraction and the city's agricultural development initiatives. Furthermore, groundwater extraction in the study area exceeds precipitation levels in most months, with only a few exceptions where it falls below. The total groundwater extraction during the period from 2006 to 2018 significantly surpasses the total rainfall amount, indicating a prolonged negative balance in groundwater resources in the study area. Consequently, the groundwater table is expected to continue declining as a consequence of this imbalance.

The direct influence of evaporation on porosity is minimal, whereas its impact on permeability is more notable, with permeability generally decreasing as evaporation increases. Furthermore, once the groundwater depth exceeds 4 m, the phenomenon of evaporation ceases to occur. Consequently, this study examines the relationship between the water table levels in monitoring wells with depths less than 4 m and their evapotranspiration. As shown in Table 1, the findings indicated a negative correlation between water table levels and evaporation. The

period of increased evapotranspiration coincided with the rainy season, causing the water table not to decrease despite increased evaporation intensity due to the impact of rainfall.

This paper employs the single-variable method to independently investigate the respective impacts of two influencing factors, namely the permeability coefficient and specific yield, on groundwater levels. The results indicate that with an increase in precipitation, regions with low hydraulic conductivity and high specific yield, like JC02 and JC20, exhibit more consistent changes in groundwater dynamics. A lower hydraulic conductivity implies reduced water flow through the geological formations, leading to slower movement. During water level fluctuations, materials with lower hydraulic conductivity act as a barrier, restricting water movement to deeper or shallower depths, thereby stabilizing the water table. Higher specific yield enhances aquifer water storage capacity, resulting in smaller water table fluctuations during recharge variations.

Qualitative factors

As an essential pathway for the transfer of atmospheric precipitation to surface and groundwater, the lithology of the unsaturated zone has a direct impact on water infiltration capacity. It is categorized into five types as illustrated in Fig. 2.

Comparing water table analyses using a single variable approach revealed that water table fluctuation is more pronounced in JC19 than in JC16. This is attributed to the lithology of the vadose zone at JC19 being Gravel-bearing clayey sand, whereas at JC16 it is Gravel-bearing silty sand. The particle diameter in JC19 is larger than in JC16, resulting in higher permeability due to coarser lithological particles. Greater permeability facilitates faster water flow through the formation, lowers storage capacity, and accelerates groundwater level dynamics.

From 2006 to 2018, the urbanization of Ji Yuan City underwent rapid development. During this period, as indicated in Fig. 6, there was a notable decrease in the area of arable land in Ji Yuan, while there was a significant rise in the area designated for construction purposes. Using JC12 as a case study, the infiltration recharge and relative proportions of various land use categories are illustrated in Fig. 7. The analysis reveals a positive correlation between the water table and the percentage of cultivated land area, and a negative correlation with the proportion of construction area.

The considerable growth in built-up land will impede vertical rainfall penetration for recharge, resulting in decreased rainfall infiltration recharge in the research area. Moreover, as urbanization speeds up, the human demand for groundwater is steadily rising, contributing to a drop in the water table.

Construction and verification of model

Model construction

Based on the analysis provided, this article considers the water table of each monitoring well as the dependent variable 'y', and the influencing factors as the independent variable 'x'. A dynamic prediction model for groundwater table is developed based on the principles of quantitative theory.

According to the principle of quantification theory I, a certain category can be deleted for a certain item in the calculation, so that $\widehat{b}_{jk} = 0$, and other $\widehat{b}_{jk}$ can be solved uniquely. In this way, the normal equation can be solved without losing generality, and the least square method can be satisfied.

According to the research model of Dong Wenquan[31].

$$y_i = \alpha_0 + \sum\nolimits_{j=1}^{m} \sum\nolimits_{k=2}^{r_j} \delta_i(j,k)\,\alpha_{jk} + \varepsilon_i, \ i = 1, 2, .n \tag{1}$$

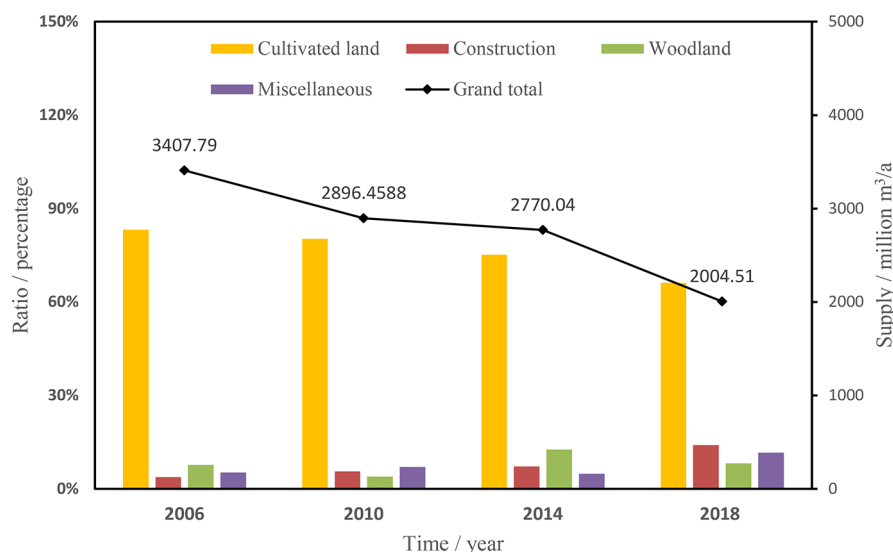Get the relationship between $\widehat{\alpha}$ and $\widehat{b}_{jk}$ as following.

Fig. 7. Infiltration recharge amount of different land use types and its proportion.

Project	React	Game	Project		React	Game
Mining quantity	x_1	− 0.036	Land use type	Building plot	δ (2,1)	− 3.133
Rainfall	x_2	0.029		Famland	δ (2,2)	5.216
Evaporation	x_3	− 0.043		Garden plot	δ (2,3)	2.742
Penetration	x_4	− 0.110		Forest land	δ (2,4)	1.143
Coefficient	x_5	− 0.335	Lithology of unsaturated zone	Gravel-bearing clayey sand	δ (1,1)	2.104
				Clay sand sand pebbles	δ (1,2)	4.291
				Sand gravel	δ (1,3)	17.371
				Medium fine sand	δ (1,4)	13.859
				Silty clay containing gravel	δ (1,5)	1.245

Table 2. The scores of each item based on quantitative theory.

Model	R	R^2	Adjusted R^2	Errors in standard estimates	Change the statistics	
					R^2 alter	Sig.F alter
1	0.889[a]	0.790	0.789	0.114	0.768	0.768

Table 3. Quantitative theoretical calculation results model summary.

$$\begin{cases} b_{11} = \alpha_0 \\ b_{1k} = \alpha_{1k} + b_{11} \\ b_{jk} = \alpha_{jk} \end{cases} \tag{2}$$

Model (1) represents a linear regression model, demonstrating the integration of quantitative theory I and regression analysis. Thus, assigning the first item of each type to 0 is followed by conducting regression analysis using SPSS software. Subsequently, transforming it into quantitative theory yields the scores for each type of purpose, i.e., the coefficients. The scores for each item and category are detailed in Table 2. The scores for each item and category are detailed in Table 2.

According to the scores of different parameters in the table above, a quantitative theoretical model for the dynamic characteristics of the water table in the research area was effectively developed.

$$\begin{aligned} \hat{y} =& 148.483 - 0.036x_1 + 0.029x_2 - 0.043x_3 - 0.110x_4 - 0.335x_5 \\ &+ 2.104\delta(1,1) + 4.291\delta(1,2) + 17.371\delta(1,3) + 13.8596\delta(1,4) \\ &+ 1.245\delta(1,5) - 3.133\delta(2,1) + 5.216\delta(2,2) \\ &+ 2.742\delta(2,3) + 1.143\delta(2,4) \end{aligned} \tag{3}$$

Based on the complete data, this paper has confirmed the existence of a linear relationship between the independent variable and the dependent variable through a single-factor analysis method, which satisfies the assumptions of Quantification Theory I. However, the conversion of qualitative variables into quantitative data may involve subjective judgments or the selection of quantification criteria, potentially affecting the objectivity and accuracy of the model. Therefore, a subsequent model validation process will be conducted to ensure the precision and validity of the model.

Test of significance
Fitting analysis   In this paper, the multiple correlation coefficient (R) is used to characterize the accuracy of the prediction model. The calculation formula is as follows.

$$R = \sqrt{\frac{S_R}{S_T}} = \sqrt{\frac{\sum_{i=1}^{n}\left(\hat{y} - \bar{y}\right)^2}{\sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}} \tag{4}$$

The results of the calculations (Tables 3, 4) demonstrate that the multiple correlation coefficient $R = 0.889 > 0.8$ for the developed model, suggesting a strong linear relationship between the baseline variables and the different categories of the model established through quantification theory I. R^2 represents the multiple correlation coefficients, providing insights into the explanatory variables' interpretation and the model's goodness of fit. The adjusted R^2 is 0.789, signifying that the constructed model can account for 78.9% of the benchmark variables.

Model	ANOVAª				
	Sum of squares	Degree of freedom	Mean square	F	Significance
Return	123.055	12	10	794.805	0.000ᵇ
Residuals	37.248	2887	0.013		
Total	160.303	2899			

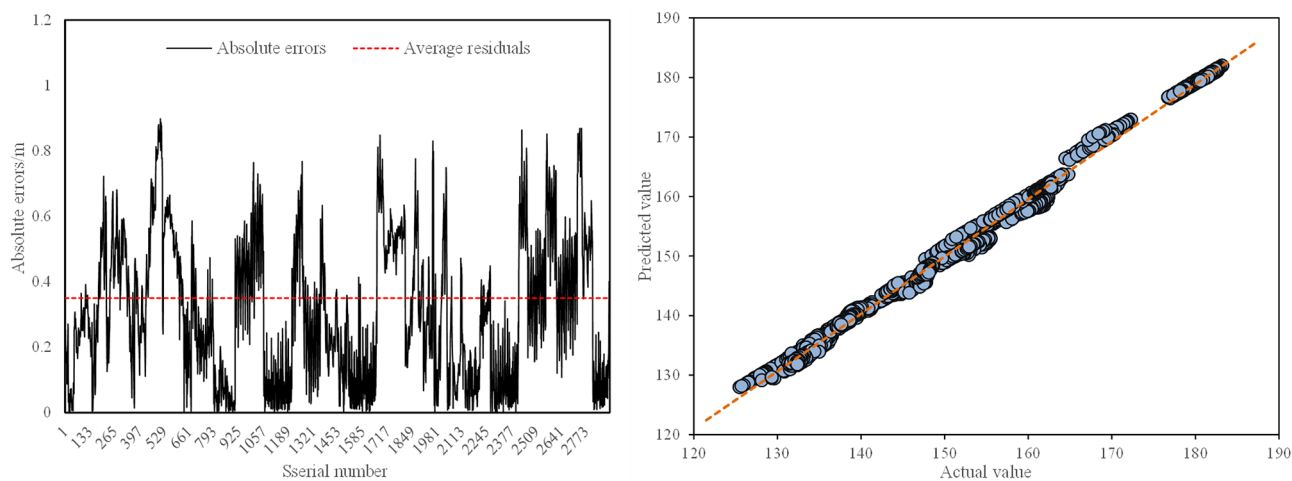**Table 4**. Summary table of regression analysis. ªPredictor. ᵇDependent variable.

Fig. 8. Residual analysis chart: (**a**) Scatter plot of predicted value and actual value. (**b**) Residual absolute value distribution map.

Residual analysis   Based on the deviation between the forecasted value and the computed actual value from the model, residual analysis is conducted followed by plotting a scatter graph of the predicted value against the actual value.

As shown in Fig. 8a, the points are distributed near the y=x curve, that is, the actual value is close to the predicted value, indicating that the prediction effect of the model is better. The absolute value distribution of residuals is shown in Fig. 8b. The maximum absolute value of residuals is 0.90 m, the minimum is 0 m, and the average is 0.35 m. The error is within the allowable error range, indicating that the prediction effect of the model is good.

Model validation
This paper selects data representing wells in different types to plot the predicted and actual values of water table.

Rainfall infiltration–evaporation type   The recharge source of this type of groundwater is rainfall infiltration, and evaporation serves as its primary discharge mechanism. As depicted in Fig. 9a, the predicted groundwater level ranges from a maximum of 161.77 m to a minimum of 157.29 m, with a forecasted fluctuation range of 4.48 m, while the actual water level fluctuation spans 5.02 m. Predicted values are overall lower than actual values. A residual analysis was conducted between the predicted and actual groundwater levels, yielding an average residual of 0.49 m. From 2006 to 2009, the predictive accuracy of the model was relatively low. Upon conducting the Mann-Kendall (M-K) test for abrupt changes, it was identified that a significant shift occurred in the JC12 water level around 2008, which likely contributed to the suboptimal dynamic simulation performance before and after this year. In contrast, the simulation showed improved results from 2009 to 2018.

Rainfall infiltration–extraction type   The recharge source of this type is rainfall infiltration, and artificial extraction constitutes its primary mode of discharge. As depicted in Fig. 9b, the predicted groundwater level in this region ranges from a maximum of 172.76 m to a minimum of 165.84 m, indicating a predicted fluctuation range of 6.92 m, the actual water level fluctuation spans 7.86 m. Predicted values are generally higher than actual values. A residual analysis conducted on the predicted and actual values reveals an average residual of 0.6 m. Notably, larger residuals are observed in 2010 and 2011. Utilizing the Mann-Kendall (M-K) test for abrupt changes, it is evident that an abrupt change in the water level of JC13 occurred around 2010, thereby accounting for the relatively poor simulation performance during this period. In other years, the simulation outcomes exhibit satisfactory accuracy.

Rainfall infiltration-runoff type   The recharge source for this type of aquifer is rainfall infiltration, with discharge occurring primarily through runoff. As illustrated in Fig. 9c, the predicted groundwater level for this type
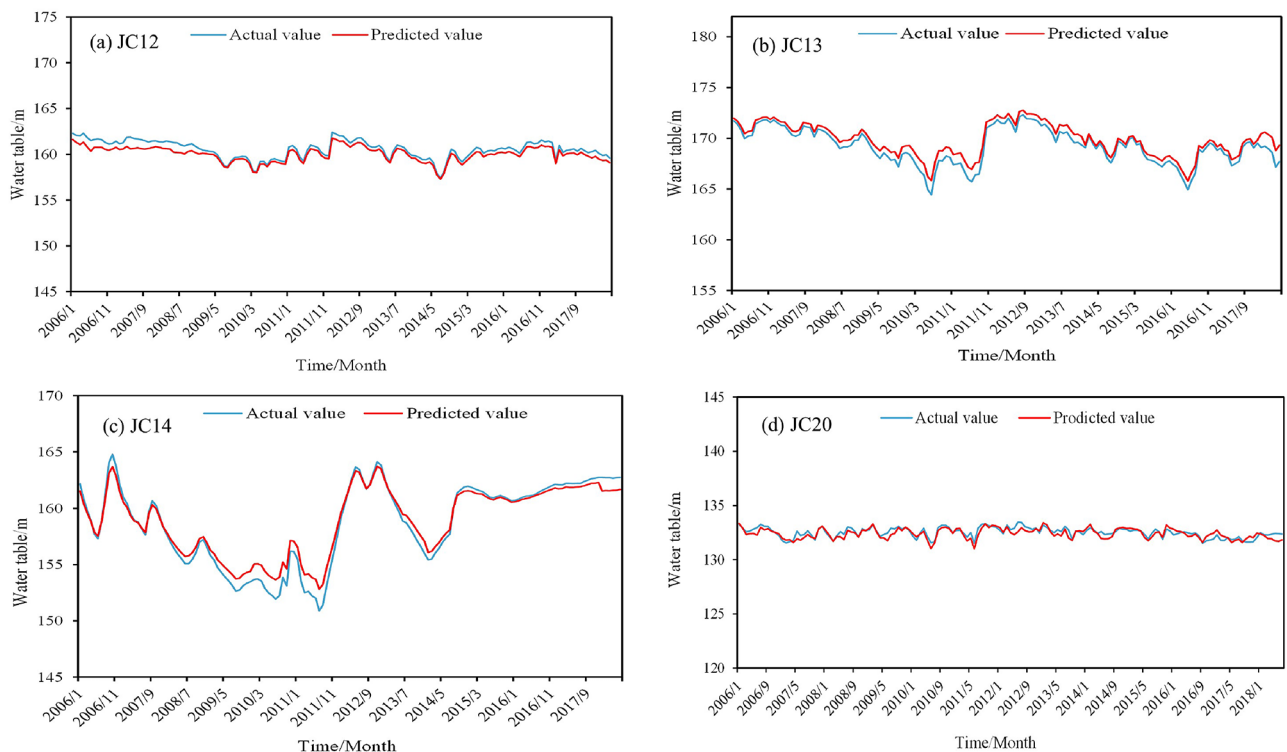
Fig. 9. Comparison of simulated water table and actual water table of different dynamic types: (**a**) Rainfall infiltration-evaporation type. (**b**) Rainfall infiltration-mining type. (**c**) Rainfall infiltration-runoff type. (**d**) Rainfall infiltration-mining-evaporation type.

ranges from a maximum of 163.71 m to a minimum of 152.82 m, resulting in a forecasted fluctuation range of 10.89 m, whereas the actual water level fluctuates within a range of 13.89 m. A residual analysis was performed on the predicted and actual groundwater levels, yielding an average residual of 0.23 m. Except for the period from 2009 to 2011, the predictive performance was satisfactory during other time frames. The Mann-Kendall (M-K) test for abrupt changes revealed a significant shift in JC14 in 2011, indicating a substantial anthropogenic influence on the water level. Consequently, the accuracy of water level predictions was compromised during these three years.

Rainfall infiltration–extraction–evaporation type   The primary recharge source for this type of groundwater is rainfall infiltration, while artificial extraction and evaporation constitute its primary discharge mechanisms. As depicted in Fig. 9d, the predicted groundwater level for this type varies from a maximum of 133.12 m to a minimum of 131.31 m, resulting in a forecasted fluctuation range of 1.81 m, while the actual water level fluctuates within a range of 1.95 m. A residual analysis comparing the predicted and actual groundwater levels yields an average residual of 0.1 m, indicating a satisfactory dynamic simulation performance for this type of water level. This model effectively reproduces the dynamic behavior of the groundwater level for this particular type.

In general, the groundwater table in the Ji Yuan Basin experienced a significant decline from 2006 to 2015. Following 2015, a decrease in groundwater exploitation due to local policy changes led to a gradual recovery of the water table in certain areas. However, there are still regions where the groundwater table continues to decline. Moreover, there was a notable spike in the groundwater table in the region from 2011 to 2012, which was linked to the unusual precipitation in the Ji Yuan Basin during 2011, resulting from the delayed effect of the rainfall. However, according to previous research data, the precipitation in Jiyuan Basin in 2012 was approximately 868 mm, with the frequency of such a significant rainfall event occurring at roughly 1.52%. This would lead to a temporary recovery of the regional groundwater level after the heavy rainfall event. Over time, the influence on the groundwater level gradually diminishes until it disappears. Consequently, such events have limited impact on the sustainability of groundwater. During the period between 2011 and 2015, the groundwater table in the district generally exhibited a sharp decrease, primarily due to the introduction of new agricultural practices and extensive groundwater extraction.

In terms of the simulation results, the average residuals for the four types of water table dynamic simulations, namely precipitation infiltration-evaporation, precipitation infiltration-mining, precipitation infiltration-runoff, and precipitation infiltration-mining-evaporation, were 0.49 m, 0.60 m, 0.23 m, and 0.1 m, respectively. It is evident that this model performs the best in dynamically simulating the water table of precipitation infiltration-mining-evaporation, while the overall performance in the dynamic simulation of the water table for the other three types is better. However, significant errors occur in individual years, particularly during periods of sudden

changes in the water table. The simulation accuracy is higher during stable water table conditions, indicating that sudden changes in the water table significantly impact the model's simulation effectiveness.

Conclusion

(1) The research indicates a decreasing trend in the groundwater level in the Ji Yuan Basin, with a drastic shift observed in 2011–2012. The primary factors influencing this decline are the persistent rise in groundwater extraction. The sudden variation in the water level can be attributed mainly to the delayed impact of precipitation.

(2) It was discovered that the persistent transformation of vast tracts of cultivable land into urban areas is impeding the vertical infiltration replenishment of groundwater in the research area, and diminishing rainfall infiltration replenishment in the vicinity. The ongoing growth of urban developments by human populations has escalated the extraction of groundwater. Ultimately, this trend will result in groundwater replenishment being surpassed by extraction in the study site, leading to a decline in the water Table .

(3) The study determined that the model excelled in replicating water table fluctuations in scenarios involving rainfall infiltration, mining, and evaporation. However, when it comes to rainfall infiltration and exploitation, as well as rainfall infiltration and mining situations, significant discrepancies were observed during years with abrupt water table changes. Nonetheless, the model performed accurately during stable periods. This study underscores how sudden water table variations can impact the model's precision.

(4) The findings of the residual analysis of the model indicate that the model can effectively forecast the dynamic properties of water tables, and the quantitative theory I principle serves as a useful theoretical framework for assessing alterations in groundwater dynamics.

The current study, while yielding the aforementioned conclusions, acknowledges that the dynamic changes in groundwater levels are exceedingly complex. Furthermore, due to the incompleteness of certain data, there are numerous shortcomings that necessitate improvements through future research endeavors.

(1) Limited by the availability of data and the duration of the study, the comprehensive impact factors influencing the dynamic changes in groundwater levels were not fully considered. Consequently, the quantitative theoretical model constructed herein exhibits relatively low precision and requires further enhancement to achieve higher accuracy.

(2) As the urbanization process in Jiyuan City progresses rapidly, the groundwater levels are increasingly subject to a wider range and greater intensity of anthropogenic influences. Therefore, comprehensive, systematic, and scientific research methodologies are imperative for analyzing the dynamic characteristics of these changes. To achieve sustainable and high-quality development in Jiyuan, it is essential to adhere to objective natural laws and manage water resources scientifically and rationally.

Data availability

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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YZ W: Conceptualization, Methodology, Validation; XL W: Data curation, Formal analysis, Validation, Software; DX Z: Writing — original draft; YZ W & Y L: Writing — review & editing.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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