

**Managed aquifer recharge and ~~exploitation~~ extraction impacts on dynamics of groundwater level and quality dynamics in a typical temperate semi-arid fissured karst system
~~northern China karst area: A multi-method quantitative study~~
~~Quantitative research by multi-methods~~**

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Abstract

Managed Aquifer Recharge (MAR) is an effective approach to mitigate groundwater decline and spring depletion in karst systems impacted by excessive exploitation. However, the hydrogeological complexity of karst aquifers makes groundwater quantity and quality highly sensitive to human activities, posing challenges for MAR implementation. This study develops an integrated multi-method framework—combining isotopic analysis, flow monitoring, tracer tests, and numerical modeling—to

evaluate the effects of MAR and groundwater extraction on karst aquifer dynamics, with a case study in the Baotu Spring system (Jinan, China). To enhance the accuracy of recharge rate quantification, an enhanced isotope mixing model that reduces uncertainties in estimating groundwater recharge ratios from multiple sources was developed, and the MAR rate settings were refined by establishing a quantitative relationship between effective MAR rates and water release rates through river flow monitoring. To improve the solute transport simulations reliability, we conducted field tracer tests to constrain the effective porosity of the karst aquifer - a parameter typically poorly constrained in such systems. Furthermore, we validated the applicability of the equivalent porous media (EPM) model through rigorous hydrodynamic analysis, using field-measured fracture apertures to calculate Reynolds numbers and verify laminar flow conditions. The results demonstrate that surface water contributes >80% of recharge near MAR implementation zones, with MAR efficiency decreasing beyond critical river discharge thresholds. The karst aquifer exhibits laminar flow (effective porosity = 1.08×10^{-4}), confirming the validity of the EPM approach. Modeling reveals that MAR significantly raises water tables, though efficiency varies by different MAR sources, and MAR-induced sulfate concentrations must be maintained below 56.5, 197.8, and 339.1 mg/L to meet China's Class I, II, and III groundwater standards, respectively. These findings provide practical guidelines for MAR implementation in temperate semi-arid fissured karst systems.

Managed aquifer recharge (MAR) is an effective way to counter groundwater level decline and spring depletion caused by excessive groundwater exploitation in karst areas. However, the unique characteristics of karst groundwater systems make the groundwater quantity and quality more susceptible to human activities, posing challenges for MAR research. This research employed multi-methods including numerical simulations, isotope analysis, infiltration tests, flow monitoring and tracer tests to

quantitatively analyze the impacts of MAR and groundwater exploitation on the dynamics of groundwater level and quality in a typical northern China karst area, the Baotu Spring area in Jinan City. First, the percentage of surface water recharge in karst groundwater was calculated using isotope data with the improved two-end-member mixing model. Next, the quantitative relationship between volume of released water and actual recharge was established with data from infiltration tests and flow monitoring. Then, the actual groundwater flow velocity and effective porosity of the karst aquifers were calculated with former tracer test isochrone maps. Finally, the impacts of MAR and groundwater exploitation on dynamics of groundwater level and quality were quantitatively analyzed with a groundwater flow-solute transport model for the area. The results indicate that the MAR and groundwater exploitation in the Baotu Spring area have significantly impacted karst groundwater levels and quality. These complementary methods enhance the accuracy of decisions in MAR and groundwater exploitation.

Keywords: Managed aquifer recharge (MAR); Temperate semi-arid regionKarst groundwater; Fissured karstQuantitative analysis; Multi-methods.

1. Introduction

Managed aquifer recharge (MAR) (Sherif et al., 2023), refers to the intentional recharge of aquifers to address the ecological and environmental geological issues caused by excessive groundwater exploitation (Aeschbach-Hertig & Gleeson, 2012; Foley et al., 2011). It has been demonstrated that appropriate recharge can effectively elevate groundwater levels and improve groundwater quality to some extent (Ajur & Baalousha, 2021; Alam et al., 2021; Standen et al., 2020).

Karst groundwater constitutes a vital water resource (Hartmann et al., 2014; Medici et al., 2021), with managed aquifer recharge (MAR) in karst systems emerging as a key research focus (Zhang & Wang, 2021). Unlike pore water, karst groundwater is stored in dissolution conduits and fissures,

exhibiting high heterogeneity, rapid flow velocities, and concentrated discharge. These properties increase the susceptibility of karst aquifers to anthropogenic impacts on both quantity and quality (Allocca et al., 2014; Lorenzi et al., 2024), complicating MAR implementation. The extreme heterogeneity of karst systems results in spatially variable MAR effectiveness (Daher et al., 2011), with recharge impacts on groundwater levels and quality differing by water source. Rapid flow dynamics (Bakalowicz, 2005) lead to extensive well catchment areas, where over-exploitation can induce large-scale drawdown cones and associated geological risks (Jiang et al., 2019). Furthermore, MAR using contaminated source water may accelerate pollutant transport (H. Cao et al., 2023), jeopardizing groundwater quality (Xanke et al., 2017). Thus, quantitative assessment of MAR and extraction effects on karst groundwater is critical for ensuring sustainable and safe aquifer management.

Karst groundwater is a crucial component of water resources (Hartmann et al., 2014; Medici et al., 2021). The research of MAR in karst areas has become a prominent focus in recent years (Zhang & Wang, 2021). However, the unique characteristics of karst groundwater systems make the groundwater quantity and quality more susceptible to human activities (Allocca et al., 2014; Lorenzi et al., 2024), posing challenges for MAR research. Due to the highly heterogeneous nature of karst development, the actual effectiveness of MAR varies significantly across different locations (Daher et al., 2011). The impact of recharge on the karst groundwater level and quality at different locations and using various water sources shows significant variation. Additionally, the fast karst groundwater flow (Bakalowicz, 2005) leads to extensive catchment areas for karst groundwater exploitation wells, and over-exploitation would create large-scale groundwater level drawdown cones, causing secondary geological hazards (Jiang et al., 2019). Moreover, if poor-quality source water were used for MAR, pollutants would quickly spread downstream (H. Cao et al., 2023), severely threatening the quality of karst groundwater (Xanke

et al., 2017). Therefore, quantitatively assessing the effects of MAR and groundwater exploitation on the quantity and quality of karst groundwater will facilitate stable, efficient, and safe aquifer recharge and groundwater exploitation.

From a global perspective, significant differences exist in karst development and groundwater flow characteristics among different countries and regions. The Baotu Spring karst aquifer in Jinan, China, representing the fissured karst system in the temperate semi-arid region, exhibits remarkable hydrogeological representativeness worldwide (Liang et al., 2018). In these areas, karst aquifers typically develop in Cambrian-Ordovician carbonate formations, with their hydrogeological features being strongly controlled by geological structures. The primary aquifer medium consists of karst fissures formed by well-developed tectonic fissures, ultimately giving rise to a groundwater system dominated by an extensive network of karst fissures (Aliouache & Jourde, 2024; Jiang et al., 2022). In temperate semi-arid regions, the persistent development of dissolution is constrained by the low permeability of soluble rocks (dominated by fracture flow) and limited hydrothermal conditions, resulting in the prolonged stagnation of underground karst systems at the fracture network stage and hindering their evolution into large-scale cave or conduit systems. Moreover, such regions often feature large karst springs as concentrated discharge points of groundwater (Criss, 2010). Due to seasonal recharge fluctuations (primarily from precipitation) (Bhering et al., 2021), these springs exhibit significant discharge variations. Therefore, scientifically adjusting recharge strategies based on precipitation variability to maintain spring flow constitutes a key research issue.

In China, temperate semi-arid fissured karst groundwater systems similar to the Baotu Spring are predominantly distributed across several northern provinces, including Shandong (Liu et al., 2021), Shanxi (Zhang et al., 2018), Hebei (M. Gao et al., 2023), Henan (Yin et al., 2023) and Shaanxi (Li et al.,

2020). Globally, systems exhibiting varying degrees of similarity can be observed in certain regions, notably in the U.K (Agbotui et al., 2020), France (Ballesteros et al., 2020), Germany (Knöll & Scheytt, 2017), Italy (Pagnozzi et al., 2020), the U.S (Criss, 2010) and Canada (Perrin et al., 2011). These regions all face similar challenges related to seasonal drought and karst groundwater pollution. The research on karst groundwater at Baotu Spring and its artificial recharge practices can provide valuable insights for these areas.

Existing research on the effects of managed aquifer recharge (MAR) and extraction on groundwater level and quality has established relatively mature methodologies (Ringleb et al., 2016). However, most approaches remain qualitative or semi-quantitative. Hydrogeochemical and isotopic techniques are widely employed in MAR studies (Akurugu et al., 2022; M. Li et al., 2023). Isotopic tracers are frequently used to identify recharge sources, and the integration of multiple hydrochemical and isotopic indicators (Guo et al., 2019) allows estimation of source contributions (Deng et al., 2022). Nevertheless, this method faces challenges, including the inherent non-uniqueness of solutions and uncertainty in determining precise isotopic signatures for individual recharge source, which may compromise accuracy. Additionally, the scarcity of long-term isotopic monitoring data restricts the applicability of this approach for analyzing temporal variations in MAR effects.

There are some relatively mature research methods regarding the effects of MAR and groundwater exploitation on groundwater level and quality (Ringleb et al., 2016). However, most of these methods are either qualitative or semi-quantitative. Hydrogeochemical and isotope methods are commonly used in MAR studies (Akurugu et al., 2022; M. Li et al., 2023). By monitoring the changes in groundwater quality before and after the recharge, the impact of MAR on groundwater quality can be qualitatively analyzed. A primary issue with hydrogeochemical analysis is that its conclusions may be ambiguous, as

potential unknown sources of groundwater contamination could interfere with the results. In addition, isotopes in groundwater are often used to identify recharge sources. By combining multiple hydrochemical and isotopic indicators (Guo et al., 2019), the proportion of various recharge sources contributing to groundwater can be estimated (Deng et al., 2022). However, in many cases, due to the inability to accurately determine the isotopic values for each recharge source, this method can only provide a rough estimate. Furthermore, due to the typical lack of long-term monitoring data on groundwater isotopes, this approach is unsuitable for studying the dynamics in the effects of MAR on groundwater.

Numerical simulation serves as an effective method for MAR quantitative analysis (Medici et al., 2021; Ostad-Ali-Askari & Shayannejad, 2021; Zafarmomen et al., 2024). The selection of simulation programs depends on karst aquifer characteristics. While conduit flow process (CFP) models are suitable for well-developed karst systems (Chang et al., 2015), their application is constrained by the requirement for detailed conduit dimension data, particularly in regional-scale modeling (Jourde & Wang, 2023). Numerical simulation is a powerful tool for quantitative research of MAR (Medici et al., 2021; Ostad-Ali-Askari & Shayannejad, 2021; Zafarmomen et al., 2024). Previous studies have demonstrated the feasibility of employing a simplified equivalent porous medium (EPM) model without embedded karst conduits for regional groundwater numerical simulations in temperate semi-arid fissured karst systems with limited karst development (Kang et al., 2011; Luo et al., 2020; Scanlon et al., 2003). However, these studies often lack field investigations to verify whether groundwater flow regimes satisfy the laminar flow assumption inherent to EPM models (Agbotui et al., 2020; Medici et al., 2024). The Equivalent Porous Medium (EPM) model, represented by MODFLOW, is suitable for simulating laminar groundwater flow that adheres to Darcy's law (Jourde & Wang, 2023; Ringleb et al., 2016). In karst

regions with low development, such as the karst areas in northern China, groundwater flow is predominantly laminar, largely complying with Darcy's law. Therefore, the EPM model without inserting karst conduits embedded is well-suited for application in these regions.

When conducting MAR studies using numerical simulation methods, accurately determining the actual groundwater recharge rate is a crucial condition for ensuring the accuracy of the simulation results. In the studies of MAR primarily driven by riverbed infiltration, methods such as riverbed infiltration tests and river flow monitoring can be employed. By applying the principles of groundwater dynamics and water balance, the actual surface water recharge to groundwater can be quantitatively calculated.

Studies indicate that accurate estimation of effective porosity in karst aquifers is critical when simulating solute transport using the equivalent porous medium (EPM) model (Kidmose et al., 2023; Ren et al., 2018). Overestimation of effective porosity often leads to underestimated groundwater flow velocities, introducing significant errors in pollution control strategies (Medici & West, 2021; Medici et al., 2019). To improve EPM model reliability, effective porosity should be derived from regional-scale hydraulic tests (e.g., tracer test) (Medici & West, 2021; Worthington et al., 2019; Zhu et al., 2020).

Similarly, in MAR studies using numerical simulations, precise determination of groundwater recharge rates is essential for result accuracy (Hartmann et al., 2015). For MAR driven by riverbed infiltration, methods such as infiltration tests (Xi et al., 2015) and riverflow monitoring can quantify recharge rates via hydrodynamics and water-balance principles. Cross-validation of these methods in field studies reduces uncertainty from data limitations, enhancing MAR-related quantitative assessments (Mudarra et al., 2019). Furthermore, it has been indicated that when using the EPM model for simulating solute transport in karst groundwater, properly estimating the effective porosity of karst aquifers is critically important (Kidmose et al., 2023; Ren et al., 2018). Overestimating the effective porosity often

results in a severe underestimation of the actual groundwater velocity, leading to significant errors in karst groundwater pollution control measures (Medici & West, 2021; Medici et al., 2019). Therefore, to ensure the effective application of the EPM model in groundwater solute transport simulating, it is advisable to consider estimating the effective porosity of the karst aquifer medium using the actual groundwater flow velocity calculated from tracer tests (Medici & West, 2021; Worthington et al., 2019; Zhu et al., 2020)(Hartmann et al., 2015)(Xi et al., 2015). In MAR studies conducted in actual regions, the results of various methods mentioned above can be cross-validated to reduce the uncertainty caused by data scarcity or insufficient investigation, thereby improving the accuracy of quantitative research related to MAR (Mudarra et al., 2019).

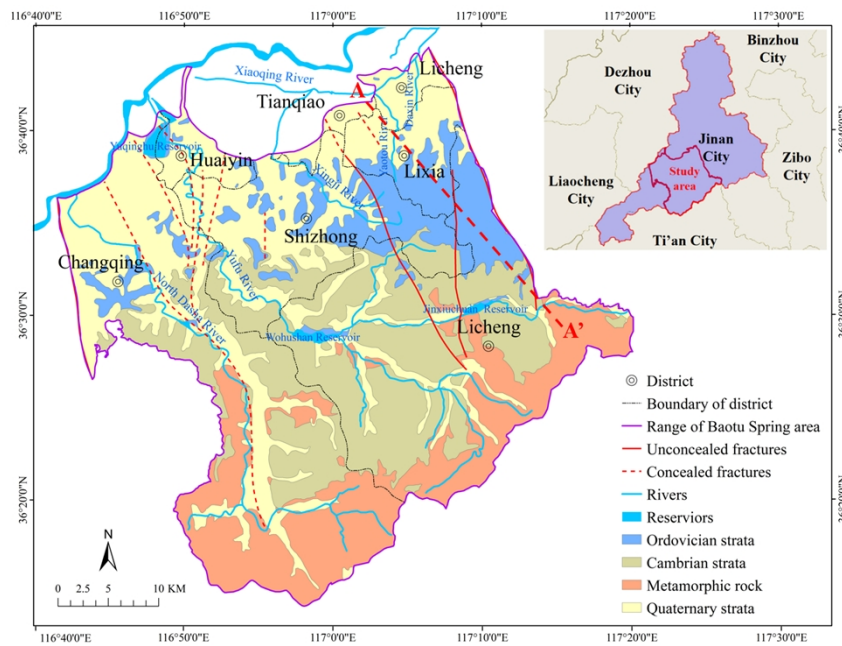
The Baotu Spring area in Jinan City is a typical representative of the karst areas in northern China (Liang et al., 2018), with karst groundwater serving as one of the crucial water supply sources. In the past decades, the increasing demand for water resources in Jinan has led to excessive groundwater exploitation, causing a decline in groundwater levels and the drying up of springs. In order to balance the needs of water supply and spring protection, Jinan City has implemented the project of MAR using the diverted water from the Yellow River (Kang et al., 2011) and the Yangtze River from the South to North Water Transfer Project in recent years. Studies have shown that there is a close hydraulic connection between surface water and karst groundwater in certain of the Yufu River and Xingji River, making them ideal sites for implementing the MAR project (J. Li et al., 2023). However, when the flow of Yufu River is excessively high, a portion of the flow downstream cannot recharge the karst groundwater. Moreover, the concentration of some hydrochemical components in the diverted water may be higher than those of the local karst groundwater—and thus long-term use of lower-quality water for recharge may lead to continuous deterioration of karst groundwater quality.

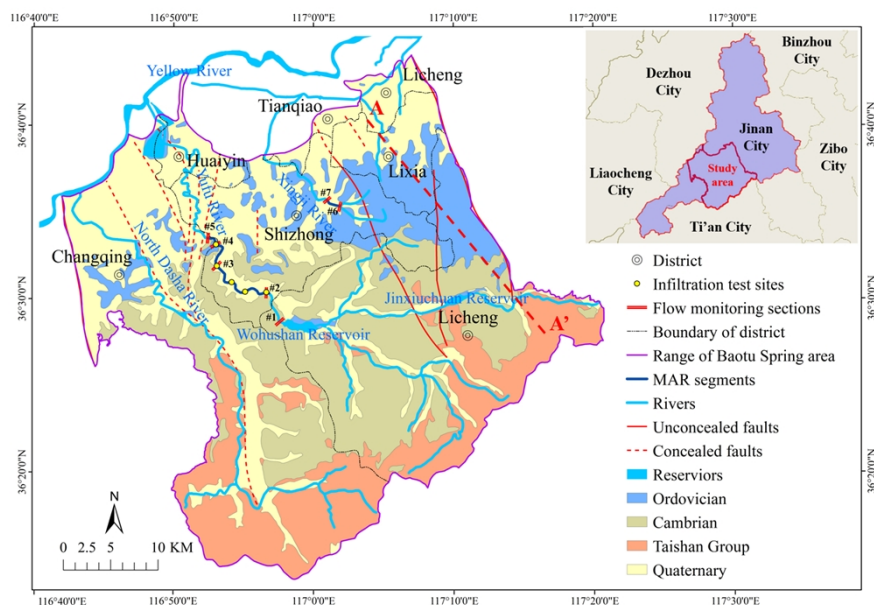
This study proposes an integrated multi-method analytical approach to quantitatively assess the effects of managed aquifer recharge (MAR) and extraction on groundwater levels and quality in temperate semi-arid fractured karst systems. The approach combines coupled numerical modeling of groundwater flow and solute transport with supplementary techniques—isotope analysis, infiltration tests, flow monitoring, and tracer tests—to improve simulation accuracy. Using Jinan’s Baotu Spring karst aquifer as a case study, we evaluate how MAR and extraction influence karst groundwater dynamics, aiming to ensure stable regional water levels, long-term water quality security, and sustainable groundwater resource utilization. Therefore, to ensure the stability of the karst groundwater level and the long-term safety of water quality, and to guarantee the sustainable exploitation of groundwater resources, the purpose of this research is to quantitatively analyze the impacts of MAR and groundwater exploitation on the dynamics of karst groundwater level and quality in the Baotu Spring area of Jinan City by multi-methods. The method employed in this study primarily focuses on the numerical simulation of coupled groundwater flow and solute transport. Complementary techniques such as isotope analysis, infiltration tests, flow monitoring, and tracer tests are also utilized to enhance the accuracy of the numerical simulations. The specific objectives of this research are as follow: (1) To determine the sources of groundwater recharge and quantify the mixing ratios and spatial distribution of recharge using multi-source data. (2) To quantify the effective infiltration recharge of the MAR segments under varying water release rates for groundwater flow modeling inputs. (3) To estimate the effective porosity of aquifers as a key parameter for groundwater solute transport modeling. (4) To establish a groundwater flow-solute transport model for the study area based on the validated the EPM model’s applicability, and to quantitatively evaluate the impacts of MAR and extraction on groundwater level and quality dynamics.

2. Material and Methods

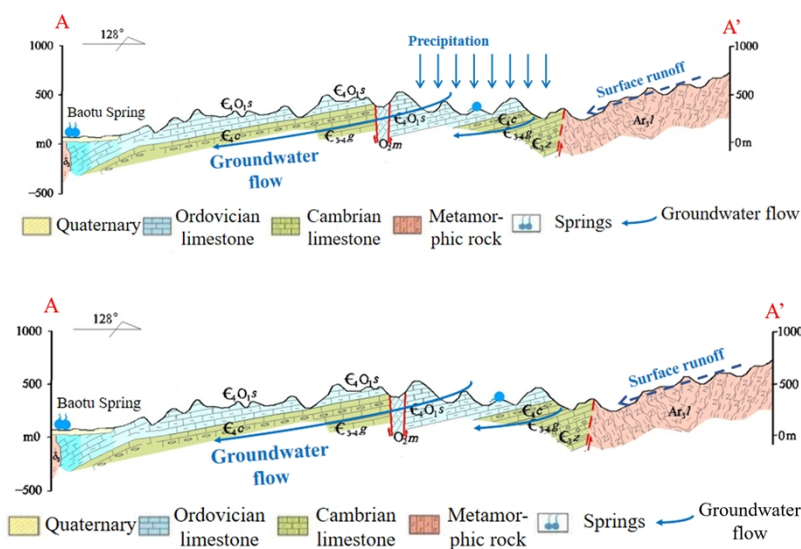
224 2.1. Study area

225 The study area of this paper is the Baotu Spring area, located in Jinan City, Shandong Province,
226 China, covering about 1,654 km² (Niu et al., 2021) (Fig. 1). The terrain of Baotu Spring area is higher in
227 the south and lower in the north, ~~featuring with~~ rolling steep mountains and deep canyons in the south,
228 low mountains and hills in the middle, and Piedmont inclined plains and alluvial plains in the north.
229 The Baotu Spring area is located in the mid-latitude inland area with a warm temperate continental
230 climate. The average annual precipitation from 1951 to 2024 is 690.4 mm, mostly falling between June
231 and September (accounting for 77% of the total), ~~and southern mountainous areas receive more~~
232 ~~precipitation than northern plains.~~





(a) Geological map



(b) Hydrogeological cross-section profile

Fig.1 Geological map and hydrogeological cross-section profile of Baotu Spring area

The main rivers in this region are the Yellow River, Yufu River, Xingji River, and North Dasha

River (Fig. 1). The Yellow River forms the study area's northwestern boundary and is mainly used for agricultural irrigation and groundwater recharge. The Yufu River is a seasonal tributary of the Yellow River, and the segments between Zhaiertou and Cuima Villages has excellent permeability, making it an ideal river for MAR (Guo et al., 2019) (Fig. 5(b)). Additionally, the Xingji River in the northeast, though small, also has a permeable riverbed making it suitable for MAR (Fig. 5(b)).

Geologically, the study area is characterized by a northward-dipping monocline predominantly composed of Paleozoic carbonate rock layers. Several large-scale NNW-trending faults are developed within this area. Except for the Dongwu Fault and Mashan Fault forming the eastern and western boundaries of the study area, respectively, the other faults are generally permeable. The stratigraphic units exposed in the study area from south to north, listed from oldest to youngest, are as follows: Archaean Taishan Group metamorphic rocks, Cambrian limestone, Ordovician limestone, and Quaternary loose sediments (Fig. 1).

~~The~~ Exploitable karst groundwater is stored in the Zhangxia Formation of the middle Cambrian, the Chaomidian Formation of the upper Cambrian, and the Majiagou Formation of the Ordovician. In the northern mountainous and hilly areas, karst groundwater is recharged by precipitation and surface water, flowing northward along strata dips (Zhu et al., 2020). In the northern piedmont alluvial plain, the karst aquifer is buried under Quaternary sediments. ~~Late Mesozoic~~ Large gabbro intrusions ~~from the late Mesozoic~~ block the northward flow, causing the water to rise along ~~fracture~~ fissures and form springs (Niu et al., 2021; Wang et al., 2022), with Baotu Spring being the most popular of them (Guo et al., 2019).

The Baotu Spring area in Jinan City is a typical representative of the karst areas in northern China (Liang et al., 2018), with karst groundwater serving as one of the crucial water supply sources. In the

~~past decades, the increasing demand for water resources in Jinan has led to excessive groundwater~~
~~exploitation, causing a decline in groundwater levels and the drying up of springs~~As a crucial water
supply source for Jinan, decades of increasing demand for groundwater have led to over-exploitation,
causing water level decline and spring drying (S. Gao et al., 2023). ~~In order to balance the needs of~~
water supply and spring protection, Jinan City has implemented the project of MAR projects using the
diverted water from the Yellow River (Kang et al., 2011) and the Yangtze River from the South-to-North
Water Transfer Project (Liu et al., 2020) in recent years. Studies have shown that there is a close hydraulic
connection between surface water and karst groundwater in certain segments of the Yufu River and
Xingji River, making them ideal sites for implementing the MAR project (J. Li et al., 2023). Most MAR
occurs along segments of the Yufu and Xingji Rivers, with minor MAR through dedicated wells in urban
areas (which are no longer used for extraction) (Wang et al., 2017). Notably, excessive flow in the Yufu
River may bypass recharge zones, and some diverted water components (e.g., hydrochemical
concentrations) may exceed local karst groundwater standards (X. Cao et al., 2023; J. Li et al., 2023;
Zheng et al., 2020), posing risks of long-term quality deterioration (J. Li et al., 2023; Zhang & Wang,
2021). Currently, few groundwater exploiting wells remain active, categorized into three groups by
location: western suburbs, western Jinan, and eastern suburbs wells. All exploiting wells, MAR wells,
and MAR river segments are mapped in Fig. 5(b).~~However, when the flow of Yufu River is excessively~~
~~high, a portion of the flow downstream and cannot recharge the karst groundwater. Moreover, the~~
~~concentration of some hydrochemical components in the diverted water may be higher than those of the~~
~~local karst groundwater, and thus long-term use of lower-quality water for recharge may lead to~~
~~continuous deterioration of karst groundwater quality.~~ In addition, only few of the groundwater
exploiting wells in the study area are still under exploitation, which could be categorized into three

groups (western suburbs wells, western Jinan wells and eastern suburbs wells) based on the locations. Most of the MAR in the study area is conducted along certain river segments of the Yufu River and Xingji River, while a small portion of the MAR is carried out through specific wells in the urban area (which are no longer used for exploitation and are now solely dedicated to MAR) (Wang et al., 2017). The locations of all these exploiting wells, MAR wells, and MAR river segments are marked in Fig. 6(b).

2.2. Groundwater sampling and recharge percentage quantification analysis

In the study area, surface water is the primary source of MAR. ~~In order to~~ To understand the current water quality status of karst groundwater and surface water in the study area, identifying the hydrochemical components in surface water that may influence groundwater quality, estimate the percentage contribution of surface water and precipitation recharge to karst groundwater, and ~~to provide~~ a basis for the groundwater flow and solute transport model setup, sampling and analysis of groundwater and surface water in the study area were conducted in June 2022. The analyzed indicators included total dissolved solids (TDS), sulphate concentration, nitrate concentration, chloride concentration, $\delta^2\text{H}\%$, and $\delta^{18}\text{O}\%$. The locations of the sampling points are shown in Fig. 5(b).

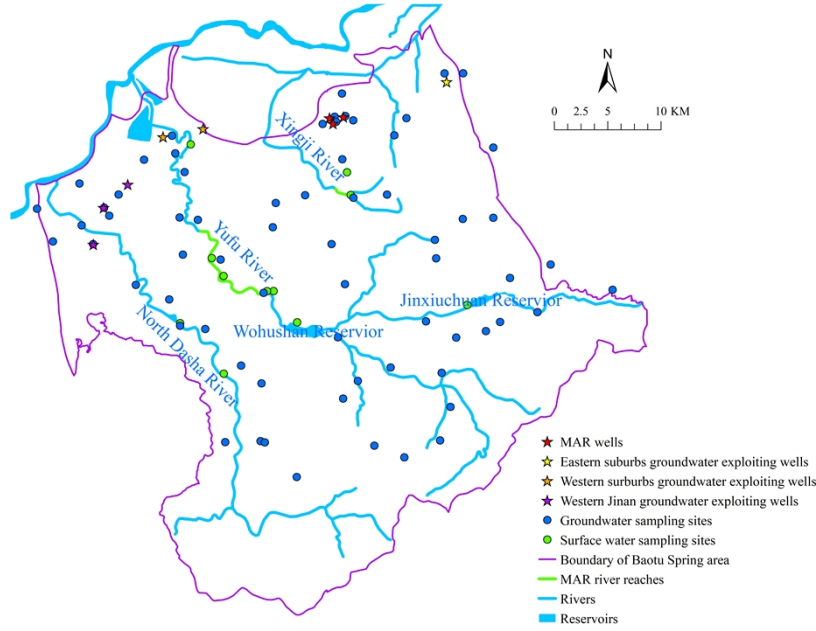


Fig.2 Locations of wells and sampling sites

After the analysis of groundwater and surface water samples, the origin and recharge sources of karst groundwater were determined by utilizing the $\delta^2\text{H}\text{‰}$ and $\delta^{18}\text{O}\text{‰}$ scatter plot of groundwater and surface water. The analysis of ^2H and ^{18}O requires referencing the Global Meteoric Water Line (GMWL) and the Local Meteoric Water Line (LMWL). The GMWL is given as (Craig, 1961):

$$\delta^2\text{H}=8\delta^{18}\text{O}+10 \quad (1)$$

Using the China Meteoric Water Line (CMWL) as the LMWL for the study area, which is:

$$\delta^2\text{H}=7.7\delta^{18}\text{O}+7 \quad (2)$$

Then, to quantitatively analyze the impacteffect of MAR from surface water on karst groundwater, $\delta^2\text{H}\text{‰}$ and $\delta^{18}\text{O}\text{‰}$ values were used to determine the proportion of groundwater recharge from surface water. Groundwater in the study area has two main recharge sources: surface water and precipitation (Liu et al., 2021). An improved two-end-member mixing model was employed to calculate the mixing ratios

of surface water and precipitation in groundwater samples. Assuming $\delta^2\text{H}\text{‰}$ and $\delta^{18}\text{O}\text{‰}$ values for surface water are x_s and y_s , for precipitation are x_p and y_p , and for groundwater are x_g and y_g , the mixing ratios from surface water (η_s) and precipitation (η_p) were calculated. The traditional two-end-member mixing model uses either $\delta^2\text{H}\text{‰}$ or $\delta^{18}\text{O}\text{‰}$ data to calculate these ratios with the Equation:

$$\begin{cases} \eta_s = \frac{x_g - x_p}{x_s - x_p} \\ \eta_p = \frac{x_s - x_g}{x_s - x_p} \end{cases} \quad (3)$$

Or:

$$\begin{cases} \eta_s = \frac{y_g - y_p}{y_s - y_p} \\ \eta_p = \frac{y_s - y_g}{y_s - y_p} \end{cases} \quad (4)$$

Due to the complexity of hydrogeological conditions (there may be unknown recharge sources affecting groundwater isotope values) and the limitations in endmembers selection (isotopic values of precipitation and surface water also vary across different regions), groundwater samples do not completely fall on the mixing line between two end-members in the $\delta^2\text{H}\text{‰}$ – $\delta^{18}\text{O}\text{‰}$ diagram. For certain samples located far from the mixing line (such as Point A in Fig. 2), calculating the mixing ratio using Eq. 3 or 4 essentially involves projecting sample Point A along the X- or Y-axis to Points $A_{(3)}$ or $A_{(4)}$, respectively, which may lead to significantly different results. To address this issue, this study proposes a method for computing the mixing ratio by projecting groundwater sample points onto the two-endmember mixing line in the $\delta^2\text{H}\text{‰}$ – $\delta^{18}\text{O}\text{‰}$ diagram (it is reasonable to assume that using the closest point on the mixing line, i.e., the orthogonal projection of the sample point $A_{(5)}$, yields a more reliable mixing ratio). For some samples, the mixing ratios calculated using Equation (3) or (4) differ significantly. This paper proposes a method that calculates the mixing ratio by projecting groundwater sample points onto the precipitation-surface water mixing line in a $\delta^2\text{H}\text{‰}$ – $\delta^{18}\text{O}\text{‰}$ diagram. The derived Equation for calculating the mixing ratio is as follows:

$$\begin{cases} \eta_s = \frac{(x_g - x_p)(x_s - x_p) + (y_g - y_p)(y_s - y_p)}{(x_s - x_p)^2 + (y_s - y_p)^2} \\ \eta_p = \frac{(x_s - x_g)(x_s - x_p) + (y_s - y_g)(y_s - y_p)}{(x_s - x_p)^2 + (y_s - y_p)^2} \end{cases} \quad (5)$$

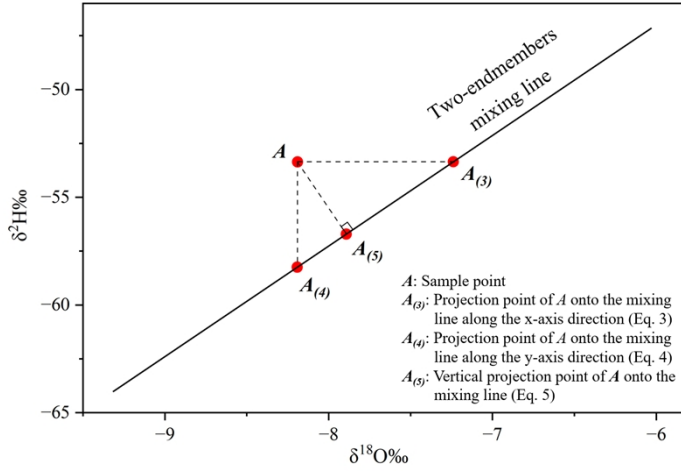


Fig. 2 Schematic diagram illustrating the method for calculating two-endmember mixing proportions

In this research, the minimum $\delta^2\text{H}\text{‰}$ and $\delta^{18}\text{O}\text{‰}$ values of karst groundwater samples are considered as the values of precipitation recharge end-members, which are -64.56 and -9.30, respectively. The average $\delta^2\text{H}\text{‰}$ and $\delta^{18}\text{O}\text{‰}$ values of surface water samples are considered as the values of surface water recharge end-members, which are -50.53 and -6.815, respectively. Using Eq. 5, the mixing ratio for all karst groundwater samples could be calculated. It should be noted that although unauthorized sewage discharge might influence groundwater isotopic values, strict pollution controls in the study area (given Baotu Spring's significance) make this factor negligible for this study.

2.3. Infiltration test and flow monitoring of rivers

Based on field surveys, a large volume of released water in the Yufu River results in some flow escaping downstream and failing to infiltrate and recharge karst groundwater, thereby reducing the effective MAR rate. To verify this and investigate the infiltration capacity of an MAR river segments, we selected five equidistant sites along the MAR segment of Yufu River and measured the permeability

coefficient of the riverbed based on in-situ double-ring infiltration test (Li et al., 2019) (Fig. 3). Then, the infiltration coefficient of the Yufu River MAR segment was calculated using the double-ring infiltration test results. The theoretical maximum recharge capacity was then determined based on the river's area.

Additionally, the flow monitoring data from multiple segments of the Yufu River and Xingji River from 2014 to 2016 were collected (Fig. 13). According to the principle of water balance, the difference in flow between the cross-sections of the MAR river segment is considered as the effective MAR rate. For Yufu River, the water is released in sSection #1, and the effective MAR rate equals the difference between the flow rate at sSection #1 and sSection #5 (Eq. 6). For Xingji River, the water is released in sSection #6, and the effective MAR rate equals the difference between the flow rate at sSection #6 and sSection #7 (Eq. 6). Then, based on the statistical data of the water release rate, the quantitative relationship between the water release rate and the effective MAR rate is analyzed.

$$\begin{cases} Q_{Eff(Yu)} \equiv Q_1 - Q_5 \\ Q_{Eff(Xing)} \equiv Q_6 - Q_7 \end{cases} \quad (6)$$

In the equation, $Q_{Eff(Yu)}$ and $Q_{Eff(Xing)}$ denote the effective MAR rates of the Yufu River and the Xingji River, respectively, while Q_1 through Q_7 represent the flow rates of section #1 to section #7, correspondingly.

It should be noted that although the 2014–2016 flow monitoring data from two hydrological years are sufficiently representative (reflecting the stable infiltration capacity of the river channels, as no large-scale construction occurred after 2016), it remains necessary to calculate the maximum infiltration capacity to account for scenarios requiring high water release rates during extreme dry years or months. Therefore, we selected five sites along the MAR segment of Yufu River and measured the permeability coefficient of the riverbed based on in-situ double-ring infiltration test (Li et al., 2019) (Fig. 13). The infiltration test was performed at the riverbed edges (the river still maintains a small flow during the dry

season). Then, the infiltration coefficient of the Yufu River MAR segments ~~was~~ were calculated using the double-ring infiltration test results. The theoretical maximum recharge capacity ~~was finally~~ then determined based on the river's area.

Additionally,

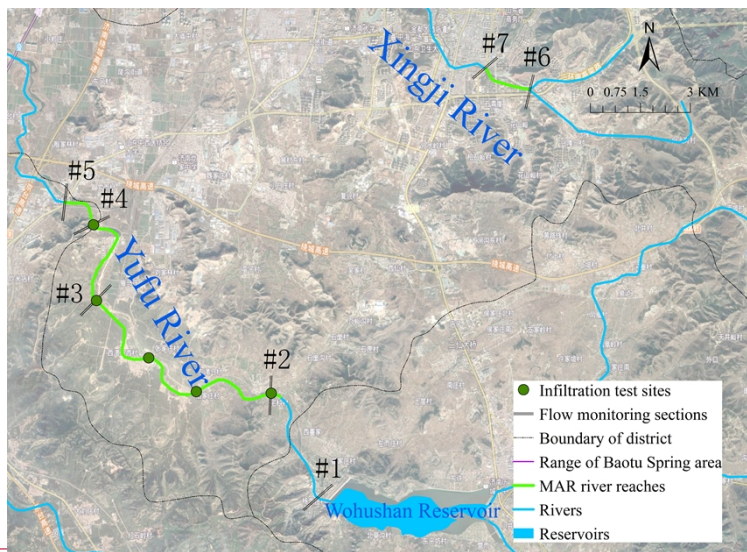


Fig.3 The locations and field photographs of infiltration test sites and flow monitoring sections

2.4. Estimation of effective porosity from tracer tests

Effective porosity is a crucial parameter for simulating groundwater solute transport. The actual groundwater velocity determined by tracer tests can be used to calculate the effective porosity of karst fissured aquifers (Zuber & Motyka, 1994), using the following Equation:

$$n_f = \frac{KI}{v_t} \quad (7)$$

This Equation is derived ~~based on~~ from Darcy's Law. In the equation, “K” represents the hydraulic conductivity (m/d), “I” is the hydraulic gradient, and “v_t” is the actual groundwater velocity (referring to the advective flow velocities governing the transport). ~~There are t~~wo large-scale tracer tests ~~which have~~

been-were conducted at Cuima village in year 1989 and in Xingji River in year 2016 (Zhu et al., 2020).

To determine the parameters required in the groundwater solute transport model, the actual groundwater flow velocity and the effective porosity of the karst aquifer were calculated based on the data from the two tracer tests (Fig. 3).

First, three groundwater flow lines were extracted from the groundwater flow field, and several calculation points for groundwater flow velocity and effective porosity were selected at equal intervals. Flow lines #1 and #2 represent the diffusion direction of the tracers from Cuima Village, while flow line #3 represents the diffusion direction of the tracers from Xingji River. Using the isochrone map of tracer peak concentration diffusion, the actual groundwater flow velocity was calculated based on the horizontal distance between adjacent isochrones at each calculation point. The hydraulic gradient at the calculation points on flow lines #1 and #2 was calculated using 1989 groundwater level monitoring data, and the hydraulic gradient on flow line #3 was calculated using 2016 data. The permeability coefficient (K) for each calculation point was determined using the groundwater flow model established in this research. Finally, the effective porosity at each calculation point was calculated using Eq. 7.

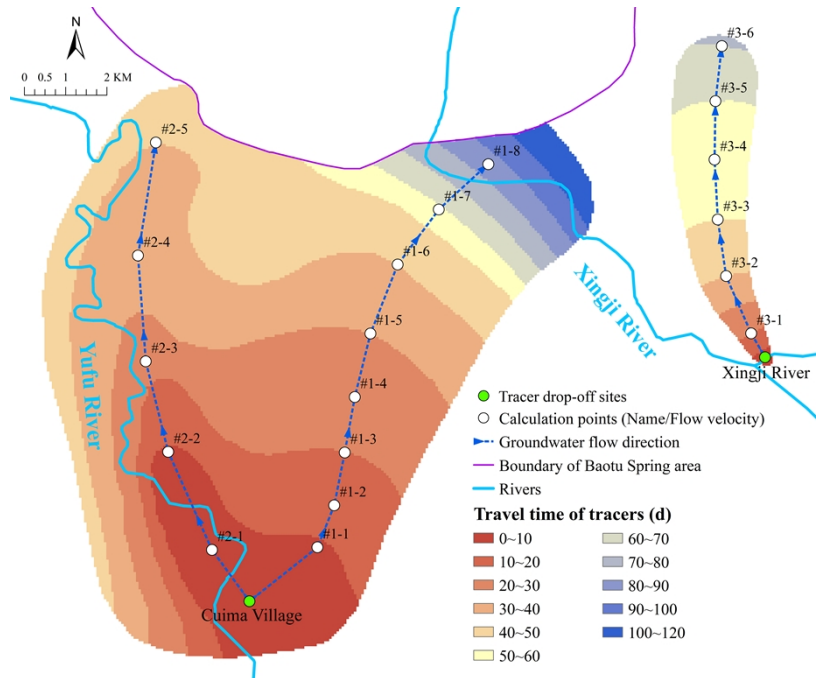


Fig.3 Tracer tests conducted in Cuima Village and Xingji River

2.5. Groundwater flow-solute transport simulation

Numerical simulation is used to predict groundwater level and quality in this research. As mentioned in the introduction, the EPM model without inserting embedded karst-conduits embedded is capable for groundwater flow simulation in karst regions with low development like the northern China karst areas.

To verify this, we identified some typical karst fissure outcrops in the Ordovician limestone exposure area (Fig. 4) and measured the mechanical apertures of the fissures. The measurements show that the maximum mechanical aperture of the karst fissures is approximately 6 mm, while the minimum is less than 1 mm. For natural karst fissures, the hydraulic aperture used for flow calculations is typically much smaller than the mechanical aperture, with their ratio (generally less than 0.15 for karst fissures) determined by the fissure geometry and filling characteristics (Zhang & Nemcik, 2013; Zimmerman & Bodvarsson, 1996). For conservatism, we set the mechanical aperture at 6 mm and the ratio of hydraulic

aperture to mechanical aperture at 0.15 to determine the maximum Reynolds number (Re). Based on the findings in Section 3.3 (Tab.1 provided in the Supplement), the maximum actual groundwater flow velocity in the study area's runoff zone is approximately 216 m/d (0.0025 m/s). Using these data, Eq. 8 yields a rough estimate indicating that the Re of karst groundwater flow in the study area (≤ 2.24) is significantly lower than the critical Re (2000). Therefore, the flow regime in the karst fissures is laminar, justifying the use of the EPM model for simulation.

Consequently, the GMS software was used to establish a karst groundwater flow and solute transport model for the Baotu Spring area. The MODFLOW 2005 and MT3DMS packages were employed to solve the groundwater flow and solute transport equations using the finite difference method.

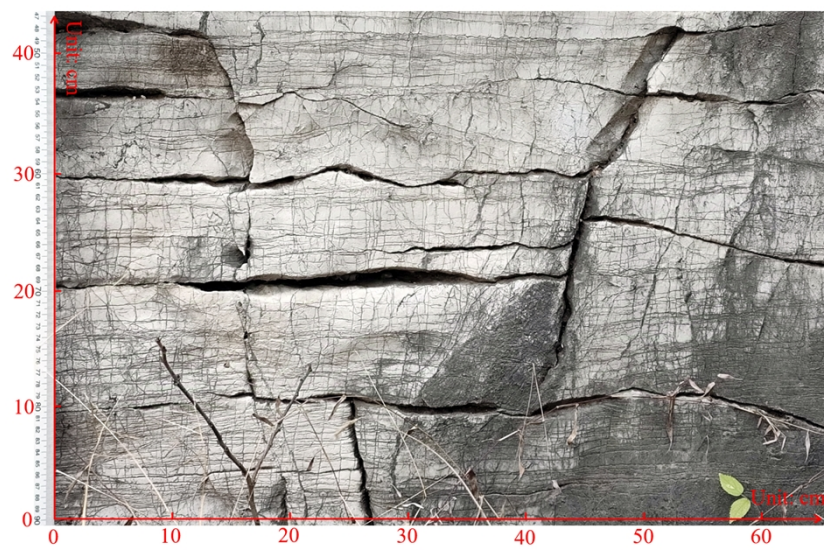




Fig. 4 Outcrop of karst fissures in the study area

$$Re = \frac{\rho v L}{\mu} \leq \frac{998 \times 0.0025 \times 0.006 \times 0.15}{1.002 \times 10^{-3}} \equiv 2.24 \quad (8)$$

Where, Re : Reynolds number (dimensionless);

ρ : Fluid density (kg/m^3);

v : Characteristic flow velocity (m/s);

L : Characteristic length (m), defined here as the hydraulic aperture of the fissures;

μ : Fluid dynamic viscosity (kg/(m.s)).

The numerical model encompasses the Baotu Spring area, simplifying the stratigraphy into four units: Quaternary ~~porous~~ phreatic aquifer, intrusive rock aquitard, Ordovician-Cambrian karst aquifer, and the aquitard below the Mantou Formation (Fig. 5(a)). The Ordovician-Cambrian karst aquifer is the main aquifer and the target aquifer for MAR and groundwater ~~extraction~~ exploitation. In Fig. 5(a), the vertical (Z -axis) scale is exaggerated fivefold to enhance the visualization of topographic undulations and stratigraphic profile variations. The boundaries of the Ordovician-Cambrian karst

aquifer are ~~delineated inset as~~ Fig. 5(b). Additionally, the boundaries of other strata are all impervious.

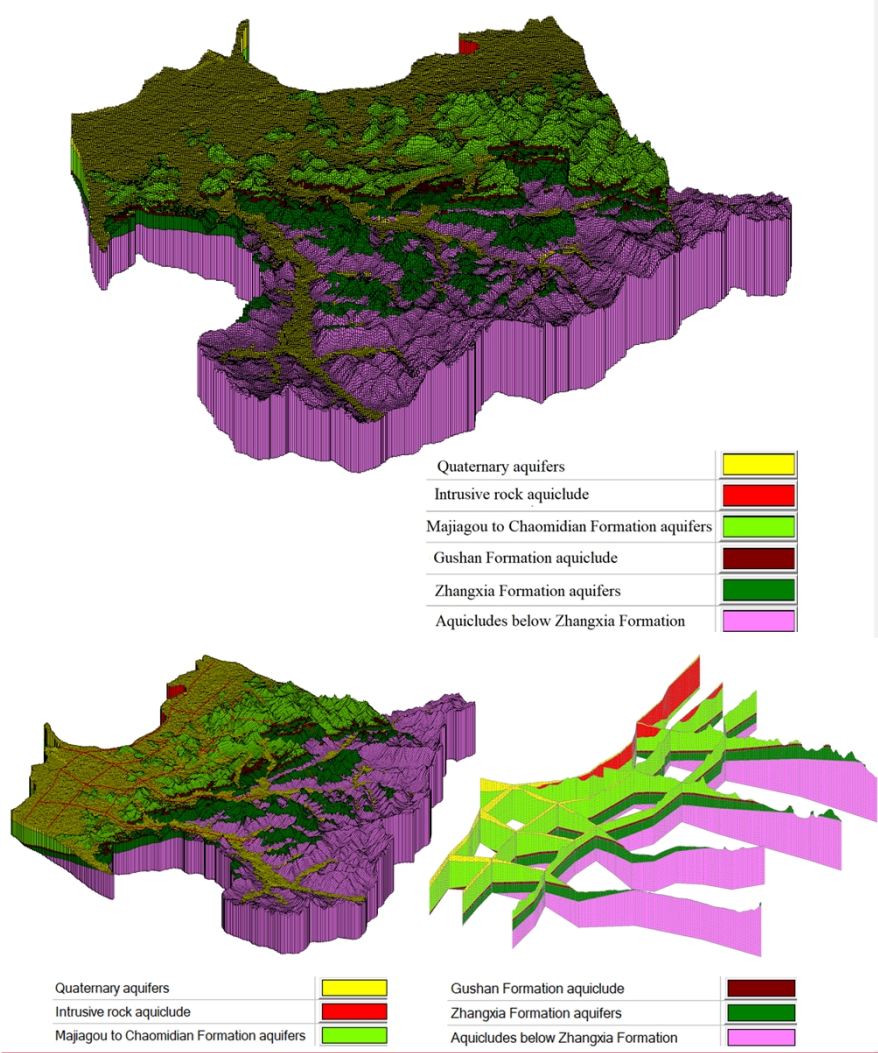
The model's source and sink terms include precipitation recharge, MAR from rivers and wells, groundwater ~~extractionexploitation~~, spring discharge, agricultural irrigation ~~extractionexploitation~~, and agricultural irrigation re-infiltration. Precipitation recharge is calculated based on precipitation quantity, infiltration recharge coefficient, and recharge zone area. The infiltration recharge coefficient ~~accounts~~ ~~foreconsiders~~ surface lithology, urbanization, and agricultural development. The MAR from rivers mainly occur through the Yufu and Xingji Rivers, and the ~~actual MAR rate~~~~effective MAR rate~~ is discussed in Section 3.2. The locations of MAR wells, groundwater ~~exploiting-extracting~~ wells and MAR river segments are displayed in Fig. 5(b).

The hydraulic conductivity K consists of horizontal hydraulic conductivity K_x and vertical hydraulic conductivity K_y . The zoning and values of K_x are mainly based on the hydrogeological tests, and then identified and verified using groundwater level monitoring well data. K_y is uniformly set to 0.1 times K_x . The remaining hydrogeological parameters (specific yield, ~~storativity~~~~storage-coefficient~~, and ~~dispersivity~~~~dispersivity~~) are taken as empirical values. The determination of effective porosity has been discussed in Section 2.4. The simulation period spans from January 1, 2020, to December 31, 2022, with each stress period lasting one month.

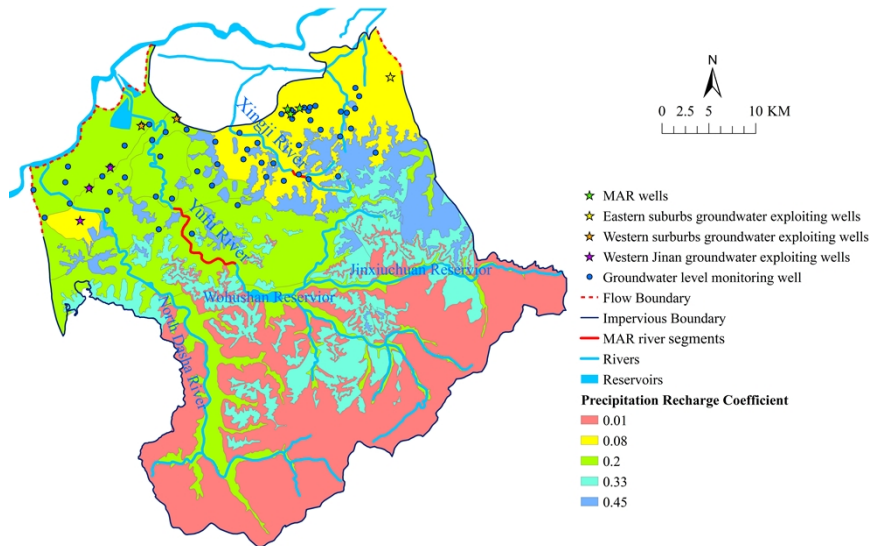
Next, the ~~impact~~~~effect~~ of MAR and groundwater ~~exploitation-extraction~~ on the dynamics of karst groundwater levels was quantitatively analyzed using a groundwater flow model, with Baotu Spring's water level serving as a representative indicator. The considered MAR are from Yufu River, Xingji River, and MAR wells. For the simulation period of 2020-2022, the net variations of Baotu Spring water level caused by MAR and groundwater ~~extractionexploitation~~ were calculated.

Finally, to quantitatively compare the effects of various MAR and groundwater

extractionexploitation on the dynamics of Baotu Spring water level, the water level net variation after 1, 2, and 3 years of continuous recharge and extractionexploitation at a constant flow rate was calculated and compared.



(a) Geological model



(b) Settings of groundwater flow model

Fig. 5 Geological model and groundwater flow model

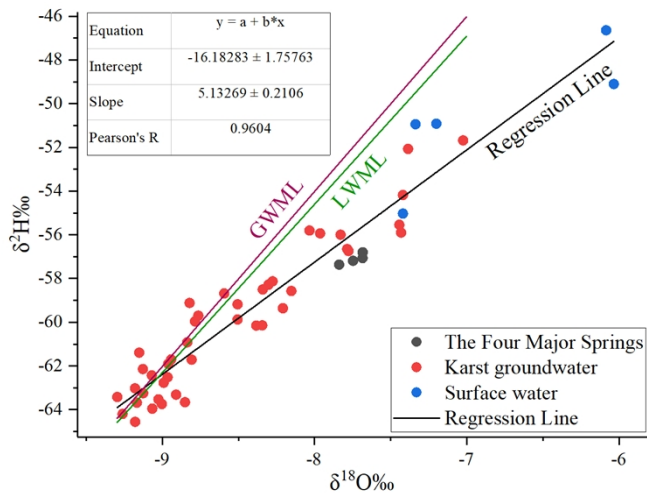
For the solute transport simulation, sulphate is selected as the representative solute because its concentration in the surface water used for MAR is higher than that in the groundwater, while the concentrations of other solute components are either similar to or lower than those in the groundwater. The simulation is based on the groundwater flow model from-spanning 2020 to 2022, with all recharge/discharge values averaged over this period to mitigate seasonal flow variations. The initial sulphate concentration in karst groundwater is uniformly set at 50 mg/L, reflecting the average concentration in high-quality water from the wells in western suburbs. The model then simulates the dynamics of sulphate concentration in karst groundwater after 2, 6, and 18 months of continuous recharge with sulphate concentrations of 150 mg/L, 250 mg/L, and 350 mg/L in the MAR water.

3. Results and Discussion

3.1. Mixing percentages of groundwater recharge sources

A scatter plot of the $\delta^2\text{H}\%$ and $\delta^{18}\text{O}\%$ of groundwater and surface water is generated in Fig. 6. It

shows that karst groundwater samples are distributed near the LMWL, indicating that the karst groundwater in the study area originates from precipitation (Liu et al., 2021). The isotopic enrichment of ^2H and ^{18}O in surface water samples is significantly higher than that in karst groundwater samples, exhibiting a typical evaporation effect. Additionally, the karst groundwater samples gradually deviate from the LMWL with the enrichment of ^2H and ^{18}O , indicating the mixing of precipitation and surface water. This suggests that the karst groundwater is significantly recharged by surface water.



areas, as well as the northwestern Yellow River alluvial plain, the mixing percentage of surface water recharge is generally less than 20%. In contrast, in the middle and lower segments of the Yufu River and North Dasha River basins, as well as the Xingji River basin, the mixing percentage of surface water recharge is relatively high. The highest mixing percentage is near the MAR segments of the Yufu River and Xingji River. For example, in the villages along the MAR segment of the Yufu River, the mixing percentage of surface water recharge in wells ZhaiET, Cui1, and J97 exceeds 80%, while in wells A2-30 and Ji1 near the Xingji River MAR segment, and the Springs downstream, it exceeds 50%. These results highlight that the MAR from the Yufu River and Xingji River is a significant component of karst groundwater resources, emphasizing the importance of MAR projects in ensuring groundwater resources and raising regional groundwater levels.

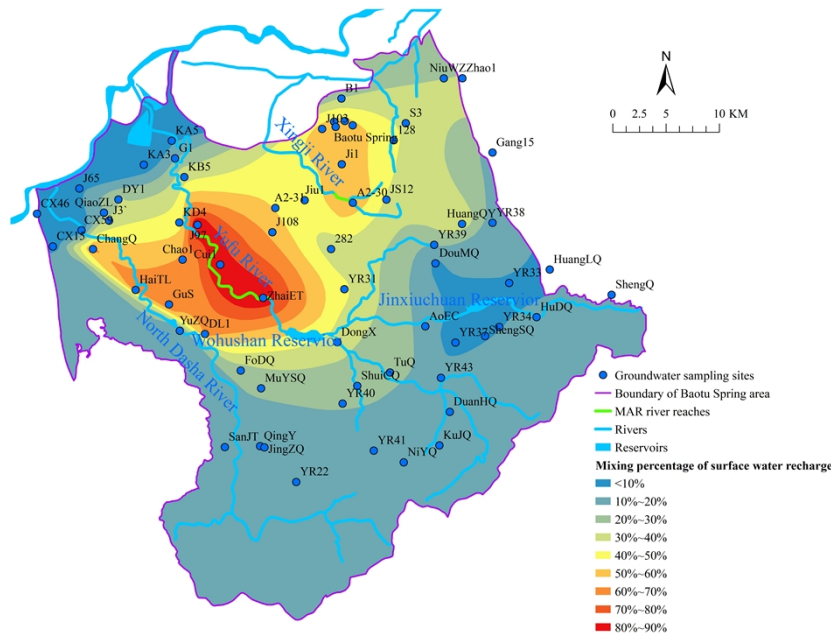
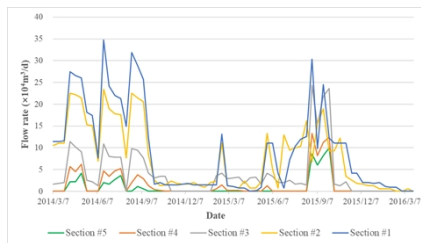


Fig. 7 Mixing percentage of surface water recharge in groundwater

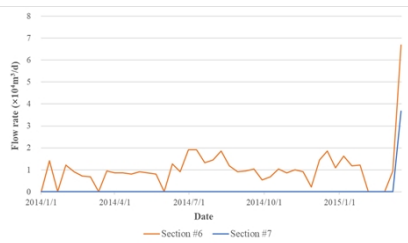
3.2. Infiltration efficiency of MAR river segments

According to the test results of in-situ double-ring infiltration test, the bed permeability coefficient of the Yufu River MAR segment ranges from 1.96 to 2.76 m/d, with an average of 2.30 m/d across five sites. According to high-resolution satellite images, the Yufu River MAR segments (Fig. 4), from Section #1 to Section #5, approximately covers an area of 0.50 km². Assuming a vertical infiltration hydraulic gradient of 1, the theoretical maximum MAR rate for the Yufu River MAR segments, calculated using Darcy's Law, is approximately $114.9 \times 10^4 \text{ m}^3/\text{d}$.

Based on field surveys, large volume of released water in the Yufu River results in some flow escaping at the Section #5, failing to infiltrate and recharge karst groundwater, thereby reducing the actual MAR rate. To verify this, Firstly, in order to investigate the relationship between effective MAR rates and water release rates, we analyzed flow data from 2014 to 2016 (Fig. 8). analysis of flow data from 2014 to 2016 (Fig. 8) was conducted, revealing the relationship between actual MAR rates and water release rates. Since the MAR segment of the Yufu River is divided into four segments by five flow monitoring sections, whereas Xingji River has only one MAR segment due to a single upstream and downstream section, the upstream and downstream flow rates were analyzed separately for each segment to assess groundwater infiltration capacity. Based on the data in Fig. 8, we plotted the flow relationships between upstream and downstream sections for each segment (Fig. 9, where $Q_1 \sim Q_7$ represent the flow rates of section #1~section #7, in units of $10^4 \text{ m}^3/\text{d}$).



(a) Yufu River



(b) Xingji River

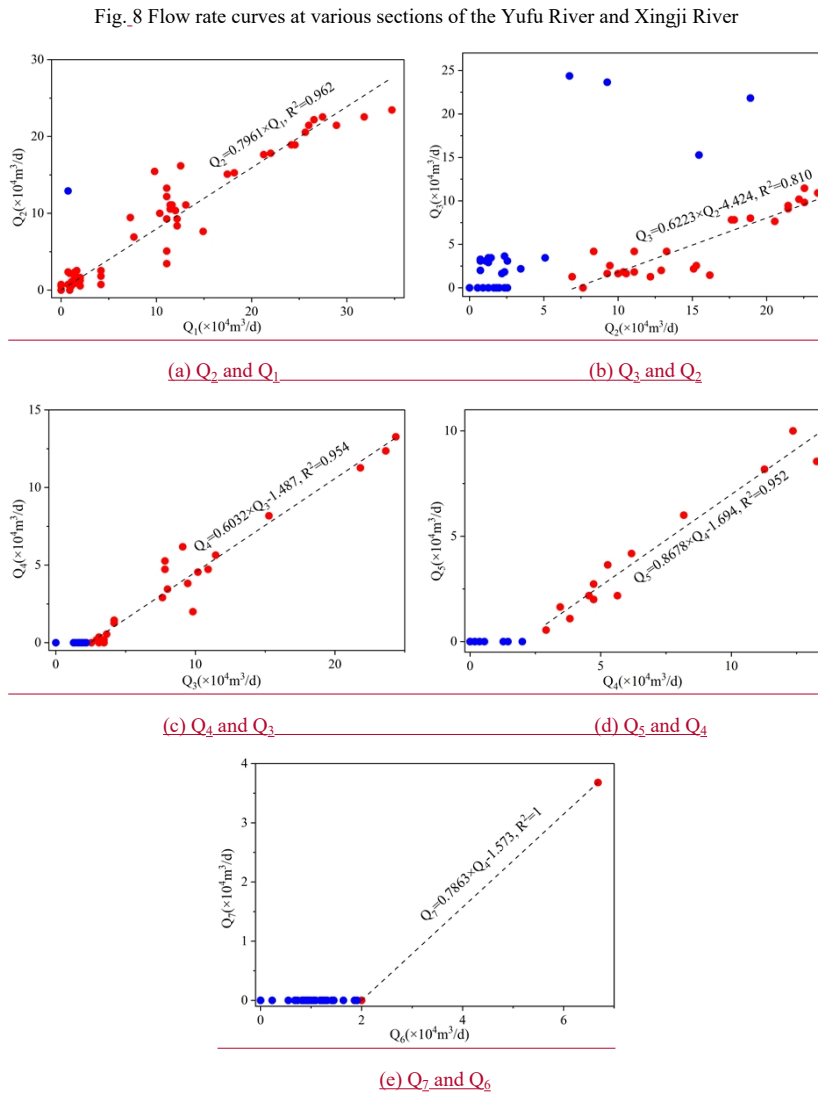


Fig. 9 Graphical representation of the flow rate relationship between upstream and downstream sections in MAR river segments

In Fig. 9(a), the single blue data point shows Q_2 significantly exceeds Q_1 , indicating higher downstream flow than upstream flow, which suggests an additional recharge source between section #1 and section #2. Thus, this point was excluded from the fitting function. Similarly, four blue points in Fig.

9(b) that deviate markedly from the fitted line were also excluded. Furthermore, Figures 9(b)-9(e) show that when upstream flow is low, downstream flow is nearly zero, suggesting complete infiltration of river water into groundwater below a certain threshold of flow, defined as the "critical flow rate." Data analysis reveals that when flow exceeds this critical flow rate (Eq. 9), upstream and downstream flows generally follow a linear relationship (Eq. 9), with Pearson R^2 all exceeding 0.810.

$$\begin{cases} (1). Q_2 = 0.7961 \times Q_1 \quad (Q_1 \geq 0, R^2 = 0.962) \\ (2). Q_3 = 0.6223 \times Q_2 = 4.424 \quad (Q_2 \geq 7.109, R^2 = 0.810) \\ (3). Q_4 = 0.6032 \times Q_3 = 1.487 \quad (Q_3 \geq 2.465, R^2 = 0.954) \\ (4). Q_5 = 0.8678 \times Q_4 = 1.694 \quad (Q_4 \geq 1.952, R^2 = 0.952) \\ (5). Q_7 = 0.7863 \times Q_6 = 1.572 \quad (Q_6 \geq 2, R^2 = 1) \end{cases} \quad (9)$$

Then, by combining Eq. 9 with Eq. 6, the following relationships are established: the effective MAR rate in the Yufu River is quantitatively related to Q_I (Eq. 10), while that of the Xingji River correlates with Q_6 (Eq. 11).

$$\begin{cases} Q_{Eff(Yufu)} \equiv Q_1 \quad (Q_1 \leq 20.44) \\ Q_{Eff(Yufu)} = 0.7449 Q_1 + 5.214 \quad (Q_1 > 20.44) \end{cases} \quad (10)$$

$$\begin{cases} Q_{Eff(Xingj)} \equiv Q_6 \quad (Q_6 \leq 2) \\ Q_{Eff(Xingj)} = 0.2137 Q_6 + 1.573 \quad (Q_6 > 2) \end{cases} \quad (11)$$

In the equation, the units of Q_I to Q_7 , as well as $Q_{Eff(Yufu)}$ and $Q_{Eff(Xingj)}$, are all $10^4 \text{m}^3/\text{d}$.

According to Eq. 10, when the water release rate does not exceed $20.44 \times 10^4 \text{m}^3/\text{d}$, the effective MAR rate for Yufu River equals the water release rate, indicating full infiltration of surface water before section #5. However, when the water release rate exceeds $20.44 \times 10^4 \text{m}^3/\text{d}$, the effective MAR rate is less than the water release rate, as some surface water flows past section #5 without complete infiltration. Similarly, Eq. 11 demonstrates that the Xingji River follows a similar pattern to the Yufu River.

When the water release rate does not exceed $21.6 \times 10^4 \text{m}^3/\text{d}$, the actual MAR rate equals the water release rate, indicating full infiltration of surface water before Section #5. However, when the water release rate exceeds $21.6 \times 10^4 \text{m}^3/\text{d}$, the actual MAR rate is less than the water release rate, as some surface water flows past Section #5 without infiltrating karst groundwater. Calculations confirm that when the

water release rate exceeds $21.6 \times 10^4 \text{ m}^3/\text{d}$, the relationship between the actual MAR rate and the water release rate follows Equation (7):

$$Q_{\text{Act}} = 0.843 \times Q_{\text{Rel}} + 3.396 \quad (7)$$

Where, Q_{Act} is the actual MAR rate in Yufu River (m^3/d), and Q_{Rel} is the water release rate in Yufu River Section #1 (m^3/d).

Likewise, in Xingji River, the relationship between the actual MAR rate and the water release rate follows Equation (8) when the water release rate exceeds $2 \times 10^4 \text{ m}^3/\text{d}$.

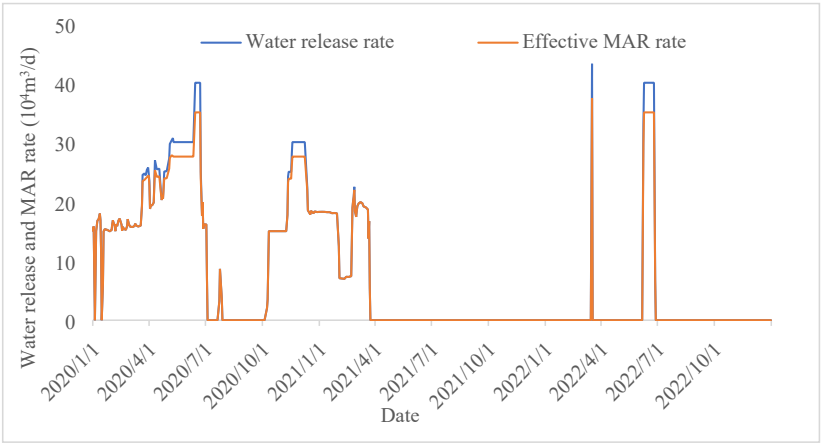
$$Q_{\text{Act}} = 0.214 \times Q_{\text{Rel}} + 1.573 \quad (8)$$

Where, Q_{Act} is the actual MAR rate in Xingji River (m^3/d), and Q_{Rel} is the water release rate in Xingji River Section #6 (m^3/d).

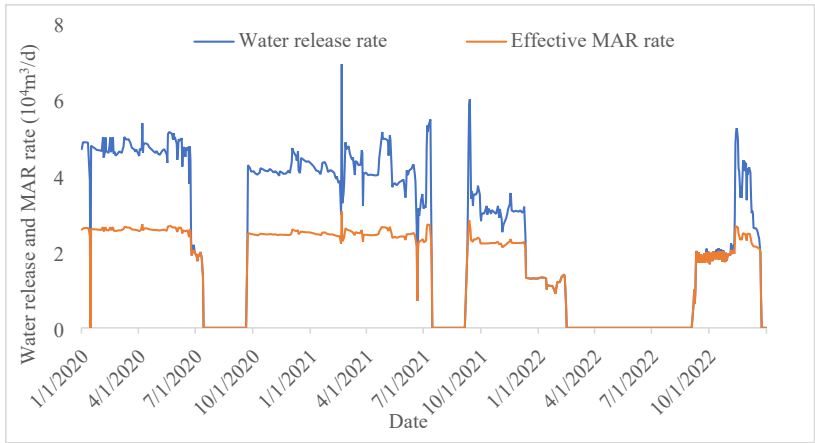
According to the test results of in-situ double-ring infiltration test, the streambed permeability coefficient of the Yufu River MAR segment ranges from 1.96 to 2.76 m/d, with an average of 2.30 m/d across five sites. According to high-resolution satellite images, the Yufu River MAR segments (Fig. 14), from sSection #1 to sSection #5, approximately covers an area of 0.50 km^2 . Assuming a vertical infiltration hydraulic gradient of 1, the theoretical maximum MAR rate for the Yufu River MAR segments, calculated using Darcy's Law, is approximately $114.9 \times 10^4 \text{ m}^3/\text{d}$. It should be noted that during the monitoring period (2014–2016), the maximum flow rate of the Yufu River was $34.73 \times 10^4 \text{ m}^3/\text{d}$, much less than this value. This indicates that although a water release rate exceeding $20.44 \times 10^4 \text{ m}^3/\text{d}$ may lead to partial waste of recharge water, further increasing the water release rate can still enhance groundwater recharge.

Finally, the effective MAR rates of the Yufu River and Xingji River from 2020 to 2022 ~~were~~ was calculated, as shown in Fig. 10, ~~respectively~~. These calculations were used as surface water recharge

inputs for the groundwater flow model.



(a) Yufu River



(b) Xingji River

Fig. 10 Water release rate VS. Effective MAR rate in Yufu River and Xingji River

3.3. Effective porosity of karst aquifers estimated from tracer tests

As discussed in Section 2.4, the effective porosity at each calculation point was calculated using Eq. 7, with the process and results shown in Tab.1 (provided in the Supplement). According to Tab.1, the groundwater flow velocity in the study area ranges from 52.4 to 216 m/d. Obviously, and the effective

porosity of the aquifer varies widely, with the maximum, minimum, and average values being 4.39×10^{-4} , 1.28×10^{-5} , and 1.08×10^{-4} , respectively. Consistent with these findings, the effective porosity of Cretaceous Chalk in northeastern England's Yorkshire ranges from 3.7×10^{-4} to 4.1×10^{-3} (Agbotui et al., 2020), while Jurassic Limestone and Magnesian Limestone exhibit values of 1×10^{-4} (Foley et al., 2012) and 3×10^{-4} (Medici et al., 2019), respectively. This variability is closely related to the heterogeneity of the karst aquifer, aligning with studies in similar carbonate rock regions in the UK and Austria (Medici & West, 2021; Worthington et al., 2019). Studies have indicated that the effective porosity of karst systems exhibits significant scale effects, primarily attributed to the heterogeneity of groundwater flow velocities caused by the non-uniform development of karst conduits and fissures. For regional groundwater studies, large-scale tracer tests and dilution tests should be employed to determine the effective porosity, which typically ranges between 10^{-4} and 10^{-3} —considerably lower than previously recommended values (0.1–0.01) (Medici & West, 2021). In this paper, the average effective porosity (1.08×10^{-4}) from all calculated points on three flow lines from the Cuima Village and Xingji River tracer tests was used to represent the karst aquifer's effective porosity for groundwater solute transport modeling.

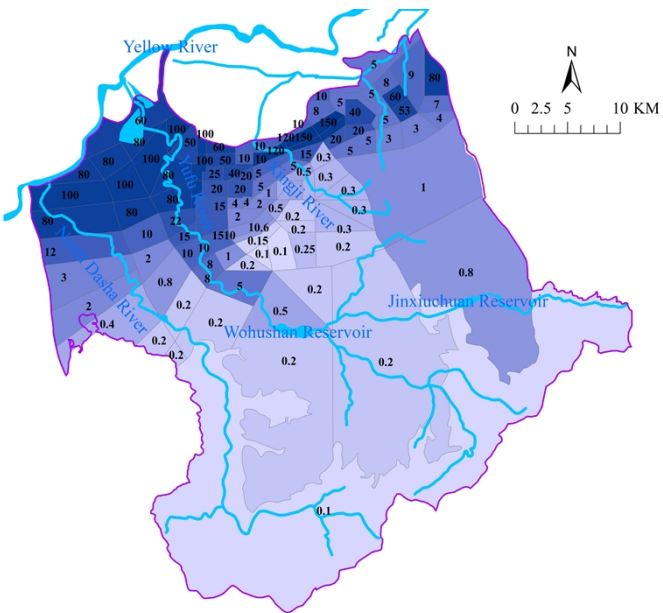
Tab.1 Effective porosity at the calculation points

Name	Flow velocity (m/d)	Permeability (m/d)	Hydraulic gradient	Effective porosity
#1-1	233.6	10	4.23E-03	1.81E-04
#1-2	240.3	1	3.85E-03	1.60E-05
#1-3	266.9	2	1.70E-03	1.28E-05
#1-4	295.2	4	1.16E-03	1.58E-05
#1-5	225.5	20	1.20E-03	1.07E-04
#1-6	148.3	20	3.85E-04	5.19E-05
#1-7	82.4	120	3.01E-04	4.39E-04
#1-8	52.4	10	3.07E-04	5.85E-05
#2-1	449.6	10	2.46E-03	5.47E-05
#2-2	293.2	22	1.03E-03	7.70E-05
#2-3	193.5	80	1.67E-04	6.89E-05
#2-4	356.3	80	2.78E-04	6.24E-05
#2-5	307	50	4.42E-04	7.21E-05

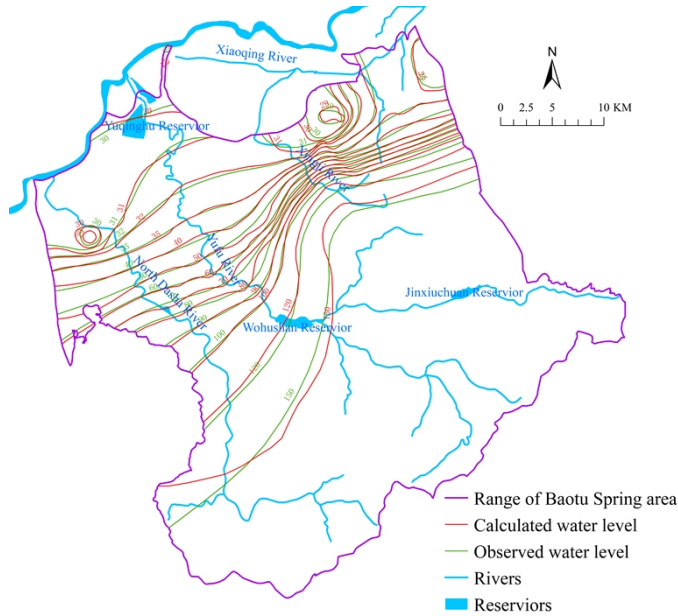
#3-1	63	0.3	1.07E-02	5.09E-05
#3-2	96.8	0.3	1.26E-02	3.90E-05
#3-3	165.1	1	1.29E-02	7.83E-05
#3-4	287.7	20	2.08E-03	1.45E-04
#3-5	275.7	120	9.88E-04	4.30E-04
#3-6	71.8	8	8.65E-04	9.64E-05
Max	449.6	1	1	4.39E-04
Min	52.4	1	1	1.28E-05
Average	216	1	1	1.08E-04

3.4. Impact Effects of MAR and groundwater extraction/exploitation on groundwater level

According to the identification and verification of the groundwater flow model, the horizontal hydraulic conductivity of karst aquifers is exhibited/shown in Fig. 11(a). The calculated and observed groundwater flow field as of December 31, 2022, are exhibited/shown in Fig. 11(b), and the calculated and observed groundwater levels for the representative monitoring wells are shown in Fig. 11(c) to 11(f) (provided in the Supplement).



(a) Horizontal hydraulic conductivity of karst aquifers (Unit: m/d)



(b) Groundwater flow field (Unit of water level: m)

Fig. 11 Identification and verification result of the groundwater flow model

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The net variations of Baotu Spring water level caused by MAR and groundwater extraction/exploitation were simulated and are displayed in Fig. 12. The "net variations in/of the Baotu Spring water level" in Fig. 12 refers to the portion of groundwater level fluctuation in Baotu Spring caused by MAR and groundwater extraction/exploitation. These variations are calculated using a numerical model based on actual MAR and groundwater extraction/exploitation data. It shows that the water level of Baotu Spring rises with MAR and drops with groundwater extraction/the water level of Baotu Spring clearly rises with MAR and drops with groundwater exploitation. There is also a lag in the impact/effect of these factors on the water level.

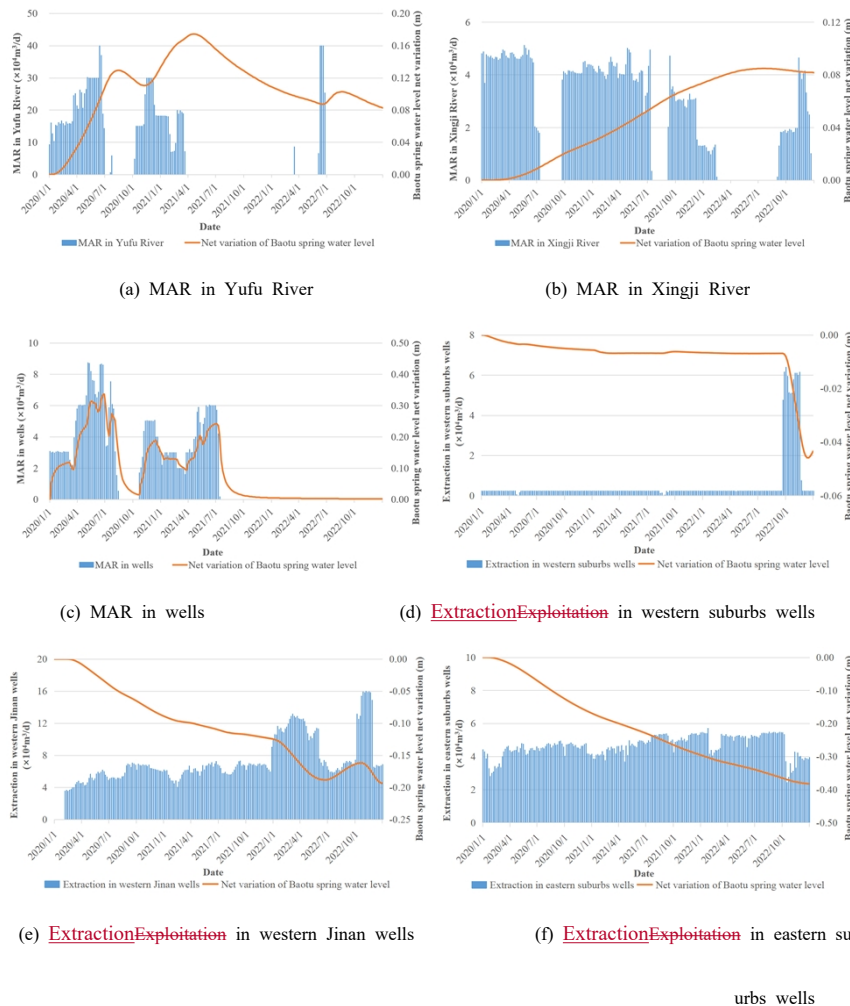


Fig. 12 Net variations ~~in~~of the Baotu Spring water level caused by MAR and groundwater

~~extraction~~exploitation (based on data in 2020-2022)

Then, the water-level net variation after 1, 2, and 3 years of continuous recharge and exploitation at a constant flow rate was calculated and compared, with detailed results shown in Tab.2. Note that due to maximum recharge capacity constraints, scenarios with recharge rates of Xingji River and MAR wells exceeding $5 \times 10^4 \text{ m}^3/\text{d}$ were not included. Tab.2(a) illustrates the impact of MAR on Baotu Spring's water

level. It shows that, with the same recharge rate and duration, the MAR in wells has the greatest effect, followed by Xingji River, and Yufu River has the least impact. Despite this, Yufu River's maximum recharge capacity greatly exceeds that of Xingji River and the MAR wells. Additionally, the water level rise under MAR wells recharge remains almost unchanged within the three years, indicating that the maximum effect is achieved within the first year. This rapid response is due to the proximity of the MAR wells to Baotu Spring (0.75 km, 0.81 km, and 0.35 km, respectively) and the high permeability ($k=150$ m/d) of the shared karst aquifer.

In practice, the most suitable MAR source should be chosen based on the following strategies. Firstly, MAR in wells yields the best results and raises the Baotu Spring water level the fastest, but it has a low maximum recharge capacity. Therefore, MAR in wells should be prioritized for a rapid short-term rise in the Baotu Spring water level. Secondly, MAR in Xingji River is less effective and also has a low maximum capacity, making it suitable for maintaining a small long-term rise in the Baotu Spring water level in conjunction with MAR in wells. Thirdly, MAR in Yufu River is the least effective but has a high maximum capacity, so for a significant long-term rise in the Baotu Spring water level, all three sources should be considered, with MAR in Yufu River being the primary source.

The water level net variation following continuous recharge and extraction at a constant flow rate over 1, 2, and 3 years was computed and compared, with results presented in Tab.2. Due to maximum recharge capacity limitations, scenarios exceeding 5×10^4 m³/d for Xingji River and MAR wells were excluded. Tab.2(a) demonstrates the impact of MAR on Baotu Spring's water level, revealing that well-based MAR yields the greatest effect, followed by Xingji River, while Yufu River exhibits the least influence despite its substantially higher maximum recharge capacity. Notably, well-based MAR induces minimal water level variation beyond the first year, attributable to their proximity to Baotu Spring (0.75

km, 0.81 km, and 0.35 km) and the high permeability ($k=150$ m/d) of the shared karst aquifer. Optimal MAR source selection should consider operational strategies: well-based MAR, despite limited capacity, is most effective for rapid short-term water level elevation; Xingji River MAR, with moderate efficacy and capacity, suits sustained minor water level augmentation when combined with well-based MAR; whereas Yufu River MAR, though least efficient, offers substantial capacity and should serve as the primary source for significant long-term water level increases in conjunction with other sources.

Tab.2(b) illustrates the impact of groundwater exploitation on Baotu Spring's water level. Overall, the exploitation in eastern suburbs wells has the most significant impact on Baotu Spring's water level, followed by the western suburbs wells, with the western Jinan wells having the least impact. Between 2020 and 2022, daily average exploitation rate was 5,339 m³/d for western suburbs wells, 70,852 m³/d for western Jinan wells, and 46,487 m³/d for eastern suburbs wells. Therefore, to minimize the impact on the water level of Baotu Spring while ensuring the basic groundwater exploitation needs in the area, western suburbs wells still hold significant exploitation potential and consideration may be given to transferring a portion of exploitation from eastern suburbs wells to western suburbs wells.

Tab.2(b) delineates groundwater extraction effects on Baotu Spring's water level, indicating that eastern suburbs wells exert the strongest influence, followed by western suburbs wells, with western Jinan wells showing minimal impact. Given recorded extraction rates (2020–2022) of 5,339 m³/d (western suburbs), 70,852 m³/d (western Jinan), and 46,487 m³/d (eastern suburbs), strategic redistribution of extraction from eastern to western suburbs wells could mitigate Baotu Spring's water level decline while meeting regional groundwater demand. This approach capitalizes on the underutilized extraction potential of western suburbs wells.

Tab.2 The effect on groundwater level net variation at Baotu Spring resulting from a constant rate of

continuous MAR and groundwater ~~extraction~~exploitation over 1 year, 2 years, and 3 years

(a). The effect on groundwater level rise resulting from MAR

MAR rate ($\times 10^4 \text{m}^3/\text{d}$)		Duration of groundwater recharge		
		1 year	2 years	3 years
Yufu River	2	19 mm	31 mm	36 mm
	5	49 mm	76 mm	90 mm
	10	97 mm	152 mm	179 mm
	20	194 mm	300 mm	353 mm
	30	266 mm	409 mm	480 mm
Xingji River	2	23 mm	60 mm	89 mm
	5	38 mm	100 mm	148 mm
MAR wells	2	85 mm	86 mm	86 mm
	5	212 mm	214 mm	216 mm

(b). The effect on groundwater level drop resulting from groundwater ~~extraction~~exploitation

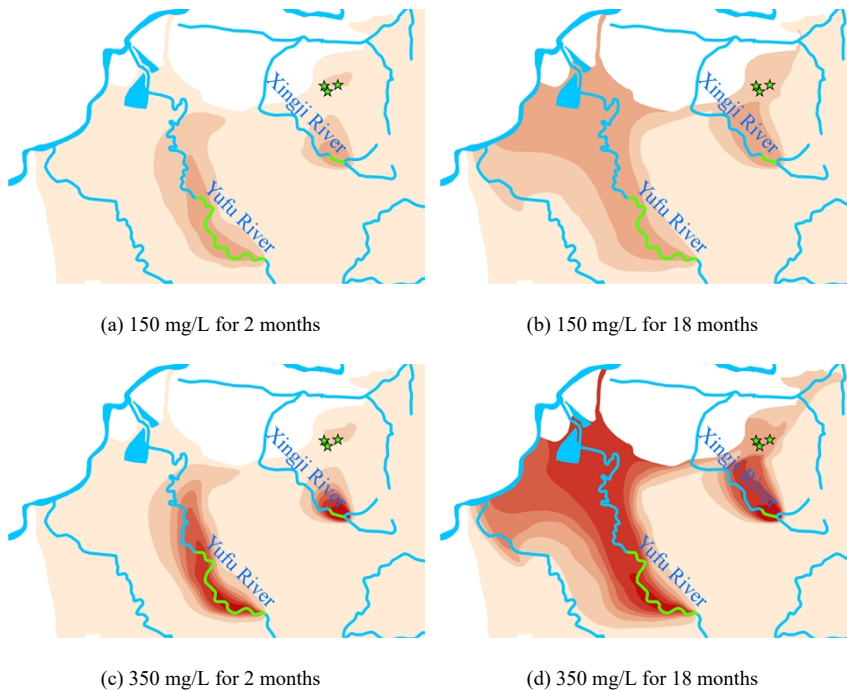
Groundwater extraction exploitation rate ($\times 10^4 \text{m}^3/\text{d}$)		Duration of groundwater extraction exploitation		
		1 year	2 years	3 years
Western suburbs wells	5	115 mm	138 mm	142 mm
	10	230 mm	283 mm	293 mm
Western Jinan wells	5	87 mm	106 mm	107 mm
	10	175 mm	218 mm	221 mm
Eastern suburbs wells	5	199 mm	322 mm	382 mm
	10	397 mm	643 mm	765 mm

3.5. ~~Impact~~Effects of MAR on groundwater quality

Based on the groundwater solute transport model established in this paper, simulations were conducted to monitor the dynamics of sulphate concentration in karst groundwater after continuous recharge of water with sulphate concentrations of 150 mg/L, 250 mg/L, and 350 mg/L over periods of 2 months, 6 months, and 18 months. As shown in Fig. 13 ([The other subfigures of Fig. 13 are provided in the Supplement](#)), with prolonged recharge duration and deteriorating recharge water quality, the sulphate concentrations in karst groundwater increase and the affected area of karst groundwater quality expands continuously, indicating an increasing ~~impact~~effect of MAR on karst groundwater quality over time. Therefore, deteriorating water quality from MAR poses risks to groundwater, and strict control and

monitoring of recharge water quality are necessary.

Additionally, sulphate concentrations in karst groundwater reach stability after 12--18 months of continuous recharge, and a linear regression established a quantitative relationship between the sulphate concentrations in karst groundwater and in MAR water (Fig. 14). In practice, target values for sulphate concentrations in karst groundwater should be preset, and the minimum control standards for sulphate concentrations in MAR water could be calculated using the relationship shown in Fig. 14. For example, according to China's Groundwater Quality Standards, the sulfate concentrations in Class I, II, and III groundwater must not exceed 50, 150 and 250 mg/L, respectively. Thus, it can be calculated that to ensure karst groundwater meets Class I, II, and III standards, the sulfate concentration in the MAR water source must not exceed 56.5, 197.8 and 339.1 mg/L, respectively.



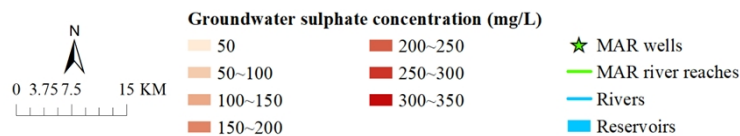


Fig.13 Evolution of sulphate concentration in karst groundwater under MAR

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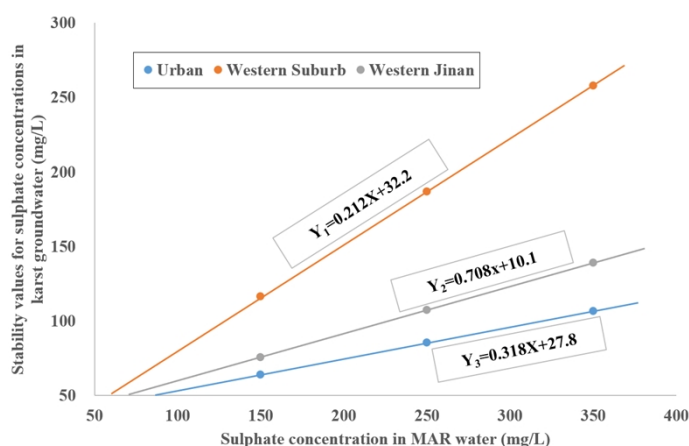


Fig.14 Linear relationships between sulphate concentrations in karst groundwater and MAR water

4. Conclusions

In this research, the impacts of MAR and groundwater exploitation on the dynamics of karst groundwater level and quality in the Baotu Spring area of Jinan City were quantitatively analyzed by multi-methods. This study focuses on temperate semi-arid fissured karst systems, proposing an integrated multi-method quantitative approach combining isotopic analysis, flow monitoring, tracer tests, and numerical modeling. The methodology was developed to investigate the impacts of managed aquifer recharge (MAR) and extraction on karst groundwater level and quality dynamics, with a case study conducted in the Baotu Spring karst system, Jinan, China.

The main conclusions are summarized as follows: (1) The conventional two-endmember mixing model for recharge estimation was enhanced by integrating $\delta^2\text{H}$ (‰) and $\delta^{18}\text{O}$ (‰) data from both surface water and groundwater, which reduced uncertainties in estimating groundwater recharge ratios from

multiple sources. The calculated mixing ratios of groundwater recharge indicate that surface water accounts for over 80% and 50% of groundwater recharge near the MAR segments of Yufu River and Xingji River, respectively. Firstly, the $\delta^2\text{H}\text{‰}$ and $\delta^{18}\text{O}\text{‰}$ values of groundwater and surface water reveals that surface water is an essential source of groundwater recharge and plays a crucial role in maintaining groundwater volume. In the southern metamorphic rock and Cambrian Zhangxia Formation limestone outcrop areas, as well as the northwestern Yellow River alluvial plain, the surface water recharge proportion is generally less than 20%. Near the MAR segments of the Yufu River and Xingji River, the mixing percentage of surface water recharge exceed 80% and 50%, respectively.

(2) The relationship between effective MAR rates and water release rates was quantified through flow monitoring and infiltration tests, thereby improving recharge rate quantification accuracy. Results indicate that when water release rates surpass a critical threshold ($20.44 \times 10^4 \text{ m}^3/\text{d}$ for Yufu River and $2 \times 10^4 \text{ m}^3/\text{d}$ for Xingji River), partial surface water flows downstream, diminishing the effective MAR rate. (3) Based on large-scale regional tracer tests, Secondly, the analysis of the rivers' flow monitoring results reveals that some surface water will flow out downstream when the water release rate of the Yufu River and Xingji River exceeds $20.44 \times 10^4 \text{ m}^3/\text{d}$ and $2 \times 10^4 \text{ m}^3/\text{d}$, respectively, reducing the actual MAR rate. However, according to the analysis of the infiltration test results, the theoretical maximum recharge capacity of the Yufu River to karst groundwater is about $114.9 \times 10^4 \text{ m}^3/\text{d}$.

the effective porosity of the investigated karst aquifer was estimated to be approximately 1.08×10^{-4} , which enhances the reliability of solute transport simulations. This value is comparable to results reported from similar karst terrains in Europe. (4) Thirdly, the isoline map of tracer peak concentration diffusion estimated the effective porosity of the karst aquifer in the study area to be 1.08×10^{-4} , providing a reference for solute transport modeling in similar hydrogeological conditions. According to the

simulations of the groundwater flow model, MAR effectively raises karst groundwater levels, and the effectiveness varies for the three MAR sources. MAR in wells has the best effect and fastest response, followed by the MAR in Xingji River, though both have low maximum recharge capacities. The MAR from Yufu River has a lower effect but the highest maximum recharge capacity. Furthermore, transferring some amount of the groundwater exploitation from eastern suburbs wells to western suburbs wells might reduce the impact on the water level of Baotu Spring.

Using image data from exposed fissures to measure apertures, a maximum Reynolds number ($Re \approx 2.24$) for karst groundwater flow was calculated, confirming laminar flow conditions and validating the EPM model's applicability for the studied karst system. (5) Groundwater flow and solute transport modeling was employed to assess the effects of MAR and extraction on groundwater levels and quality. The results indicate that MAR significantly raises karst groundwater levels, though efficiency varies by different MAR sources. Prolonged recharge with poor-quality MAR water may degrade groundwater quality, and the maximum allowable sulfate concentrations in MAR water to meet China's Class I, II, and III groundwater standards are 56.5 mg/L, 197.8 mg/L, and 339.1 mg/L, respectively. Finally, poor quality of MAR water would negatively affect karst groundwater, and there is a linear relationship between the concentration of hydrochemical component in MAR water and karst groundwater, allowing for the pre-setting of karst groundwater quality targets and the determination of minimum standards for MAR water quality based on this relationship.

Overall, the methodology proposed in this study effectively analyzes the impacts of MAR and extraction on groundwater level and quality. The integrated approach leverages multi-source data to achieve quantitative results. These findings provide a reference for MAR implementation in temperate semi-arid fissured karst systems with hydrogeological conditions similar to the Baotu Spring area.

~~In summary, the MAR projects in the Baotu Spring area of Jinan City have significantly impacted the dynamics of karst groundwater level and quality. Proper planning and monitoring of the amount and quality of MAR and groundwater exploitation are essential for maintaining groundwater levels, ensuring continuous spring flow, and safeguarding groundwater quality.~~

Statements and Declarations

Data availability

The data underlying this article were provided by 801 Institute of Hydrogeology and Engineering Geology, Shandong Provincial Bureau of Geology & Mineral Resources by permission. Data will be shared on request to the corresponding author with permission.

Author Contribution

The respective contributions of all authors to this paper are as follows:

Cao H.: Conceptualization, Methodology, Writing-Original Draft.

Dong W. H.: Writing-Review and Editing, Supervision, Project administration.

Hu C. P., Chen H. L.: Resources, Funding acquisition, Investigation, Data Curation.

Qian J. L.: Investigation, Data Curation.

Liu C. W., Lyu M. H., Gao S.: Resources, Funding acquisition.

Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

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