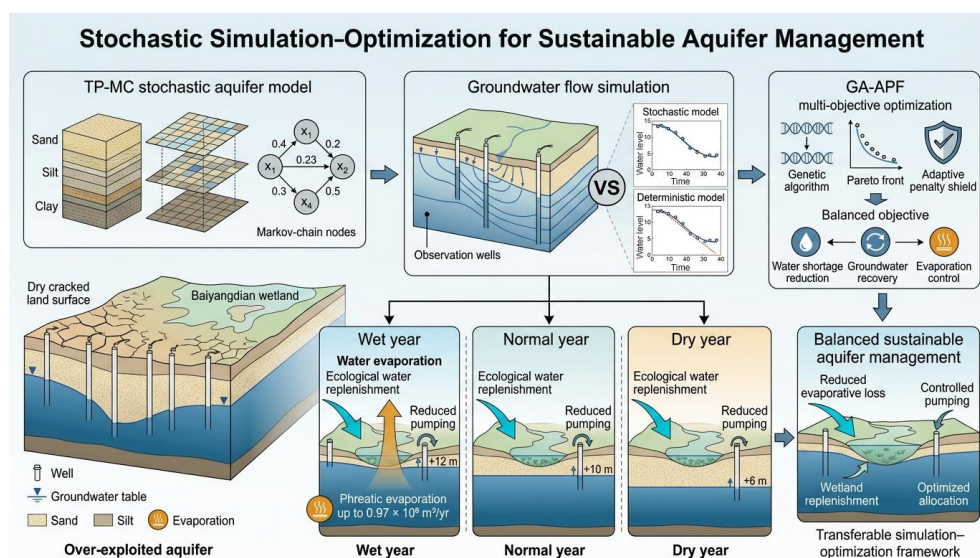




1 **A Stochastic Simulation-Optimization Approach for Groundwater Flow**
2 **Modeling and Management in an Over-Exploited Aquifer**
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14 GRAPHICAL ABSTRACT



15

16 Abstract

17 To guide the sustainable management of the over-exploited Western Baiyangdian
 18 Plain aquifer, this study developed an integrated simulation-optimization framework. A
 19 high-resolution stochastic aquifer model, constructed using Transition
 20 Probability/Markov Chain (TP-MC) geostatistics, was coupled with a groundwater
 21 flow model and a multi-objective optimization algorithm solved via a genetic algorithm
 22 with an adaptive penalty function (GA-APF). The stochastic model demonstrably
 23 outperformed its deterministic equivalent in replicating observed hydraulic heads.
 24 Scenario projections for 2035 indicate that combining ecological water replenishment
 25 with pumping reductions could raise groundwater levels by approximately 12, 10, and
 26 6 m in wet, normal, and dry years, respectively. However, this recovery concurrently
 27 increases phreatic evaporation, reaching up to $0.97 \times 10^8 \text{ m}^3/\text{yr}$ in wet years, revealing
 28 a critical management trade-off. The optimization model effectively balanced
 29 competing objectives, reducing projected water shortage rates to 11.86–14.06% by
 30 2035 while simultaneously mitigating evaporative losses. This framework provides a
 31 robust, transferable tool for restoring and optimally allocating water resources in
 32 stressed aquifer systems.



33 **Keywords: Integrated simulation-optimization, Transition Probability /**
34 **Markov Chain, Stochastic aquifer modeling, Water resources management,**
35 **Western Baiyangdian Plain**
36



1. Introduction

Groundwater serves as a vital freshwater resource for sustaining socioeconomic development and ecological balance, particularly in arid and semi-arid regions (Famiglietti, 2014). The North China Plain (NCP)—one of the world's most intensively exploited aquifer systems—has experienced severe groundwater depletion due to long-term over-extraction, leading to declining water tables (Liu et al., 2008; Cao et al., 2013), land subsidence (Gong et al., 2018), and ecosystem degradation, including wetland loss (Cui et al., 2002). In response, management measures such as pumping restrictions (Kendy et al., 2004), ecological water replenishment (Xia et al., 2011), and inter-basin water transfer projects (e.g., the South-to-North Water Diversion) have been implemented (Liu et al., 2013; Long et al., 2020). Nevertheless, the efficacy of these interventions is strongly modulated by complex aquifer heterogeneity and the dynamic interplay between climate change and anthropogenic pressures (Wada et al., 2012; Taylor et al., 2013). A clear understanding of how groundwater flow systems respond to such management actions is therefore essential for designing sustainable groundwater management strategies (Sophocleous, 2000).

Groundwater flow numerical modeling has been an essential tool for analyzing aquifer behavior and informing resource management since the 1970s (McDonald and Harbaugh, 1988; Anderson et al., 2015). A primary challenge in improving simulation reliability is the accurate characterization of aquifer heterogeneity, which governs the spatial variability of key hydrogeological parameters such as hydraulic conductivity (Gelhar, 1993; Renard and Allard, 2013). To represent such heterogeneity, geostatistical methods (e.g., kriging) and conditional stochastic simulation techniques (e.g., T-PROGS) have been widely adopted (Carle, 1999; Rubin, 2003). For example, Freeze et al. (2021) employed numerical experiments to investigate the influence of heterogeneity and anisotropy on groundwater flow systems. Despite these methodological advances, practical applications continue to be constrained by data scarcity and uneven spatial coverage, often resulting in overly simplified models (Hill and Tiedeman, 2007; Zhou et al., 2014).



66 In the context of groundwater management, simulation-optimization (S-O)
67 frameworks that integrate numerical models with evolutionary algorithms—such as
68 genetic algorithms (GAs)—have become powerful tools for addressing multi-objective
69 regulation problems (Reed et al., 2013; Singh, 2014). In the North China Plain, for
70 instance, studies by Zhang et al. (2014) and Li et al. (2017) employed numerical models
71 to predict groundwater-level changes under the South-to-North Water Diversion project
72 and to evaluate artificial-recharge scenarios. Similarly, Wang et al. (2020) developed a
73 model for the Baiyangdian area to assess groundwater recovery following ecological
74 water replenishment. To improve optimization efficiency, adaptive penalty functions
75 have also been introduced to handle constraints more effectively (Lin et al., 2004; Wu
76 and Simpson, 2005).

77 Despite these advances, significant knowledge gaps remain. First, inadequate
78 characterization of aquifer heterogeneity—largely due to limited borehole and
79 geophysical data—often leads to spatially smoothed parameter fields that poorly
80 represent actual aquifer architecture (Fiori et al., 2007; Bianchi and Pedretti, 2017).
81 This compromises the predictive accuracy of numerical models, especially in regions
82 with pronounced sedimentary heterogeneity (de Marsily et al., 2005; Zarlenga et al.,
83 2018). Second, most current simulation-optimization studies rely on loosely coupled
84 frameworks, in which the numerical model and the optimization algorithm are executed
85 sequentially rather than being iteratively integrated (He et al., 2009; Matott et al., 2009).
86 This approach introduces considerable computational inaccuracies and limits the
87 capacity to identify optimal solutions (Harp and Vesselinov, 2013). Third, focused
88 research on the Western Baiyangdian Plain—a critical area that has undergone intensive
89 groundwater management interventions since 2015—remains scarce (Zhang et al.,
90 2022). The combined impacts of pumping reduction, ecological water replenishment,
91 and natural heterogeneity on groundwater flow responses are still poorly quantified
92 (Huang and Pang, 2011; Cao et al., 2016; Liu and Zheng, 2021), highlighting the need
93 for advanced integrated S-O frameworks incorporating high-resolution heterogeneity
94 characterization (Knowling et al., 2019).



95 To bridge these gaps, this study focuses on the Western Baiyangdian Plain (WBP)
96 and aims to develop an integrated framework that couples advanced characterization of
97 aquifer heterogeneity with a tightly coupled simulation-optimization scheme. The
98 specific objectives are to: (1) construct a high-resolution groundwater flow model by
99 integrating multi-source data with conditional stochastic simulation techniques to
100 accurately represent aquifer heterogeneity; (2) establish a tightly coupled simulation-
101 optimization framework by embedding the numerical model within a multi-objective
102 evolutionary algorithm, thereby enabling dynamic feedback between the simulation and
103 optimization processes; and (3) propose optimal groundwater regulation strategies
104 under scenarios of pumping reduction and ecological replenishment, and evaluate their
105 impacts on both groundwater level recovery and potential environmental trade-offs.
106 This work is expected to enhance the realism of groundwater simulations and provide
107 a robust decision-support tool for sustainable groundwater management in the North
108 China Plain.

109 **2. Methodology**

110 **2.1 Study area**

111 The Western Baiyangdian Plain (WBP) is situated in the central North China Plain
112 (approximately 13,500 km²; Fig. 1). The topography is generally flat, sloping gently
113 from northwest to southeast (gradient <4‰), with elevations mostly below 100 m
114 except in the western Taihang foothills. Geomorphologically, it comprises four units:
115 (1) Old Alluvial-Pluvial Plain (30–100 m; 1–4‰ slope), (2) New Alluvial-Pluvial Plain
116 (10–30 m; 1–2‰ slope), (3) Alluvial Plain (~10 m; 0.5–1‰ slope), and (4) Lacustrine-
117 Alluvial Plain around Baiyang Lake (7–10 m; 0.2–0.7‰ slope).

118 The climate is continental monsoon (semi-humid to semi-arid), with a mean annual
119 temperature of 13.79°C and mean annual precipitation of 526 mm. Precipitation is
120 highly variable, with approximately 70% falling between June and September. Annual
121 evapotranspiration ranges from 350 to 500 mm. Major seasonal rivers (Juma, Tang) and
122 reservoirs (Wanguai, Xidayang, Angezhuang) constitute key surface water features.
123 Baiyang Lake, a critical wetland once prone to desiccation, has recovered significantly



124 due to large-scale ecological water replenishment projects (e.g., South-to-North Water
125 Diversion).

126 Groundwater occurs in a Quaternary unconsolidated sediment aquifer system,
127 classified into four groups (I–IV; Fig. 2). Groups I and II form the shallow system,
128 accounting for >80% of extractions due to the lack of regional aquitards and
129 commingled pumping, which has caused severe environmental issues (depression cones,
130 land subsidence, fissures). Groups III and IV constitute the deeper system, separated by
131 a continuous clay aquitard. Recharge originates from precipitation, surface water
132 seepage, and irrigation return flow; discharge is dominated by pumping. This long-term
133 over-exploitation underscores the urgent need for sustainable groundwater management
134 in the WBP.

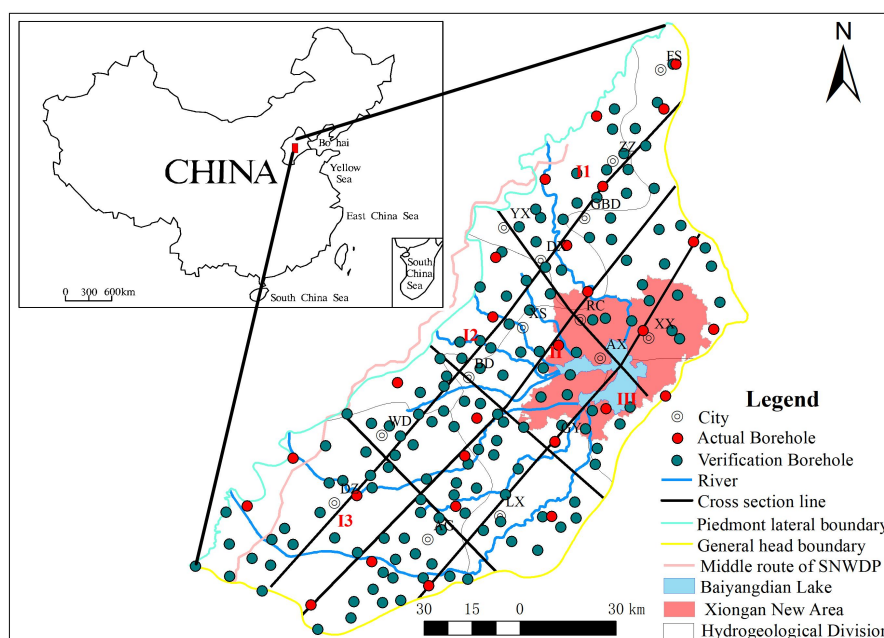


Fig.1. Location and model boundaries of the Baiyangdian Lake Basin, China

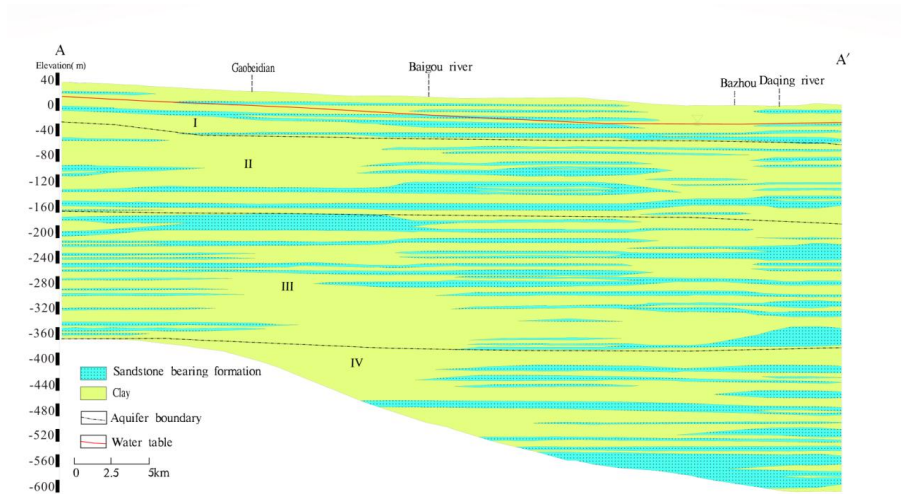


Fig.2. Hydrogeological cross-section of the plain area of the Baiyangdian Lake Basin, China

2.2 Data Sources

The study utilized a comprehensive dataset for the Western Baiyangdian Plain, summarized in Table 1.

Table 1. Summary of data sources for the Western Baiyangdian Plain study

Data Category	Specific Content	Temporal Range / Source	Main Use
Hydrogeological data	Lithology and stratigraphic information from 200 boreholes	Regional geological survey	Construction of aquifer structure model;3D lithofacies characterization Calculation of precipitation infiltration recharge; model source/sink terms
Meteorological data	Monthly precipitation and evapotranspiration	2018–2019 / China Meteorological Administration	Quantification of groundwater recharge from rivers, reservoirs, and water transfers
Hydrological data	River discharge, ecological water replenishment from the SNWDP and reservoirs	Governmental records	Model calibration and validation, assessment of model reliability
Groundwater monitoring data	Regional groundwater level from observation wells	2018–2019	Baseline-year water use analysis; construction of optimal regulation model for planning year
Socioeconomic data	Agricultural, industrial, domestic water use;2035 water demand projections for 2035	2019 statistical records / regional development plans	

2.3 Development of the Stochastic Groundwater Flow Model



144 **2.3.1 Groundwater Flow Numerical Simulation**

145 The multilayer aquifer system is conceptualized as two main units: a combined
 146 shallow system (Aquifers I & II) and a distinct deep system (Aquifer III), separated by
 147 a regional aquitard (Fig. 1). Grouping Aquifers I and II is justified due to discontinuous
 148 intervening aquitards and strong hydraulic connectivity resulting from pervasive
 149 pumping. In contrast, the deep system is isolated by a continuous aquitard.

150 Groundwater flow is predominantly horizontal due to extensive lateral continuity,
 151 with recharge and discharge exhibiting transient behavior. Pronounced heterogeneity in
 152 hydraulic parameters is incorporated. Consequently, the Baiyangdian Lake Basin (BLB)
 153 groundwater system is represented as a three-dimensional, three-layer transient flow
 154 model with heterogeneity and horizontal anisotropy (Chi et al., 2022). All lateral
 155 boundaries are simulated as general-head boundaries to account for potential
 156 groundwater exchange.

157 **2.3.2 Spatial Stochastic Model of Aquifer Hydraulic Conductivity**

158 To capture the pronounced heterogeneity of the aquifer system, a three-dimensional
 159 stochastic lithology model was developed using the Transition Probability-Markov
 160 Chain (TP-MC) method, constrained by lithological data from approximately 200
 161 boreholes.

162 (1) Lithofacies Classification and Model Theory

163 The aquifer media were classified into three lithofacies: fine sand (FS), coarse sand
 164 and gravel (CSG), and silty clay (SC) (Ritzi et al., 2007).

165 The TP-MC model is governed by the transition probability, $t_{jk}(h)$, defined as the
 166 conditional probability of transitioning from lithofacies j to lithofacies k over a lag
 167 distance vector h (Carle and Fogg, 1997; Weissmann and Fogg, 1999):

$$168 \quad t_{jk}(h) = P(k | j) \quad (1)$$

169 The three-dimensional Markov chain model was constructed based on a transition
 170 rate matrix R . For any given direction ϕ , the corresponding transition probability matrix
 171 $T(\phi)$, is computed via matrix exponential (Koltermann et al., 1996):



$$T(h_\phi) = \exp(R_\phi h_\phi) \quad (2)$$

where h_ϕ is the lag distance in direction ϕ . In accordance with Walther's law, the lateral transition rates were derived from their vertical counterparts to characterize the three-dimensional distribution of lithofacies (Carle et al., 1997; Weissmann et al., 1999).

(2) Conditional Simulation and Model Validation

Conditional simulation of lithofacies was implemented using a hybrid approach that integrates Sequential Indicator Simulation (SIS) with the Simulated Annealing (SA) algorithm (Carle et al., 1997; Deutsch et al., 1998).

The local conditional probability, $P(j|x)$, for the occurrence of facies j at an unsampled location x was estimated using cokriging (Carle et al., 1997).

182

$$P(j|x) = \sum_{i=1}^n \lambda_i I_i \quad (3)$$

where I_i are indicator values from neighboring data, and λ_i are cokriging weights.

The initial SIS model was iteratively optimized to minimize the discrepancy between the simulated transition probabilities, $t_{jk}(h)_{sim}$, and their measured counterparts, $t_{jk}(h)_{meas}$. This was achieved by minimizing the following objective function O (Carle and Fogg, 1997; Deutsch and Journel, 1998):

189

$$O = \sum_{j=1}^n \sum_{k=1}^n \sum_h [t_{jk}(h)_{sim} - t_{jk}(h)_{meas}]^2 \quad (4)$$

Based on the calibrated vertical and lateral transition rate matrices, thirty stochastic lithofacies realizations were generated. The model's predictive accuracy was evaluated using 30 validation boreholes (15% of total dataset), with a consistency threshold $\Psi_0 = 0.5$. The overall model consistency across all realizations ranged from 0.54 to 0.63, confirming the reliability of the stochastic simulations (Proce et al., 2004).

(3) Upscaling to Hydraulic Conductivity (K)

The 3D stochastic lithofacies realizations were upscaled to generate corresponding 2D horizontal hydraulic conductivity (K) fields for numerical groundwater flow modeling. This was achieved using a volume-weighted arithmetic averaging method



(Eq. 2.5). The process resulted in 30 equally probable K-field realizations, each capturing the spatial heterogeneity inherent in the aquifer system.

$$HK_h = \sum_{g=1}^n k_{lg} h_{lg} \quad (5)$$

where K_h is the effective hydraulic conductivity of a grid cell. k_{lg} is the hydraulic conductivity of an individual lithological unit within corresponding vertical column, h_{lg} is the thickness of that unit (serving as the weight), and n is the total number of such units in the column.

2.4 Multi-Objective Groundwater Management Model

2.4.1 Optimization Model Formulation

(1) Objectives:

The management model has two primary objectives: first, to minimize the total water shortage rate across the 19 management subunits; and second, to minimize the average depth to groundwater across all subunits.

$$F_1 = \min \sum_{i=1}^a \sum_{k=1}^3 \left(\frac{D_{ik} - Q_{jk}}{D_{jk}} \right)^2 \quad (6)$$

$$F_2 = \min \sum_{i=1}^a \frac{h_{at} - h_{amin}}{h_0 - h_{amin}} \quad (7)$$

where i represents the administrative division at the county/district scale (19 management zones; $a = 1$ to 19), a denotes the number of management zones, with a ranging from 1 to 19; D_{ik} is the groundwater demand of the k -th sector in the i -th management zone (10^4 m^3), Q_{jk} is the groundwater supply allocated to the k -th sector in the i -th management zone (10^4 m^3), and D_{0ik} is the total water demand of the k -th sector in the i -th management zone (10^4 m^3). T_i represents the number of years required for the i -th management zone to achieve the appropriate groundwater level depth, h_{at} denotes the calculated groundwater level depth (m) for the a -th management zone at time step t , h_{amin} is the ecologically suitable groundwater level depth for the a -th management zone (m), and h_0 is the water table depth at the end of the baseline year



225 2019 (m).

226 (2) Constraints:

227 ①Constraint on Groundwater Depth

$$228 \quad h_{imin} \leq h_{it} \leq h_{imax} \dots\dots\dots(8)$$

229 Where h_{it} is the simulated groundwater depth (m) in management zone i during
 230 period t . h_{imin} is the permissible minimum groundwater depth (m) for zone i (the
 231 ecologically suitable depth), h_{imax} is the permissible maximum groundwater depth (m)
 232 for zone i .

233 ②Water Balance Constraint

$$234 \quad \Delta V_{it} = P_{it} + R_{it} + N_{it} + M_{it} - Q_{it} - E_{it} - O_{it} \dots\dots\dots(9)$$

235 Where ΔV_{it} is the groundwater storage change (10^4 m^3) in zone i during period t .
 236 P_{it} is precipitation infiltration recharge (10^4 m^3), R_{it} is lateral recharge (10^4 m^3), N_{it} is
 237 surface water recharge (10^4 m^3), M_{it} is irrigation return flow(10^4 m^3), Q_{it} is groundwater
 238 extraction (10^4 m^3), E_{it} is phreatic evaporation (10^4 m^3), O_{it} is lateral outflow (10^4 m^3).

239 ③Water Replenishment Constraint

$$240 \quad O_i \leq D_i \dots\dots\dots(10)$$

241 Where O_i is the groundwater supply (10^4 m^3) allocated to zone i , and D_i is the
 242 groundwater demand (10^4 m^3) of zone i .

243 ④Groundwater Extraction Constraint

$$244 \quad O_i \leq D_{imax} \dots\dots\dots(11)$$

245
 246 Where D_{imax} is the maximum groundwater extraction capacity (10^4 m^3) for zone i .

247 ⑤Non-negativity Constraint

$$248 \quad O_i \geq 0 \dots\dots\dots(12)$$

249 **2.4.2 Solution Algorithm: Adaptive Penalty Function Genetic Algorithm (APF-GA)**

250 The multi-objective optimization problem was transformed into a single-objective
 251 formulation using the ideal point method combined with a weighting scheme (Hsu and



252 Cheng, 2002; Cheng et al., 2008). To handle constraints effectively, an Adaptive Penalty
 253 Function (APF) was integrated into a Genetic Algorithm (GA), forming an APF-GA
 254 framework (Deb, 2000). This framework dynamically adjusts penalty coefficients
 255 based on the feasibility proportion of the evolving population (Wu and Simpson, 2001).
 256 Key GA parameters were set as follows: population size of 100, maximum of 200
 257 generations, crossover probability of 0.80, and mutation probability of 0.05, consistent
 258 with common practices for groundwater management problems (Singh and Minsker,
 259 2008). Finally, the optimization procedure was executed in a tightly coupled manner
 260 with the numerical groundwater flow model.

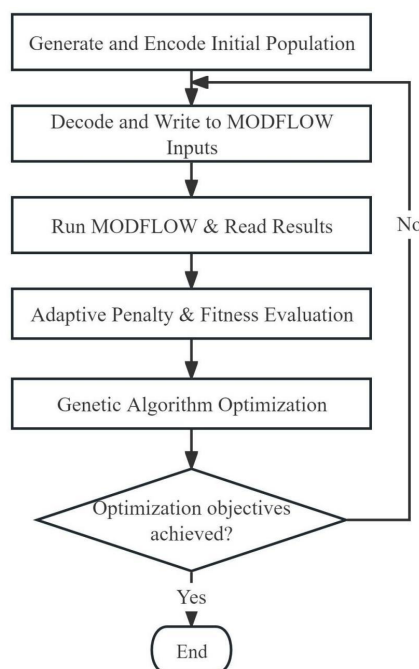


Fig.3. Flowchart of the Adaptive Penalty Function Genetic Algorithm

2.4.3 Water Demand and Supply Projection

Water demands for domestic, industrial, and agricultural sectors in 2035 were projected using a quota-based method informed by regional water efficiency policies (Wang et al., 2016). Concurrently, available water supplies—including surface water sources (e.g., South-to-North Water Diversion Project and local reservoirs) and groundwater—were estimated based on master planning documents for the basin (Fang



et al., 2018).

3.Results

3.1 Performance of the Stochastic Groundwater Flow Model

3.1.1 Characterization of Aquifer Heterogeneity

A high-resolution heterogeneous aquifer model was successfully constructed using the TP-MC geostatistical method. The aquifer media were classified into three lithofacies: fine sand, sandy gravel/coarse sand, and silty clay. The model accurately reproduces the spatial distribution and architectural patterns of these facies (Figs. 4). Validation against borehole data yielded an overall simulation consistency ranging from 0.54 to 0.63. The equivalent horizontal hydraulic conductivity (K) field, derived from the stochastic lithofacies model (e.g., Realization #30 in Fig. 5), exhibits pronounced heterogeneity. Notably, within the alluvial-pluvial fan units, the K field displays a clear decreasing trend from the western piedmont zone eastward.

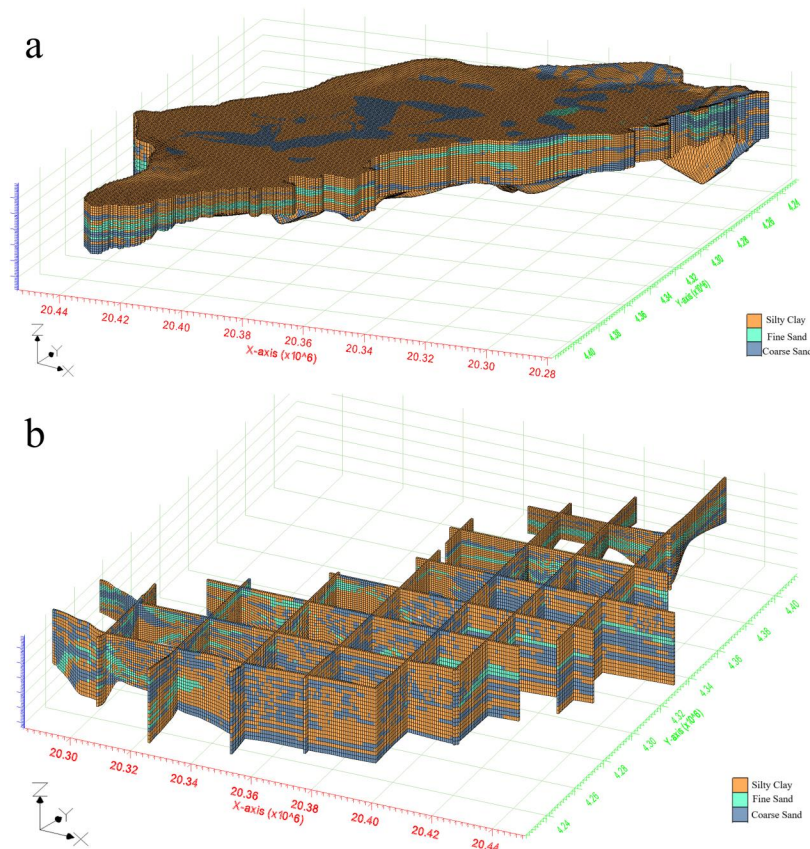


Fig. 4. Sedimentary Facies in the Heterogeneous Structural Model(a Three-Dimensional Distribution ,b Two-Dimensional Cross-Sectional View)

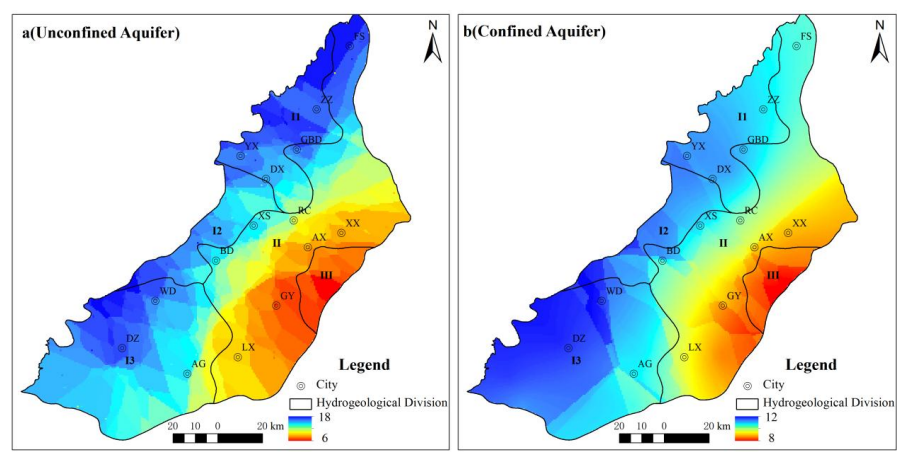


Fig. 5. Hydraulic conductivity fields of aquifers after stochastic model simulation



3.1.2 Model Calibration and Validation

The stochastic modeling approach demonstrated superior performance compared to the deterministic model in replicating the dynamics and spatial patterns of the observed groundwater flow system. The simulated groundwater flow directions and the extent of depression cones generated by the stochastic model showed close agreement with field observations, as illustrated in Fig. 6.

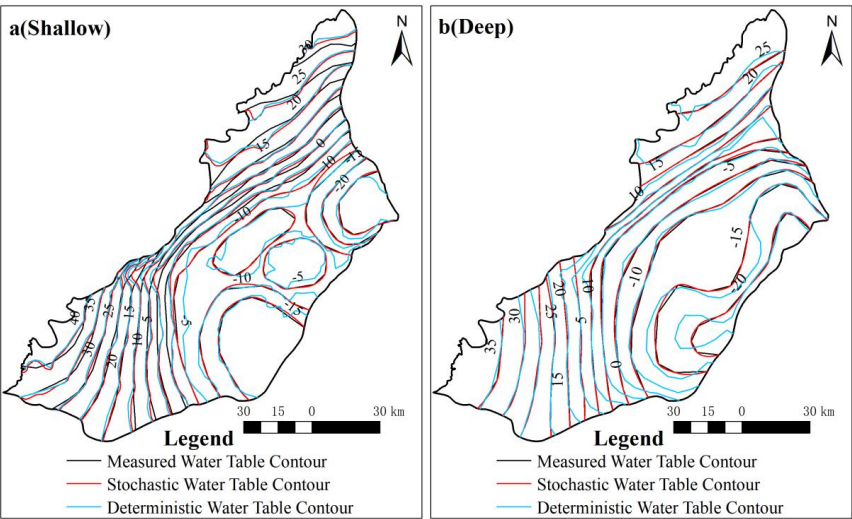


Fig. 6. Match between simulated and measured groundwater flow fields

The stochastic model ensemble demonstrated a superior fit to observed water levels at monitoring wells compared to the deterministic model (Fig. 7). As shown in Fig. 8, the mean error of the stochastic ensemble decreased with an increasing number of realizations, converging toward a stable value, whereas the error of the deterministic model remained constant. Among all realizations, Realization #30 yielded the smallest error and was therefore selected for subsequent scenario analysis and predictions.

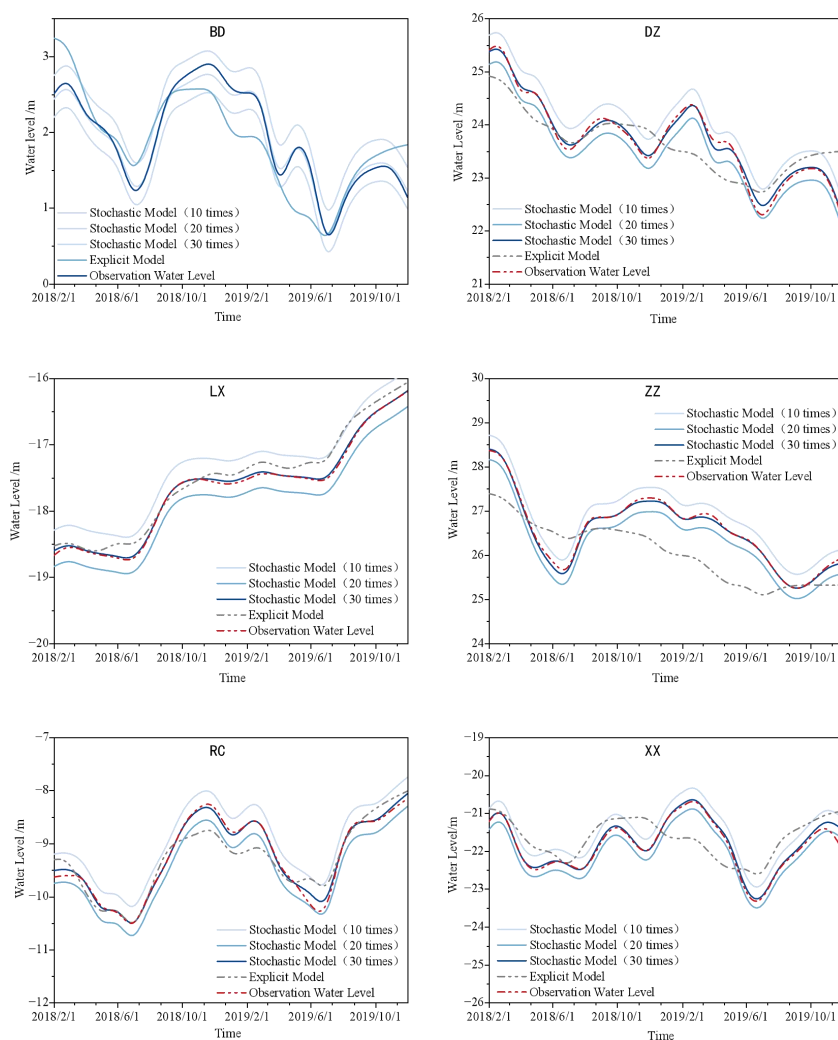


Fig. 7. Time-series of simulated versus observed groundwater levels in representative monitoring wells.

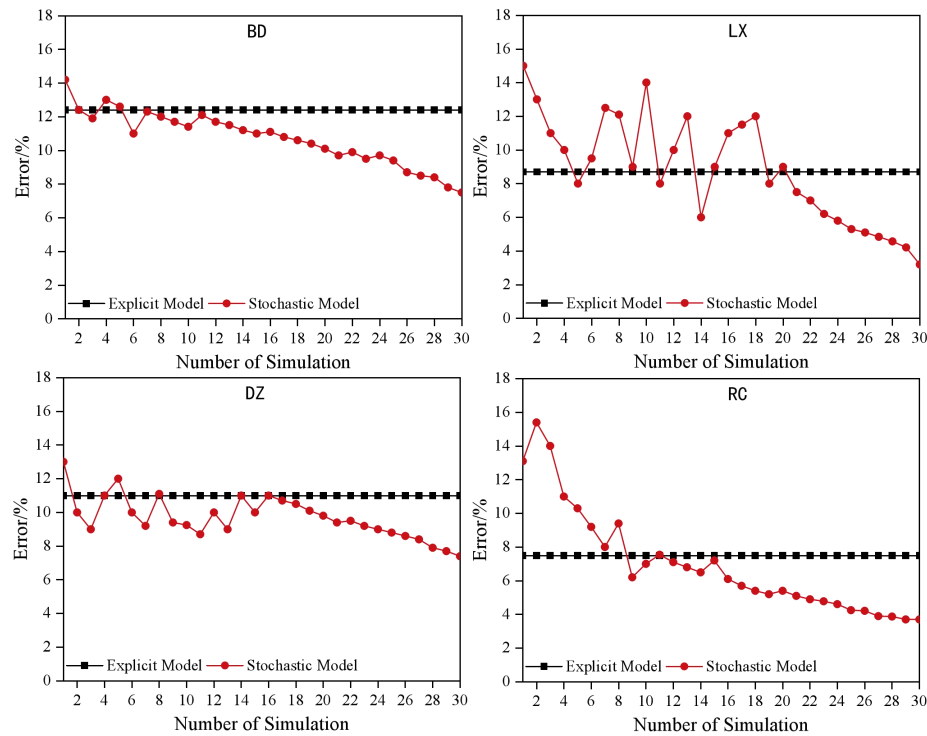


Fig. 8. Error analysis between observed and simulated groundwater levels

Table 2 Average annual groundwater budget (2018–2019) ($10^8 \text{ m}^3/\text{a}$)

Balance Component	Shallow Aquifer			Deep Aquifer		
	Stochastic	Deterministic	Proportion	Stochastic	Deterministic	Proportion
Precipitation	10.82	10.15	60.24%	-	-	-
Infiltration	3.91	3.63	21.77%	0.1	0.08	8.13%
Lateral Inflow	0.88	0.95	4.90%	-	-	-
River-channel	2.02	1.75	11.25%	-	-	-
Infiltration	0.2	0.19	1.11%	-	-	-
Irrigation Return	0.13	0.12	0.72%	1.13	1.04	91.87%
Flow	17.96	16.79	-	1.23	1.12	-
Baiyangdian	1.03	0.98	4.50%	0.12	0.1	5.04%
Lake Infiltration	20.93	20.85	91.36%	2.24	2.17	94.12%
Vertical Leakage	0.24	0.19	1.05%	-	-	-
Phreatic	0.71	0.67	3.10%	0.02	0.03	0.84%
Evaporation	22.91	22.69	-	2.38	2.3	-
Vertical Leakage	-4.95	-5.9	-	-1.15	-1.18	-
Total Inflow						
Total Outflow						
Budget Balance						

The groundwater budget for the shallow aquifer during the calibration period (2018–2019) indicated a persistent water deficit. Average annual recharge was $17.96 \times$



310 $10^8 \text{ m}^3/\text{a}$, while discharge reached $22.91 \times 10^8 \text{ m}^3/\text{a}$, resulting in a net depletion of 4.95
311 $\times 10^8 \text{ m}^3/\text{a}$ (Table 2). The notable differences in these water balance components,
312 compared to the deterministic model, underscore the stochastic model's enhanced
313 capability to capture the impact of aquifer heterogeneity on regional groundwater fluxes.

314 **3.2 Prediction of Groundwater Level Trends under Future Scenarios**

315 **3.2.1 Scenario Setup**

316 To inform sustainable groundwater management, a set of future scenarios was
317 developed around three key drivers: groundwater extraction rates, ecological water
318 replenishment volumes, and precipitation patterns. The scenario design adhered to the
319 following principles: (1) climate-informed precipitation projections based on
320 downscaled CMIP6 models; (2) priority-driven water allocation prioritizing domestic
321 use; and (3) restoration-focused management emphasizing enhanced replenishment and
322 reduced extraction.

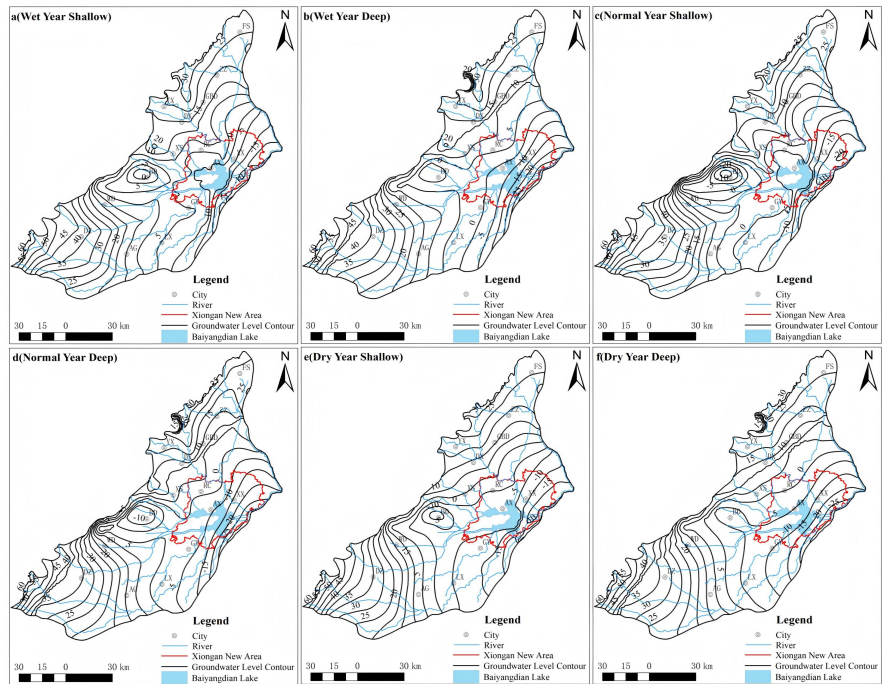
323 Future precipitation projections were derived from three CMIP6 climate scenarios
324 (SSP1-2.6, SSP2-4.5, SSP5-8.5). The sustainable SSP1-2.6 scenario, projecting a slight
325 decrease in mean annual precipitation (approximately 10.14 mm) relative to the
326 historical baseline, was selected as the primary climate forcing. Ecological water
327 replenishment was modeled following the "Action Plan for Comprehensive
328 Management of Groundwater Over-exploitation in North China," using major rivers as
329 conveyance pathways with recharge volumes at maximum planned capacities.
330 Groundwater extraction reductions were designed based on provincial policy targets,
331 implementing a 25% reduction in shallow aquifer pumping and a 20% reduction in deep
332 aquifer pumping relative to the 2019 baseline.

333 **3.2.2 Groundwater Level Responses**

334 Under the combined implementation of extraction reduction and ecological
335 replenishment, simulated regional groundwater levels in 2035 exhibit a clear overall
336 recovery trend across all scenarios (Fig. 9). In the shallow aquifer, the projected water-
337 level rise relative to baseline is approximately 12 m in wet years, 10 m in normal years,
338 and 6 m in dry years. Changes in the deep aquifer follow a similar spatiotemporal



339 pattern but are of smaller magnitude.



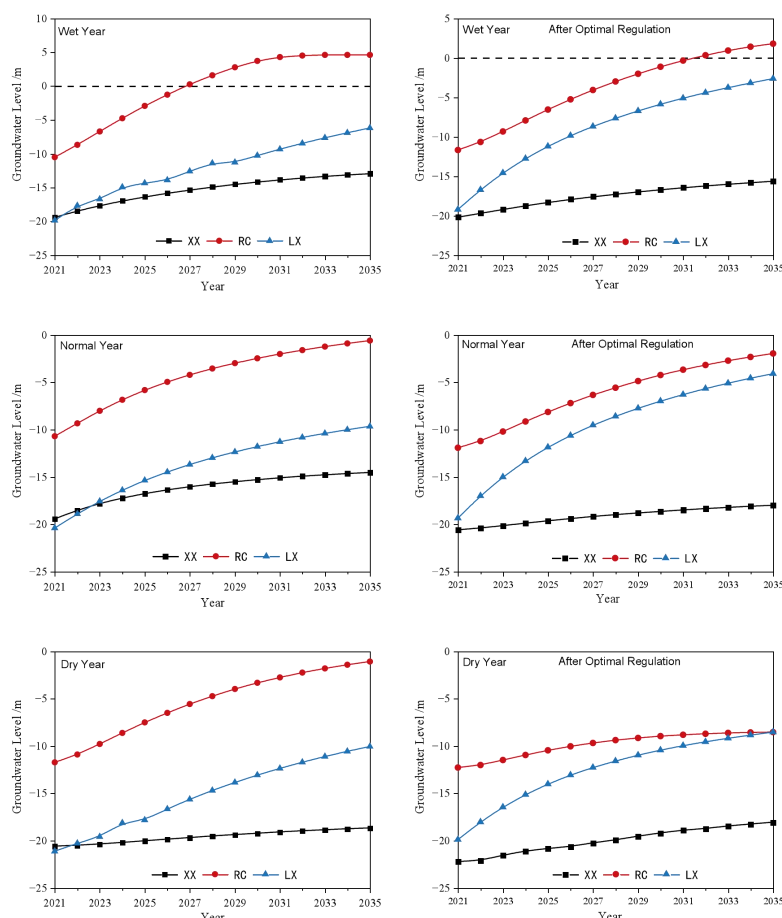
340
341 Fig. 9. Groundwater level contours for different hydrological year types(2035)

342 Spatially, the most significant groundwater level changes occur in two distinct
343 zones: (1) the region north of the Xiongxian–Rongcheng–Xushui line, and (2) the area
344 south of the Gaoyang–Wangdu line (Fig. 10). Within these responsive zones, the
345 simulated maximum rise in shallow groundwater levels reaches approximately 31 m
346 under wet-year conditions, 20 m under normal conditions, and 2 m under dry conditions.
347 The peak response in the deep aquifer is concentrated along the Wangdu–Baoding–
348 Xushui–Gaobeidian line, with maximum water-level changes ranging from 18–20 m in
349 wet years to 3–16 m in dry years.

350 The simulated management scenarios lead to differential recovery patterns among
351 major historical groundwater depression cones (Fig. 10). Specifically: (1) the
352 Rongcheng cone exhibits the most substantial recovery, with water levels rising by
353 approximately 15.14 m in wet years, 10.12 m in normal years, and 7.66 m in dry years;
354 (2) the Gaoliqing cone shows significant but more stable recovery across climates, with
355 rises of 13.67 m (wet), 12.74 m (normal), and 11.07 m (dry); and (3) the Xiongxian



356 cone demonstrates more modest recovery, with increases of 6.47 m, 4.90 m, and 3.93
357 m under wet, normal, and dry conditions, respectively. This hierarchy of recovery
358 (Rongcheng > Gaoliqing > Xiongshan) underscores the varying hydraulic connectivity
359 and stress history of each cone within the regional flow system.



360
361 Fig. 10. Water level change at the center of the groundwater depression cone under different
362 hydrological year types

363 The simulated groundwater budget components exhibit systematic variations across
364 climate scenarios (Table 3). Key recharge fluxes show strong dependence on
365 precipitation: (1) precipitation infiltration increases from $7.83 \times 10^8 \text{ m}^3$ in dry years to
366 $11.76 \times 10^8 \text{ m}^3$ in wet years; (2) river infiltration shows a corresponding rise from 1.01
367 $\times 10^8 \text{ m}^3$ to $1.64 \times 10^8 \text{ m}^3$. A critical finding is the substantial increase in phreatic

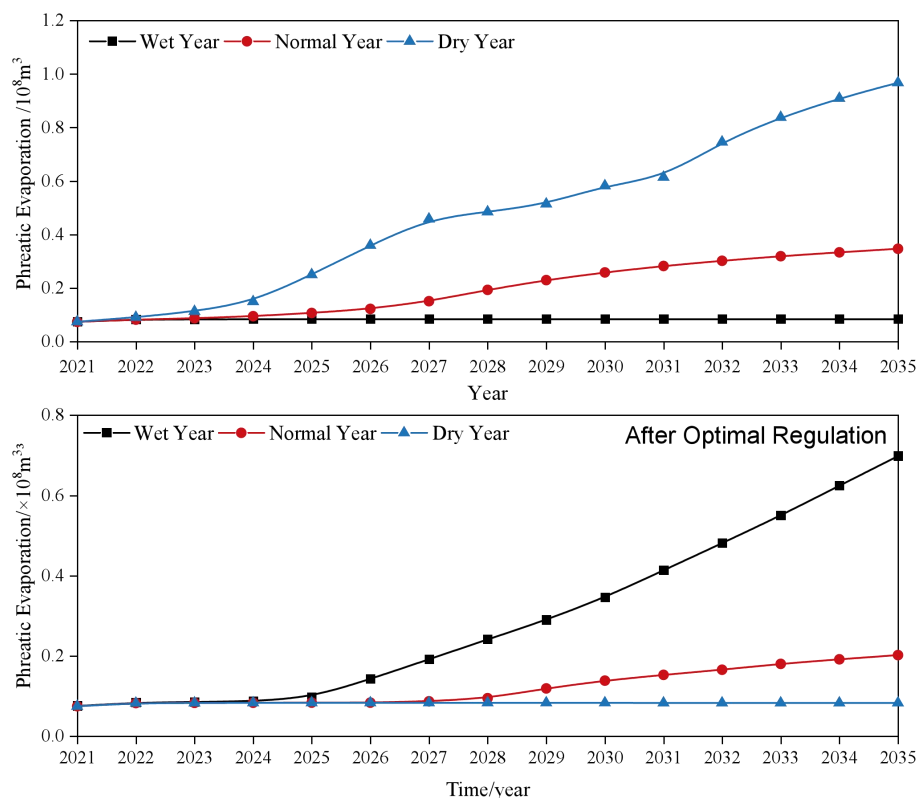


368 evaporation, which rises from $0.08 \times 10^8 \text{ m}^3$ in dry years to $0.97 \times 10^8 \text{ m}^3$ in wet years.
 369 This nearly order-of-magnitude increase, a direct consequence of rising water tables
 370 (Fig. 11), highlights a significant trade-off: while managed aquifer recovery is
 371 successful, it concurrently elevates the risks of increased evaporative losses and
 372 potential soil salinization.

373 Table 3 Groundwater balance under different scenarios in 2035 (10^4 m^3)

Balance Component		Wet Year	Normal Year	Dry Year
Recharge	Precipitation Infiltration	117581.16	100218.87	78340.11
	Lateral Inflow	6963.20	7212.90	10764.16
	River Channel Infiltration	15272.99	13936.47	10143.25
	Baiyangdian Lake Infiltration	234.32	535.34	1232.91
	Artificial Extraction	181486.45	181486.45	181486.45
Discharge	Lateral Outflow	20527.5	18821.59	14221.32
	Phreatic Evaporation	9687.51	3479.04	844.69

374



375

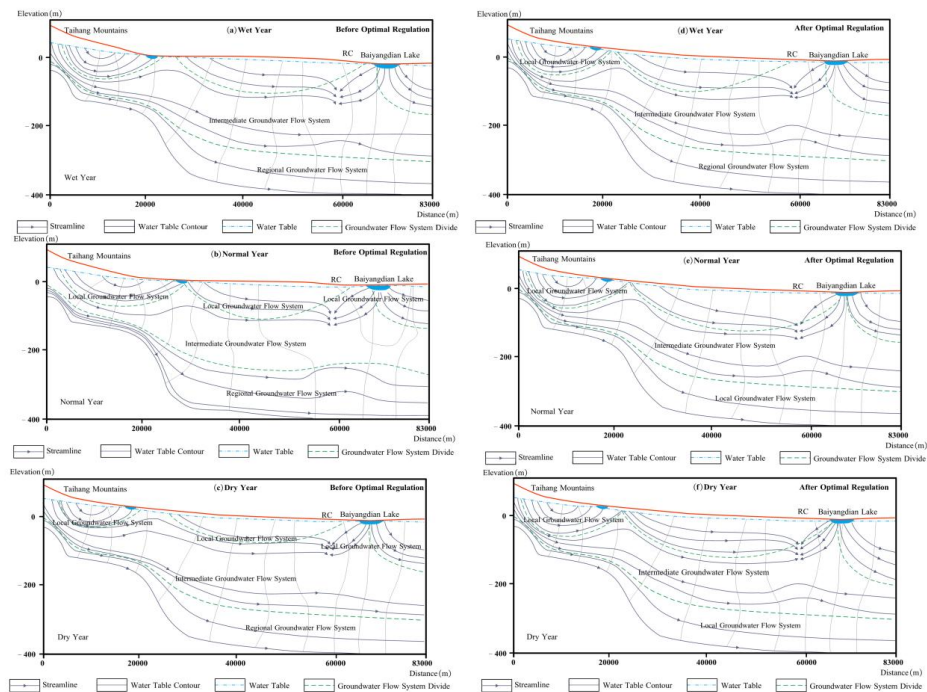
376 Fig. 11. Variation in phreatic evaporation across different hydrological year types

377 3.2.3 Evolution of Vertical Groundwater Flow Systems

378 The preceding analysis demonstrates that precipitation, ecological replenishment,



379 and extraction rates are key drivers altering the characteristics of local groundwater
380 flow systems (Fig. 12). To deepen the understanding of how these changes in recharge
381 and discharge affect vertical groundwater circulation, a comparative analysis of the
382 resulting flow systems was conducted, assuming that a dynamic equilibrium (quasi-
383 steady state) is approached by the end of the simulation period (2035).



384 Fig. 12. Schematic diagram of groundwater flow patterns in typical cross-sections under different
385 hydrological year types
386

387 The analysis demonstrates that variations in precipitation, ecological water
388 replenishment, and groundwater extraction collectively reshape the architecture of local
389 groundwater flow systems. Under scenarios characterized by increased recharge and
390 reduced extraction, the active groundwater circulation depth becomes progressively
391 shallower, and its areal extent contracts. This trend is quantified across major
392 geomorphic units: (1) in the Alluvial-Pluvial Plain, circulation depth decreases from
393 approximately 100 m in dry years to about 60 m in wet years; (2) in the Alluvial Plain,
394 it decreases from 150 m to 120 m; and (3) in the Alluvial-Lacustrine Plain, a more
395 moderate reduction occurs, from 120 m to 110 m.



3.3 Optimal Groundwater Regulation Based on Multi-Objective Management

3.3.1 Optimization Model and Scheme

A multi-objective optimization model was developed and tightly coupled with the validated stochastic groundwater flow model. The model aimed to simultaneously minimize (1) the total regional water shortage rate and (2) the average depth to the water table across all 19 management subunits. The resulting optimal management scheme prioritizes ecological water replenishment via selected river channels and implements spatially differentiated groundwater pumping reductions, with cutbacks ranging from 20% to 30% based on the severity of historical over-exploitation in each region.

3.3.2 Regulation Results and Analysis

The optimization results for the baseline year (2019) demonstrate a significant improvement in regional water supply reliability. Total water shortage decreased from $534.72 \times 10^6 \text{ m}^3$ to $477.31 \times 10^6 \text{ m}^3$, corresponding to a reduction in the shortage rate from 21.43% to 19.13%. Furthermore, the spatial distribution of water shortage rates across computational units became more equitable and improved markedly, as shown in Fig. 13. These outcomes collectively validate the effectiveness and practical applicability of the developed optimization model.

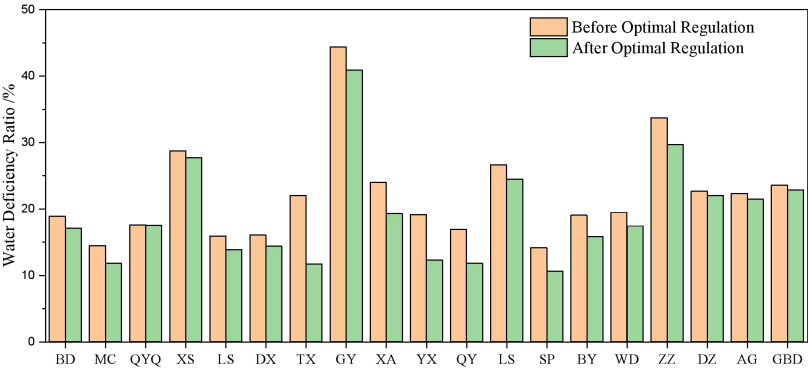
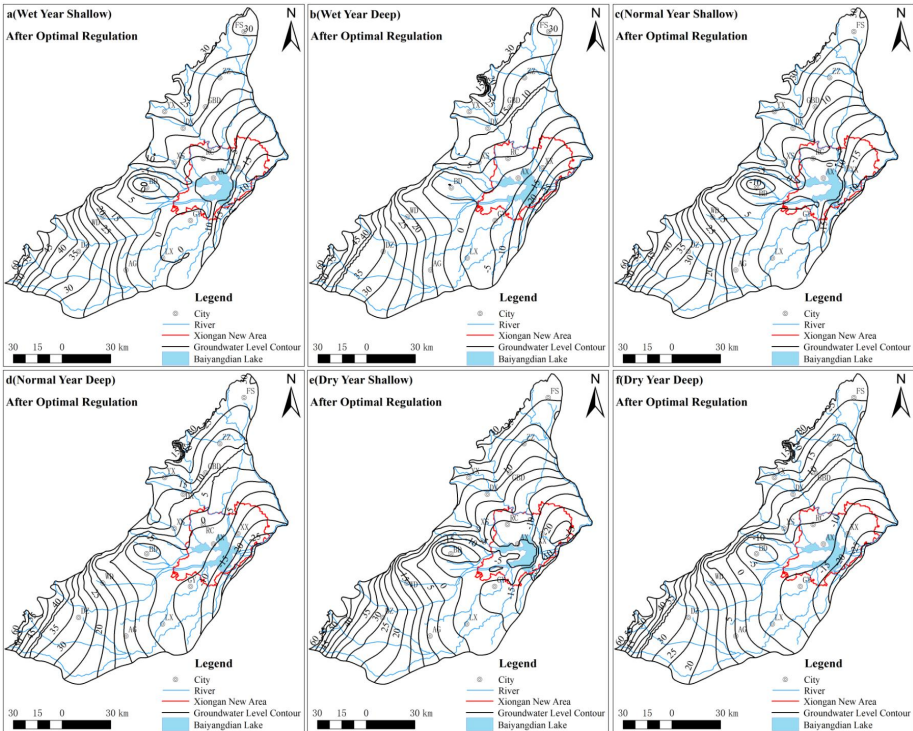


Fig. 13. Water shortage rate comparison (before vs. after optimization) for computational units in the western plain of Baiyangdian Lake (2019)

Under the optimal regulation scheme, groundwater levels are projected to maintain an overall rising trend through 2035. However, the rate of recovery is more measured and sustainable compared to the steep rise projected under the unregulated scenario (Fig. 14). Importantly, a discernible degree of water-level recovery is also achieved at the



420 centers of major historical depression cones, indicating that the optimization model
421 successfully reconciles the regional recovery goal with the targeted remediation of
422 critically over-exploited zones.



423
424 Fig. 14. Groundwater level contour maps after optimal regulation for different hydrological year
425 types (2035)

426 Table 4 Groundwater balance after optimal regulation for the planning year (2035)

Balance Component		Wet Year	Normal Year	Dry Year
Recharge	Precipitation Infiltration	117581.16	100218.87	78340.11
	Lateral Inflow	5476.02	5686.32	10288.77
	River Channel Infiltration	16362.79	15167.3	12129.5
	Baiyangdian Lake Infiltration	211.11	437.92	1075.79
Discharge	Artificial Extraction	162486.45	162486.45	162486.45
	Lateral Outflow	21028.54	19538.18	15314.62
	Phreatic Evaporation	6984.31	2025.61	832.99

427 A key outcome of the optimal management scheme is the substantial reduction of
428 non-beneficial phreatic evaporation. Compared to the unregulated scenario, phreatic
429 evaporation under wet-year conditions is reduced by $0.27 \times 10^8 \text{ m}^3/\text{a}$, declining from
430 $0.97 \times 10^8 \text{ m}^3/\text{a}$ to $0.70 \times 10^8 \text{ m}^3/\text{a}$ (Table 4). This reduction quantitatively demonstrates
431 the model's effectiveness in resolving a critical trade-off: it simultaneously improves



432 water supply reliability while strategically controlling water table rise, thereby
 433 minimizing unproductive evaporative losses.

434 Implementation of the optimized management scheme induces systematic
 435 adjustments in the configuration of local groundwater flow systems (Table 5).
 436 Specifically, the active circulation depth becomes slightly shallower overall. Spatially,
 437 the areal extent of local flow systems contracts in the Alluvial-Pluvial Plain and the
 438 Lacustrine-Alluvial Plain but exhibits a slight expansion in the Alluvial Plain. This
 439 spatial reorganization of groundwater flow pathways directly contributes to the
 440 previously noted reduction in phreatic evaporation, particularly in topographically low-
 441 lying and ecologically vulnerable areas.

442 Table 5 Characteristics of changes in local groundwater flow systems along typical cross-sections
 443 under different optimal regulation scenarios in 2035

Period	Location	Circulation Depth	Change vs. Pre-regulation	Flow Path Length	Change vs. Pre-regulation
Wet Year	Alluvial-Pluvial Plain	<50 m	Decreased by 10 m	10 km	Decreased by 2 m
	Alluvial Plain	<130 m	Increased by 10 m	22 km	Increased by 2 m
	Alluvial-Lacustrine Plain	<100 m	Decreased by 10 m	10 km	Decreased by 2 m
Normal Year	Alluvial-Pluvial Plain	<60 m	Decreased by 10 m	10 km	Decreased by 2 m
	Alluvial Plain	<130 m	Increased by 10 m	27 km	Increased by 2 m
	Alluvial-Lacustrine Plain	<100 m	Decreased by 10 m	10 km	Decreased by 2 m
Dry Year	Alluvial-Pluvial Plain	<100 m	No change	12 km	No change
	Alluvial Plain	<160 m	Increased by 10 m	31 km	Increased by 1 m
	Alluvial-Lacustrine Plain	<110 m	Decreased by 10 m	9 km	Decreased by 1 m

444

445 In this study, the main factors affecting the natural attenuation of naphthalene were
 446 analyzed by the samples of groundwater in the riparian infiltration zone, and then the
 447 influence mechanism of DOM on the natural attenuation of naphthalene was identified
 448 by the biodegradation experiment, the key parameter of natural attenuation of
 449 naphthalene under the influence of DOM were obtained, especially the parameter of
 450 competitive inhibition of DOM on the process of naphthalene biodegradation. Finally,



451 numerical model was used to characterize the natural attenuation of naphthalene under
452 the influence of DOM during river water infiltration, and the natural attenuation
453 potential of naphthalene in the riparian infiltration zone was quantitatively evaluated.

454 **4. Discussion**

455 **4.1. Mechanism of Improved Simulation by Stochastic Approach**

456 The superior performance of the TP-MC model stems from its ability to capture
457 depositional architectural elements. Unlike traditional variogram-based methods (e.g.,
458 kriging) that model only two-point continuity, TP-MC explicitly simulates the geometry,
459 connectivity, and asymmetry of geological units (e.g., channel belts), yielding more
460 geologically plausible heterogeneity (Carle and Fogg, 1997; Weissmann and Fogg,
461 1999). This is critical in the heterogeneous, anisotropic Baiyangdian West Plain. The
462 stochastic model delineates interconnected high-K paleo-channels that control focused
463 recharge and depression cone evolution—features that are homogenized in
464 deterministic models. Consequently, it better explains key observations: (1) steep
465 hydraulic gradients around cone margins and (2) dynamic water-level fluctuations in
466 hydrographs. These results affirm that accurately representing heterogeneity is not
467 merely a technical improvement but a prerequisite for reliable flow and transport
468 prediction (Ritzi et al., 2004).

469 **4.2. Trade-offs in Groundwater Restoration and Management Implications**

470 This analysis uncovers a critical management trade-off: aggressive groundwater
471 restoration, while reversing depletion, can drive substantial phreatic evaporation (up to
472 0.97×10^8 m³/a; Fig. 12), directly counteracting replenishment efforts and increasing
473 salinization risk in shallow areas (Konikow and Kendy, 2005). This challenges the goal
474 of simply "maximizing" water levels, necessitating the pursuit of an "optimal" recovery
475 target that balances storage gains against water loss and environmental costs.

476 The coupled simulation-optimization framework is designed to resolve this trade-
477 off. By co-optimizing water supply and water table depth, it avoids excessively shallow
478 conditions, thereby significantly reducing non-beneficial evaporation in the optimal
479 scheme (Fig. 12). This validates the framework's utility and marks a paradigm shift



480 from reactive extraction control to proactively engineering a sustainable aquifer state—
481 one that integrates quantity and quality objectives (e.g., salinization mitigation), a
482 dimension often missing from traditional water-balance models (Singh, 2014).

483 **4.3. Comparison with Previous Studies and Generality of Findings**

484 While previous regional models of the North China Plain have relied on
485 homogeneous layers or zones (Zhang et al., 2009; Liu et al., 2021), our TP-MC based
486 stochastic approach reveals that such simplifications likely underestimate local flow
487 dynamics and management response patterns (Weissmann et al., 2002). The novel
488 integration of this method with a multi-objective optimization framework for a heavily
489 exploited system like the WBP addresses this gap.

490 The identified trade-off between water-level recovery and increased evaporation is
491 likely generic to shallow aquifers in arid/semi-arid regions undergoing managed
492 recharge (cf. High Plains, Indo-Gangetic Basins). Consequently, our methodology and
493 insights are widely transferable. The key management implication is a paradigm shift:
494 from merely "raising water levels" to defining a "target operational window." This
495 window should balance competing needs—keeping levels deep enough to avoid
496 salinization and excessive evaporation, yet shallow enough to ensure sustainability,
497 ecosystem health, and equitable access.

498 **5. Conclusion**

499 This study developed an integrated stochastic simulation-optimization framework
500 to manage groundwater over-exploitation in the Baiyangdian West Plain. The principal
501 conclusions are:

502 The TP-MC stochastic model provides a geologically faithful representation of
503 heterogeneity, significantly improving simulation reliability over traditional
504 homogeneous models. The stochastic ensemble achieved a superior fit to observed
505 hydraulic heads, with Realization #30 selected for scenario analysis.

506 Managed interventions (reduced extraction, enhanced replenishment) enable
507 substantial groundwater recovery, with projected water-level rises of up to 12 m in wet
508 years. However, this recovery triggers a critical trade-off: increased phreatic



509 evaporation (up to $0.97 \times 10^8 \text{ m}^3/\text{a}$ in wet years) and associated salinization risk,
 510 challenging the paradigm of simply maximizing water levels.

511 The multi-objective optimization model successfully balances water supply
 512 security with minimizing evaporative loss. Under the optimal scheme, water shortage
 513 rates are reduced to 11.86–14.06% by 2035, while phreatic evaporation is reduced by
 514 $0.27 \times 10^8 \text{ m}^3/\text{a}$ in wet years, providing a robust strategy for sustainable management.

515 The framework and findings are transferable to other over-exploited basins. They
 516 advocate for a paradigm shift in groundwater management: moving beyond simple
 517 water balancing to explicitly account for heterogeneity and proactively navigate hydro-
 518 ecological trade-offs by defining a "target operational window" for sustainable aquifer
 519 states.

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 527 in vestigation, data curation. CW: investigation, data curation. SnD: resources, funding acquisition.

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