

## Research Article

# Groundwater level response to different withdrawal scenarios (Case study: Talesh Aquifer, Iran)

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**Abstract:** Groundwater resources are vital for sustaining agricultural productivity and ecological balance, particularly in regions facing increasing water demand and climatic variability. This study investigates the response of groundwater levels to different withdrawal scenarios in the Talesh aquifer, northern Iran, using MODFLOW (Modular Finite-Difference Groundwater Flow Model) integrated with the Groundwater Modeling System (GMS) software (Version 10.4). The model was calibrated and validated using observed data from 2005 to 2018 under both steady and transient conditions. Seven scenarios of groundwater extraction were simulated, including 5%, 10% and 15% increases and decreases relative to the baseline withdrawal rates, to evaluate potential impacts on groundwater storage and sustainability from 2019 to 2024. Statistical indices such as Root Mean Square Error (RMSE), Mean Absolute Error (MAE) and Mean Error (ME) confirmed the model's reliability in reproducing observed groundwater levels. Results indicated that maintaining current groundwater withdrawal rates leads to continued groundwater level declines of up to approximately 3.12 m in localized areas of the aquifer, whereas a 15% reduction in groundwater withdrawals can result in substantial groundwater recovery, with water level rises exceeding 2.40 m at specific locations during the simulation period. The results of this study highlight the critical necessity of groundwater withdrawal management policies to balance groundwater withdrawal with natural recharge, ensure water security and support sustainable agriculture.

**Keywords:** Aquifer sustainability; Hydrogeological simulation; Groundwater recharge; MODFLOW; Scenario analysis; Spatial modeling

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## Introduction

Groundwater is globally recognized as the most vital source of freshwater, accessible in nearly all regions and fundamental for environmental sustainability, human welfare and economic development (Samani et al. 2021; Shaikh and Birajdar, 2024). Despite its abundance, groundwater

resources face significant depletion risks due to combined pressures from climate variability, climate change, and intensified human activities such as population growth, agricultural expansion, and industrialization (Gazal and Eslamian, 2021; Zhou et al. 2026). These pressures have led to widespread declines in groundwater levels, degradation of water quality, land subsidence, and ecosystem disruption, raising urgent concerns about the long-term sustainability of this resource worldwide.

In Iran, the situation is particularly critical. Groundwater levels have steadily decreased in most aquifers over the past decades (Eslamifar et al. 2024; Kashani and Safavi, 2025), threatening agricultural productivity and ecological balance of regions such as the Talesh plain in northern Iran. Talesh's reliance on groundwater is high due to

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insufficient surface water supply, compounded by recurrent droughts and escalating agricultural water withdrawals (Sarkheil and Rad, 2015). These trends have led to instability in the agricultural systems and significant adverse effects, including aquifer depletion, wetland desiccation, and land subsidence (Zareian et al. 2016). Similar patterns of groundwater stress and environmental impact have been reported globally in arid and semi-arid regions, underscoring the need for integrated management frameworks (Morsy, 2023; Zerouali et al. 2024).

The key scientific challenges arising from these observations include quantifying how groundwater levels spatially and temporally respond to various extraction regimes and external climate factors, and developing sustainable groundwater management strategies that balance agricultural demands, ecosystem preservation, and socio-economic considerations. Addressing these challenges requires comprehensive models capable of simulating groundwater flow dynamics under changing environmental and anthropogenic conditions (Guo et al. 2021; Rekha et al. 2025). Numerical modeling tools such as MODFLOW, coupled with decision-support systems, have been increasingly utilized worldwide to assess groundwater sustainability and to optimize management practices. For instance, Morsy (2023) applied MODFLOW alongside multi-criteria decision analysis to optimize groundwater use in Egypt's Western Desert, identifying zones suitable for sustainable extraction. Similarly, Zerouali et al. (2024) developed a GIS-MODFLOW coupled Decision Support System for managing withdrawals in Morocco's Berrechid aquifer, addressing the impacts of drought and over-extraction on water availability for agriculture and domestic use. These examples highlight how integrating spatial data with groundwater modeling enhances management capabilities.

Agricultural water management strategies have been extensively studied, given that nearly 70% of global groundwater withdrawals are used for agricultural production (including food, fiber, livestock, and industrial crops) and their critical role in groundwater depletion (Pointet, 2022). In semi-arid regions such as southern New Mexico, Eslamifar et al. (2024) employed system dynamics modeling to analyze fallowing strategies that reduce water use by leaving specific croplands uncultivated in rotation cycles. Their findings demonstrated significant reductions in groundwater withdrawals (up to 20% for certain crops) while balancing economic impacts, illustrating the poten-

tial for adaptive agricultural practices to alleviate groundwater stress.

In the North China Plain, Ou et al. (2025) combined agricultural management strategies with climate change projections using the SWAT-GW model (Soil and Water Assessment Tool (SWAT) coupled with a groundwater (GW) model), showing that optimized cropping patterns and irrigation limits could maintain groundwater levels despite climate pressures, though sometimes at the cost of reduced yields. This balance between water sustainability and food security is a core challenge in groundwater management under climate uncertainty.

In New Zealand, Wöhling et al. (2025) used a detailed 3D groundwater-surface water model to investigate how different allocation scenarios affect groundwater storage and spring flows in the Wairau aquifer, emphasizing the complex interplay between natural recharge, human use, and climate impacts. Their results reinforced the importance of scenario simulations and uncertainty analysis for setting sustainable extraction limits. These international studies reflect a global consensus on the necessity of integrated, model-based approaches to groundwater management, combining hydrogeological data, climate projections, and socio-economic factors.

Within Iran, the application of such integrative modeling and management is still developing but is urgently needed. The Talesh plain, which is far from the Sefidrud River and outside its irrigation network, experiences critical groundwater depletion due to over-reliance on limited groundwater resources (Sarkheil and Rad, 2015). Given the complex interactions between climate variability, human activities, and aquifer responses, sustainable groundwater management must be founded on reliable simulations of groundwater level changes under different withdrawal and climate scenarios. Moreover, experience from other regions suggests that coupling groundwater models with decision-support tools can facilitate more informed groundwater withdrawal management (Eslamifar et al. 2024; Zerouali et al. 2024).

This study, therefore, aims to fill this gap by modeling groundwater level changes in the Talesh aquifer for past (2005–2018) and future (2019–2024) periods under various extraction scenarios, providing actionable insights for sustainable water resource management in northern Iran. This study contributes to the existing body of research in several significant ways. First, it presents a comparative assessment of incremental changes in groundwater withdrawals ( $\pm 5\%$ ,  $\pm 10\%$ ,  $\pm 15\%$ ) to

quantify their impacts on aquifer storage (an analysis not previously conducted for the Talesh aquifer). Second, the research integrates MODFLOW-based groundwater modeling with withdrawal management policy scenarios, marking the first such application in the study area. By combining scientifically calibrated modeling with practical management strategies, it bridges the gap between technical simulation and real-world water governance. Additionally, scenario-based simulations offer insights into the sustainability of current groundwater extraction practices, showing how withdrawal rates impact groundwater storage and water level fluctuations.

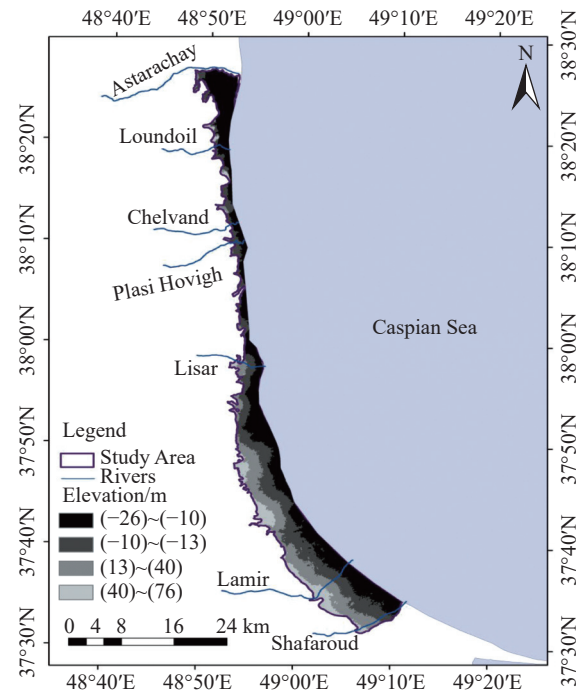
## 1 Materials and methods

### 1.1 Study area

The Talesh Plain is located in northwestern Iran, covering an area of 592.6 km<sup>2</sup> between 48°48'—49°11' E longitude and 37°31'—38°27' N latitude. The aquifer under study occupies about 488.5 km<sup>2</sup> (82% of the plain). Geographically, the plain is elongated and narrow, stretching 106.6 km in length with an average width of 5.72 km. It is bounded by the Astarachay River to the north, the Shafaroud River to the south, the Caspian Sea to the east, and the Talesh highlands to the west. Elevations range from –26 m to 76 m, with an average of –1.67 m relative to sea level. The plain has a gentle slope from west to east toward the Caspian Sea, which directs both surface water drainage and groundwater flow. An overview of the study area is provided in Fig. 1.

The climate of the region is humid, with an average annual rainfall of 1,139 mm, making it one of the high-rainfall zones of Iran. Surface water plays a key role in regional hydrology. Major rivers draining the basin include the Astarachay, Loundoil, Lamir, Chelvand, Plasi-Hovigh, Lisar, and Shafaroud, which together contribute to surface runoff estimated at about 178 Million Cubic Meters (MCM) per year. These rivers not only provide water resources but also interact with the aquifer system, influencing recharge and discharge dynamics.

Geologically, the plain is composed mainly of Quaternary alluvial and fluvial deposits with relatively high permeability. Borehole and geophysical surveys reveal that the aquifer is unconfined and primarily consists of sand, silt and clay, with the coarsest materials concentrated in the central plain and finer sediments distributed toward the upstream and downstream areas. The maximum



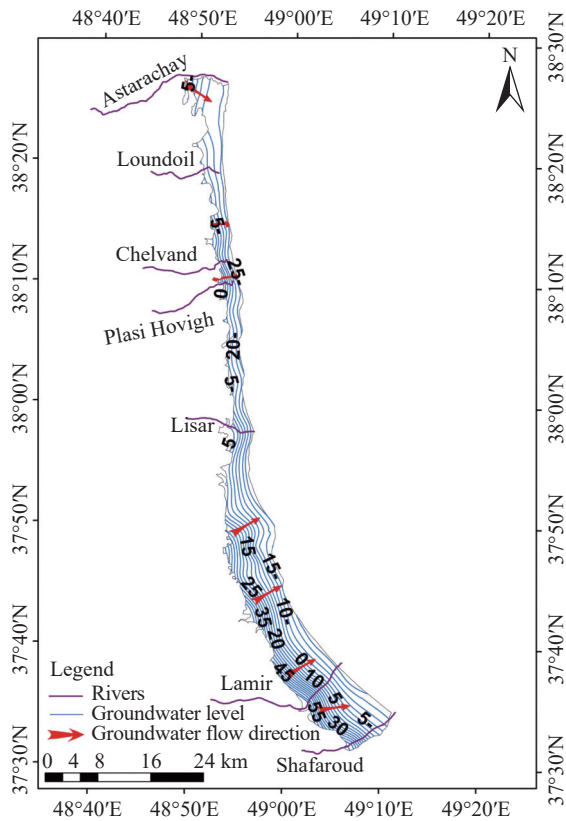
**Fig. 1** Overview of the study area (Talesh Plain)

aquifer thickness reaches 222 m in the central zone. Despite minor textural variability, the aquifer is hydrogeologically homogeneous and functions as a single continuous system (Tula Rud Gil Consulting Engineers Co. 2024). All observation wells used in this study are screened within this aquifer. These geological, topographic, and hydrological characteristics form the foundation for constructing the hydrogeological conceptual model of the Talesh aquifer. Fig. 2 shows the map of groundwater contour lines and the corresponding flow direction within the study area.

### 1.2 Hydrogeological conceptual model

The hydrogeological conceptual model was developed to represent the recharge-discharge balance, boundary conditions, and hydraulic properties of the Talesh aquifer. Groundwater recharge occurs through multiple mechanisms. Direct infiltration of precipitation contributes about 29.9 MCM/year, while infiltration from riverbeds and runoff from surrounding hills contributes around 40.9 MCM/year. Return flow from agricultural wells adds about 1.8 MCM/year, while return flow from drinking and industrial wells contributes 15.3 MCM/year. Additional recharge originates from springs and qanats (2.8 MCM/year) and infiltration of diverted surface water from rivers and irrigation channels (12.8 MCM/year) (Mahab Ghods Consulting Engineers Co. 2012).

Groundwater discharge from the aquifer occurs



**Fig. 2** Groundwater contour lines and the flow direction in the study area

through several pathways. Agricultural wells withdraw approximately 53.9 MCM/year, while drinking and industrial wells account for about 25.5 MCM/year. Springs and qanats discharge around 18.7 MCM/year, evaporation losses are estimated at 6.5 MCM/year, aquifer outflow is about 1.29 MCM/year, and groundwater drainage contributes an additional 1.59 MCM/year. According to previous studies, the average groundwater discharge from the aquifer to the Caspian Sea is about 29.1 MCM/year (Mahab Ghods Consulting Engineers Co. 2012). These recharge and discharge components highlight the growing imbalance between inputs and outputs, which has already led to noticeable groundwater level declines in recent decades.

The aquifer boundaries are defined by impermeable formations in the west and the Caspian Sea in the east, with the Astarachay and Shafaroud rivers representing partial hydraulic boundaries in the north and south. In the conceptual model, impermeable areas were treated as no-flow boundaries, while connections to rivers and the sea were represented as constant-head boundaries. Groundwater levels measured in October 2005 were used as the initial steady-state condition for numerical modeling.

Hydraulic parameters of the aquifer, including hydraulic conductivity, storage coefficients, and

anisotropy, were estimated from borehole data and pumping tests, and calibrated using the PEST (Parameter ESTimation) method. The conceptual model was then translated into a numerical groundwater flow model using MODFLOW, in which aquifer geometry, recharge and discharge zones, and boundary conditions were applied at the model-cell scale. Both steady-state and transient simulations were performed to reproduce groundwater dynamics.

### 1.3 Data collection and preprocessing

In this study, the MODFLOW model, developed by the U.S. Geological Survey (USGS), was used to simulate groundwater levels in the Talesh aquifer. MODFLOW is widely regarded for its flexibility, accuracy, and ability to model various groundwater flow processes, making it a standard tool for simulating groundwater in heterogeneous aquifers (Harbaugh et al. 2000; Harbaugh, 2005). The simulation was performed using GMS version 10.4, a user-friendly graphical interface that facilitates the setup, calibration, and analysis of MODFLOW models. GMS enables the easy integration of diverse data types, such as Digital Elevation Models (DEMs), piezometric data, and well locations, which are essential for accurate model representation. Figs. 3 and 4 illustrate the land use map and the spatial distribution of piezometric and pumping wells of the Talesh Plain, respectively.

A range of hydrogeological, meteorological, and topographic data were required for building the groundwater model. Hydrogeological data for the Talesh aquifer were obtained from the Iran Water Resources Management Organization (Tamab) and the Meteorological Organization of Guilan Province for the period from 2005 to 2018. These datasets provided key information about the aquifer's physical properties, including hydraulic conductivity, storage coefficients, and porosity.

Topographic data for the region were sourced from a DEM derived from the Shuttle Radar Topography Mission (SRTM) altitude data (Zandbergen, 2008). The DEM was used to create the model's topography and establish its groundwater flow boundaries. Groundwater levels and flow patterns were further analyzed using piezometric maps and data from 12 observation wells. Additionally, 11,220 pumping wells were considered in the model to estimate groundwater extraction rates.

The highest groundwater recharge rates in the Talesh aquifer occur in the northern parts of the plain. In the model's recharge package, the initial

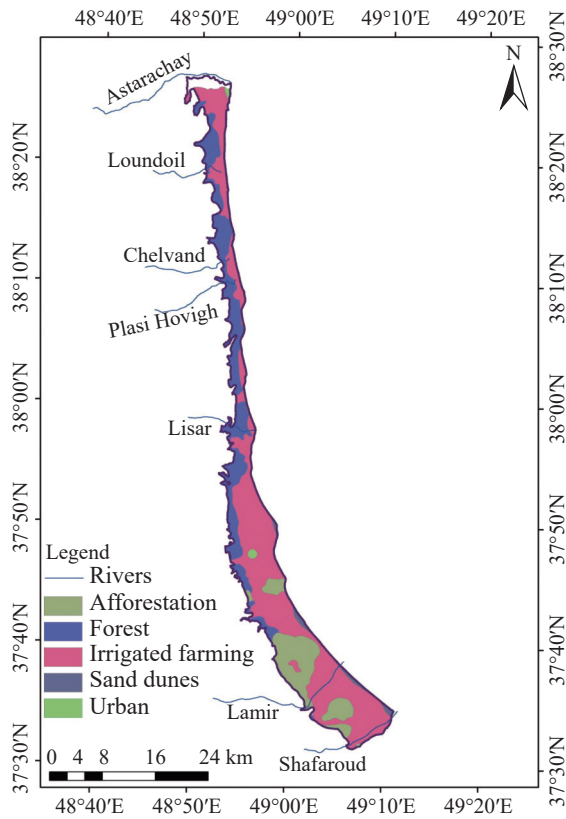


Fig. 3 Land use map of the Talash Plain

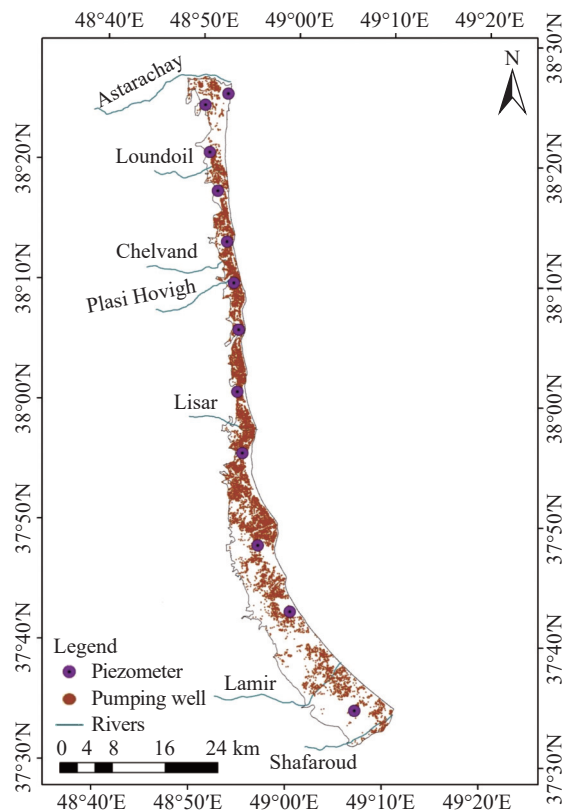


Fig. 4 Distribution of the piezometric and pumping wells in the Talash plain

recharge rate from rainfall was set at 0.00024 m/day (Varalakshmi et al. 2014). Recharge was calculated using the Eq. (1):

$$R = \frac{P}{365} \times a \tag{1}$$

Where:  $R$  is aquifer recharge from rainfall (m/day),  $P$  is annual rainfall (m) and  $a$  is the percentage of recharge from the rainfall. The aquifer storage coefficient was set at 0.07 (7%), while the specific yield was assumed to be 0.04 (4%) (Tula Rud Gil Consulting Engineers Co. 2014).

### 1.4 Model setup

The groundwater modeling approach used in this study is illustrated in the flowchart presented in Fig. 5. In the numerical model, parameter zoning was implemented by assigning hydraulic properties and other relevant parameters to each 500 m × 500 m grid cell based on regional hydrogeological conditions. Hydraulic conductivity, storage coefficients, and specific yield values were derived from field measurements, pumping tests, and published studies and then applied to the corresponding cells. Recharge rates, which may be influenced by land use, were set according to Tula Rud Gil Consulting Engineers Company (2014). This approach ensures that spatial variations in hydrogeological properties are represented in the model, making the simulations consistent with observed groundwater dynamics across the study area. Once the data were compiled, the next step was to set up the groundwater model. The area of interest was discretized into a grid with 500 m × 500 m cells. This cell size was chosen as a compromise between model accuracy and computational efficiency. Each grid cell was assigned appropriate hydraulic parameters based on the regional hydrogeological conditions.

Initial hydraulic properties, such as horizontal hydraulic conductivity, vertical hydraulic conductivity, specific storage, and porosity were assigned based on field measurements and published data. For example, the initial recharge rate was set at 0.00024 m/d, derived from the average annual rainfall for the study area. The recharge rate was further adjusted during calibration to reflect local recharge dynamics.

Boundary conditions for the model were defined using the topographic data and observed groundwater levels. In areas where the aquifer interacts with surface water bodies such as rivers and streams, constant-head boundaries were applied, assuming a fixed groundwater level at those locations (In the study area, the aquifer is hydraulically connected to surface water bodies such as

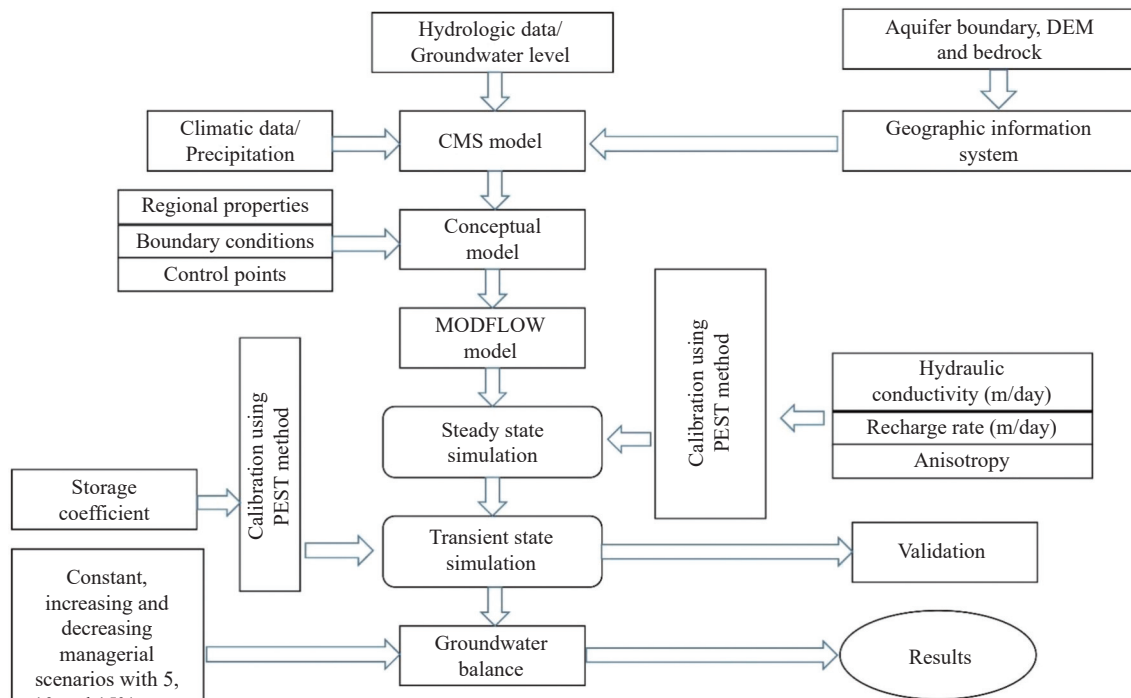


Fig. 5 Flowchart of groundwater modeling used in this study

rivers and streams; these surface water bodies were therefore represented as constant-head boundaries in the numerical model, and a fixed groundwater level was assumed at these locations to reflect the hydraulic interaction between groundwater and surface water). For other regions, natural (no-flow or specified flux) boundary conditions were assumed.

### 1.5 Model calibration

Calibration is a critical step in ensuring that the model accurately reflects real-world conditions. The calibration process involved both manual and automatic adjustments of model parameters. In the manual calibration phase, the groundwater recharge rate, hydraulic conductivity, and anisotropy were adjusted to match observed groundwater levels, particularly for the steady-state period in October 2005.

After manual adjustments, the model was further calibrated using PEST software, which automates the parameter estimation process by minimizing the residual errors between observed and simulated groundwater levels. PEST uses an optimization algorithm to find the best-fit parameters, reducing the difference between simulated and measured groundwater heads. The primary objective was to achieve a low RMSE between the observed and simulated groundwater levels.

The calibration was assessed using statistical

measures such as ME, MAE, and RMSE, as defined in the following Eqs. 2–4:

$$ME = \frac{1}{n} \sum_{i=1}^n (h_m - h_s)_i \quad (2)$$

$$MAE = \frac{1}{n} \sum_{i=1}^n |(h_m - h_s)_i| \quad (3)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (h_m - h_s)_i^2} \quad (4)$$

Where:  $n$  is the number of pumping wells,  $h_m$  and  $h_s$  are the observed and simulated groundwater levels, respectively. After successful manual calibration, automatic calibration was conducted to optimize nonlinear parameters such as hydraulic conductivity and storage coefficient over a transient period (2005–2015), using PEST.

### 1.6 Model validation

Once calibrated, the model was validated by running simulations using data from 2015 to 2018, which were not included in the calibration process. This validation step provided an independent test of the model's accuracy in predicting groundwater levels beyond the calibration period.

### 1.7 Scenario analysis

To investigate the potential future impacts of

groundwater extraction on the aquifer, several management scenarios were tested. These scenarios included:

- (1) Constant water withdrawal;
- (2) 5%, 10%, and 15% increase in groundwater extraction;
- (3) 5%, 10%, and 15% decrease in groundwater extraction.

Each scenario was simulated for a five-year projection period (2019–2024). For each run, the total pumping rates were adjusted according to the specified percentage change. The model was executed separately for each scenario, and the resulting outputs were extracted for comparison.

## 2 Results

### 2.1 Groundwater levels and calibration under steady-state conditions

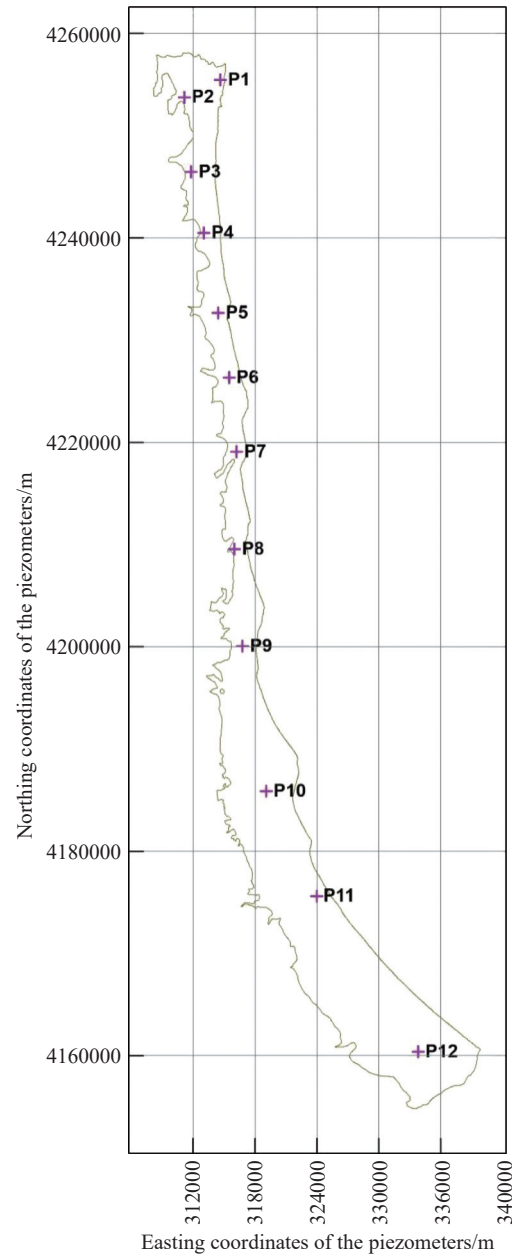
The groundwater balance under steady-state conditions is shown in Table 1. The difference between the groundwater input and output was 0.007 MCM. Fig. 6 shows the locations of piezometers in the GMS grid system for the steady-state condition. Fig. 7 depicts the groundwater conditions based on piezometric data for October 2005. At 1-meter contour intervals, all wells are represented in green, clearly showing the observational and simulated values, along with their differences. The results revealed that the average error between observed and estimated groundwater levels during the steady-state calibration phase was 0.26 m. The maximum observational error occurred in piezometer P11 at 0.43 meters, while the minimum error of 0.08 meters was observed in piezometer P8.

**Table 1** Groundwater balance in steady state

Input (MCM)	Output (MCM)	Difference (MCM)
1.923	1.916	0.007

### 2.2 Parameter estimation and spatial variability

The estimated parameters, including storage coefficient, hydraulic conductivity and groundwater recharge, were transferred from GMS 10.4 software to GIS 10.3 software (Fig. 8). These parameters demonstrated regional variation across the aquifer. Based on the transient calibration results, the specific yield ranged from 0.047 to 0.103. Hydraulic conductivity values ranged from a minimum of 6.31 m/d to a maximum of 21.65 m/d. The



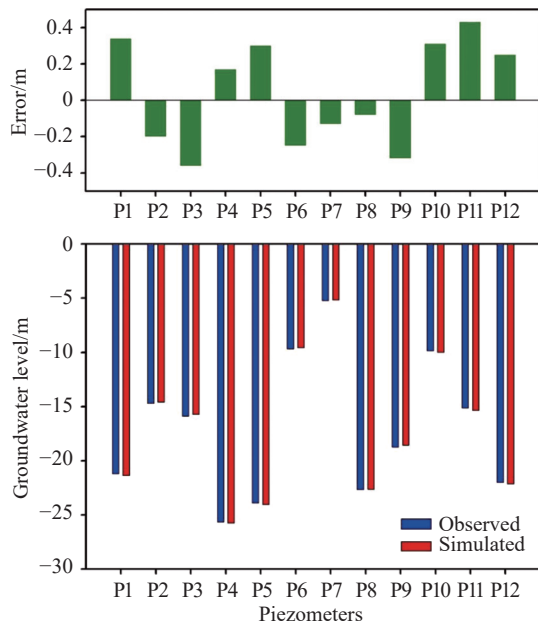
**Fig. 6** Locations of piezometers in the GMS grid system for the steady-state condition

highest recharge rate in the middle regions of the aquifer was estimated at 0.01645 m/d. In addition, the anisotropy ranged from 0.48 to 9.16.

### 2.3 Groundwater fluctuations under unsteady-state conditions

Fig. 9 shows the observed and simulated groundwater level fluctuations in transient conditions for 12 observation wells. Low values of ME, MAE, and RMSE indicate the model's strong capability to simulate groundwater levels (Table 2).

During the steady-state calibration phase (2005–2006), the ME, MAE, and RMSE were –0.51,



**Fig. 7** Observed and simulated groundwater level during the steady state condition

0.36, and 0.32, respectively. In the transient calibration phase (2005–2015), these values were 0.28, 0.18 and 0.28, respectively. During the validation phase, the values were calculated as  $-0.41$ , 0.29, and 0.36, respectively, confirming the conceptual model's good accuracy for simulating groundwater levels in the study area.

## 2.4 Groundwater balance and deficits

According to the results presented in Table 3, the groundwater balance of the Talesh aquifer shows an average deficit of  $-6.37$  MCM, indicating that the outflow exceeds the inflow. The maximum and minimum differences between input and output occurred in 2016 (9.40 MCM) and 2012 (3.97 MCM), respectively. The highest input was recorded in 2017 (150.24 MCM), while the lowest input was in 2005 (124.96 MCM). These results highlight excessive groundwater withdrawal as a critical factor in the aquifer's negative balance (Table 3).

## 2.5 Impact of groundwater withdrawal scenarios on groundwater level fluctuations

To evaluate the impact of groundwater withdrawal variations on water level fluctuations, the GMS model was updated based on the reference period of 2005–2018, and simulations were performed for 2019 and 2024 under seven management scenarios (Fig. 10 and Table 4). In 2019 (Fig. 10a), ground-

water level changes exhibited a spatially heterogeneous pattern across the aquifer. Groundwater level declines of up to approximately 1.52 m were observed over large portions of the study area, while limited and scattered zones showed slight water level rises, indicating localized short-term recovery superimposed on the overall declining trend observed at the end of the calibration period.

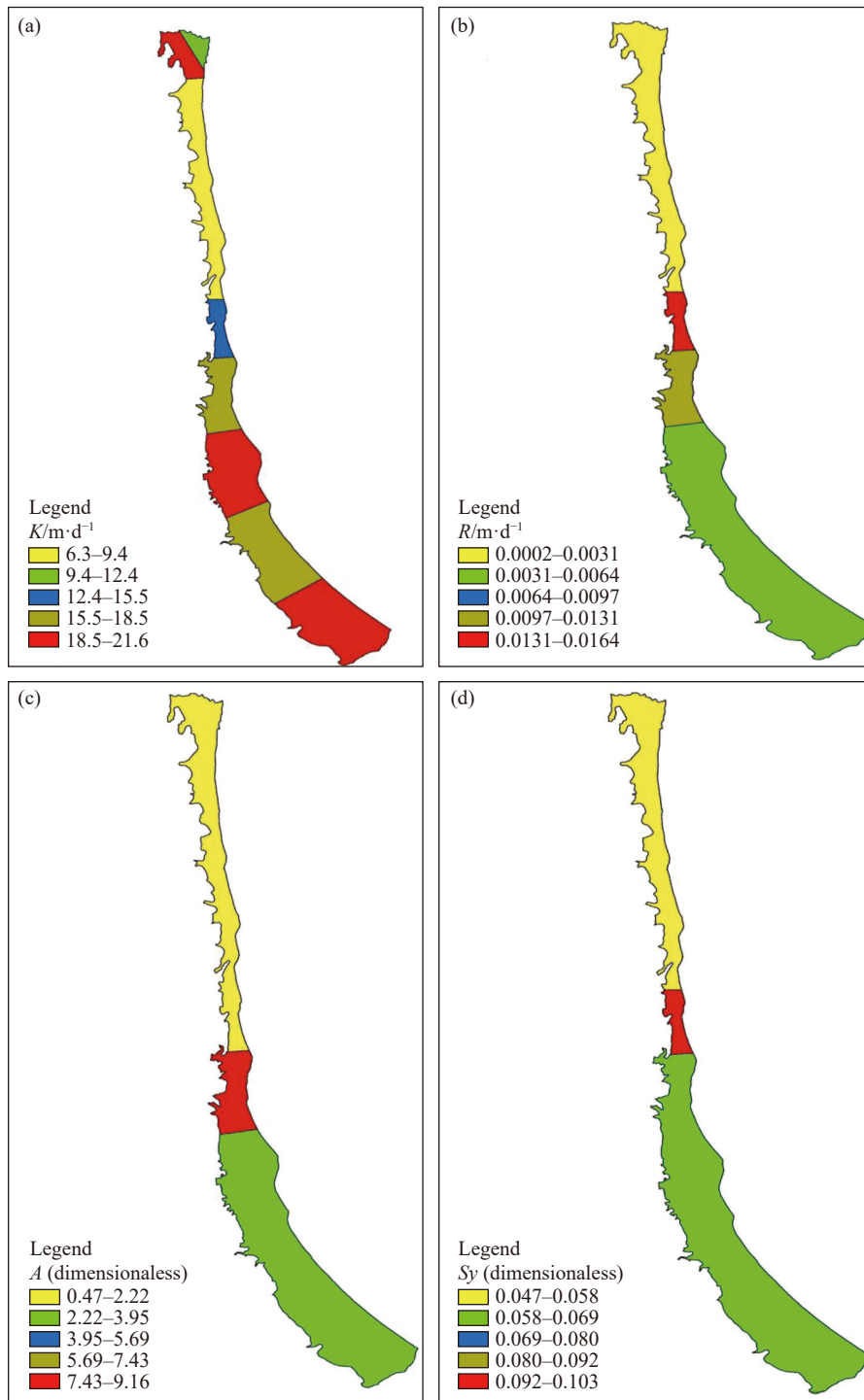
Under the constant-withdrawal scenario for 2024 (Fig. 10b), groundwater level declines intensified and expanded spatially, with drawdown values generally ranging between about 0.71 and 3.12 m across extensive parts of the aquifer. Only small and discontinuous areas exhibited minor recovery, suggesting that maintaining current abstraction rates is insufficient to prevent cumulative groundwater depletion over time.

With a 5% reduction in withdrawal (Fig. 10c), the magnitude of drawdown was moderated, generally falling within the range of approximately 1.78 to 2.93 m. Although the overall spatial pattern remained comparable to that of the constant-withdrawal scenario, localized zones of partial groundwater recovery emerged, reflecting the system's positive response to reduced pumping. In contrast, a 5% increase in withdrawal (Fig. 10d) resulted in a noticeable intensification of drawdown, with maximum declines reaching approximately 3.50 m in areas characterized by higher abstraction stress.

Similar spatial behavior was observed under the 10% adjustment scenarios. In the 10% reduction scenario (Fig. 10e), groundwater level declines of up to about 2.94 m were simulated over broad portions of the aquifer, while several isolated zones exhibited water level rises of up to approximately 2.38 m. Conversely, the 10% increase scenario (Fig. 10f) led to an expansion of drawdown extent and severity, with maximum declines approaching 3.67 m in the most affected areas.

The 15% adjustment scenarios further highlight the sensitivity of the aquifer system. A 15% reduction in withdrawal (Fig. 10g) produced widespread groundwater recovery across much of the study area, with water level rises exceeding 2.40 m in several zones, although localized drawdown of up to about 2.73 m persisted. In contrast, a 15% increase in withdrawal (Fig. 10h) resulted in severe and spatially extensive drawdown, with maximum declines of approximately 3.88 m and only negligible areas showing positive water level change.

Overall, the results demonstrate that increases in groundwater abstraction lead to a disproportionately greater intensification of drawdown, whereas even moderate reductions in pumping can substantially improve groundwater levels. The spatial



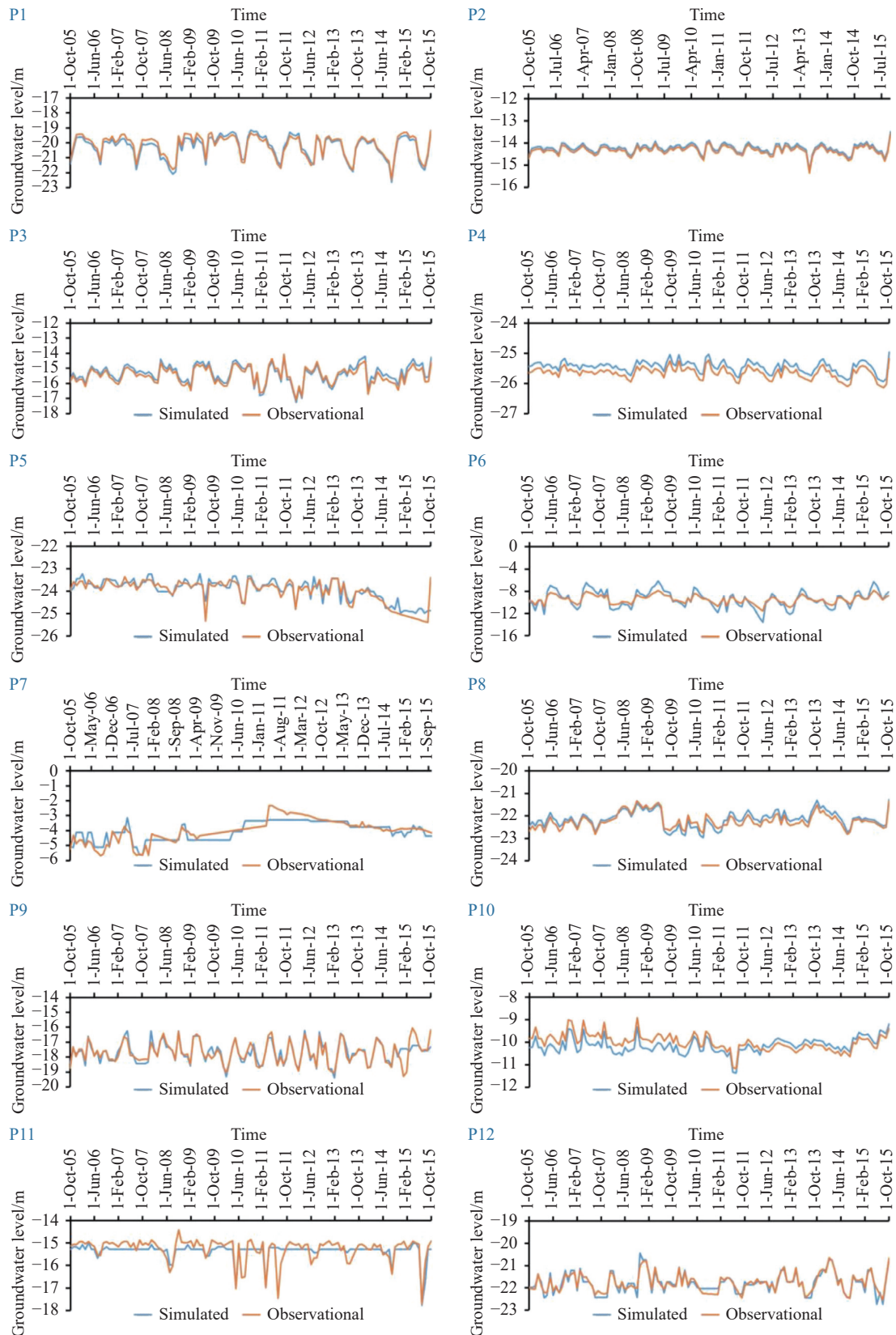
**Fig. 8** Spatial distribution of hydrogeological parameters in the Talesh aquifer: (a) Hydraulic conductivity ( $K$ ); (b) Recharge ( $R$ ); (c) Anisotropy ( $A$ ) and (d) Specific yield ( $S_y$ )

patterns of simulated changes are strongly influenced by the elongated geometry of the basin and the distribution of pumping stresses, resulting in non-uniform and discontinuous zones of decline and recovery rather than clearly defined directional trends. This behavior underscores the high sensitivity of the aquifer to abstraction rates and highlights the necessity of optimized, basin-scale groundwater management.

### 3 Discussions

#### 3.1 Model performance and calibration accuracy

The conceptual groundwater model (MODFLOW) demonstrated strong performance in replicating observed groundwater levels, with minimal dis-



**Fig. 9** Comparison between observed and calculated groundwater level during unsteady calibration state

crepancies between observed and simulated values during both steady-state and transient calibration phases. The average calibration error under steady-state conditions was only 0.26 meters, indicating

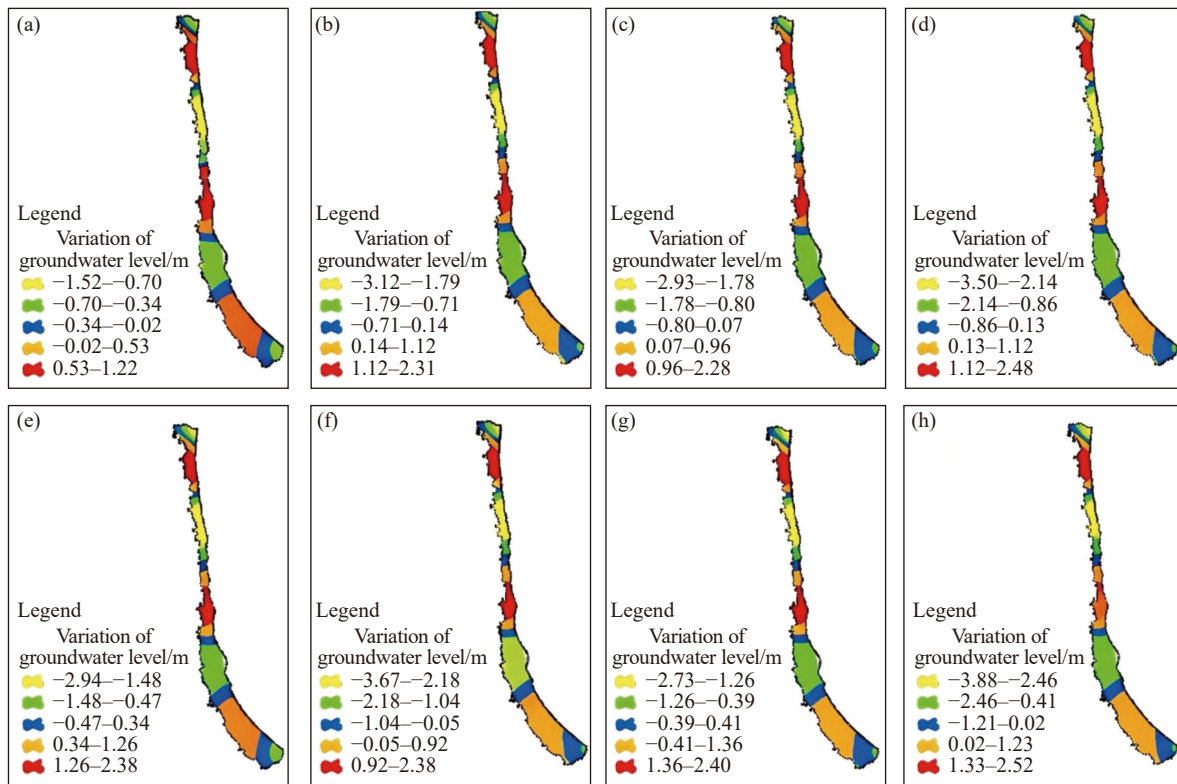
that the model closely represented actual aquifer behavior. Furthermore, the low RMSE, MAE and ME values obtained during transient calibration and validation phases further confirm the robust-

**Table 2** Error values in different levels of calibration and verification of GMS

Year	ME (m)	MAE (m)	RMSE
2005—2006 (Steady-state calibration phase)	-0.51	0.36	0.32
2005—2015 (Unsteady calibration phase)	0.28	0.18	0.28
2015—2018 (Verification phase)	-0.41	0.29	0.36

**Table 3** Groundwater balance of the Talesh aquifer in the unsteady state

Year	Input (MCM)	Output (MCM)	Difference (MCM)
2005	124.96	130.28	-5.32
2006	139.90	144.44	-4.54
2007	140.49	146.31	-5.82
2008	128.09	132.96	-4.87
2009	144.96	150.88	-5.92
2010	146.79	153.78	-6.99
2011	136.59	144.51	-7.92
2012	144.27	148.24	-3.97
2013	138.01	142.54	-4.54
2014	138.40	146.99	-8.59
2015	137.62	143.69	-6.07
2016	137.09	146.49	-9.40
2017	150.24	156.43	-6.18
2018	142.10	151.06	-8.96
<b>Average</b>	<b>139.25</b>	<b>145.62</b>	<b>-6.37</b>



**Fig. 10** Variations of groundwater level in different scenarios

Notes: (a) baseline-2019; (b) constant withdrawal for 2024; (c) 5% reduction in withdrawal for 2024; (d) 5% increase in withdrawal for 2024; (e) 10% reduction in withdrawal for 2024; (f) 10% increase in withdrawal for 2024; (g) 15% reduction in withdrawal for 2024; (h) 15% increase in withdrawal for 2024

**Table 4** Groundwater balance (MCM) under different groundwater management scenarios

Year	Constant withdrawal	Withdrawal increase/%			Withdrawal decrease/%		
		5	10	15	5	10	15
2019	-6.58	-6.91	-7.19	-7.52	-6.30	-5.92	-5.45
2020	-7.35	-7.44	-8.08	-8.45	-6.88	-6.71	-6.22
2021	-5.21	-5.42	-5.79	-6.03	-4.90	-4.61	-4.32
2022	-4.25	-4.54	-4.71	-4.96	-3.91	-3.73	-3.41
2023	-7.66	-8.14	-8.39	-8.86	-7.17	-6.84	-6.48
2024	-6.44	-6.79	-7.12	-7.46	-6.14	-5.74	-5.43
<b>Average</b>	<b>-6.25</b>	<b>-6.54</b>	<b>-6.88</b>	<b>-7.21</b>	<b>-5.88</b>	<b>-5.59</b>	<b>-5.22</b>

ness and reliability of the model. Such accuracy is crucial for decision-making, as even minor errors in groundwater modeling can lead to substantial misjudgments in water resource management. These findings establish a solid foundation for using the model to simulate various management scenarios and assess their potential impacts on aquifer sustainability.

### 3.2 Groundwater balance and over-extraction

One of the most important findings of this study is the identification of a negative groundwater balance in the Talesh aquifer, where groundwater extraction consistently exceeded natural recharge between 2005 and 2018. The average annual deficit of -6.37 MCM highlights a chronic imbalance that threatens the long-term sustainability of the aquifer. This situation mirrors global trends in groundwater depletion, as reported in studies such as Du et al. (2024) for the North China Plain, where unsustainable pumping practices led to severe declines in groundwater storage. Similarly, Meyer et al. (2019) documented saltwater intrusion caused by over-extraction in the Danish-German border region, further illustrating the serious consequences of persistent negative water balances. The Talesh case, therefore, adds to the growing body of evidence that over-extraction is a primary driver of groundwater depletion worldwide, regardless of climate or recharge potential.

### 3.3 Relationship between withdrawal scenarios and water level fluctuations

The results of the different management scenarios clearly demonstrate a direct but nonlinear relationship between groundwater abstraction rates and water level response. Increasing withdrawals not only intensifies the overall decline in groundwater

levels but also expands the extent and severity of the critical drawdown zones in an accelerating manner. Conversely, moderate reductions in pumping can lead to partial recovery, while more substantial reductions (e.g., 15%) result in widespread groundwater recovery. This behavior indicates the high sensitivity of the aquifer to variations in withdrawal rates and the cumulative effects of long-term abstraction.

The spatial analysis further reveals that certain parts of the basin appear more vulnerable to increased withdrawals, whereas others show higher recovery potential, reflecting local hydrogeological heterogeneity. Overall, the findings suggest that implementing withdrawal management policies (even at relatively small scales) can effectively prevent progressive depletion of the aquifer. This pattern is consistent with previous studies, such as Basso et al. (2013) in the Ogallala aquifer, where higher pumping rates were directly associated with accelerated declines in groundwater levels. Therefore, the outcomes of this study provide a robust scientific basis for formulating sustainable groundwater management strategies at the basin scale.

## 4 Conclusion

This study investigated groundwater level changes in the Talesh aquifer under various extraction scenarios using the MODFLOW model. The results show that over-extraction has led to substantial declines in groundwater levels, while reductions in pumping can initiate partial recovery, and larger reductions (e.g., 15%) can lead to more extensive groundwater recovery. Scenario analyses revealed a clear, nonlinear and sensitive relationship between extraction rates and water level fluctuations, highlighting the high sensitivity of the aquifer to changes in withdrawal. The model's performance during both steady-state and transient calibration phases confirmed its reliability in representing observed groundwater behavior, providing

confidence in the scenario-based predictions. These findings underscore the critical need for implementing sustainable groundwater management strategies to maintain the aquifer's long-term balance. Effective management and controlled extraction can prevent further depletion, support aquifer resilience and ensure a stable water supply for the region. Overall, this study provides a quantitative foundation for informed decision-making and emphasizes the importance of aligning groundwater use with the aquifer's natural recharge capacity to secure its sustainability.

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