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Optimization of Hydrogeological Parameters and Forecasting Dynamic Behavior of Marvast Aquifer (Yazd) using a Numerical Model

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Abstract
The Marvast alluvial aquifer in Yazd Province (central Iran) has experienced increasing groundwater abstraction for agricultural and industrial purposes, causing continuous decline in groundwater levels, disruption of aquifer balance, and serious threat to its long-term sustainability. In this study, the aquifer was simulated under steady-state and transient conditions over a nine-year hydrological period from November 2012 to September 2021. The calibration and validation results with R^2=0.92 and RMSE=1.06 m, confirmed the accuracy and reliability of the model. The average hydraulic conductivity and specific yield were estimated at 10 m/day and 5%, respectively, indicating the heterogeneity of the alluvial sediments, resulted in a non-uniform aquifer response to groundwater abstractions. The highest groundwater-level decline, with an average annual rate of about 0.7 m, occurred in the northern areas where pumping wells are highly concentrated. Groundwater level predictions with continuation of current conditions up to September 2030 (scenario I) indicated that groundwater depletion will be continued in the northern parts of the aquifer, with a cumulative decline of 6.5–7 m. Given the proximity of the northeastern aquifer boundary to the Marvast Desert, this trend may increase the risk of saline water intrusion and groundwater quality deterioration. As compared with scenario I, groundwater level is projected to rise averagely about 0.62 m under 10% reductions in groundwater abstraction (scenario II) with the most pronounced improvement at the north. Therefore, sustainable groundwater management measures including abstraction control and artificial recharge are essential in this critical aquifer.

Keywords: Groundwater Simulation, Hydraulic Conductivity, Specific Yield, Drawdown, Heterogeneity.

Introduction

Population growth, expansion of agricultural and industrial activities, and climate change have recently intensified pressure on groundwater resources in arid and semi-arid regions (UNESCO, 2022; Jasechko et al., 2024). However, excessive and long-term abstraction from groundwater aquifers has led to significant declines in water levels and the development of hydrological imbalances across many plains, particularly in agricultural areas developed in dry regions (Noori et al., 2021; Ashraf et al., 2021; Jasechko et al., 2024). Under such circumstances, studies of groundwater flow system and balance calculations are essential for understanding aquifer behavior and supporting sustainable groundwater resource management (Anderson et al., 2015; Harbaugh, 2005). A fundamental component of groundwater balance studies is the accurate determination of hydrogeological parameters, including hydraulic conductivity and

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storage coefficient (specific yield), as these parameters reflect the physical, lithological, and hydraulic properties of the porous medium (Anderson et al., 2015; Harbaugh, 2005). Software platforms such as groundwater modeling system (GMS), in conjunction with the MODFLOW suite, facilitate three-dimensional simulation of groundwater flow while accounting for boundary conditions, heterogeneity, and spatiotemporal variability. These tools are highly effective for calibrating hydrogeological parameters and forecasting dynamic behavior of the aquifer (Bear, 1979; Diersch, 2014; Harbaugh, 2005; Zheng & Bennett, 2002).

Several studies have demonstrated the effectiveness of numerical modeling in aquifer analysis. Majdi et al. (2005) simulated groundwater flow in the northwestern Ahvaz aquifer using Visual MODFLOW, calibrating hydraulic parameters to accurately predict temporal water table variations. Jamali Zadeh et al. (2020) modeled the Rafsanjan plain aquifer, highlighting severe water table declines due to over-extraction and emphasizing the necessity of regulated abstraction. Bayat et al. (2020) performed three-dimensional MODFLOW simulations for the Karvan aquifer, evaluating several scenarios involving precipitation, surface recharge, and pumping variations, and showed that reduced pumping and enhanced recharge improved water levels and aquifer sustainability. On an international scale, Mustafa & Mawlood (2024) developed a 3D groundwater flow model for the Erbil basin using GMS and MODFLOW 2000, calibrated via the PEST algorithm, illustrating the model precision in analyzing aquifer dynamics and management under climatic variability. Additionally, Mattas et al. (2025) predicted groundwater levels over a ten-year horizon in the Serre's aquifer (Greece), highlighting the critical role of numerical modeling in sustainable aquifer management.

The Marvast aquifer is located in arid regions of Yazd province (central Iran), where the groundwater serves as the primary source of water supply. It has experienced a considerable decline in groundwater levels in response to intensified groundwater abstractions for agricultural and industrial purposes. Under these circumstances, examining the aquifer hydrodynamic coefficients (transmissivity and storage coefficient) is essential for understanding its flow behavior and predicting future groundwater level variations, helping for sustainable water management and effective resource planning. Therefore, the present study was aimed to simulate the Marvast alluvial unconfined aquifer under both steady-state and transient conditions, utilizing a numerical model in GMS in order to optimize the hydraulic parameters of the aquifer. Furthermore, groundwater level variations were simulated for the next hydrological years up to September 2030. The findings of this study provide a comprehensive understanding of the aquifer dynamic behavior, enabling the assessment of the impacts of recharge and abstraction patterns on water table drawdowns, which can serve as a scientific and practical basis for sustainable groundwater management in this arid area.

Study area

The study area is the Marvast plain at the southernmost part of Yazd Province (central Iran) between longitudes 53°51′ to 54°19′ E and latitudes 30°08′ to 30°35′ N. The total area of the Plain is approximately 1152.4 km², of which the aquifer covers around 428.4 km². The highest elevation within the study area is about 3100 m, corresponding to the western highlands, while the lowest point located at the aquifer outlet lies at an elevation of 1510 m. The Marvast Plain is characterized by an arid climate. The average annual precipitation recorded at the Marvast meteorological station (elevation 1546 m) was 70.78 mm, while the mean values of minimum and maximum air temperatures were measured at –0.8°C and 37.9°C, respectively. The average annual potential evaporation reached 2202.3 mm, reflecting the high rate of evapotranspiration in this area.

Geologically, the Paleozoic formations at the western highlands represent the oldest geological units, whereas the young Quaternary alluvial and fluvial deposits cover the plain surface. The old alluvial terrace deposits (Qt^1) are extensively developed in the western and southwestern parts of Marvast, while the younger alluvial fan deposits (Qt^2) extend from the mountain foothills toward lower-lying areas, forming the main body of the alluvial aquifer. Bavanat River that crossing the Marvast plain from west to the eastern salt playa (Marvast Kavir) is the only surface water resource in the region. In contrast, desert deposits, consisting mainly of clay, silt, and salt, dominate the eastern parts of the plain, creating an evaporitic zone. Location map of the Marvast aquifer is presented in Fig. 1.

The Marvast unconfined aquifer, trending in a north–south direction, is bounded by mountainous formations to the west and the Marvast Kavir (salt playa) to the east, representing one of the most important hydrogeological units in the region. According to statistical reports by Yazd Regional Water Authority, 175 active deep and semi-deep wells are distributed across the aquifer, with total annual abstraction of about 49.9 million cubic meters (MCM). Groundwater level fluctuations are being monitored through 29 piezometers, indicating a continuous declining trend in recent years. Hydrologically, there is no permanent river within the area, and the all-surface flows are seasonal. The natural groundwater flow direction extends from the southwest toward the northeast, effectively governing the recharge and discharge dynamics of the aquifer. Based on hydrogeological analyses and groundwater Iso-potential map (Fig. 2), the main inflow boundaries were delineated along the western parts, whereas the principal outflow boundaries occur in the east. The occurrence of closed groundwater-level contours on the Iso-potential map (Fig. 2) reflects the high density of pumping wells and concentrated discharge in the northern part of the aquifer.

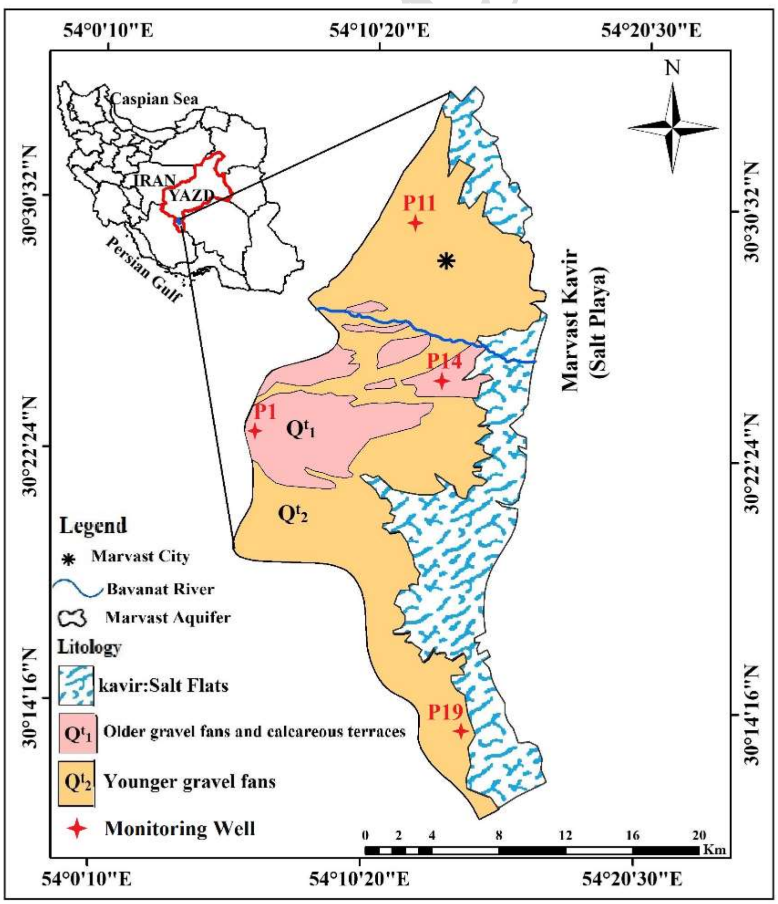

Figure 1. Location map and geological setting of the Marvast aquifer in Yazd Province, central Iran

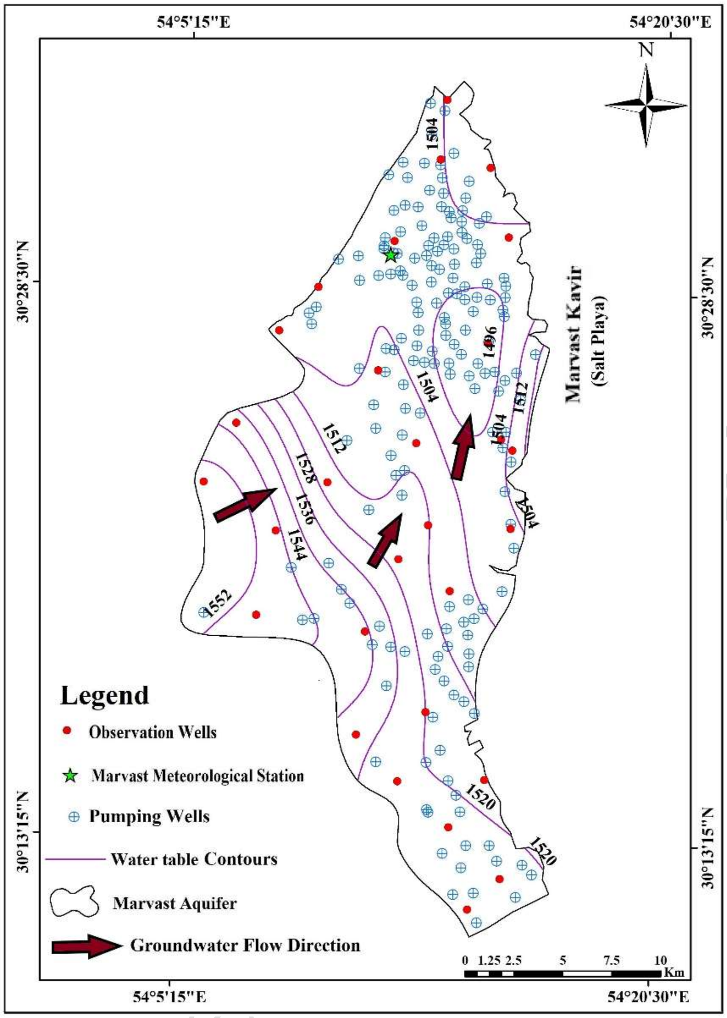

Figure 2. Iso-potential map of the Marvast aquifer (September 2021)

Materials and Methods

Numerical Modeling of the Marvast Aquifer

In this study, groundwater flow in the Marvast aquifer was simulated using MODFLOW numerical code in Groundwater Modeling System (GMS). MODFLOW employs the finite-difference method to perform both quantitative and qualitative simulations of groundwater systems under steady-state and transient conditions in two- and three-dimensional domains (Goodarzi et al., 2020). A key advantage of GMS is its seamless integration with Geographic Information Systems (GIS), enabling efficient data management throughout all stages of model input, processing, and output generation. Recharge and discharge sources of Marvast aquifer, including pumping wells and surface infiltration, as well as calibrated parameters such as hydraulic conductivity and specific yield, were incorporated into the conceptual model using distinct spatial coverages. Following the development of the conceptual framework, the model was discretized into a numerical grid. Considering the hydrogeological characteristics of the Marvast aquifer, the computational grid comprised 97 columns and 221 rows, with each cell measuring 200 × 200 m, yielding a total of 21,437 cells, of which 11,165 were active (Fig. 3). Based on the available hydrogeological data and groundwater flow direction maps, the western boundary of the aquifer was assigned as the main inflow zone, whereas the eastern boundary was defined as the primary outflow zone. The northern and southern boundaries were treated as no-flow (impermeable) boundaries. The bottom elevation map of the aquifer was processed in geographic information system (GIS) based on borehole data that reached the bedrock, and subsequently imported into the model. A 10-m resolution digital elevation model (DEM) was used to define the surface topography within the model domain (Fig. 4). Based on the isopach (equal thickness) map of the alluvial sediments (Fig. 4c), the maximum thickness of the alluvial deposits is approximately 200 m in the southern part of Marvast, while the minimum thickness is about 50 m along the margins of the aquifer.

The numerical modeling procedure was carried out under the following stages:

1. Steady-state simulation (November 2012): Initial heads were assigned based on observed groundwater levels, and boundary conditions were implemented using the General Head Boundary (GHB) package. Calibration was conducted to optimize hydraulic conductivity values, providing the basis for subsequent transient simulations.
2. Transient simulation (December 2012 – September 2020): The transient model was run over an eight-year period to evaluate temporal variations in groundwater levels and flow dynamics.
3. Advanced calibration using PEST: Automated calibration with the PEST module in GMS enabled more accurate estimation of key hydrodynamic parameters including hydraulic conductivity and specific yield.
4. Model validation (October 2020-September 2021): The calibrated model was validated over a 12-month stress period. High accuracy between simulated and observed groundwater levels confirms the model suitability for groundwater management and decision-support applications.
5. Prediction: A business-as-usual scenario (Scenario I) was formulated and implemented to comprehensively evaluate the hydro-dynamic response of the Marvast aquifer up to September 2030 (October 2021 to September 2030**)**. In this scenario, current abstraction rates, recharge patterns, and boundary conditions were maintained unchanged to enable the analysis of potential variations in groundwater table, flow directions, and overall aquifer stability under existing management practices. The results of this scenario provide valuable insights into the long-term behavior of the groundwater system and offer critical guidance for evidence-based management strategies and decision-making in the Marvast aquifer. In addition, a 10% reduction in abstractions scenario (Scenario II) was implemented to investigate the effects of groundwater exploitation management strategies on the hydro-dynamic response of the aquifer over the nine-year simulation period (October 2021 to September 2030). In this scenario, all other model components, including boundary conditions, recharge rates, and hydrogeological parameters, were kept unchanged in order to isolate the effect of changes in abstraction patterns on flow behavior and water table fluctuations. The purpose of this scenario was to analyze the sensitivity of the groundwater system to reduced abstraction, evaluate the effectiveness of control measures in modifying hydro-dynamic conditions, and provide a framework for assessing the impacts of reduced stress on the sustainability of the Marvast aquifer.

Results and Discussion

Steady-state and Transient simulation of Marvast Aquifer

To accurately evaluate the hydrodynamic behavior of the Marvast aquifer, a conceptual model was firstly developed and subsequently converted into a numerical framework. The simulation was initiated using groundwater level data from November 2012 as the initial condition. The steady-state calibration process primarily focused on hydraulic conductivity, and the simulated results exhibited a strong agreement with the observed groundwater levels at 29 monitoring wells. Given the temporal variability of hydrogeological parameters, transient simulations were performed for the period between December 2012 and September 2020.

The comparison between simulated and observed groundwater levels confirmed the accuracy of the calibration process and the model's reliability in reproducing the actual behavior of the Marvast aquifer. The simulated groundwater heads showed strong agreement with the observed data with the coefficient of determination (R^2) about 0.99, indicating excellent model performance and high reliability of the results under varying boundary conditions and hydrological stresses. Model accuracy was further evaluated using the Root Mean Square Error (RMSE), which was calculated as 1.06 m. Fig. 5 demonstrates a close match between simulated and observed groundwater levels, confirming the robustness of the transient simulation of the Marvast aquifer. Fig. 6 presents the equipotential (contour) map of hydraulic head for September 2021, showing both observed and simulated groundwater levels. This comparison illustrates the spatial agreement between model outputs and observed data.

Sensitivity analysis represents a critical step in evaluating the performance of numerical groundwater models, aimed at quantifying the influence of individual parameters on model responses during both the calibration period and future simulation scenarios. In this process, all calibrated parameters are held constant except for the selected variables, allowing the identification of those parameters exerting the greatest impact on model outputs (MacDonald & Arlen, 1988). Parameters exhibiting high sensitivity require particular attention during both the calibration process and field data collection (Anderson et al., 2015). In the present study, an initial assessment of parameter sensitivity was conducted using a trial-and-error approach. Subsequently, a more rigorous analysis was performed through automated parameter estimation using PEST, combined with the implementation of pilot points to evaluate the spatial sensitivity of key model parameters, including hydraulic conductivity and specific yield.

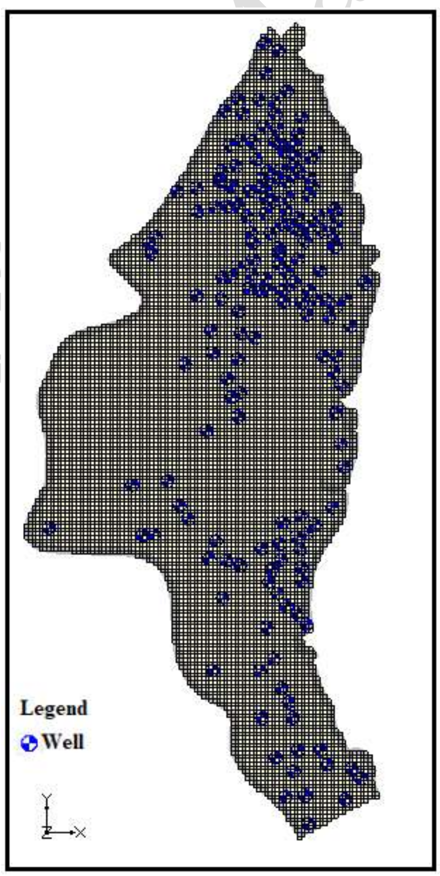

Figure 3. Model grid of the Marvast aquifer in GMS, representing location of pumping wells

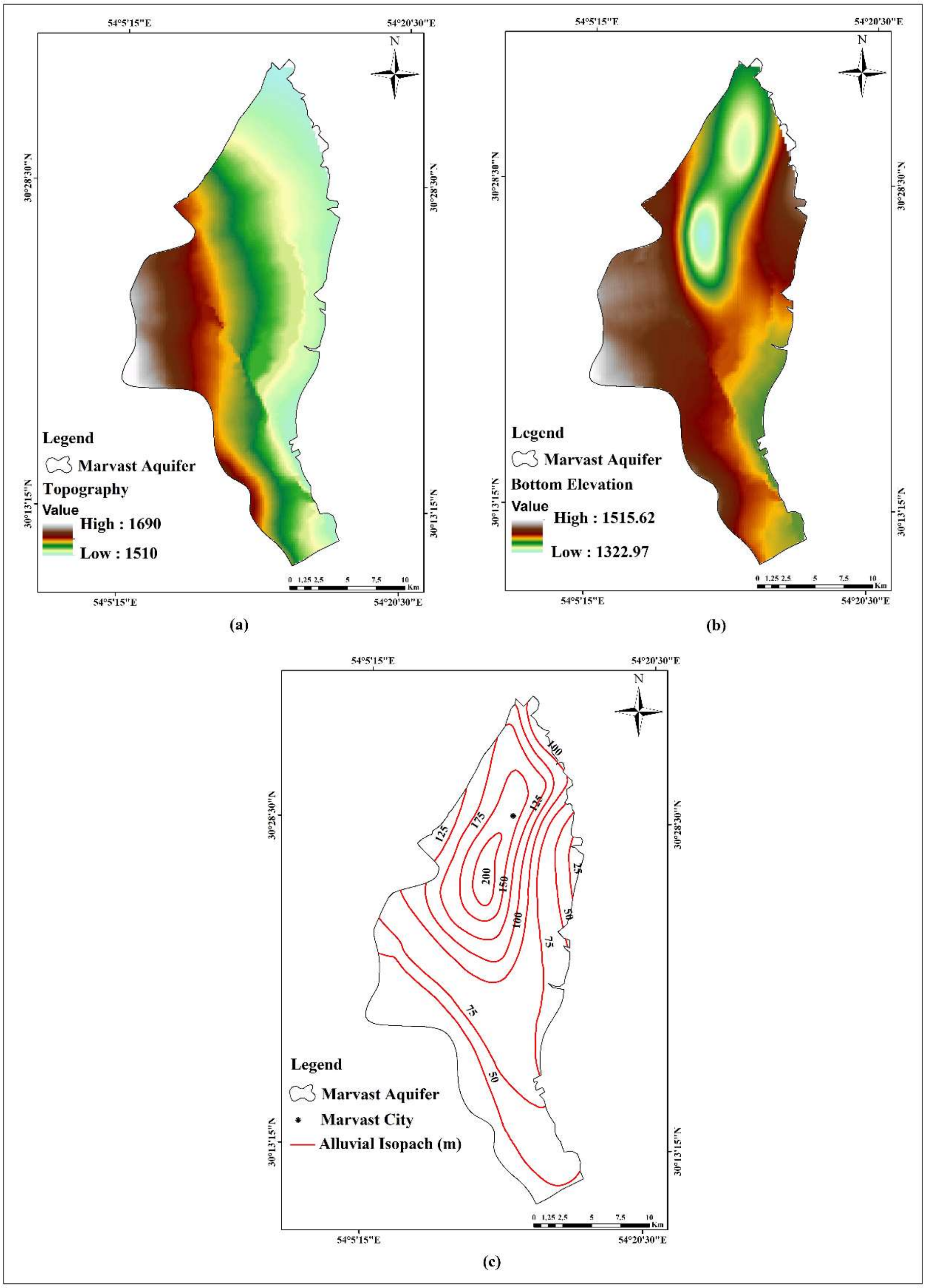

Figure 4. Topographic map of the ground surface (a), bottom elevation map (b) and alluvium isopach (equal thickness) map (c) of the Marvast aquifer

Based on the results obtained from the sensitivity analysis of hydraulic conductivity and specific yield parameters, it was found that the western and southern parts of the aquifer exhibit the highest sensitivity to hydraulic conductivity. In contrast, the western, northern, and eastern sectors of the aquifer show the greatest sensitivity to specific yield. These spatial sensitivity patterns indicate pronounced heterogeneity in the aquifer's hydrodynamic properties and underscore the critical importance of recognizing such heterogeneity in enhancing the accuracy of numerical modeling and improving groundwater resource management decisions (Fig. 7).

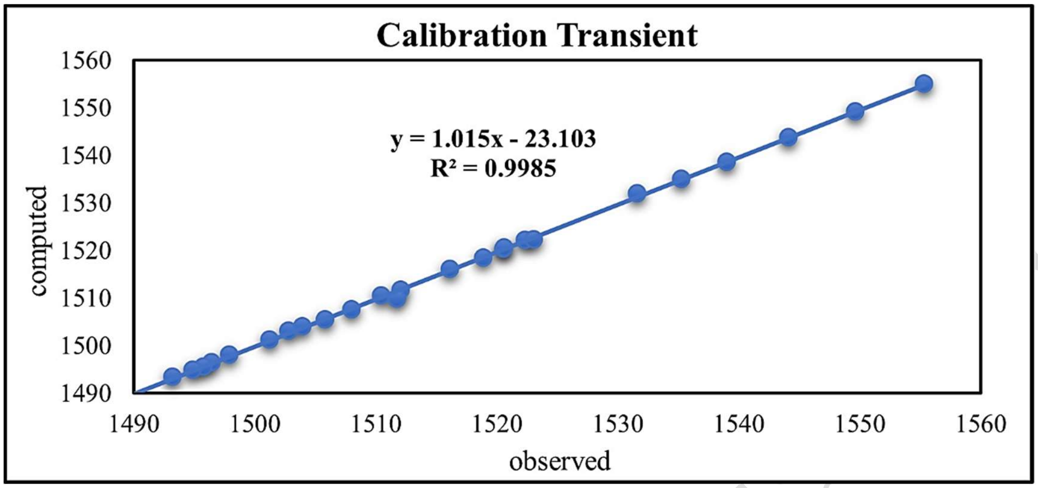

Figure 5. Observed vs. simulated groundwater levels of Marvast aquifer during transient calibration process

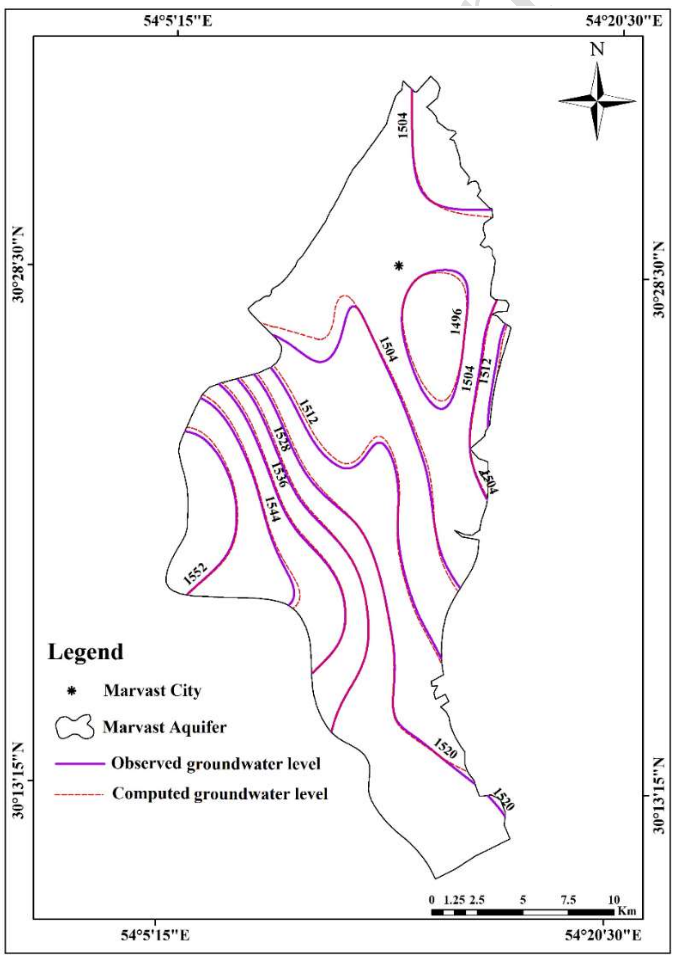

Figure 6. Comparison of observed and simulated groundwater contours in Marvast aquifer (September 2021)

The most important outcome of the model calibration is the close agreement between simulated and observed groundwater levels (Schneider et al., 2022; Hill & Tiedeman, 2007). The strong correspondence between observed groundwater levels in the piezometers and those simulated by the numerical model over the one-year validation period from October 2020 to September 2021 indicates that the model is capable of satisfactorily reproducing groundwater flow behavior within the aquifer. As shown in Fig. 8, the hydrographs generated by the numerical model are compared with observed piezometric data during the validation period for a number of selected observation wells located in the northern (P11), southern (P19), western (P1), and central parts (P14) of the aquifer (Fig. 1). Overall, the comparison between groundwater levels simulated by the numerical model and those measured in the piezometers confirms the accuracy and reliability of the numerical model in simulating groundwater flow in the Marvast aquifer.

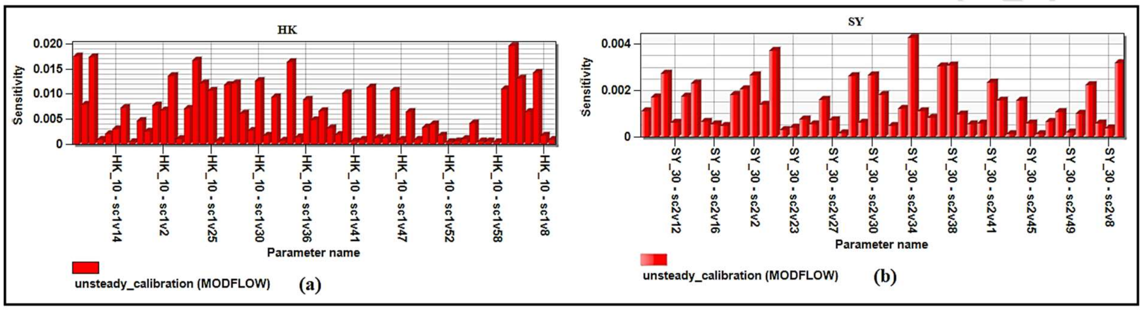

Figure 7. Sensitivity analysis of hydraulic conductivity (a) and specific yield (b) for the Marvast aquifer

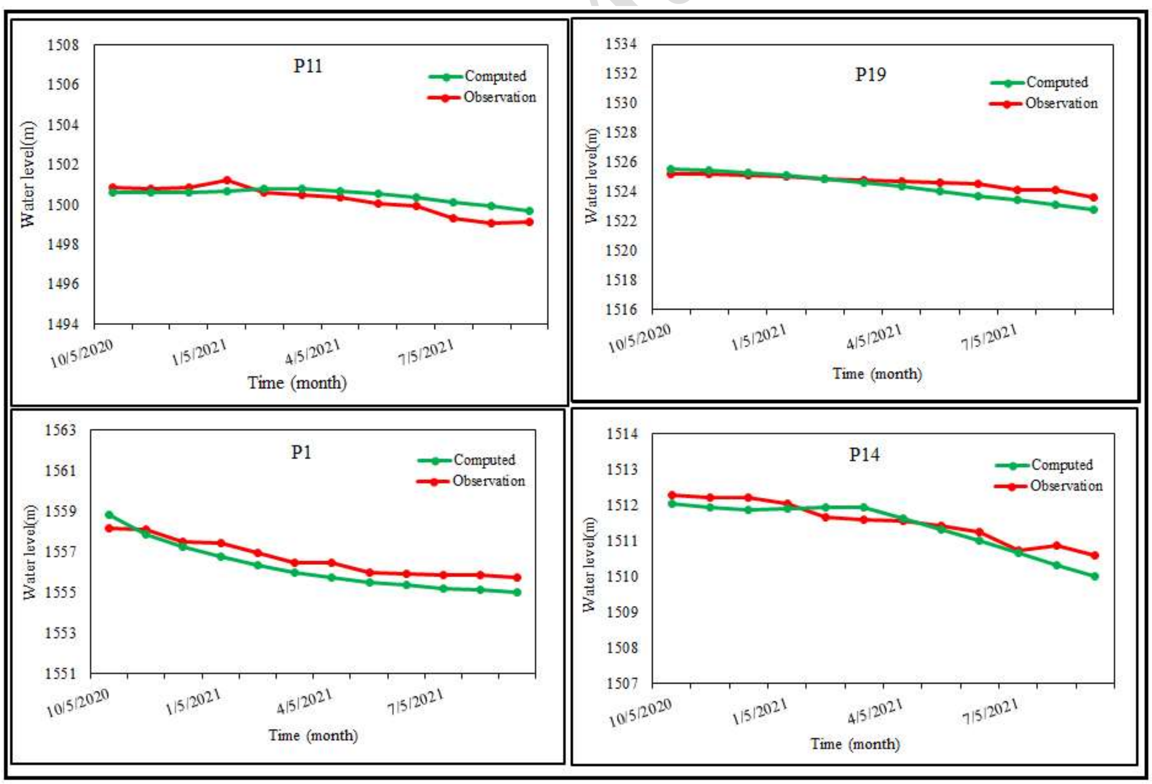

Figure 8. Comparison of simulated and observed hydrographs for selected piezometers located in the northern (P11), southern (P19), western (P1) and central parts (P14) of the Marvast aquifer during validation stage

Simulated Iso-potential map and water budget of the Marvast Aquifer

Based on the simulated groundwater potentiometric map (Fig. 9), the water table elevation in September 2021 was estimated at 1,565 m in the western part of the Marvast aquifer and around 1,485 m in the northeastern sector. This distribution indicates a dominant groundwater flow direction from the southwest to the northeast. The configuration of equipotential lines reveals that the primary inflow of the aquifer is supplied by the highlands along the western margin of the plain, whereas the eastern boundary serves as the main discharge zone of the regional groundwater system. The pronounced curvature of equipotential lines in the northern and northeastern sectors reflects the high concentration of pumping wells and the resulting intensification of local hydraulic gradients. These steep hydraulic gradients in the northeastern aquifer, which borders the Marvast Kavir (salt playa), reduce local hydrostatic pressure and enhance the relative velocity of the groundwater flow, thereby facilitating the intrusion of saline groundwater into the aquifer. The decline in groundwater levels in these areas not only disrupts natural flow regimes but also significantly increases the vulnerability of the aquifer to salinization and water quality deterioration, denoting important implications for sustainable groundwater management and resource protection.

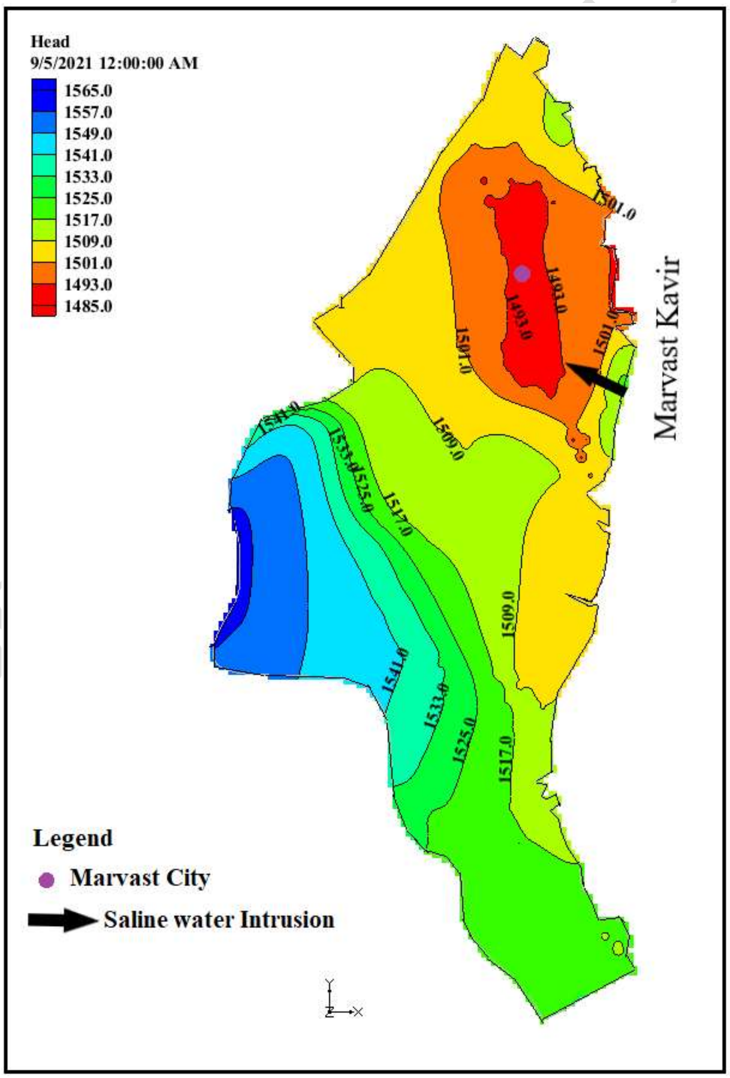

Figure 9. Simulated potentiometric map of the Marvast aquifer (September 2021)

To quantify the contributions of inflow and outflow components including surface water, groundwater fluxes, and pumping withdrawals, the aquifer water balance for the final year of the simulation period (October 2020 to September 2021) was evaluated (Table.1). Total inflow to the aquifer was estimated at 42.5 × 10^6 m^3 yr^{-1}, comprising surface and subsurface inflows and natural recharge. It must be mentioned that total surface recharge is a combination of natural recharge from rainfall and induced-floods (Bavanat River) and artificial recharge from two basins at the west of Marvast city. Total outflow amounted to 56 × 10^6 m^3 yr^{-1}, including agricultural, industrial, and domestic pumping, as well as surface and subsurface discharge. Consequently, the annual water balance exhibited a deficit of 13.5 × 10^6 m^3 yr^{-1}, indicating continued depletion of groundwater storage and a sustained decline in the regional water table.

Furthermore, based on the simulated cumulative groundwater drawdown over a nine-year period (December 2012 to September 2021), the largest drawdowns in groundwater levels were observed in the northern and northeastern sectors of the aquifer, with an average annual drawdown of approximately 0.7 m (Figure 10). This spatial pattern is directly linked to the high density of pumping wells and intensified groundwater abstraction in these regions. In contrast, the southern and southwestern sectors, despite exhibiting relatively steeper hydraulic gradients, experienced significantly smaller declines, primarily due to the lower hydraulic conductivity of aquifer materials and reduced pumping rates.

Optimization of hydrogeological parameters

Fig. 11 presents the results of the calibration of hydraulic conductivity (K) and specific yield (Sy). The analysis revealed that hydraulic conductivity varies from 1 to 19 m/day, with higher values predominantly observed in the western, central, and southern sectors, consistent with the coarser grain size of sediments in these areas. Similarly, specific yield ranges from 1% to 15%, with higher values primarily associated with coarse alluvial deposits in the same regions. These calibrated parameters provide a robust basis for simulating groundwater flow and ensure the reliability and accuracy of the numerical model. Collectively, these figures and their associated results provide a comprehensive understanding of the spatial heterogeneity of hydraulic properties, and the aquifer response to groundwater abstraction, which is essential for sustainable groundwater management and effective planning in the Marvast region.

Considering the aquifer area of 428.4 km^2, the average annual groundwater level decline of approximately 0.62 m, and the calibrated mean specific yield ($Sy \approx 0.05$), the change in storage was calculated ($\Delta V=0.05*428.4*10^6*0.62 = 13.3$ MCM) which is consistent with the simulated annual groundwater deficit of 13.5 MCM (Table 1), confirming reliability of the simulated hydrodynamic coefficients of the aquifer.

Table 1. Groundwater flow balance of the Marvast aquifer under transient validation period (Oct 2020 – Sep 2021)

Budget Term	**Flow in (MCM yr^{-1})**	**Flow out (MCM yr^{-1})**
Specified Head	7.9	3.1
General Head	19.8	4.4
Wells	0	48.6
Recharge	14.7	0
Total Flow in (Source)/ Flow out (Sink)	**42.5**	**56.0**
In - Out	**-13.5**	

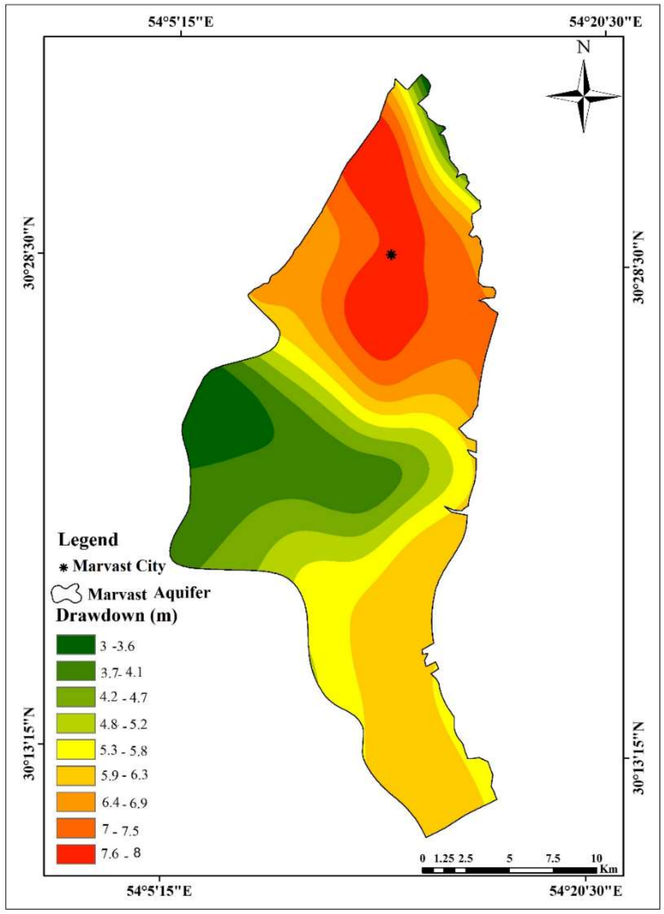

Figure 10. Simulated map of cumulative groundwater drawdown in the Marvast aquifer (2012–2021)

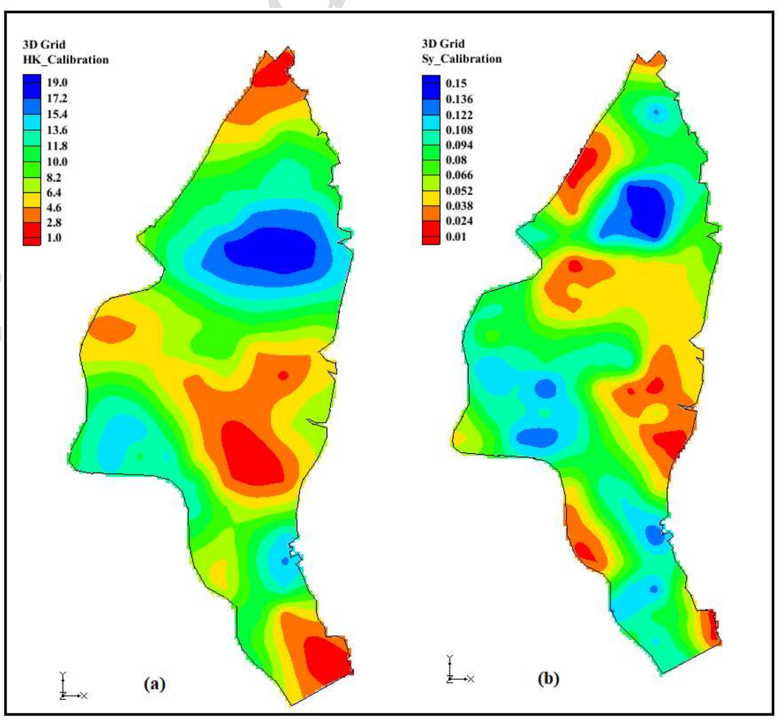

Figure 11. Calibration of hydraulic conductivity (a) and specific yeild (b) of the Marvast aquifer using numerical model

Forecasting water table trends in the Marvast aquifer

One of the principal advantages of numerical groundwater flow models is in their capability to support water resources planning, evaluate management scenarios, and facilitate strategic decision-making at the aquifer scale (Lozano Hernández et al., 2024; Tripathi & Baghel, 2025). The water balance assessment of the Marvast aquifer for the final year of the simulation period (October 2020 to September 2021) indicates an annual depletion of approximately 13.5 MCM from groundwater storage, reflecting a persistent imbalance between recharge and abstraction and an intensification of quantitative stress on the aquifer. Under such conditions, projecting future groundwater level variations based on prevailing recharge and pumping trends is essential for elucidating the dynamic response of the aquifer and for formulating effective and sustainable management strategies. Accordingly, groundwater level variations in the Marvast aquifer were simulated up to September 2030 under the following scenarios using the calibrated numerical model developed within the GMS environment.

Scenario I: Continuation of recent conditions (business-as-usual)

In this scenario, current abstractions and recharge patterns and values were maintained unchanged. The simulation result (Fig. 12) depicts the spatial distribution of groundwater levels at the end of the projection horizon. The findings demonstrate that, should current abstraction and recharge patterns persist, the most pronounced groundwater level declines will occur in the northern and northeastern parts of the aquifer, where average drawdowns of approximately 6.5 to 7m are expected. From a hydrogeological perspective, the concentration of substantial groundwater level declines in the northern and northeastern parts of the aquifer has critical implications due to the immediate proximity of the Marvast aquifer to the desert. Continued lowering of hydraulic heads is expected to enhance the hydraulic gradient from adjacent saline desert zones toward the aquifer, thereby increasing the likelihood of saline water front advancement and progressive groundwater salinization. If sustained, this process poses a serious threat not only to groundwater quality but also to the long-term sustainability of groundwater exploitation in the region. Consequently, the design and implementation of targeted management interventions, particularly control of abstractions and managed aquifer recharge strategies focused on the northern and northeastern sectors as quantitatively and qualitatively vulnerable zones, are deemed imperative.

Scenario II: 10% reduction in pumping from production wells

In this scenario, the effect of a 10% reduction in groundwater pumping by agricultural, industrial, and domestic wells was evaluated over the nine-year simulation period (October 2021 to September 2030). The results indicated that a controlled reduction in abstraction can effectively moderate groundwater-level decline and improve the hydrodynamic condition of the aquifer under exploitation-induced stress. This finding is consistent with large-scale and scenario-based groundwater modeling studies that have emphasized the importance of abstraction management in reducing pressure on groundwater systems (de Graaf et al., 2017; White et al., 2019). According to the model results, implementation of this management strategy has led to increase in the water table 0.62 m on average as compared with the continuation of current conditions represented by the business-as-usual scenario (Fig. 13). The spatial pattern of change showed that recovery is more pronounced in the northern part of the aquifer. This response is likely related to the higher density of pumping wells and the greater concentration of localized hydraulic stress in this area; therefore, reducing abstraction in this region produced a faster and more evident recovery of groundwater levels. Overall, the results of this scenario indicate that even a relatively limited reduction in groundwater abstraction, if implemented continuously and strategically, can serve as an effective management measure for mitigating groundwater-level decline and enhancing the sustainability of the Marvast aquifer.

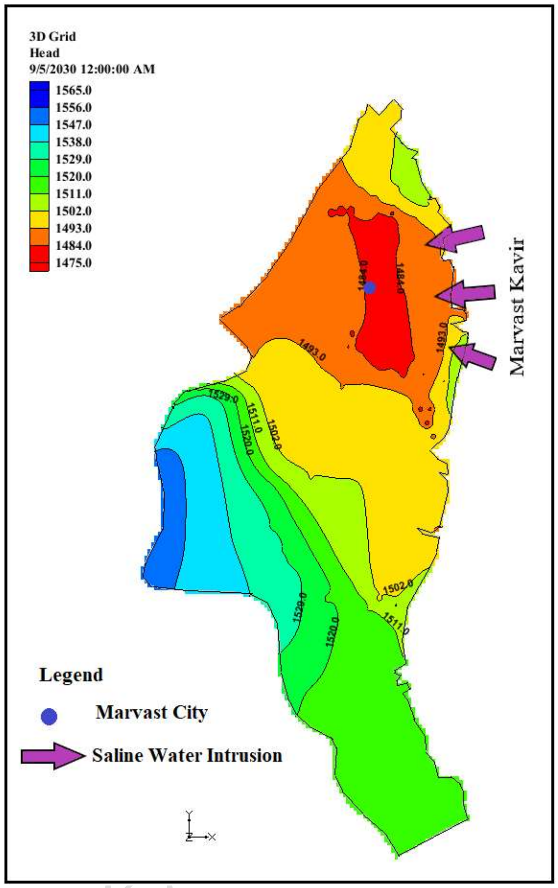

Figure 12. Forecasting spatial distribution of groundwater levels in the Marvast aquifer in September 2030

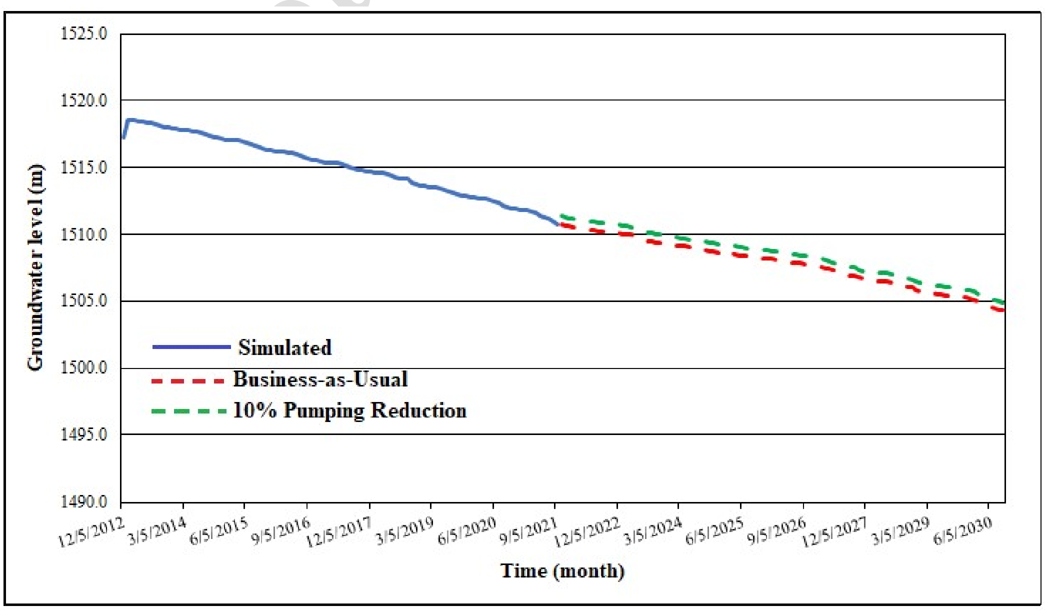

Figure 13. Diagram illustrating groundwater level responses of the Marvast aquifer under the continuation of current conditions (business-as-usual scenario) and 10% reduction of groundwater pumping scenario

Conclusion

In this study, the unconfined alluvial aquifer of Marvast (Yazd Province, central Iran) was numerically simulated in GMS environment over a nine-year hydrological period (November 2012 to September 2021) under both steady-state and transient conditions. Calibration results indicated that horizontal hydraulic conductivities range from 1 to 19 m/day, with higher values concentrated in the western, central, and southern parts of the aquifer. The specific yield (storage coefficient) was estimated to vary between 1 and 15%, with relatively higher values in the western and central zones. These spatial patterns reflect the controlling role of lithology, grain size distribution, permeability and aquifer thickness on groundwater dynamic and storage. These findings underline the importance of incorporating spatial variability in model parameterization to improve simulation accuracy and support more reliable groundwater management. The water balance analysis for the final year of the simulation period indicated an annual deficit of approximately 13.5 MCM, confirming that groundwater abstractions exceeded natural recharge. The largest groundwater level drawdowns with an average annual decline rate of about 0.7 m occurred in the northern and northeastern parts of the aquifer, where the high density of agricultural, industrial, and municipal pumping wells are observed. Simulation of groundwater levels with continuation of current conditions up to 2030 suggests that the northern and northeastern zones will remain critical, with a projected cumulative groundwater level decline of approximately 6.5–7 m. The significance is further increased due to proximity of these areas to the Marvast desert (Kavir). Continued groundwater level decline is expected to intensify hydraulic gradients from saline desert margins toward the aquifer, facilitating the inland migration of saline water (salt water intrusion) and leading to deterioration of groundwater quality. This process represents a serious long-term threat to both the quantity and quality of groundwater resources. To evaluate the impact of management measures, a scenario involving 10% reduction in abstractions was implemented over the simulation period (October 2021 to September 2030). The results indicated an average groundwater-level rise of approximately 0.62 m relative to the baseline condition represented by the business-as-usual scenario, with more pronounced effects in the northern parts of the aquifer. The results highlighted the sensitivity of these areas to changes in abstraction rates, demonstrating the effectiveness of demand management in improving aquifer conditions. Overall, the results emphasized the necessity of controlling groundwater abstraction and implementing targeted managed aquifer recharge (MAR) strategies, particularly in the northern and northeastern regions. Such measures can enhance hydraulic head, reduce unfavorable gradients, limit saline intrusion from adjacent desert areas, and finally improve the long-term quantitative and qualitative sustainability of the Marvast aquifer.

Conflicts of Interest:

The authors declare that they have no conflict of interest.

Authors' Contributions:

Farzaneh Moradi: Conceptualization, Methodology, Investigation, Original Draft Preparation
Hadi Jafari: Conceptualization, Methodology, Investigation, Data Curation, Review & Editing, Supervision

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