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Original Article

Impacts of Land Surface Characteristics on Groundwater Quality and Quantity: A Case Study of Qazvin Plain, Iran

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Abstract

Background: The Qazvin Plain is one of Iran's largest and most important agricultural regions. It is situated on the Qazvin aquifer. Understanding the relationship between surface features such as topography, land use, and soil type with the quantitative and qualitative characteristics of the aquifer is crucial for this region.

Methods: In this study, the Soil and Water Assessment Tool (SWAT) model was used to delineate the hydrological response units (HRUs) of the plain. These units were calculated based on common characteristics, including land use, topography, and soil type. Additionally, the MODFLOW model was used to simulate groundwater levels based on the hydraulic conductivity (K) map, well pumping tests, and other parameters. This model served as a quantitative indicator of groundwater resources. Furthermore, the spatial distribution map of electrical conductivity (EC) values was used as a qualitative indicator of groundwater resources. In the Qazvin aquifer, EC is the most important limiting factor for water quality. The relationship between these factors was then analyzed using geographically weighted regression (GWR).

Results: The values of EC with a statistic of $R^2 = 0.66$ and groundwater level with a statistic of $R^2 = 0.79$ were controlled by surface characteristics, indicating a strong relationship between these variables and surface features.

Conclusion: This research can highly assist water and environmental resource managers and decision-makers in managing the quantity and quality of water in this region.

Keywords: Groundwater quality, SWAT, MODFLOW, Regression, Pollution

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Introduction

Groundwater resources play a crucial role in agriculture, industry, and domestic water supply. Quantitatively, they serve as a strategic reserve during droughts and surface water shortages, while qualitatively, they often exhibit superior quality compared to surface water due to natural filtration through soil layers. However, unsustainable exploitation and pollution from human activities threaten both the quantity and quality of these vital resources. Therefore, sustainable management and protection of groundwater are essential to meet future demands. The relationship between surface characteristics—such as land use, topography, and soil type—and groundwater dynamics is a critical area of environmental research. Land use significantly influences groundwater recharge and surface runoff, affecting both groundwater availability and quality. For instance, urbanization increases impervious surfaces, leading to higher runoff and reduced infiltration, while agricultural activities contribute to groundwater contamination through fertilizers and pesticides.[1,2] Topography also plays a key role in groundwater distribution and movement. Steeper slopes promote rapid runoff, limiting infiltration and recharge, whereas flatter terrains enhance water infiltration and groundwater replenishment. Moreover, elevation and slope gradients influence groundwater flow direction and velocity, affecting resource distribution.[3,4] Soil type further governs groundwater recharge by regulating water retention and permeability. Clay-rich soils retain water but have low permeability, slowing infiltration, whereas sandy soils allow for rapid water percolation, potentially increasing contamination risks.[5,6] The interaction of these surface characteristics creates complex hydrological dynamics. For example, agricultural land on gentle slopes with sandy soils may experience higher contamination risks due to fast infiltration of pollutants, while urban areas on steep slopes may face reduced recharge and increased flooding risks.[7] Understanding these relationships is crucial for sustainable groundwater management, particularly in water-scarce regions. Effective management strategies must account for the interplay of land use, topography, and soil type to optimize groundwater recharge and protect water quality. Measures such as green infrastructure in urban areas and best management practices in agriculture can enhance groundwater sustainability.[4] Many of Iran's plains face challenges related to groundwater depletion and contamination, threatening water security. The Qazvin Plain, one of the country's largest agricultural regions, relies heavily on the Qazvin aquifer for irrigation and domestic use. However, population growth, agricultural expansion, and climate change have intensified pressures on water resources. Understanding the region's groundwater dynamics is therefore essential for sustainable resource management.[8,9]

Groundwater resources in the Qazvin Plain are influenced by various surface characteristics, including topography, land use, and soil type. These factors not only affect the quantity of groundwater resources but also cause changes in its quality.[10] The interplay between these surface features and groundwater characteristics necessitates a comprehensive approach to study and manage these resources effectively.[11]

In this study, we employed the Soil and Water Assessment Tool (SWAT) to delineate hydrological response units (HRUs) in the Qazvin Plain, categorizing areas based on land use, topography, and soil type to analyze hydrological processes.[12] Additionally, we utilize the MODFLOW model to simulate groundwater levels, incorporating data from hydraulic conductivity maps, well pumping tests, and other relevant parameters.[13] These simulations provide quantitative insights into groundwater availability.[14] To assess groundwater quality, we analyze the spatial distribution of electrical conductivity (EC) values, which serve as an indicator of water salinity and its suitability for various uses.[15] By integrating these models and analyses, we aim to clarify the relationships between surface characteristics and groundwater properties in the Qazvin Plain.[16]

The findings of this research will provide valuable insights for water resource managers and policymakers, aiding in the sustainable management of groundwater in the region.[17] By identifying the key factors influencing groundwater quantity and quality, this study will support informed decision-making to ensure the long-term viability of this critical resource.

Materials and Methods

In this study, the characteristics of the land surface were examined in relation to the quantity and quality of groundwater resources. The data on groundwater EC, river networks, and aquifer-related parameters—including operational well statistics, observation wells, well pumping test results, and climatic data—were obtained from the Qazvin Regional Water Company. Moreover, land-use data and a digital elevation model were generated using remote sensing techniques, while soil type maps were sourced from the official FAO website. The Qazvin Regional Water Company measures the EC parameter twice a year by sampling from 100 wells across the Qazvin aquifer, and this parameter was mapped using the inverse distance weighting interpolation method. The groundwater level map was developed using the MODFLOW model. These datasets were then integrated into HRUs derived from the SWAT model, incorporating soil data, land use, slope, and sub-basin information. Finally, the geographically weighted regression (GWR) model was applied to analyze the relationships between independent and dependent variables.

Study Area

The Qazvin Plain, located in north-central Iran, is a geographically and historically significant region known for its fertile lands. It lies between 49°20′–50°34′ E and 35°38′–36°21′ N, at the southern foothills of the Alborz Mountains, forming part of the Namak Lake Basin (Figure 1). The plain covers approximately 4737 km^2 and has an average annual precipitation of 256.6 mm. The climate is predominantly cold and dry, with warmer temperatures during summer. The Qazvin Plain contains the largest aquifer in the Namak Lake Basin, making it a key water resource for the region.[8]

MODFLOW Model

For modeling water movement in soil and the behavior of aquifers, comprehensive information about the hydraulic characteristics of the studied area is essential. An aquifer is a subsurface geological formation capable of storing and transmitting groundwater. Using the hydraulic data of an aquifer, precise modeling can be conducted, minimizing discrepancies during the calibration phase. To enhance the model's accuracy and its resemblance to real-world conditions, various factors such as soil structure properties and the type of groundwater tables must be considered. Important factors in this context include soil layer composition, hydraulic conductivity, storage coefficient, specific yield, salinity levels in soil and groundwater, and other related parameters, all of which are critical in building an accurate groundwater model.

In this study, version 10.7 of the GMS software was used for aquifer modeling. One of the models available in this software is the MODFLOW model, which is used for quantitative modeling. MODFLOW is a numerical model for simulating groundwater flow, developed by the United States Geological Survey (USGS). Creating a MODFLOW model involves defining a 3D Grid. Grids serve as graphical interfaces for storing data in the conceptual model. The higher the number of grids or cells per unit area, the greater the computational accuracy. Each cell has its own specific hydraulic characteristics, such as hydraulic conductivity, porosity, or recharge rate. Aquifers and impermeable layers are modeled as horizontal layers. Each layer can represent various conditions, such as an unconfined aquifer or a confined aquifer.[18]

This model determines where water enters or exits the

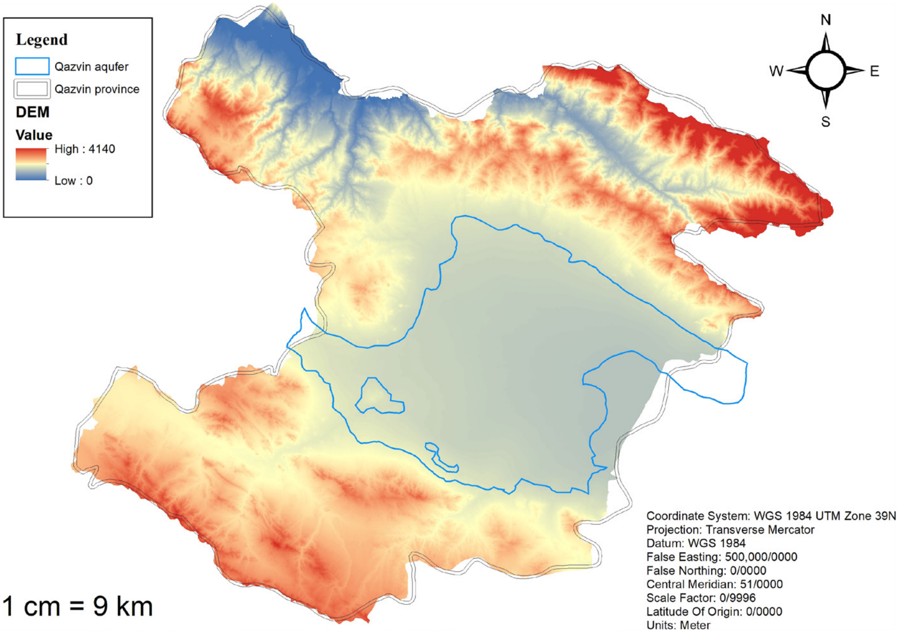

Figure 1. Study Area (Qazvin Aquifer)

system (e.g., rivers, wells, or closed boundaries). In this model, hydraulic conductivity, permeability, recharge or evaporation rates, well locations, and pumping rates were used as inputs. The resulting outputs include the calculation of water level distribution (Head) in cells and flow rates at the desired times and locations.

SWAT Model (Soil and Water Assessment Tool)

The SWAT is one of the most comprehensive and widely used models for hydrological simulation and water resource management. Developed by the United States Department of Agriculture (USDA), SWAT is designed to assess the impacts of land and water management on water and soil resources. It can simulate hydrological processes, soil erosion, nutrient transport, and pollution at the watershed scale.[19] For simulation purposes, a watershed must be divided into sub-basins. This subdivision is particularly beneficial when different areas of the watershed have heterogeneous soil types or land uses, as these variations significantly influence hydrological processes. Each sub-basin is further categorized into distinct components, including climate, ponds/wetlands, HRUs, groundwater, and the main watercourse that drains each sub-basin.

HRUs represent homogeneous land areas within a sub-basin that share the same land cover, soil type, and management practices. in this study, the input data, such as digital elevation model information, stream networks, land use, and soil data, were first entered into the model. Subsequently, the watershed of the study area and the outlets of the plains were identified. The SWAT model processed these data and created a network of sub-basins and HRUs with distinct hydrological characteristics.[20,2].

In this research, we required locations to integrate surface feature data with groundwater levels. For this purpose, the locations of HRUs were used, as they represent common surface characteristics of the land surface, making them an effective means of examining the influence of these features on groundwater resources.

Integrating Land Surface Data and Aquifer Data

To correlate groundwater quantity and quality in the Qazvin Plain with land surface characteristics, we required locations that accurately represent common surface features and allow for their division among neighboring regions. In this study, we used the HRUs generated by the SWAT model. These HRUs, defined by shared land characteristics, enabled a detailed analysis of how surface features influence groundwater properties within each region. This approach overcomes the limitations of other models typically combined with SWAT or MODFLOW.

Geographically Weighted Regression

GWR is a statistical technique designed to analyze spatial relationships between variables. Unlike traditional regression models that assume a uniform relationship across a study area, GWR allows these relationships to vary locally, making it particularly useful in fields such as geography, urban planning, environmental science, and public health.[22-24] In this study, GWR was employed to examine the relationship between groundwater head, EC, and HRUs. By estimating local regression coefficients, GWR effectively identifies spatial patterns and variations in these relationships. The results indicate that GWR successfully captures spatial heterogeneity, providing valuable insights into groundwater system dynamics.[25]

Results and Discussion

Groundwater Head Map

The hydrogeological map of the Qazvin aquifer illustrates various groundwater head levels measured in meters above sea level. The highest groundwater head is indicated in dark red at the center of the map, ranging from 1350 to 1440 m above sea level. The groundwater head levels decrease concentrically from the center outward (Figure 2).

After optimizing the model, the results were validated using a comparison plot of calculated data versus observed data (Figure 3), as well as a simulation error plot (Figure 4). Based on the results, the calculated data closely matched the observed data, and the simulation errors were minimal, providing confidence in the obtained results.

HRUs Map

The HRU map of the Qazvin Plain is presented in

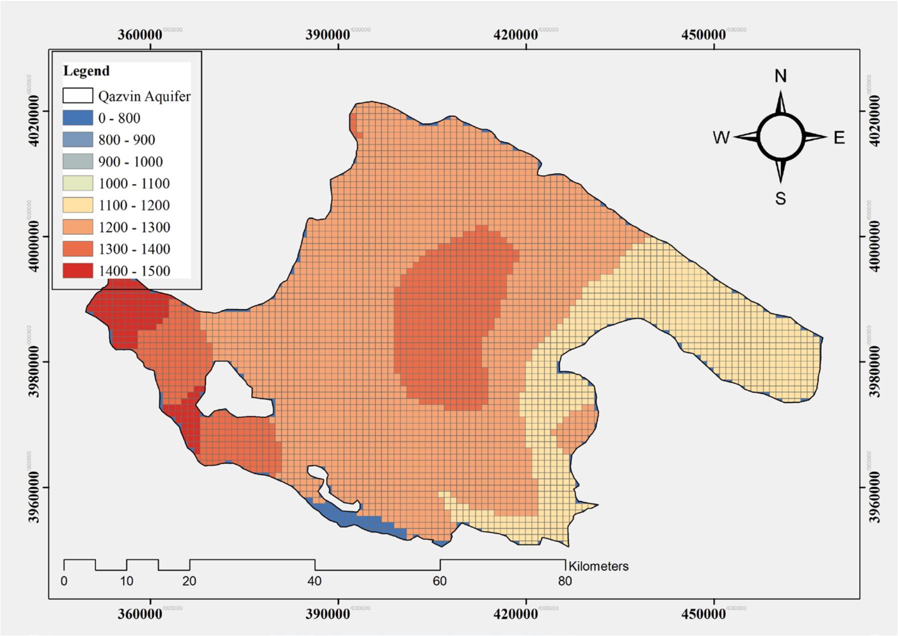

Figure 2. Groundwater Head (Groundwater Level of Qazvin Plain)

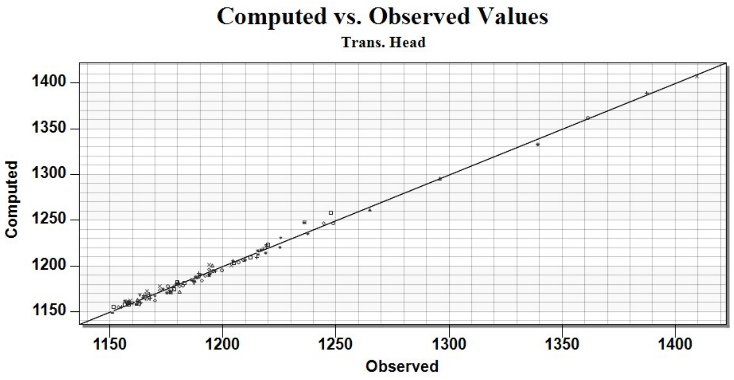

Figure 3. Comparison Plot of the Calculated Data Versus the Observed Data

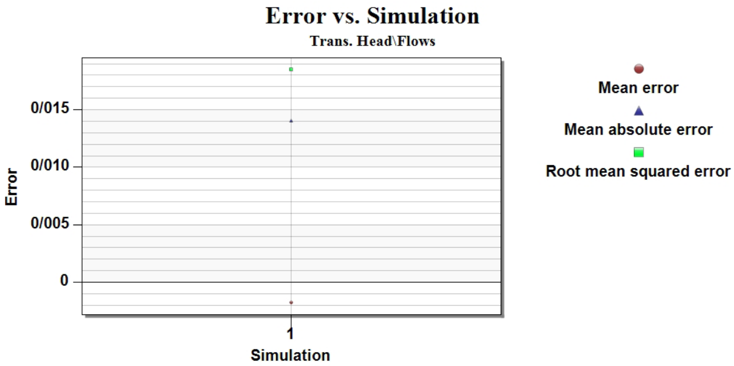

Figure 4. Simulation Error Plot

Figure 5. In the SWAT model, HRUs represent unique combinations of land use, soil type, and slope within a watershed. By dividing the watershed into these homogeneous units, SWAT can more accurately simulate hydrological processes such as runoff, infiltration, and evapotranspiration. This detailed approach enhances water resource analysis and management by accounting for land variability and its influence on water movement and quality.

Geographically Weighted Regression

Figures 6 and 7 illustrate the GWR map, which standardizes the statistical analysis of the relationship between groundwater head, EC, and land surface characteristics.

This map uses color gradients to represent standardized residual values, with dark blue indicating values below -2.5 standard deviations and red indicating values above 2.5 standard deviations. The R^2 values obtained were 0.65 for EC and 0.79 for groundwater head, demonstrating a significant relationship between the dependent variables and the studied parameters.

Electrical Conductivity

GWR was employed to analyze the relationship between the EC of groundwater resources in the Qazvin Plain and various land surface parameters, including land use, sub-basin, soil type, and slope. The results of this analysis

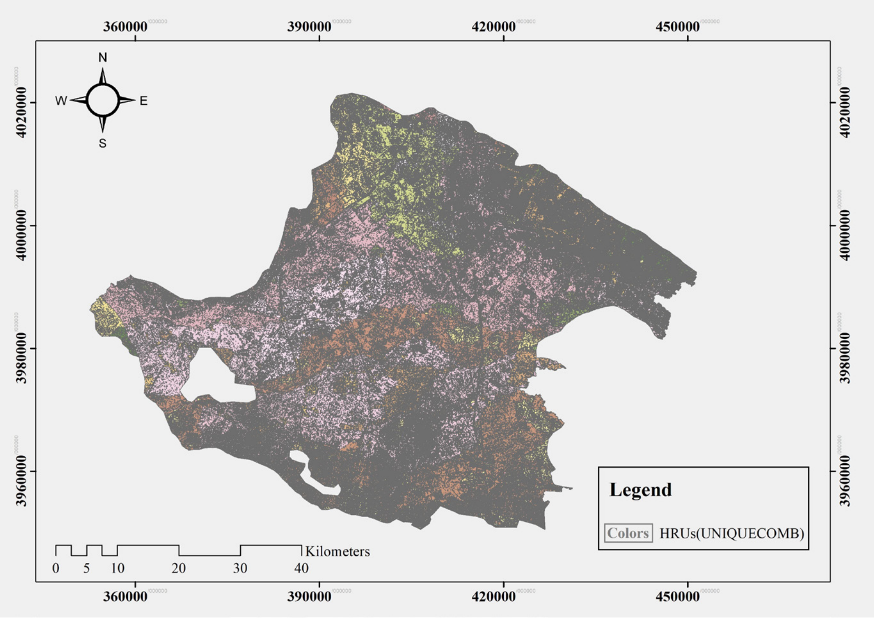

Figure 5. HRUs map of the Qazvin Plain

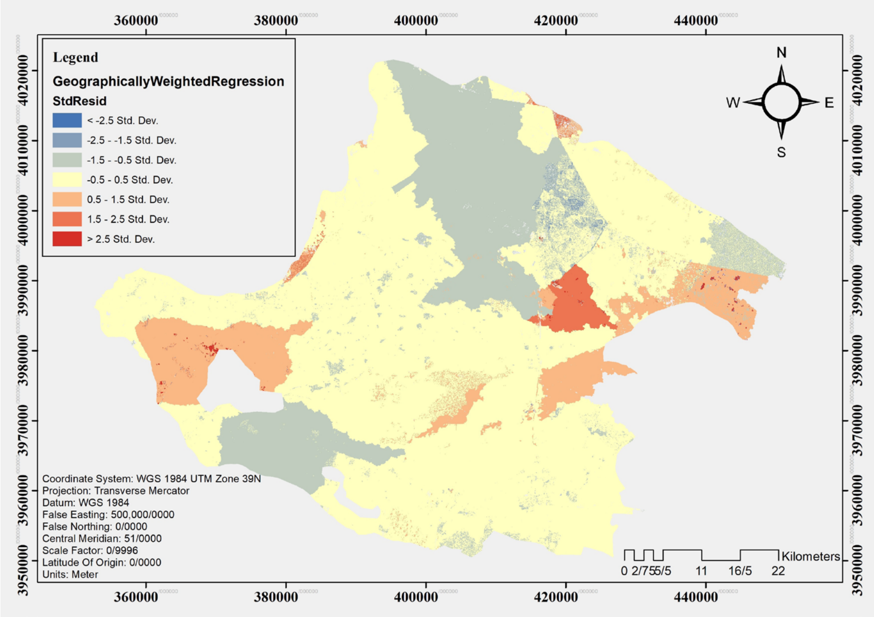

Figure 6. Residual Standard Error Map for the EC Model

reveal a significant correlation between these parameters and EC (Table 1).

The R^2 value of 0.659 shows that the GWR model was able to explain about 66% of the variations in EC. This value indicates a relatively high accuracy of the model in predicting EC based on the examined parameters. Additionally, the adjusted R^2 value of 0.64 confirms that the model fits well with the data and avoids overfitting. The AIC c value of 5722.465 indicates the quality of the model. A lower AIC c value means a better model, and this value shows that the selected GWR model is optimal. The sigma value (434.603) also presents the standard deviation of the model errors, providing information about the accuracy of the predictions.

The sum of squared residuals (68302418.080) shows the amount of model errors. This value illustrates that the model still has errors that can be reduced by improving the model and adding other explanatory variables.

Groundwater Head

GWR was used to analyze the relationship between groundwater head and land use parameters, sub-basin, soil type, and slope. The results of this analysis indicate a significant relationship between these parameters and groundwater head (Table 2).

The R^2 value of 0.797 shows that the GWR model was able to explain about 79.7% of the variations in groundwater head. This value indicates a relatively high accuracy of the model in predicting groundwater head based on the examined parameters. In addition, the Adjusted R^2 value of 0.788 confirms that the model fits well with the data and avoids overfitting. The AIC c value of 4623.286 indicates the quality of the model. A lower Akaike information criterion correction (AICc)

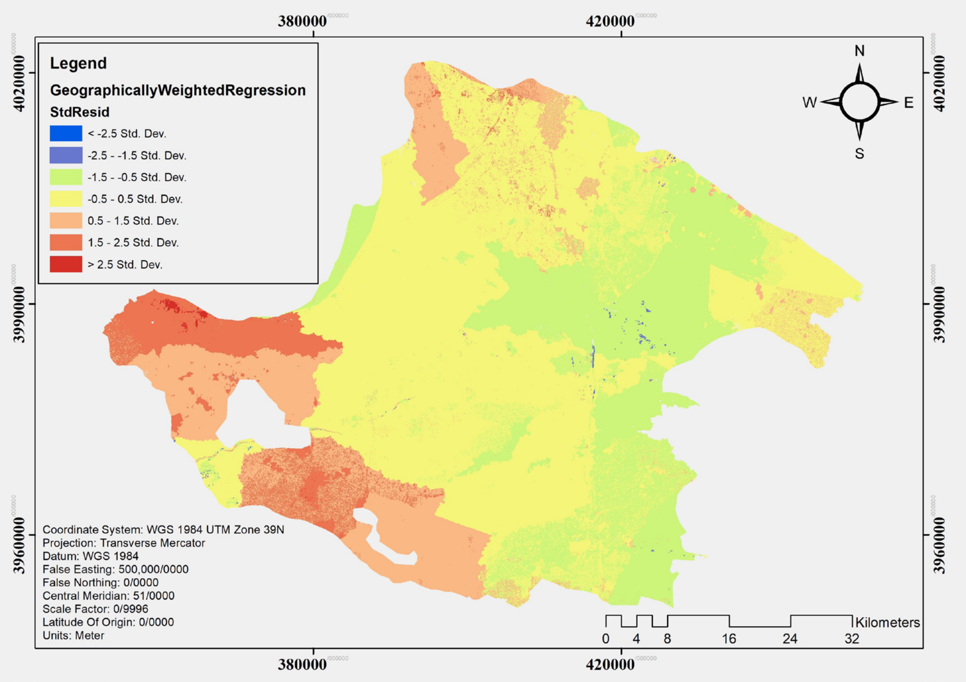

Figure 7. Residual Standard Error Map for the Groundwater head model

Table 1. GWR results for EC model

Objectid	Varname	Variable	Definition
1	Bandwidth	26097.87	
2	Residual squares	68302418.08	
3	Effective number	19.38	
4	Sigma	434.60	
5	AIC c	5722.46	
6	R2	0.66	
7	R2 adjusted	0.64	
8	Dependent field	0	EC
9	Explanatory field	1	Soil
10	Explanatory field	2	Slope
11	Explanatory field	3	Land use
12	Explanatory field	4	Sub basin

Table 2. GWR Results for Groundwater Head Model

Objectid	Varname	Variable	Definition
1	Bandwidth	24962.009	
2	Residual squares	364362.63	
3	Effective number	21.57	
4	Sigma	28.0398	
5	AIC c	4623.286	
6	R^2	0.79	
7	R^2 adjusted	0.79	
8	Dependent field	0	Groundwater head
9	Explanatory field	1	Sub basin
10	Explanatory field	2	Land use
11	Explanatory field	3	Soil
12	Explanatory field	4	Slope

value means a better model, and this value shows that the selected GWR model is optimal. The sigma value (28.040) also indicates the standard deviation of the model errors, providing information about the accuracy of the predictions. The sum of squared residuals (364362.627) indicates the amount of model errors. This value shows that the model still has errors that can be reduced by improving the model and adding other explanatory variables.

The results showed an impressive R^2 value of 0.79 for the relationship between groundwater head and surface characteristics, and an R^2 value of 0.66 for the relationship between EC values and surface characteristics. This high correlation indicates a strong relationship between groundwater levels and EC values with surface hydrological features. This study demonstrates the effectiveness of using integrated MODFLOW and SWAT models, along with GWR, to model and examine the relationship between groundwater levels and surface hydrological features. An R^2 value above 0.79 for the relationship between groundwater levels and surface features, as well as an R^2 value of 0.66 for the relationship between EC values and surface characteristics, indicates the robustness of our approach in predicting groundwater levels and EC based on surface features. These results have significant implications for water resource management and planning, providing a reliable method for assessing and managing groundwater resources. One of the most important factors that must be managed to improve the quantitative and qualitative status of groundwater resources in this area is land use. Agricultural, industrial, and urban use is increasing in this plain, and its current growth policy should be reviewed. Furthermore, due to the reduction in natural land cover, especially on slopes, due to the slope conditions in the region and the presence of salt-containing geological formations in the region, policies to restore natural ecosystems should be pursued to prevent erosion.

Our findings were consistent with previous studies that have used integrated MODFLOW and SWAT models to analyze surface and groundwater interactions. For example, Yifru et al[26] demonstrated the effectiveness of using an integrated SWAT-MODFLOW model to assess river-aquifer interactions, highlighting the model's capability to enhance performance and reduce uncertainty through calibration techniques. Similarly, Sisay et al[27] identified significant interactions between surface and groundwater systems in the Modjo River Basin using SWAT and MODFLOW, reporting substantial fluxes between the systems.

The application of GWR in our study further supports the findings of previous research emphasizing the importance of spatially variable relationships in hydrological modeling. Studies have shown that GWR can improve prediction accuracy by accounting for local variations in data, which is crucial for understanding complex hydrological processes.

In comparison to similar studies, our results highlight the strong correlation and high accuracy of the integrated modeling approach. For example, Yifru et al[26] and Sisay et al[27] both reported high R^2 values and emphasized the importance of integrated models for understanding surface-groundwater interactions. Our study contributes to this body of knowledge by demonstrating the added value of incorporating GWR to capture spatial variations and improve model accuracy.

This study, like other similar research, identified that topographical features, stream networks, land use, and soil types play essential roles in influencing the level and quality of groundwater. Topography impacts the patterns of surface water flow and its infiltration into the soil, with steeper areas potentially exhibiting lower infiltration rates. Stream networks act as channels for collecting and directing water flow, which determines the recharge zones for groundwater. Land use affects evaporation, transpiration, and infiltration rates through vegetation and surface cover types. Soil type, on the other hand, determines water retention capacity and the speed of its movement within the ground. These factors can regulate groundwater levels and alter the concentration of dissolved minerals, which in turn affects the EC of groundwater.[28-32]

Conclusion

This study utilized the MODFLOW model in GMS software for groundwater level extraction and the SWAT model in GIS software to delineate HRUs, integrating groundwater EC and level data into HRU polygons and applying GWR to examine relationships between groundwater levels, EC, and surface characteristics. Strong correlations were found, with R^2 values of 0.79 for groundwater head and 0.66 for EC versus surface features, demonstrating the effectiveness of the integrated approach in predicting groundwater behavior based on surface hydrological properties. The findings highlight the importance of managing land use—such as agricultural, industrial, and urban activities—to improve groundwater quantity and quality, while also emphasizing the need for policies to restore natural ecosystems and prevent erosion caused by reduced land cover. Future research should focus on refining models, incorporating additional influencing factors, and expanding datasets to better understand surface-groundwater interactions and enhance model applicability across diverse hydrological contexts.

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Authors' Contribution

Conceptualization: Mohamad Parsi Mehr.
Data curation: Eisa Solgi.
Investigation: Mohamad Parsi Mehr, Eisa Solgi.
Methodology: Mohamad Parsi Mehr, Eisa Solgi .
Project administration: Eisa Solgi.
Resources: Mohamad Parsi Mehr, Eisa Solgi.
Software: Mohamad Parsi Mehr.

Supervision: Eisa Solgi.
Validation: Eisa Solgi.
Visualization: Mohamad Parsi Mehr.
Writing–original draft: Mohamad Parsi Mehr.
Writing–review & editing: Mohamad Parsi Mehr, Eisa Solgi.

Competing Interests

The authors declared that there is no conflict of interest.

Ethical Approval

Not applicable.

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