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Original Article

Changes in groundwater dynamics in the transboundary Ravi river basin using MODFLOW modelling framework

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Abstract

The groundwater resources of the Ravi river basin are facing increasing pressure due to agricultural, domestic, industrial and urban water needs. However, groundwater changes in this basin have not been assessed using a spatially distributed modelling approach. This study used MODFLOW-NWT to assess spatial and temporal fluctuations in groundwater levels across 12 districts of Punjab, Pakistan. The model integrated land-use, soil, climatic and groundwater data. The aquifer was divided into three layers of 80 m, 120 m and 300 m, using a grid size of 6 km × 6 km. Data from 739 piezometric wells (2000–2019) were used for model calibration and validation. During calibration, R^2, Pearson r and NSE ranged from 0.77–0.84, 0.77–0.84 and 0.91–0.95, respectively. During validation, the corresponding values ranged from 0.89–0.92, 0.98 and 0.89–0.92, respectively. The results indicate that groundwater levels declined at an average rate of 0.5–1.0 m/year, reaching 2–3 m/year in some areas, particularly around Lahore, Sheikhupura, Faisalabad and Pakpattan. Sensitivity analysis using the Parameter Estimation (PEST) package evaluated the influence of horizontal (Kh) and vertical (Kv) hydraulic conductivity, recharge (RCH), specific yield (Sy) and specific storage (Ss). Groundwater depletion was spatially variable and particularly significant in areas with high agricultural and urban water demand. Although the 6 km × 6 km grid supports regional assessment, it may not capture local groundwater variations. This quantitative assessment can support regional groundwater management by identifying depletion hotspots and informing targeted interventions, including rainwater harvesting and managed aquifer recharge, to improve groundwater storage and recovery.

Keywords: Aquifer recharge, Groundwater depletion, Groundwater modelling, Hydrological assessment, Managed aquifer recharge, Water security

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Introduction

Groundwater is an important component of the global water cycle and plays a crucial role in providing water for drinking and agriculture (Scanlon et al., 2023). It helps sustain river baseflow and wetlands in regions with limited surface water flows (Bao et al., 2026; Banerjee and Ganguly, 2023). Accordingly, the growing demand for water and changes in land use impose a burden on aquifer systems. The over-exploitation of groundwater is also resulting in degradation of water quality. Groundwater depletion and degradation have been intensified by climate change in many parts of the world, such as the North China Plain (Kuang et al.,2024; Long et al., 2025), the High Plains of the United States (Kunwar et al., 2026; Wang et al., 2025). Groundwater-related issues do not occur exclusively in specific regions, but rather in transboundary groundwater systems where the changes in groundwater quantity and quality may have cross-border implications (Maass-Morales et al., 2024; Rubin et al., 2024).

In transboundary river basins, the use of groundwater and surface-water resources is affected by different management regimes (Rubin et al., 2024). One such example is the Ravi river basin, shared between India and Pakistan. This river basin is home to over 50 million people, with groundwater playing a significant role in agriculture and domestic water supply (Godara et al., 2024). Numerous studies conducted in the Ravi river basin have reported various problems such as decline in quality of groundwater, and ecological degradation (Ashraf et al., 2022; Mahajan et al., 2024). Changes in water balance of the basin resulting from altered river flow in the upper part of the basin, have weakened the opportunities for natural groundwater recharge (Ahmed et al., 2020). Such changes make it necessary to quantitatively assess the groundwater conditions and identify the causes for groundwater depletion.

To investigate the groundwater levels and flows, computer-based groundwater models present a suitable opportunity especially in regions with limited ground observations. However, the selection of the model in a transboundary basin like Ravi is important, due to the differences in data coverage, resolution and reliability between the datasets. Researchers have used various groundwater modeling approaches such as simple water-balance approaches, lumped models and fully coupled surface-water and groundwater models, i.e., ParFlow and MIKE SHE. Fully integrated models can simulate many hydrological processes but most of them require a lot of information related to climate, soil, land-use, surface-water flows, and aquifer properties. For transboundary basins, getting such data can be challenging, especially in cases where monitoring networks are sparse and data-sharing agreements between riparians does not exist (Rahimi et al., 2026; Ben-Zur et al., 2025).

On the other hand, Standalone groundwater models like MODFLOW present a suitable option for evaluating aquifer behavior and can be used efficiently with limited data. In MODFLOW, important surface and groundwater processes are presented using built-in packages like the Streamflow routing (SFR) packages. The SFR package enables the investigation of the interactions between rivers and canals with the aquifer without using a fully coupled hydrological model. Many researchers have used MODFLOW and similar frameworks to explore groundwater dynamics in a data-limited scenario (Dillon et al., 2019; Larsen et al., 2022; Borzì, 2025). Advances in MODFLOW like MODFLOW-NWT extend the capability to account for nonlinear groundwater-flow conditions and the SFR package allows for surface-water and groundwater exchange (Ringleb et al., 2016; Zeydalinejad et al., 2026). Although groundwater modelling has been used by various researchers in the Ravi river basin but the detailed quantitative assessment of changes in groundwater is still limited.

To fill this gap, a spatially distributed groundwater model for the Pakistani side of the Ravi river basin has been developed in this study using MODFLOW-NWT framework. Available groundwater, surface-water, climate, land-use, soil, and topographic data are integrated into the model, which includes the river package and SFR package to model the interactions between the river bottoms and the aquifer. The primary objectives of this study are: (1) to quantify the spatial and temporal changes in groundwater levels and flow patterns in the study area; (2) to evaluate the relative importance of the various groundwater stresses, especially irrigation abstraction and recharge related processes; and (3) to determine the consequences of the observed groundwater trends for long-term groundwater management in the study area. The results can be used to quantify the groundwater situation in a data deficient area of the transboundary Ravi river basin and help future groundwater monitoring, management and cooperation between the riparian countries.

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Material and Methods

Study area

The Ravi river basin, a waterway stretching 720 km originating from Kangra, Himalayas, within Himachal Pradesh, India. The basin covers an area of approximately 38,248 square kilometers, with 14,036 square kilometers situated in India (as the catchment area) and 24,212 square kilometers in Pakistan (forming the flood plain). As the Ravi river crosses through the Amritsar and Gurdaspur districts of Punjab, it serves as the international boundary between India and Pakistan until it exits Indian territory at the village of Goina (Kakarmani), approximately 80 kilometers downstream. Ravi river enters Pakistan near the village of Jassar in the Narowal district of Punjab, Pakistan. For this study, twelve districts were selected including Faisalabad, Kasur, Khanewal, Lahore, Nankana Sahib, Narowal, Okara, Pakpattan, Sahiwal, Sheikhupura, Toba Tek Sing, and Vehari. The map of the study area is shown in Figure 1.

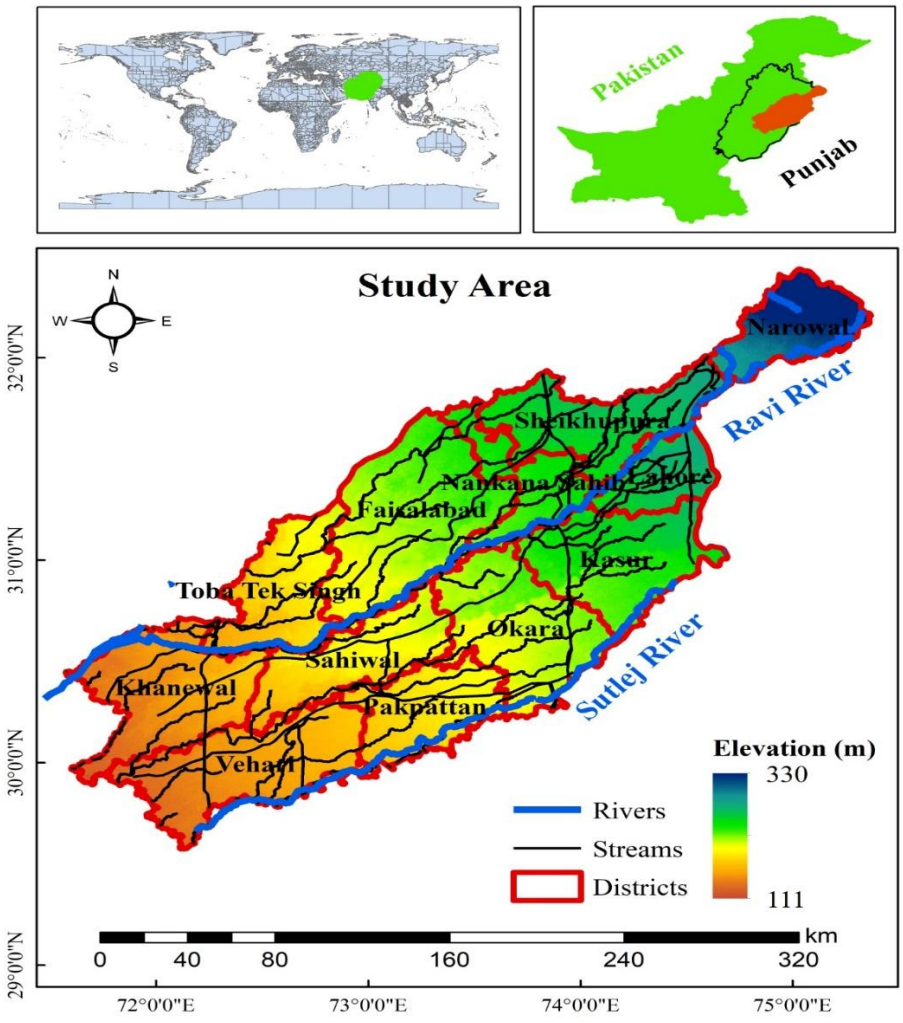


Figure-1. Location of study area Ravi river basin. The study area includes all the districts lying over the Ravi river, representing district boundaries with red polygons, rivers with blue lines, and stream network with black lines.

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Soil in the basin is generally clay and silt with fertile alluvial soils in the upper layers along the riverbed and floodplain. The study area experiences majority of annual rains during the summer monsoon (July and August). The annual mean precipitation of the study area is 620 mm and the annual relative humidity values vary between 45 and 85%, while the mean wind speed varies between 0.1 and 1.6 m/s. The flow of the Ravi river is highly variable seasonally and annually due to its dependence on the snow melting from the Himalayas, monsoon rainfall and regulation of water from upstream (Ullah et al., 2024). A study by Ahmed et al. (2023) using the river-flow data of 1991–2015, has recorded a 36% decline in annual mean flow at the Ravi Riverfront in a post-dam scenario as opposed to pre-dam scenario. The study also revealed a statistically significant downward flow trend at the Ravi Syphon gauging station, which is reported to be about 380.98 ft³/s per year.

Groundwater modelling

A numerical simulation model was employed to study groundwater systems in the study area. The modeling utilized MODFLOW-NWT, supported by a graphical user interface (GUI) offered by ModelMuse-NWT (Rashidi et al., 2025). These two software tools are commonly used for groundwater modeling. MODFLOW-NWT is open source, highly efficient, and widely used in groundwater research (Attea et al., 2025; Kishor et al., 2025). It can model three-dimensional groundwater flow using the finite difference method (Provost et al., 2025). The model integrates Darcy's equation with the principle of mass conservation to solve the governing equation for groundwater flow in a porous medium. MODFLOW-NWT provides a numerical solution to this governing equation for groundwater flow through a porous medium (Khadri and Pande, 2016).

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(Kz\frac{\partial h}{\partial z}\right)-W=Ss\frac{\partial h}{\partial t} \quad (1)$$

where K_x, K_y, and K_z denote the hydraulic conductivity values along the x, y, and z axes, respectively, S_s represents the specific storage of the porous material, and t represents time. The variable W represents the rate of inflow (recharge) and outflow (discharge) per unit volume (T^{-1}). MODFLOW-NWT simulations, flow equilibrium is maintained within each model cell to ensure mass conservation. At constant density, the continuity of flow is expressed through the following equation:

$$\sum Qi = Si\frac{\partial h}{\partial t}\partial V \quad (2)$$

Where Qi is the flow rate per cell (L3/T), Ss specific storage (L-1), ∂h is the change in head concerning time ∂t, and ∂V is the change in volume in cells (L3).

Model parameters and boundary conditions

Three layers were used to represent the aquifer system with thicknesses of 80 m for the upper layer, 120 m for the middle, and 300 m for the lower. The top layer is the shallow soil and unsaturated zone, which was assigned to a relatively low hydraulic conductivity. The second and third layers are the primary layers of abstraction (of groundwater by the tubewells) in the study area. The top ground surface was modeled in ModelMuse using a Digital Elevation Model (DEM) with a resolution of 30 m × 30 m from the Shuttle Radar Topography Mission (SRTM) data. Various studies have used SRTM data for hydrological modelling of the groundwater (Ahmad et al., 2025; Esmaeili et al., 2026). A grid size of 6 km × 6 km was used for the MODFLOW-NWT model. A transient simulation was then performed to simulate changes in groundwater levels for a period between 2000 to 2019. The model elevation at the upstream section was 216 m and the downstream section was 105 m. The mean bottom elevations of the first, second and third layers were 80, -120 and -300 m, respectively, below the common vertical datum.

The rivers and canals situated in the study area were included in the model using the River Package in MODFLOW-NWT. The General Head Boundary (GHB) conditions were also used to represent head-dependent exchanges between the aquifer and surrounding water bodies. River and canal networks were digitized in ModelMuse using the polyline tool (Zana et al., 2025). Groundwater abstraction was represented using the Well Package. Pumping data were derived from district-level raster datasets and assigned to the second and third layers.

The precipitation and irrigation were considered as recharge in the groundwater budget and evapotranspiration was considered as a loss. The inputs in ModelMuse were presented and spatial data was prepared, by importing the shapefiles of land use and hydrogeological zones in GIS. The evapotranspiration was simulated using the

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Evapotranspiration Package and the upper layer of the model was recharged with rainfall and irrigation. The timing of all recharges, pumping and evapotranspiration inputs was tied to the model stress periods to simulate the seasonal and annual variations in groundwater conditions.

Handling data in ModelMuse

In the case of MODFLOW-NWT based modelling, ModelMuse allocates values to the individual model cells based on a specified sequence. The default value in the model is set for the first cells using a formula. Selected areas are then provided with more specific values using spatial objects, such as polygons, polylines and points. These objects override the default values in those areas that coincide with the model grid. If two or more objects overlap a cell, then the value of the last object to be processed is used. Two-dimensional datasets were primarily used in this study to specify the upper and lower limits of the model. This enabled the presentation of the vertical structure and spatial variation of the aquifer in the model.

Creating objects and setting parameters

The formulas and spatial objects were used to assign model parameters in ModelMuse. The parameters used were set as follows:

- Kx (horizontal hydraulic conductivity): Polygon objects to represent the canal command areas were used to assign the values.
- Ky (hydraulic conductivity in the Y-direction): Ky was assumed to be the same as Kx which assumed isotropic hydraulic conductivity in the horizontal direction.
- Kz (vertical hydraulic conductivity): Kz was assumed to be 1/10 of Kx.

Initial heads were estimated by adding 15 m to the bottom elevation of the upper aquifer as an estimate for the initial saturated thickness in the upper aquifer. Layer bottom elevations: Bottom elevations of the layers were determined from layer elevations and thickness. For example, the bottom of the second layer was obtained by subtracting its thickness from the bottom elevation of the first layer. Spatial data on recharge and groundwater abstraction were assigned using shapefiles. Rainfall and canal seepage recharge were estimated for each model cell, based on information from previous studies and the delineated canal command areas (Bailey et al., 2025; Guo et al., 2026). These recharge values were used in the top model layer to represent the natural recharge as well as recharge from irrigation channels.

The abstraction from groundwater was depicted by the pumping rate of tube wells. The location of tubewells were extracted from the district level rasters. The pumping rates were assigned to the second and third layers of the model (where majority of the tube wells extract groundwater). Similarly, the inputs of recharge and abstraction were compared to ensure a true representation of the groundwater balance in the model. The data from 739 piezometers were obtained from the Punjab Irrigation Department to equip the model with point information on groundwater levels. The initial hydraulic heads for the transient simulation were determined from observations recorded in the year 2000. The model was calibrated and validated under transient conditions to evaluate the model's ability to represent the temporal and spatial changes in groundwater levels.

Stress periods and initial heads

The transient groundwater model was simulated using annual stress periods over the 2000–2019 period. Annual groundwater-level change was assessed by comparing simulated groundwater heads at the ends of successive annual stress periods. Annual drawdown was calculated as the difference between the groundwater head at the end of the preceding year and that at the end of the current year. Cumulative drawdown was calculated relative to the initial groundwater head at the beginning of the 2000 simulation. Accordingly, the cumulative drawdown mapped for 2000 represents the groundwater-level change at the end of the first annual stress period, whereas the maps for subsequent years show the accumulated change relative to the same initial reference condition.

The model then runs through successive stress periods to represent changes in groundwater conditions during the study period. The location of the tubewells used for this study is shown in Figure 2.

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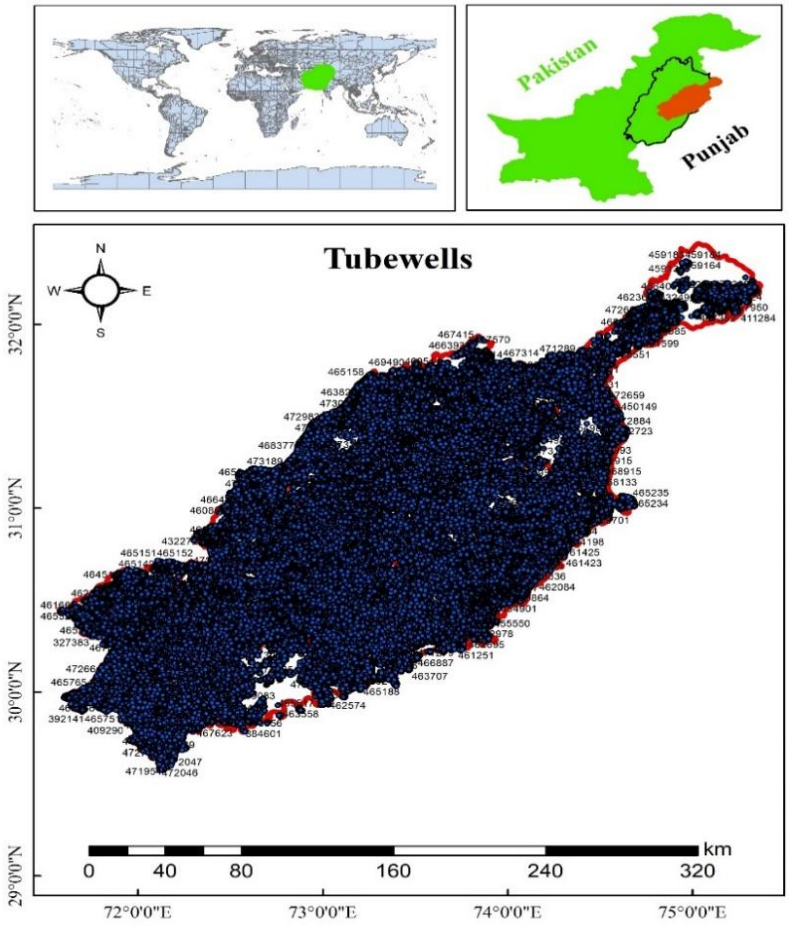


Figure-2. Presents the distribution of tubewells in the Ravi river basin, Punjab, Pakistan. Inset maps show the global location of Pakistan, the Punjab province, and the delineated study area.

Model sensitivity and uncertainty

Groundwater models present a simplified version of nature and hence are subject to a degree of uncertainty. This uncertainty may be due to the uncertain nature of the input data, the spatial and temporal distribution of groundwater observations. The other reasons for the uncertainty may be the assumptions regarding aquifer properties and boundary conditions. Accordingly, sensitivity analysis was performed before calibration using the Parameter Estimation (PEST) package (Ammari et al., 2025), to observe the impact of the model parameters i.e., horizontal (Kh) and vertical (Kv), hydraulic conductivity, recharge (RCH), specific yield (Sy), and specific storage (Ss).

The composite scaled sensitivity (CSS) values were used in the sensitivity analysis. The hydraulic conductivities (horizontal and vertical) of the upper aquifer, recharge, specific storage and specific yield were the most sensitive parameters in the model, in the order listed. Therefore, the results obtained from these ranges of parameters were selected for calibration of model. The selected ranges were also compared with the ranges from regional studies (Maples et al., 2020; Sarkar and Lakshmikanthan, 2026). The calibrated model showed an RMSE of 7.32-8.69 and a normalized RMSE of 4.8% compared to the observed hydraulic heads. These values are considered as good match between the simulated and observed groundwater levels. However, some uncertainty was observed owing to the limited observation and hydrological well data. Hence, the models' results are suitable for evaluation of groundwater trends and identifying groundwater stress at the local scale, rather than precise predictions. The inclusion of more monitoring wells can help to better simulate the future model and to reduce uncertainty.

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Model calibration

The objective of the calibration process was to achieve the best groundwater model by adjusting several parameter values as per actual conditions or meet acceptable criteria. This study employed transient state model calibration and validation. The statistical metrics are calculated using the following equations:

$$NSE = \frac{1 - \sum_{i=1}^{N}(Q_{obs} - Q_{sim})}{\sum_{i=1}^{N}(Q_{obs} - \bar{Q}_{obs})^2} \quad (3)$$

$$R^2 = \frac{[\sum_{i=1}^{N}(Q_{obs} - \bar{Q}_{obs})(Q_{sim} - \bar{Q}_{sim})]^2}{\sum_{i=1}^{N}(Q_{obs} - \bar{Q}_{obs})^2 \sum_{i=1}^{N}(Q_{sim} - \bar{Q}_{sim})^2} \quad (4)$$

$$PB(\%) = 100 \times \frac{\sum_{i=1}^{N}(Q_{obs} - Q_{sim})}{\sum_{i=1}^{N} Q_{obs}} \quad (5)$$

$$MAE = \frac{1}{N}\sum_{i=1}^{N}|Q_{obs} - Q_{sim}| \quad (6)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(Q_{obs} - Q_{sim})^2} \quad (7)$$

Q_{obs} , $\bar{Q}_{obs}$ - observed and mean observed value, respectively, $_{im}$, $\bar{Q}_{sim}$ - simulated and mean simulated value, respectively.

Results and Discussion

Model parameters were calibrated by tuning the hydrogeological parameters determined during the sensitivity analysis. Calibration was performed in the years 2005 and 2010 and the years 2014 and 2019 used for validation. The figures 3 and 4 show a good agreement between the groundwater head observed and simulated results in both the calibration and validation periods. The model results show a R^2 value of 0.84, NSE of 0.95, Pearson correlation coefficient (r) of 0.84 and mean absolute error (MAE) of 4.28 m for the year 2005. The corresponding results for 2010 were 0.77, 0.91, 0.77, and 4.18 m, respectively. These results suggest that the model shows good results in simulating the spatial groundwater head variation of the calibration period.

The model was also found to have a good performance in validation. For year 2014, the simulated and observed heads showed an R^2 of 0.92, NSE of 0.92, and Pearson r of 0.98, with an MAE of 4.44 m. For year 2019, the corresponding values were 0.89,0.89, 0.98, and 6.35 m, respectively. The high NSE and correlation values for validation years suggest that the model was able to capture the groundwater-level patterns outside the calibration period, as suggested by (Sun et al., 2022).

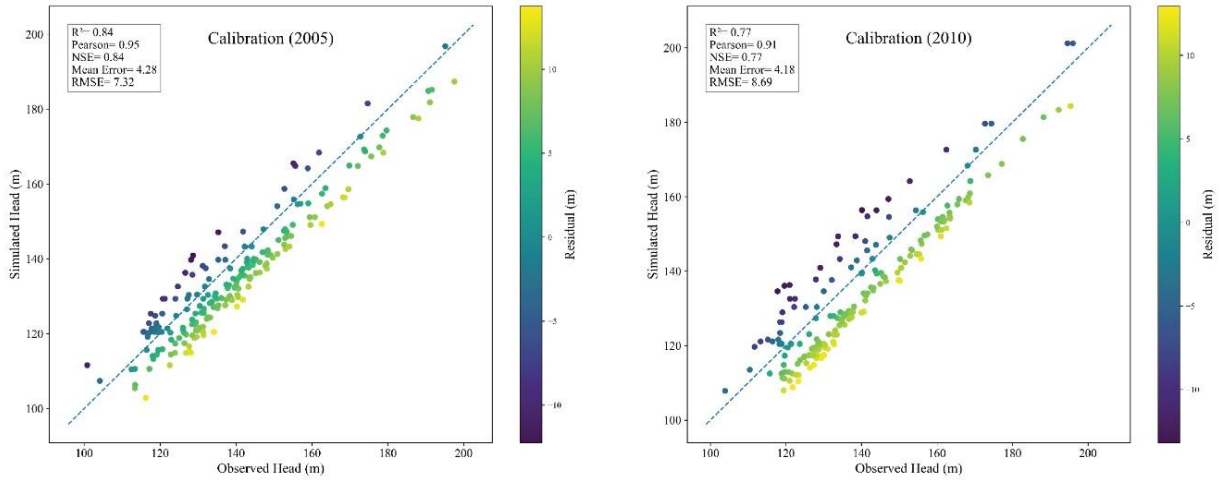


Figure-3. Comparison of simulated and observed groundwater head for the calibration years 2005 and 2010.

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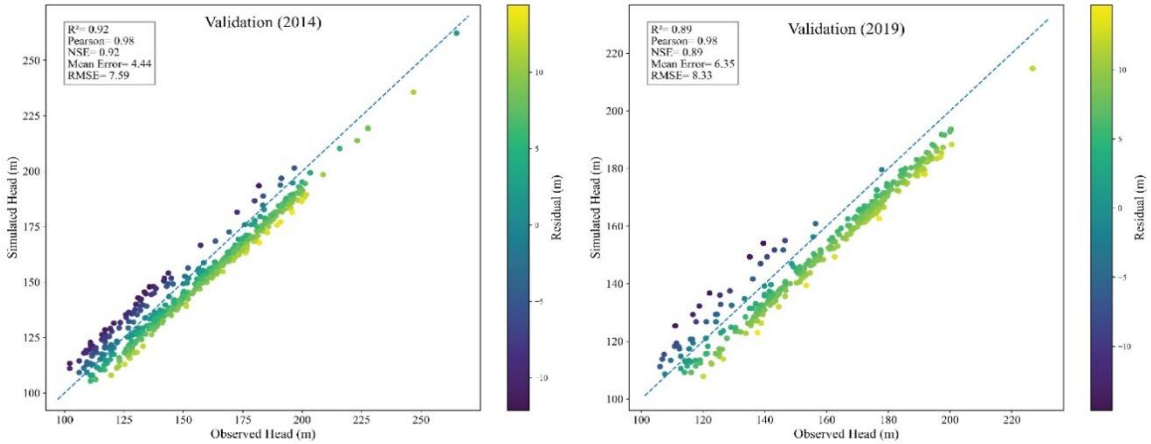


Figure-4. Comparison of simulated and observed groundwater head for the validation years 2014, and 2019.

The statistical results for all four years are presented in Table 1. The model performed consistently throughout the calibration and validation periods, which suggested its applicability to analyze groundwater-level changes throughout the study area.

Table-1. Statistical performance indicators for model calibration and validation.

Year	Model phase	R^2	NSE	Pearson r	MAE (m)	RMSE (m)
2005	Calibration	0.84	0.95	0.84	4.28	7.32
2010	Calibration	0.77	0.91	0.77	4.18	8.69
2014	Validation	0.92	0.92	0.98	4.44	7.59
2019	Validation	0.89	0.89	0.98	6.35	8.33

Spatiotemporal patterns of groundwater drawdown

Figure 5 shows groundwater drawdown in the study area over the last 20 years (2000-2019). The change in cumulative drawdown was determined from the initial groundwater head at the start of the 2000 simulation. The 2000 map is therefore a cumulative drawdown at the end of the first annual stress period. The highest mapped drawdown class increased from 2.0–2.3 m in 2000 to 4.0–4.5 m in 2004, 5.0–6.5 m in 2008, and 8.0–9.0 m in 2013. It further increased to 8.0–10.0 m in 2015 and reached 10–13 m in localized model cells by 2019. These values are the maximum drawdowns per area, and do not represent annual percent decreases, or basin average changes. Spatial distribution shows that groundwater depletion was not even throughout the model domain and that certain cells were subject to more cumulative groundwater depletion than other cells in the vicinity. The annual groundwater-level differences give information about changes between successive simulation years, and the cumulative drawdown shows the total changes from the initial groundwater condition.

The spatial pattern indicates that groundwater depletion is more significant in regions with higher water use for agricultural, domestic and industrial purposes. This depletion is more prominent in the vicinity of metropolitan cities and farming hubs. This variation suggests that groundwater stress is not uniform throughout the basin, and that local water-use patterns influence the changes.

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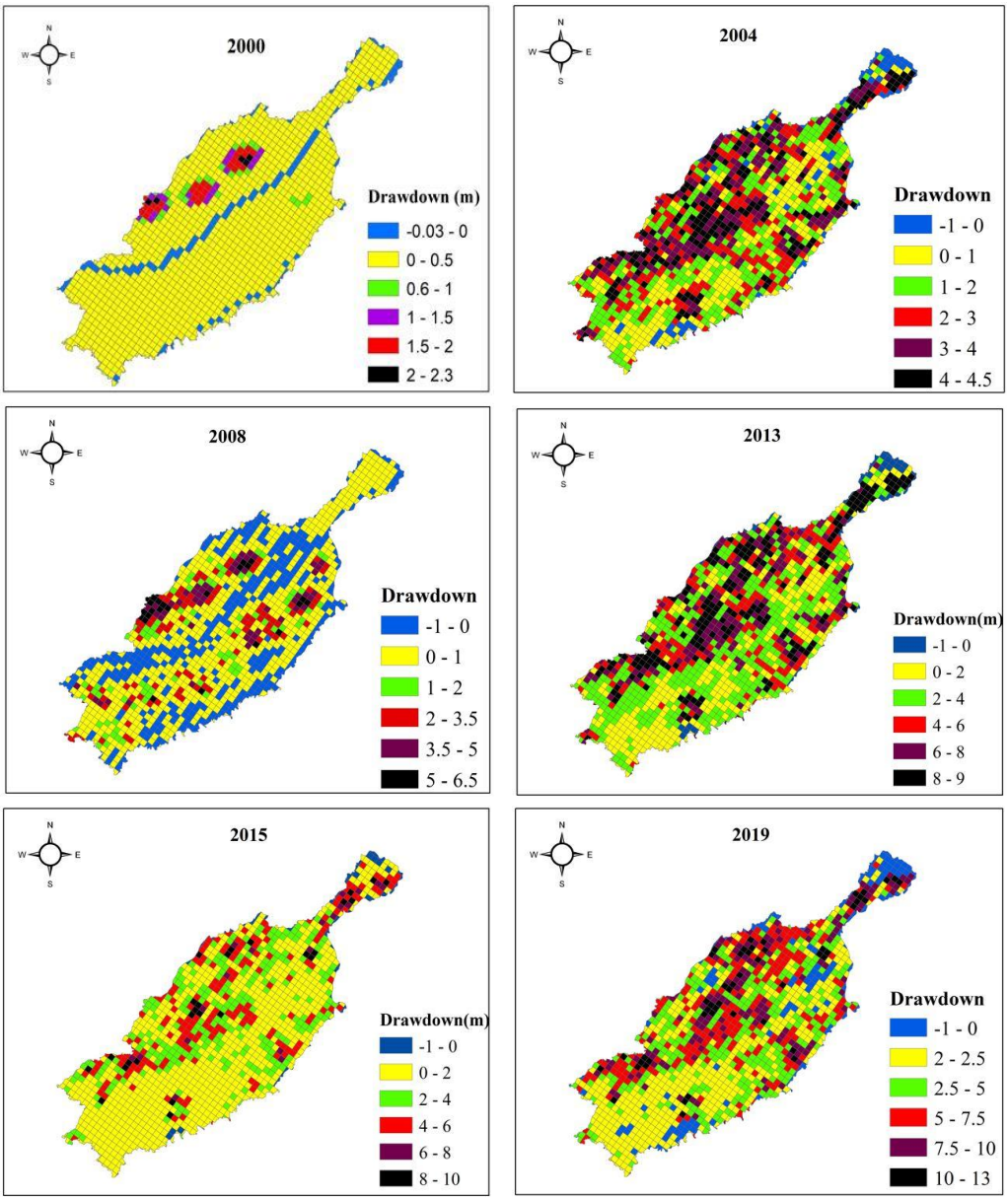


Figure-5. Spatial distribution of cumulative groundwater drawdown in the modelled Ravi River Basin for selected years (2000, 2004, 2008, 2013, 2015 and 2019). Drawdown represents the cumulative groundwater-level decline relative to the initial groundwater head at the beginning of the 2000 simulation. The 2000 map represents drawdown at the end of the first annual stress period.

Regional impact analysis

The model results indicate that groundwater drawdown varies spatially between districts based on varying land use, population, irrigation needs and industrial activity. The groundwater depletion in Lahore is significant, given its huge population and the growing demand for water from industries. Sahiwal, Pakpattan, Nankana Sahib and Sheikhupura are mainly agricultural districts where groundwater is mainly used for irrigation. When high demands for irrigation exist, especially with flood irrigation, it can lead to increased groundwater abstraction. Faisalabad is an industrial city of the region, where there is considerable use of water for industries in addition to agricultural uses. The demand of these sectors puts more pressure on local groundwater resources. Groundwater depletion in Okara is linked to agricultural activities and the growing urbanization.

However, the spatial patterns alone do not establish the contribution of each sector to groundwater depletion. Quantifying these contributions would require more detailed pumping records and simulations in which individual groundwater stresses are varied systematically.

In addition to overexploitation, the changes in the flows of Ravi River are also impacting the groundwater levels. Historically, flow from the river was an important source of recharge to the aquifer. But the upstream regulation and diversion have impacted the amount and timing of river flow reaching the downstream part of the basin. Thus, the decrease in river flow has consequently decreased the opportunities for groundwater recharge in this part of Ravi River basin. However, the present study did not quantify river–aquifer exchanges or isolate the effects of changing river flows through scenario simulations. Groundwater changes reported here should therefore be viewed as a potential influence of river-flow changes, but not as evidence that these changes caused the decline in groundwater

Groundwater depletion at similar rates has been reported in other highly stressed groundwater systems, including the Central Valley of California and the North China Plain, where high-intensity groundwater extraction has caused significant stresses on groundwater resources (Di Nunno and Granata, 2025; Du et al., 2024). Impacts of river regulation above have also been reported, for example in the Murray-Darling Basin, Australia, with reported impact on groundwater stress due to reduced river flows (Clark et al., 2025) and the Colorado River, USA, where reduced flows caused by river regulation have been reported to have led to increased groundwater stress (Abdelmohsen et al., 2025).

Although the model provides a better representation of the groundwater levels observed, there are some uncertainties due to limitations of the available data and assumptions of the aquifer system. Groundwater simulation is influenced by spatial and temporal observations of groundwater, uncertainty in estimates of hydraulic properties and recharge. In addition, groundwater abstractions and boundary conditions are represented differently and this can also affect the simulated groundwater levels. The model grid size of 6 km × 6 km limits the ability of model to truly represent the local variations in groundwater conditions. Groundwater abstraction and other hydrological stresses are likely to have caused the observed spatial patterns, but it is not possible to quantify the effects from the simulated groundwater-level changes. Likewise, the impact of Ravi River changes on the groundwater recharge should be explored by applying quantified river–aquifer exchanges and relevant scenario analysis. Thus, the simulation results are indicative of groundwater trends and potential depletion hotspots in the region, and do not directly indicate the specific groundwater depletion controls. Likewise, the use of in-situ groundwater measurements will help to minimize these uncertainties and improve future groundwater-management evaluations, as well as by improving estimates of groundwater pumping and recharge, and through simulations of various scenarios.

Conclusion

It is evident from the results of this study that the groundwater levels in the Pakistani portion of Ravi River Basin are declining, and the rate of decline increased during the study period (2000–2019). The average estimated rate of groundwater decline is 0.5–1.0 m/year, with some spatial variation across the study area. The decline reached 2–3 m/year in some areas, particularly around Lahore, Sheikhupura, Faisalabad and Pakpattan. The model was calibrated and validated against observed groundwater levels and was found to be in good agreement with the observations. During calibration (2005 and 2010), NSE values ranged from 0.91 to 0.95, Pearson correlation coefficients (r) from 0.77 to 0.84, MAE from 4.18 to 4.28 m, and RMSE from 7.32 to 8.69 m. During validation (2014 and 2019), NSE values ranged from 0.89 to 0.92, Pearson r was 0.98 in both years, MAE ranged from 4.44 to 6.35 m, and RMSE from 7.59 to 8.33 m. These results indicate satisfactory model performance, although uncertainties remain due to limited observations and model inputs.

High abstraction of groundwater for agricultural, domestic and industrial uses is the major factor associated with groundwater decline. The reduction is not uniform across the entire basin. The most significant declines were observed around major cities such as Lahore and Faisalabad and in highly productive agricultural areas such as Sahiwal and Pakpattan. There is a need to increase the focus on groundwater abstraction and monitoring in these areas. The results indicate the necessity of better management of groundwater in the Ravi River Basin. Groundwater abstraction should be regulated effectively, including in the identified groundwater-

depletion hotspots. Adopting improved irrigation efficiency, planning irrigation and controlling pumping can reduce unnecessary groundwater abstraction. Spatial outputs of the MODFLOW-NWT model can also be used to identify suitable areas for Managed Aquifer Recharge (MAR), including rainwater harvesting, where suitable water sources and site conditions are available. These interventions may help improve groundwater storage and support aquifer recovery. The groundwater monitoring network should be expanded, especially in areas where groundwater levels are decreasing rapidly. There is also a need for better regional cooperation in groundwater assessment and management, as the Ravi aquifer system spans the India–Pakistan border. A better understanding of changes in the shared aquifer system can be achieved through shared monitoring, data exchange, and assessment of groundwater recharge and abstraction.

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Use of Generative AI Tools Statement

The authors used Generative AI to remove only grammatical mistakes from the text.

Contribution of Authors

Shauket I, Ali S & Arshad RH: Conceptualization of research, data collection and analysis.
Shauket I, Ali S, Arshad RH & Shahid MA: Designed research methodology.
Shahid MA, Khan HMS & Amin M: Investigation and literature review.
Shauket I, Ali S, Khan SN & Mehmood K: Writing of original draft.
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