Evaluating the Efficacy of Canal Networks in Mitigating Groundwater Depletion Using A MODFLOW Based Model

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Abstract
Groundwater serves as the primary source of irrigation and drinking water across the Indo-Gangetic Plains, particularly in western Uttar Pradesh, where climatic variability and growing water demand have placed immense pressure on alluvial aquifers. This study evaluates the role of canal systems in sustaining groundwater levels in Bijnor district, a region witnessing erratic rainfall patterns, intensified land use, and unsustainable extraction. A numerical groundwater flow model was developed using the MODFLOW Classic code, informed by field data from 25 lithologs, 100 observation wells, and hydrogeological parameters such as hydraulic conductivity (10–35 m/day) and specific yield (0.09–0.13). The model was calibrated in both steady-state and transient conditions, producing low RMSE and NRMS values (2.713 m and 2.9%, respectively), affirming its reliability. Baseline simulations under current abstraction and recharge patterns revealed a declining trend in groundwater levels, with projected drawdowns reaching up to 10 meters by 2065 due to combined effects of rainfall deficit and population growth. Sensitivity analysis confirmed the model's robustness against moderate parameter variations. A scenario simulating the introduction of additional canal networks significantly reduced the projected drawdown, nearly halving water level declines in critical zones. These results underscore the potential of canal systems as effective managed aquifer recharge (MAR) strategies. The study concludes that enhancing and extending canal infrastructure, improving canal conveyance efficiency, and integrating these systems with sustainable agricultural and regulatory practices can substantially improve groundwater resilience. The modeling framework developed here serves as a valuable decision-support tool for long-term groundwater planning under climatic and anthropogenic stress in similar alluvial settings.

Keywords: Groundwater flow, Canal, Recharge Sustainability, MODFLOW

1. INTRODUCTION

Groundwater has emerged as the principal buffer against climate variability in water-stressed regions worldwide. In South Asia, particularly the Indo-Gangetic Basin, groundwater sustains over 60% of agricultural irrigation and supports hundreds of millions of livelihoods [1]. However, the sustainability of this resource is being increasingly compromised by a combination of climate-induced hydrological shifts, rapid land-use transitions, and burgeoning water demand due to population growth [2, 3]. These stressors are particularly pronounced in alluvial aquifer systems, such as those underlying western Uttar Pradesh, where shallow, unconfined conditions make the aquifer system highly susceptible to overexploitation and contamination [4,5].

Recent hydroclimatic assessments indicate a growing trend of seasonal asymmetry and rainfall unpredictability across the Gangetic plains, with erratic monsoons, diminished pre-monsoon showers, and unseasonal winter rainfall events [6]. These climatic anomalies disrupt the temporal alignment between recharge availability and irrigation demand, intensifying groundwater drawdown during critical crop seasons. For example, in Bijnor district, modeling results suggest a decadal-scale deficit between recharge (1688.72 Mcum) and discharge (1742.09 Mcum) under current conditions, with projected declines of up to 10 meters under coupled climate and population stress scenarios by 2065.
In this context, the role of canal networks—originally developed for surface irrigation—has gained renewed attention as a nature-based solution to bolster groundwater recharge. Managed Aquifer Recharge (MAR) techniques, such as canal seepage, have demonstrated measurable benefits in stabilizing groundwater levels, reducing evapotranspiration losses, and improving overall aquifer storage [7,8]. In India, reengineering of canal systems in regions like Rajasthan (via the Narmada Canal) and Punjab has shown promise in mitigating groundwater overdraft [9,10].
The present study aims to assess the efficacy of canal network expansion in enhancing groundwater sustainability in the alluvial aquifer system of Bijnor. A calibrated numerical model based on MODFLOW was developed using field-validated hydrogeological data, integrating over 25 lithologs, aquifer parameterization, and a network of 100 observation wells. The model simulates future scenarios (2022–2065) under projected rainfall deficits, population growth, and the introduction of additional canal infrastructure. Through this, the study provides evidence-based insights into adaptive groundwater governance under future hydro-socio-climatic pressures.

2. Study Area

Bijnor district, located in western Uttar Pradesh, spans an area of approximately 4561 km² between 29.00°N to 29.75°N latitude and 78.00°E to 79.00°E longitude (Fig. 1). It forms part of the Indo-Gangetic Alluvial Plain and is flanked by the Ganga River to the west and the Ramganga River to the east, both of which play critical roles in the hydrological dynamics of the region. The district has a population of approximately 3.68 million (as per the latest census data), with a population density of 807 persons per km², and is primarily agrarian in land use.The region experiences a sub-humid tropical continental climate with distinct seasonal variability: hot summers, a monsoon season (June to September), and mild winters. Rainfall data from 2001 to 2022 indicate increasing temporal variability, including a shift in monsoonal patterns and rising non-monsoonal precipitation, particularly in January, October, and November, which may signal changing recharge dynamics (CGWB, 2022).
Hydrogeologically, the area is characterized by shallow alluvial aquifers consisting of interbedded layers of sand, clay, and kankar, with unconfined to semi-confined conditions prevailing. Lithologs from Central Ground Water Board (CGWB) indicate a north-south increase in sand content, correlating with higher specific yields in southern regions. Groundwater extraction is extensive, primarily for irrigation and domestic use, supported by a dense canal network spanning over 1919 km, which offers potential for managed aquifer recharge interventions (District Statistical Report, 2022). A 3D- fence diagram (Fig. 2) showcases the variation in lithology both horizontally and locally which will be manifested in variations of hydraulic parameters such as s_y (0.09- 0.130) and K (10 – 30 m/day).

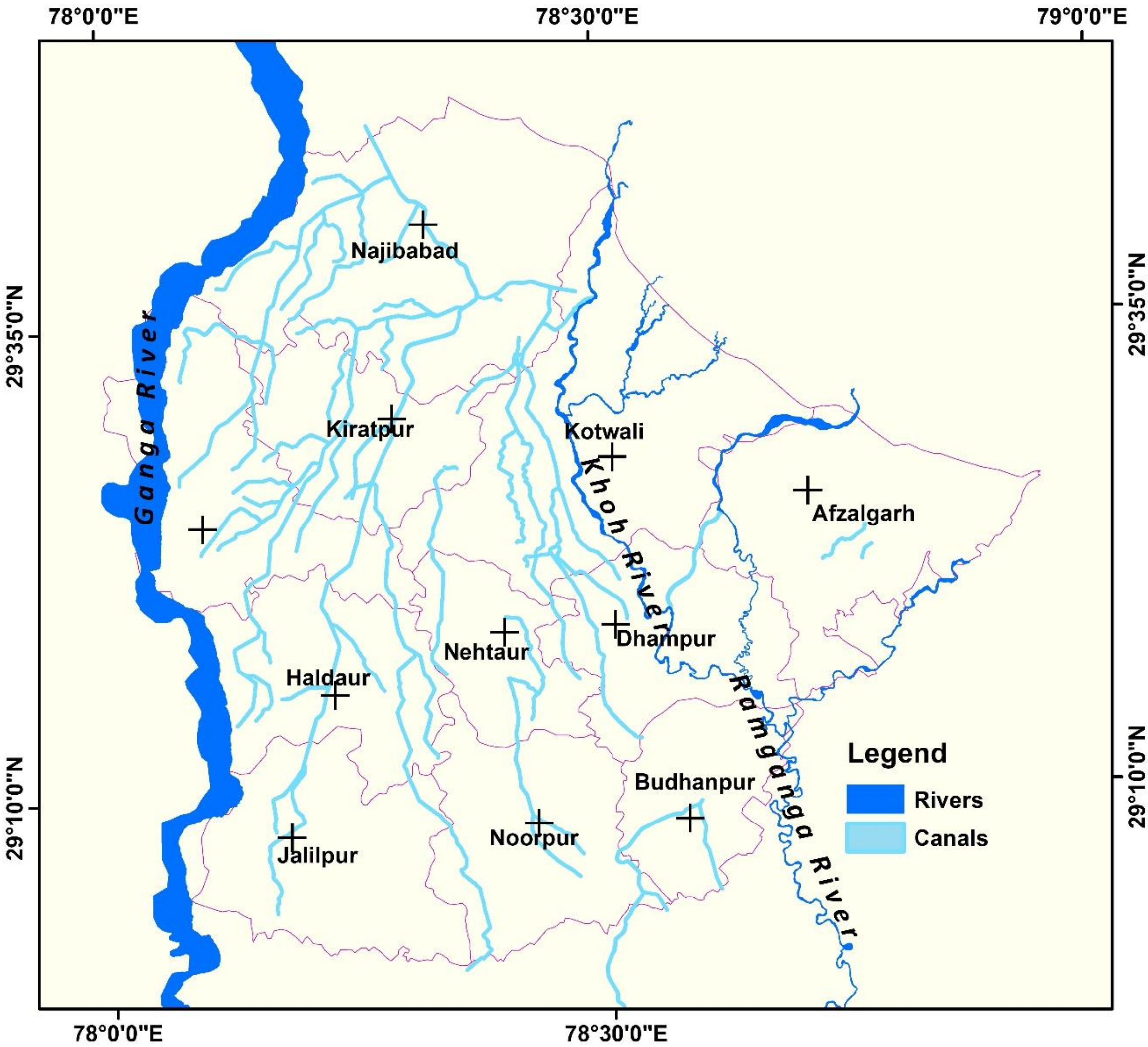

Figure 1. Location map of study area

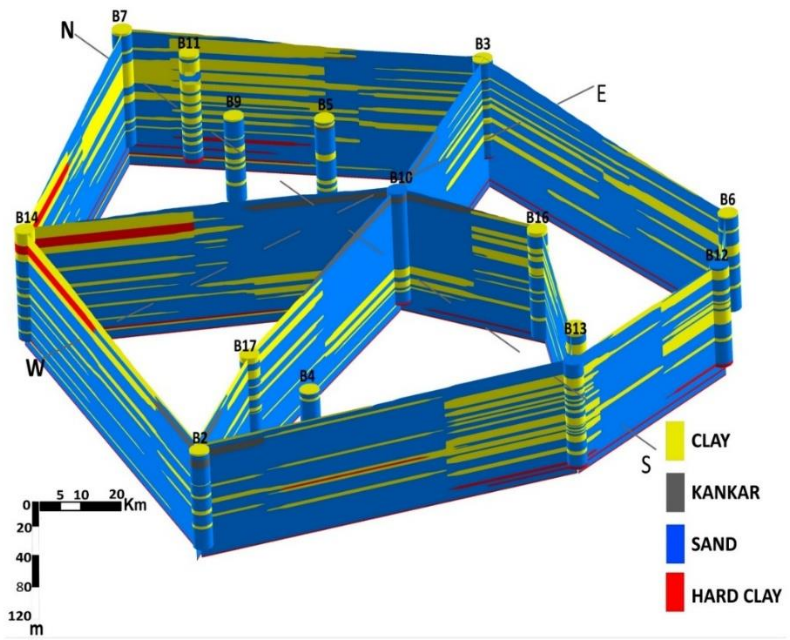

Figure 2. A 3D Fence diagram of the study area.

3. Methodology

3.1 Groundwater Flow Modeling Approach

To simulate the spatial and temporal dynamics of groundwater under current conditions, a numerical groundwater flow model was developed using the MODFLOW Classic framework provided by the U.S. Geological Survey [11]. MODFLOW solves the governing flow equation using the finite-difference method (FDM), a widely accepted approach for modeling saturated flow in heterogeneous and anisotropic porous media [12].

The model aims to reproduce steady and transient groundwater head distributions in the alluvial aquifer system of Bijnor district under existing hydrogeological and abstraction conditions, thereby establishing a reliable baseline for future scenario simulations.

3.2 Governing Equation

The transient groundwater flow in a three-dimensional saturated porous medium is described by the partial differential equation:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) \pm W = S_s \frac{\partial h}{\partial t} \qquad (1)$$

Where:

- h = hydraulic head (m),
- K_x ,K_y,K_z = hydraulic conductivity along x, y, z axes (m/day),
- S_s = specific storage (1/m),
- W = volumetric flux per unit volume representing recharge or discharge (1/day),
- t = time (day).

In unconfined aquifers, the storage term is replaced by specific yield (Sy) and the equation adapts accordingly [13].

3.3 Numerical Solution Using Finite Difference Method (FDM)

The model domain is discretized into a rectilinear grid in space and time. The finite-difference approximation for the flow equation transforms the continuous PDE into a system of algebraic equations:

$$\left(T_{i-\frac{1}{2}j} + T_{i+\frac{1}{2}j} + T_{i,j-\frac{1}{2}} + T_{i,j+\frac{1}{2}}\right) h_{i,j}^{n+1} = \sum_{adjacent\ nodes} T_{i,j}^{n+1} h_{neighbours}^{n+1} + S_{i,j} \qquad (2)$$

Where T represents transmissivity between adjacent nodes $h_{i,j}^{n+1}$ is the unknown head at time step n+1, and $S_{i,j}$ represents the net recharge/discharge.

The equation is solved iteratively using the Preconditioned Conjugate Gradient (PCG) or Strongly Implicit Procedure (SIP) solvers depending on stability and convergence needs [14].

3.4 Model Conceptualization

The model domain covers 4561 km² of Bijnor district and is discretized into a uniform grid with each cell approximately 1826 × 970 m. The Digital Elevation Model (DEM) defines the top surface, while the base of the model corresponds to the bottom of the first aquifer as derived from CGWB lithologs. However, a larger area was simulated so as to minimize the effects of the boundary. A single-layer, quasi-3D model structure (Figure 3) was adopted to reflect the dominant unconfined aquifer, with vertical variations in lithology accommodated through spatial variation in hydraulic properties. Parameter assignment included:

- Hydraulic Conductivity (K): 10 to 35 m/day

- Specific Yield (Sy): 0.09 to 0.13
- Recharge values ranged from 190 – 700 mm/year, set from pre-calculated budget.
- Pumping was taken- 4602 m^3/day taken from net gross groundwater draft
- General head boundaries were set after reading from water table contour maps.

The recharge zone 11 (Fig. 3) demarcates the introduction of new canal, which are simulated to observe the changes in water level and test the effectiveness of canals in sustenance of groundwater.

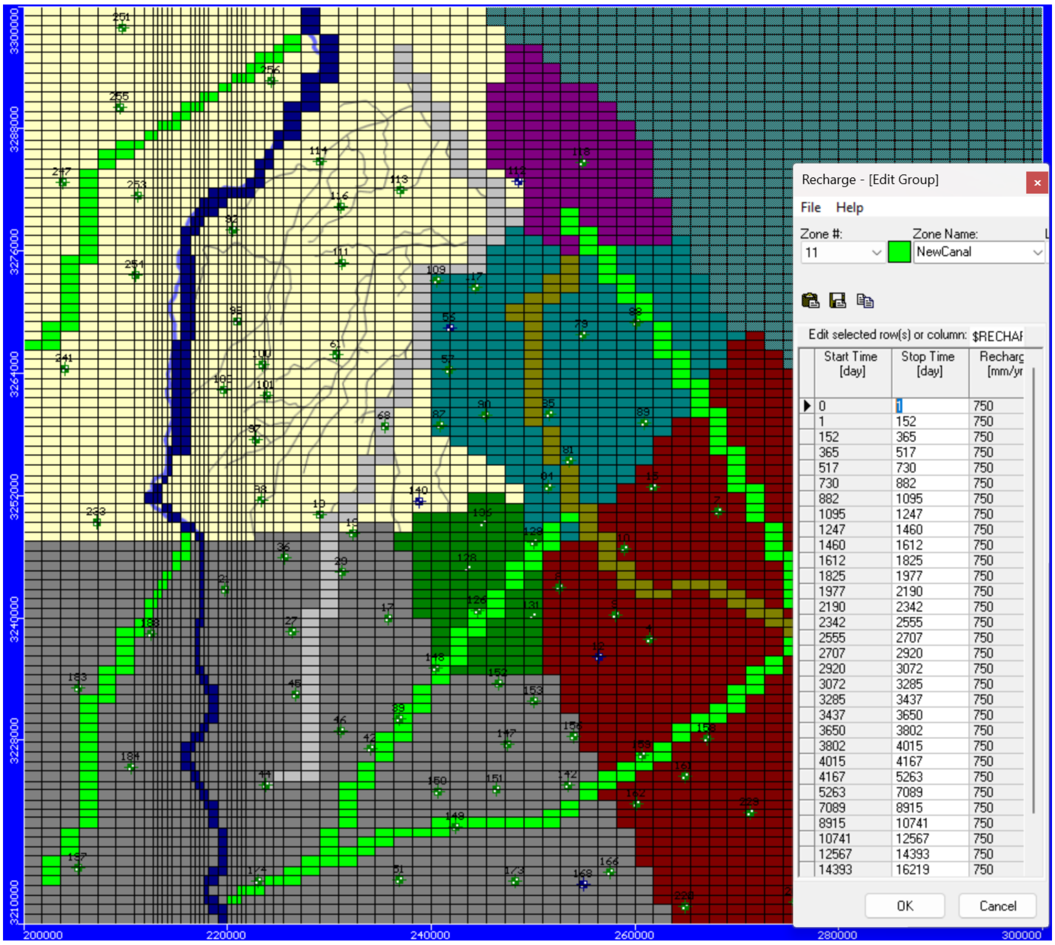

Figure 3. A screenshot representing recharge zones and observation well of the model.

4. Results and Discussion

4.1 Model Run and calibration

The groundwater flow model was initially calibrated under steady-state conditions to provide a stable reference framework. In this setup, storage terms were inactivated, allowing the calibration to focus on spatial distributions of hydraulic head without the influence of temporal fluctuations. The model was adjusted iteratively to minimize differences between observed and simulated heads using field data from 100 observation wells. The calibration yielded a Root Mean Square Error (RMSE) of 2.713 m and a Normalized Root Mean Square Error (NRMS) of 2.9%, which falls within acceptable thresholds for large-scale groundwater models [12,14]. These metrics confirm the reliability of the model in replicating the observed groundwater conditions of the Bijnor district under existing stress regimes.

Following the steady-state run, the model was transitioned to transient state simulation, where storage parameters were activated to account for temporal variations in recharge and abstraction. The transient calibration, which covered a multi-year period, resulted in a normalized RMS error of 1.903 m, while the all-time average RMS error was 2.68 m, and the NRMS remained at 2.70%. These low error values indicate a strong fit between observed and simulated heads over time, demonstrating the model's robustness under dynamic hydrological conditions.

A sensitivity analysis was also conducted to evaluate the impact of changes in specific yield (Sy) and hydraulic conductivity (K) on model outputs. Despite the regional-scale heterogeneity and observed lithological variation across the study area, the final simulation results remained relatively stable, indicating that the model is not overly sensitive to moderate parameter adjustments. Consequently, Sy and K values were kept within literature-supported and field-estimated ranges. The model’s structural integrity and stability under varied inputs reinforce its reliability for use in future scenario-based simulations involving climatic and anthropogenic stressors (Doherty & Hunt, 2010).

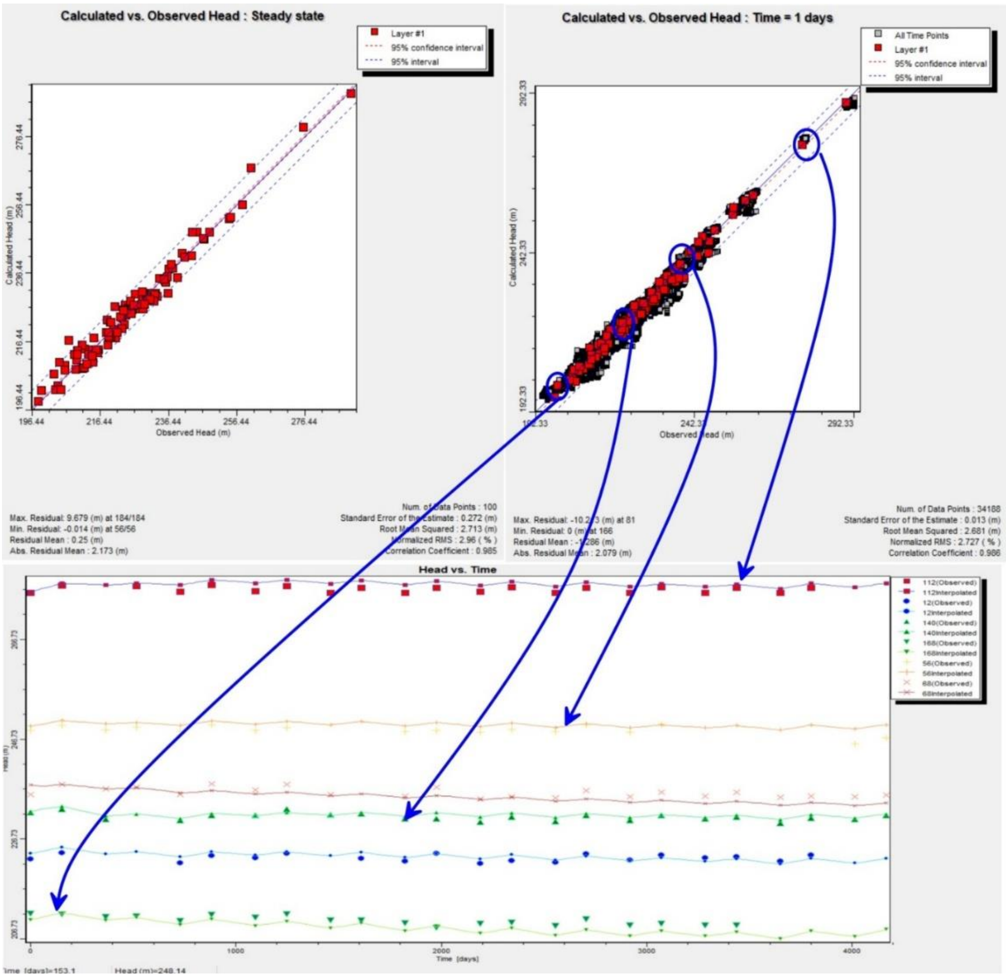

Figure 4. Snapshot of model calibration in steady-state & transient state and head vs time plot

Post calibration model was run until 2065 without the addition of canals and decline in water level from 1.96 m below ground level to as much as 10 m was recorded (See Table 1).

Table 1. Head changes in different time periods of flow model simulation.

Scenario - Population growth & Rain deficit					
Well ID	2022	2050		2065	
			Change		change

112	278.16	275.02	-3.14	269.22	-8.94
56	249.11	248.9	-0.21	247.15	-1.96
140	229.26	226.66	-2.6	223.5	-5.76
12	222.71	220.67	-2.04	217.12	-5.59
168	209.62	204	-5.62	199.92	-9.7

4.2 Model – Canal introduction

The introduction of new canals (Zone 11, Fig. 3) reduced the imminent ground water decline at almost all the groundwater stations (Fig. 5). The decline in heads reaching as much as 10 m below ground level reduced by half by the introduction of the canal. Table 2 shows selected groundwater stations with their respective heads. These heads (Table 1 and Table 2) show almost halving of the decline which highlights the effectiveness of canals in sustaining groundwater.

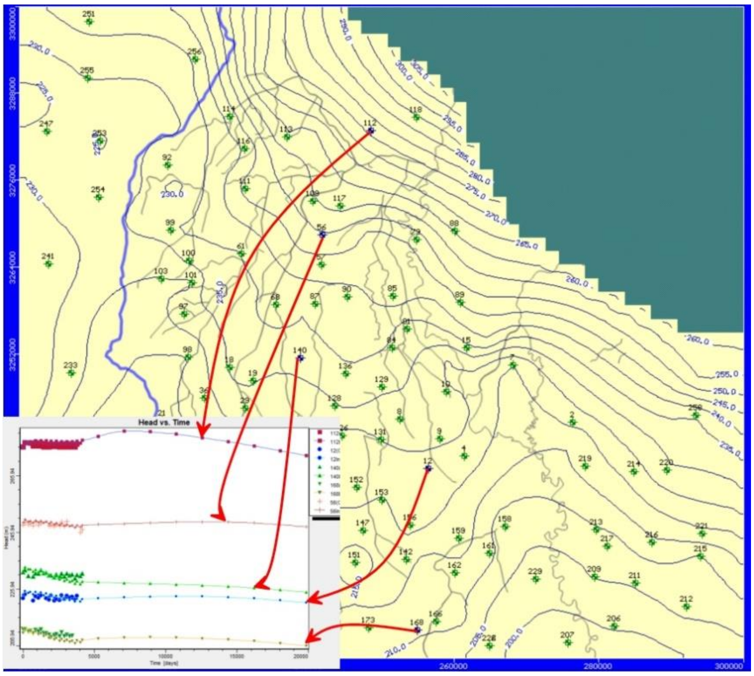

Figure 5. Water table contour plot for year 2065 and head vs time at selected stations

Table 2. Head changes in different time periods of flow model simulation (with new canals)

Scenario - Population growth & Rain deficit			
Well ID	2022	2065	
			change
112	278.16	272.93	-5.18
56	249.11	247.85	-0.61
140	228.59	224.84	-3.75
12	222.44	221.13	-1.31
168	207.96	205.94	-2.02

5. Conclusions and recommendation

The study provides a detailed assessment of groundwater conditions in Bijnor district using a calibrated MODFLOW-based flow model. Lithological analysis revealed significant heterogeneity in the aquifer system, with higher sand content and specific yield in southern and western zones contributing to better recharge potential. Model calibration under steady and transient states produced low RMS and NRMS values, affirming the model's accuracy in simulating groundwater behavior. Under baseline conditions, groundwater abstraction exceeds recharge, indicating an emerging imbalance. Spatial analysis identified drawdown hotspots near densely populated and intensively irrigated areas. Sensitivity analysis showed the model's robustness to parameter variations. The results collectively underscore the need for targeted interventions, particularly in low-permeability zones. Strategies such as canal expansion, improved recharge infrastructure, and sustainable agricultural practices are essential to reduce stress on the aquifer. Overall, the modeling framework offers a reliable decision-support tool for long-term groundwater management under climatic and anthropogenic pressures.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this research. The study was conducted independently, and no external organization influenced the design, execution, interpretation, or reporting of the results.

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References

1. Mukherjee, A., Saha, D., Harvey, C. F., Taylor, R. G., Ahmed, K. M., & Bhattacharya, P. (2020). Groundwater systems of the Indian Sub-Continent. Journal of Hydrology: Regional Studies, 29, 100694.
2. Shah, T. (2007). Groundwater governance: A tale of two tales. Water Policy, 9(S1), 103–116.
3. Taylor, R. G., Scanlon, B., Döll, P., et al. (2013). Ground water and climate change. Nature Climate Change, 3(4), 322–329.
4. Famiglietti, J. S. (2014). The global groundwater crisis. Nature Climate Change, 4(11), 945–948.
5. Scanlon, B. R., et al. (2012). Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. Proceedings of the National Academy of Sciences, 109(24), 9320–9325.
6. Mall, R. K., Srivastava, R. K., & Mishra, O. P. (2019). Water resources and climate change adaptation in India. Environmental Development, 30, 100467.
7. Ghosh, S., Vittal, H., Sharma, T., Karmakar, S., Kasiviswanathan, K. S., Dhanesh, Y., ... & Gunthe, S. S. (2016). Indian summer monsoon rainfall: implications of contrasting trends in the spatial variability of means and extremes. PloS one, 11(7), e0158670.
8. Bouwer, H. (2002). Integrated water management for the 21st century: Problems and solutions. Hydrogeology Journal, 29(4), 985–998.
9. Dillon, P., Pavelic, P., Page, D., Beringen, H., & Ward, J. (2019). Managed aquifer recharge: An introduction. Australian Government National Water Commission.
10. Rodell, M., Velicogna, I., & Famiglietti, J. S. (2009). Satellite-based estimates of groundwater

depletion in India. Nature, 460(7258), 999–1002.
11. Jain, S. K., Awasthi, A., & Singh, V. P. (2021). Enhancing groundwater recharge in India: A hydrogeological perspective. Hydrological Sciences Journal, 66(6), 937–948.
12. McDonald, M. G., & Harbaugh, A. W. (1988). A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model. USGS Techniques of Water-Resources Investigations, Book 6.
13. Anderson, M. P., Woessner, W. W., & Hunt, R. J. (2015). Applied Groundwater Modeling: Simulation of Flow and Advective Transport. Academic Press.
14. Freeze, R. A., & Cherry, J. A. (1979). Groundwater. Prentice-Hall.