Assessing the Impact of Groundwater Recharge on Underground Reservoir Replenishment in Eastern Uttar Pradesh, India

ABSTRACT

Groundwater is considered a fresh resource of water and its uses have tremendously increased in the recent past due to an increase in population, rapid urbanization, and industrialization. In India, the groundwater level is declining in some parts of the country due to over-exploitation, low or negligible recharge of aquifer systems, and unsustainable development of groundwater resources. The groundwater modeling is an important tool for studying the past and present groundwater behavior and in the development of future strategies for sustainable groundwater management plans. To study the Impact of groundwater recharge on the replenishment of underground reservoir, Ballia district of Uttar Pradesh has been selected which is one of the districts of the most populous state of India, Uttar Pradesh. An attempt has been made to develop a groundwater model using Modflow software to simulate the groundwater trends and predict future groundwater heads. The calibration and validation of the model were done for 5 years and 3 years respectively. The correlation coefficient for calibration and validation was found 0.85 and root mean square errors vary from 2.89 to 3.2m variation in future trends of groundwater heads. The results of the study show that the developed model can be effectively used to predict the future groundwater heads. The groundwater flow was observed from the northwest to southeast direction. It was predicted from the study that groundwater draft will increase by 10% with a decrease in groundwater level by approximately 0.24 m in the north-west direction by the year 2025. However, no impact was observed in the south side of the district and it was predicted that the groundwater level would remain the same in this zone during the next 3 years.

Keywords: Modflow, Groundwater, draft, modeling, Ballia, Uttar Pradesh.

1. INTRODUCTION

India is facing management issues of surface and ground water resources and thus, witnessing the fresh water scarcity in many parts of the country. Therefore, it is imperative to manage the water resources and modeling is one of the powerful tools to predict the future trends and accordingly helps in taking suitable decisions to mitigate the issues related to fresh water availability (**Kumar et al., 2022**). India receives 1200 mm average annual rainfall which seems to be good, but due to unequal spatial and temporal distribution, various parts are water stressed in terms of surface water and groundwater availability. Declining trend of groundwater levels is due to change in recharge patterns, increased groundwater draft and ever-increasing water demand in agricultural, industrial and domestic use. There is 15% rise in per capita water demand due to rapid population growth, urbanization and industrialization **(Kapupara et al., 2011)**. Approximately 40 percent of total water use in irrigated agricultural consumption is currently being met by groundwater, and the bulk of GWD (Ground Water Depletion) regions are significant in agricultural production areas **(Wada et al., 2010)**. Groundwater not only plays a significant role in providing safe drinking and irrigation water, but is also essential for food security and its impact on the environment and human health cannot be ignored **(Gleeson et al., 2016; Ali MH, 2017)**. In many countries including India, the percentage of land that is irrigated with groundwater has increased significantly since the 1960s **(Konikow, 2011).** In India during the past five decades, the number of shallow tube wells and groundwater abstraction structures has increased from 3,000 in 1951 to 8.5 million in 2001**(Singh & Singh, 2002).** Over-extraction of groundwater has caused well yields to decline and wells are drying up. In addition to having an adverse effect on water supply, groundwater level decline also results in land subsidence, a reduction in surface water flows, spring discharges and the loss of wetlands which also causes the deterioration of groundwater quality **(Konikow & Kendy, 2005; Kumari et al., 2022).**

Groundwater modelling is a powerful tool that is used for anticipating the effects of hydrological changes such as the withdrawal of groundwater and recharge of the aquifer **(Kujur & Akhtar, 2014; De & Simmers, 2002; Sahin & Tayfur, 2023)**. There are various models available for groundwater modelling. One of the globally accepted and widely used models is Modflow which utilizes the finite difference approach. Various researchers have used Modflow for simulation and prediction of groundwater heads and also studied the interactions between groundwater and surface water **(Oliveira et al., 2015; Malekinezhad & Banadkooki, 2018)**.

Groundwater resources in the State of Uttar Pradesh caters 78 percent of the irrigation needs **(CGWB, 2021)**. In the present paper, an administrative boundary (Ballia district) in the most eastern part of Uttar Pradesh was selected to study the groundwater level changes. A groundwater model was developed using Modflow software to simulate and predict groundwater heads under different scenarios.

2. STUDY AREA

For the study, Ballia district was selected which is bounded by the Ghaghra and Ganga rivers in the north and south direction respectively. It is the eastern most district of Uttar Pradesh comprising 17 administrative blocks covering an area of 3008.19 sq.km lies between 25.763556 °N latitude and 84.149561°E longitude. **Fig.1** shows the location map of Ballia District. The primary sector of Ballia's economy is agriculture. The Dharighat Lift Irrigation Canal for surface water and tube wells for groundwater are the two major irrigation sources in the district, with the former providing 72.61% and the latter 27.39% of the irrigation needs. The entire area has flat topographic zone, particularly in the area where rivers Ganga and Ghaghra confluences. The majority of the central Gangetic plain areas are composed of piedmont and flood plains. The basin has been formed by dendritic drainage and recent deposits of organic muck filled the channels **(Ravenscroft et al., 2005)**. The Gangetic alluvium contains younger and older alluvium and a thin layer of soil in the area. These formations belong to upper Pleistocene to the Holocene **(Chappell et al., 2001)**. The Central Ground Water Board's exploratory drilling reveals that these unconsolidated Quaternary sediments are covered by hard rock formations from the Archean epoch **(MoWS, 2011)**.The earlier alluvium in the region is characterised by nodules, yellow-tinted clays, silt with high calcareous concentrations, and nodules known locally as Kankar. It frequently seems unorganised and less permeable. The river-laid deposits and sandy layers of the aquifer zones are covered in lenticular beds of sand, gravel, and clays that are low in calcareous elements and found throughout in the Younger Alluvium Formation. The drainage pattern in the study region is dendritic and has a medium roughness. The study area experiences mean annual temperatures of 27^{o} C, which range from 5.4^{o}C to 41.5 ^{o}C, and average annual rainfall of 983 mm.

3. METHODOLOGY

3.1 Modelling Processes

The processes adopted in groundwater modeling are shown in **Fig. 2.** Defining the purpose is the first stage in the modelling process. The modeller must conceptualize the model to be used for prediction, system comprehension, general exercises and other tasks before starting the modeling exercise.

3.2 Model discretization

A partially differentiable governing equation and initial boundary conditions which specify the mathematical model of a groundwater system was used for the study which says that in any selected domain of saturation flow, the rate of change of storage is equal to the difference between input and outflow rates. The continuity equation and Darcy's law are used to get the governing equation as shown in equations 1, 2 and 3.

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=\nabla^2 . h=\frac{Ss}{K} . \frac{\partial h}{\partial t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

This is a partial differential equation for GW flow in Saturated Media which can be solvable by Numerical Methods.

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(Ky\frac{\partial h}{\partial y}\right)+\frac{\partial y}{\partial x}\left(Kz\frac{\partial h}{\partial z}\right)=Ss\frac{\partial h}{\partial t} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Mass inflow rate – Mass outflow rate = Change in storage with time

$$Q = -KA\,(dh/dl) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

The partial differential equation is transformed into a series of algebraic equations, which computer programmes or codes subsequently use to solve the problem. By using the MODFLOW programme to solve the three-dimensional groundwater flow equation, the groundwater head may be computed. The finite difference technique (FDM) is utilised to solve the equations. The study domain is discretised into cells (No. of columns and rows are 96 and 70 respectively) as shown in **Fig. 3(A)**.

3.3 Model inputs

Based on the conceptual model that has been built, a numerical model for an unconfined aquifer (single layer) was created. The dimensions of the model grids, the stress periods, the time steps, and the starting and boundary conditions are all part of the design of the numerical model. For the present case, two stress periods were considered, the 1st stress period covers 6 months i.e. June, July August, September, October, November and 2nd stress period covers 6 months i.e. December, January, February, March, April and May in a year were taken to simulate GW flow on daily basis. The single-layer, unconfined aquifer (100 m thickness) was conceptualised. The model layer was decided based on the available bore logs in the area. The geographical area of the study domain is 3008 Km^2 and the grid size has been taken as 1000 x 1000 m.

3.4 Initial and boundary conditions

The physical boundaries in the north and south of the study area are the Ghaghra River and the Ganga River hence “river boundary conditions” were used in these directions **{Fig. 3 (B)}**. No flux boundary was assigned in the west (as plotted water table contours are somewhat parallel and therefore flow is not possible from west to east) and flux boundary was assigned in the southwest as shown in **Fig. 3 (B).** The flux for an unconfined aquifer was calculated based on the hydraulic gradient and hydraulic conductivity. The initial hydraulic conductivity values for the younger and older alluvium were taken as 40 m/day and 30 m/day. The initial specific yield was taken as 0.9. The initial heads were taken as observed head of model start period (May, 2012). For river boundaries, river head and river bed bottom elevations were assigned to appropriate grids. The monsoonal recharge value was computed using the rainfall infiltration factor (RIF) of GEC guidelines **(GEC, 2015)**. The monsoonal recharge value of 57,855 ha-m was converted into mm/day and 1.6 mm/day was taken recharge in the study area. The recharge boundaries were used for providing recharge to respective grids for the unconfined aquifer.

The total annual groundwater draft through pumping was taken as 15,04,222 m^3/day in the study area. Accordingly, it is estimated that 500 pumps are operating uniformly in the study area and the pumping rate was provided (-) 3008 m^3/day/pumps in the unconfined aquifer **(Fig. 3 (D))**. The well package of MODFLOW was used for incorporating GW draft in the model.

4. RESULTS AND DISCUSSIONS

4.1 Model Calibration and Validation

The developed model was calibrated to reproduce the field observation, i.e. groundwater heads by tweaking the input parameters. The input parameters, such as hydraulic conductivity (K), storage coefficient/specific yield (S_y) and recharge were adjusted to calibrate the model. Simulated head values were compared with monitoring well heads using trial and error methods. The calibration was done for the period of 5 years (June, 2012 to May, 2017). Scatter-plot between observed and calculated heads have been depicted in **Fig. 4(A)**. Initially, the hydraulic conductivity values for younger and older alluvium were taken as 40 m/day and 30 m/day, respectively. These values changed to 30 m/day and 25 m/day during calibration. The calibrated value for the specified yield was 0.15 and the recharge rate was also increased by 10% from initial values. The model performance is evaluated using correlation coefficient (R), residual mean, standard error of estimate, root mean square (RMS) and it has been presented in **Table. 1.** The R value is 0.86, which is outstanding and the performance in terms of root mean square and standard error is very good. These findings demonstrate the model's strong prediction abilities.

Another set of field data was used to validate the model to check the predicting capability. If the model is not producing good results, re-calibration could be required. The calibrated model should be able to forecast head. For the present case, the model was validated for 3 years (June, 2017 to May, 2020). The scatter plots between observed and computed heads shows a good match for various stress periods **(Fig. 4 (B))**.

4.2 Simulation and Prediction of Groundwater level heads

The calibrated and validated model was used to assess the impact of increased groundwater pumping on the water table and anticipate probable future changes. The groundwater pumping was increased by 10% in the next 5 years (2% draft increase in each year) in the study area and groundwater heads were predicted. The predicted groundwater head at 2992th day (0th day), and predicted head at 4748th day (after 5th year) are shown in **Fig. 5.** Initially the groundwater heads vary from 44.84 m above mean sea level to 69.60 above mean sea level after 2992th day, and on 0th day of prediction during validation. The groundwater heads changed from 44.84 m amsl to 69.36 m above mean sea level after 5 years (4748 days). There was only a slight fluctuation between initial conditions even after 5 years of model run in the south-eastern side of the model. However, the groundwater level decline was found approximately 0.24 m in the north-western part after an increase of 10% draft in five years.

5. CONCLUSIONS

Results of the study during calibration and validation of the developed model indicate good agreement between observed and predicted groundwater heads during the five years future trends. The predicted groundwater level heads for an unconfined aquifer range from 44.84 m above mean sea level to 69.60 m above mean sea level. When pumping rate was increased by 10 %, it was observed that the predicted groundwater heads vary from 44.84 m above mean sea level to 69.36 m above mean sea level. There is very less fluctuation between the initial condition and after 5 years of model run in the south-eastern side of the model. However, the groundwater level decline was found approximately 0.24 m in the north-western part. The study reveals that the groundwater draft should be decreased in the district for sustainable management of groundwater resources.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

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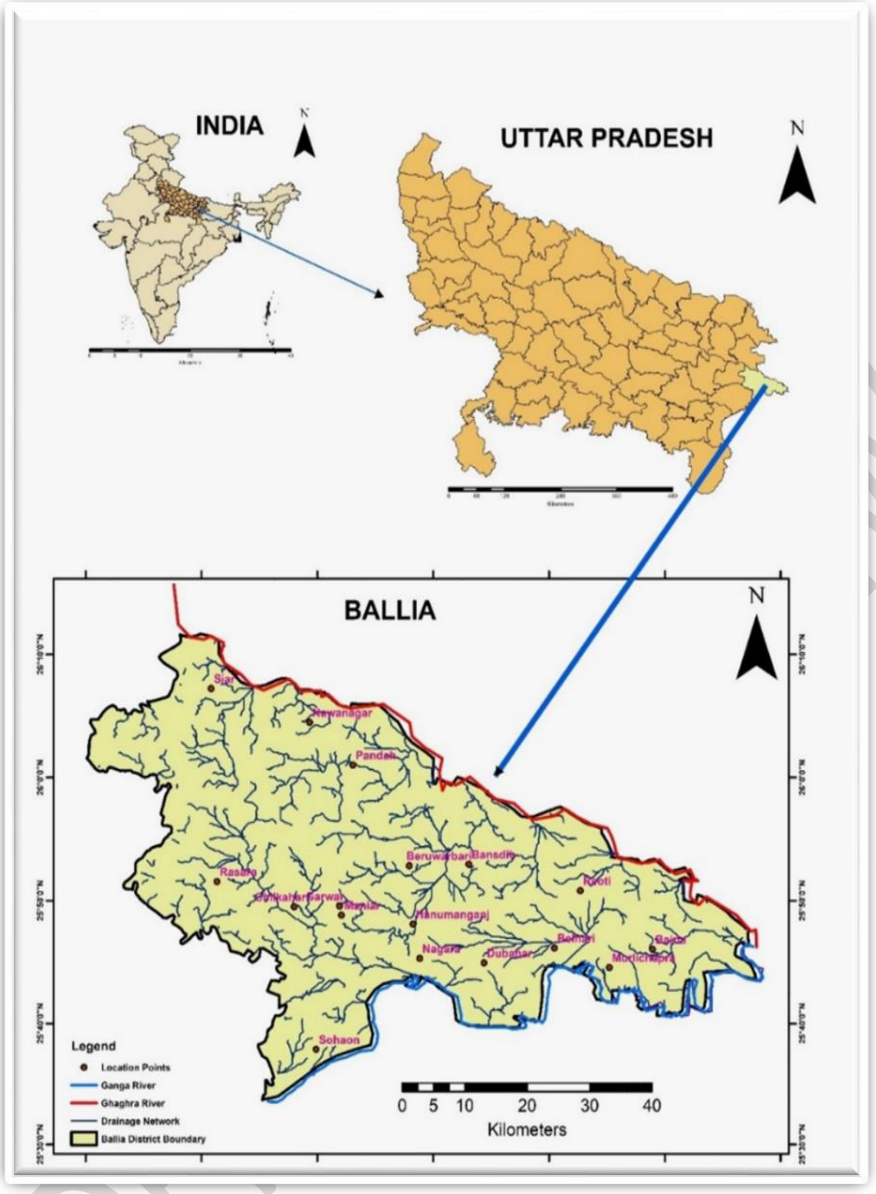


Fig. 1. Location Map of the study area (Ballia District, Uttar Pradesh)

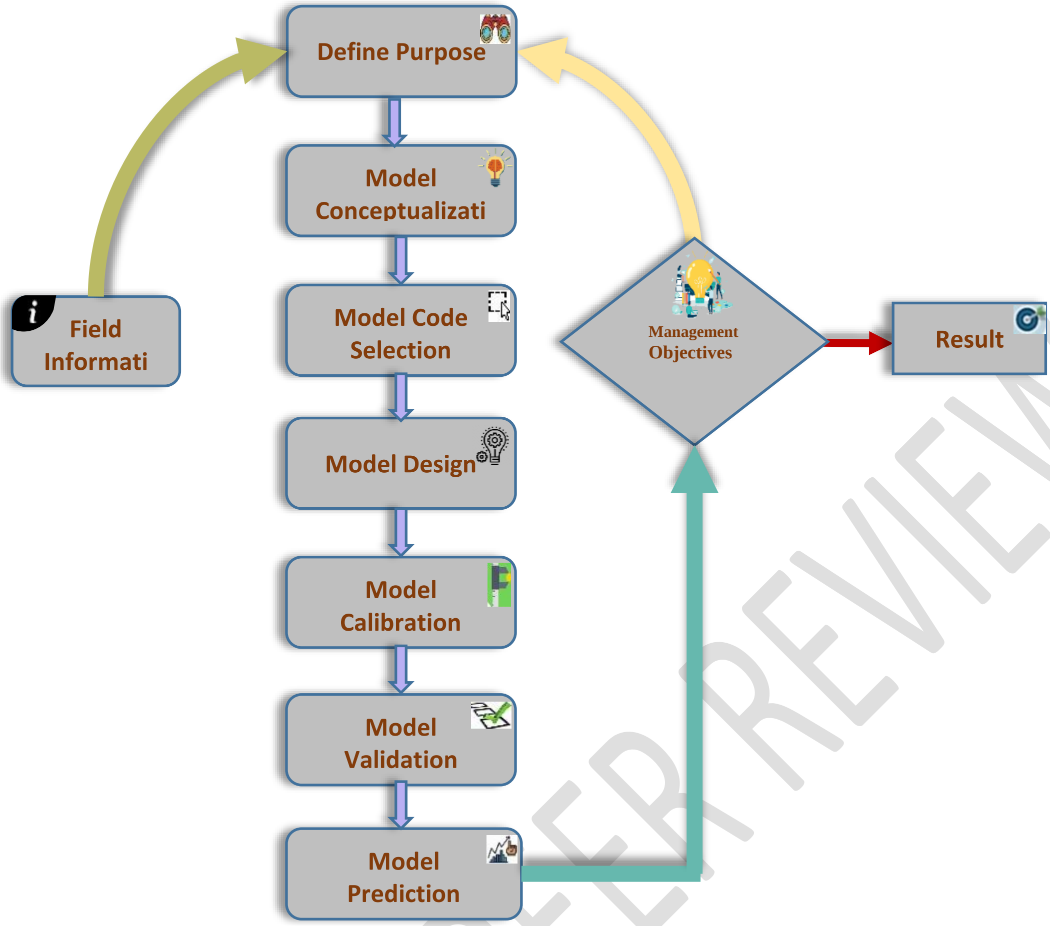


Fig 2. Flowchart showing modelling processes

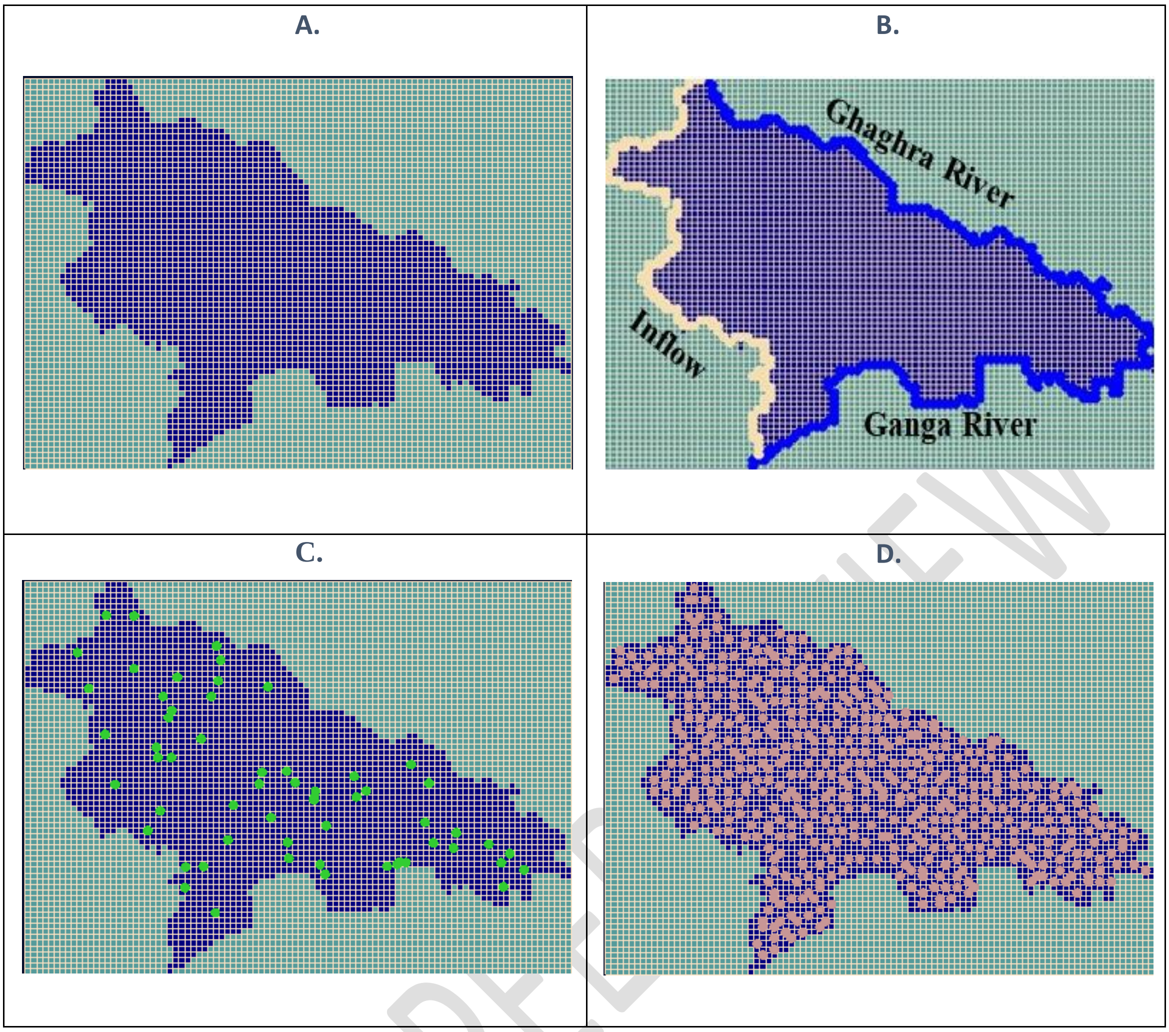


Fig 3. **(A):** Grid generated for modelling domain; **(B):** Map showing boundary conditions in the study area; **(C):** The location of observation wells in the model area; **(D):** The distribution of pumping well in the study area

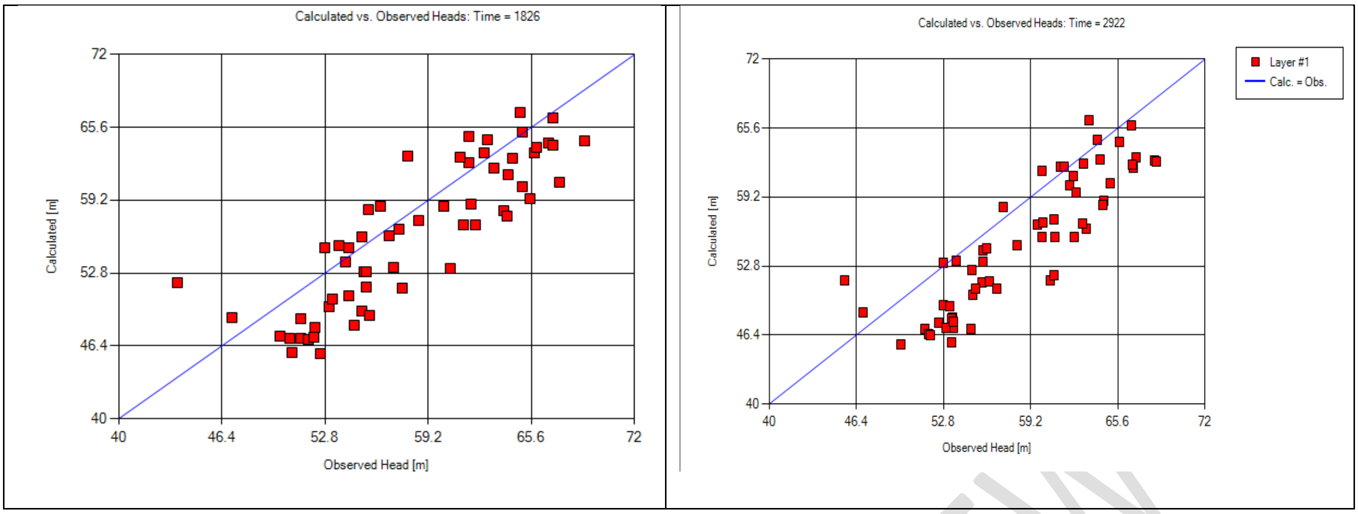
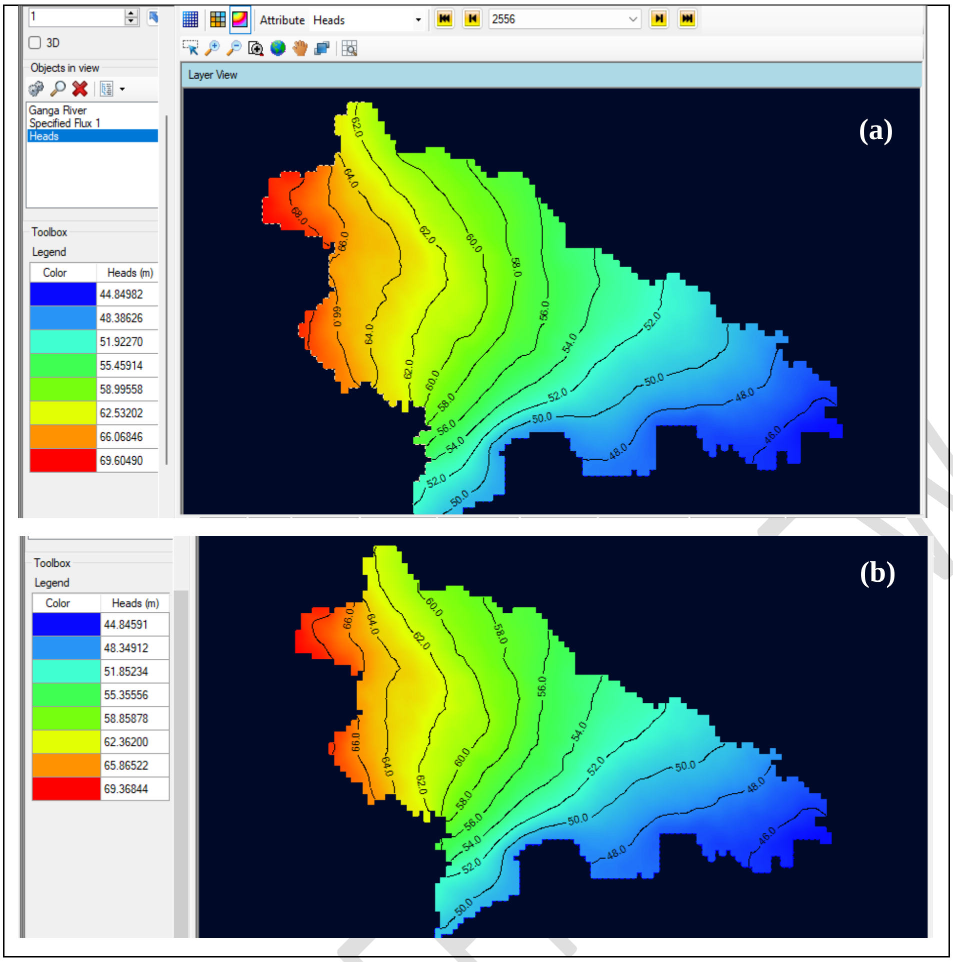


Fig 4. Scatter-Plot between observed and calculated heads for unconfined aquifer during (A) Calibration*;* (**B)**Validation

Table 1. Errors and correlation between Observed and predicted future groundwater level heads during calibration and validation

Statistical Parameters	**Calibration**	**Validation**
Std. Error of Estimate	0.39	0.43
Root Mean Square (RMS) Error	2.89 m	3.2 m
Correlation Coefficient	0.86	0.85



Ganga River
Specified Flux 1
Heads

Toolbox

Legend

Color	Heads (m)
🟦	44.84982
🟦	48.38626
🟩	51.92270
🟩	55.45914
🟩	58.99558
🟨	62.53202
🟧	66.06846
🟥	69.60490

Toolbox

Legend

Color	Heads (m)
🟦	44.84591
🟦	48.34912
🟩	51.85234
🟩	55.35556
🟩	58.85878
🟨	62.36200
🟧	65.86522
🟥	69.36844

Fig 5. Predicted Groundwater Level heads **(a)** at 0th day of prediction and **(b)** after 5 years (4748 days)