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ASSESSMENT OF SPATIAL AND TEMPORAL VARIATION OF GROUNDWATER RECHARGE IN RECHNA DOAB USING MODELING APPROACH

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Abstract

Economy of Pakistan is highly dependent on agriculture, but agricultural economy of Pakistan is under the risk as shortage of irrigation water is prevailing in the country. The Surface water resources are unable to meet the requirement of crops. Due to scarcity of surface irrigation water, agriculture has been shifting on the groundwater. Use of groundwater is increasing with time and water table is declining. Current falling scenario of groundwater table in most of areas of Pakistan is threating agriculture and food security of the country. Only way to preserve the fresh water for long time use is groundwater aquifer system and recharge is single depository of this unique water bank. Since management of aquifer system in accordance to recharge potential could be very beneficial to meet the alarming condition of water scarcity. Different studies have been conducted to estimate the behavior of groundwater in Pakistan, this study focus on the groundwater recharge potential specifically. For this, real time groundwater monitoring system is installed in the study area. Groundwater model MODFLOW is used for estimation of current groundwater potential and determination of future scenarios. This research is helpful for delineation of areas of potential recharge and formulation of stratifies for judicial use of groundwater recharge in future. Results from these research calibrated models shows that the decline in groundwater table was in normal range in areas near to the river and water bodies while a higher decline was observed in areas at a distance from water bodies. The groundwater recharge from river and watercourse seepage was the cause of this behavior.

Keywords: Groundwater Monitoring, Groundwater Modeling, Groundwater Recharge, MODFLOW.

1. INTRODUCTION

Groundwater is the primary source of freshwater. Groundwater sources supply approximately 70% of water used in rural areas and approximately 50% of water used in commercial and urban areas (Velis, Conti, & Biermann, 2017). Since 1991 to 2015, the Pakistan's average annual per capita water availability has been steadily declining, and this is expected to fall to 1400 m^3 and 1190 m^3 in 2025 and 2050, respectively (Watto & Mugera, 2016). Water demand is increasing day by day due to increase in population and required food production. Groundwater abstraction is increasing to overcome the problems of water shortage (Vaux, 2011). Over the last three decades, there has been an exponential increase in the amount of ground water structures, resulting in massive withdrawals of groundwater for different uses in various sectors. This has resulted in a number of issues concerning the quantity as well as quality of groundwater, and decrease in water table levels and the reduction of groundwater resources (Woldeamlak, Batelaan, & De Smedt, 2007). Groundwater management is especially important for enhancing agriculture, preserving and enhancing biodiversity, and maintaining the ecosystem in the areas of Rechna Doab.

The proposed study was conducted in the districts of Hafizabad, Faisalabad, and Jhang in Rechna Doab. These are semi-arid regions experiencing the minimum or negative groundwater recharge and declining water tables. These are the rice growing areas of Pakistan, so it is important to monitor the impact of groundwater recharge, due to extensive irrigation in these areas. An integrated groundwater model can be used to manage groundwater in the canal subdivision (Turnadge & Smerdon, 2014). Evapotranspiration and groundwater recharge are necessary inputs for the groundwater models as boundary conditions (Alvarez, Trovatto, Hernández, & González, 2012).

Numerous numerical techniques have been developed to deal with the complexity of groundwater systems and the limitations of analytical approach. These methods are boundary element method, finite element methods, finite volume method and finite difference method. Many window-based commercial graphical user interfaces were created during the 1990s, including Groundwater Vista, Visual MODFLOW, Groundwater Modeling Systems (GMS), and Processing MODFLOW (Akhter & Hossain, 2017). Since its 1984 debut, the "MODFLOW" finite difference groundwater flow model has been one of the most popular models for groundwater flow analysis (Li et al., 2016). Application of GIS combined with modeling greatly benefited both the visualization of model development and model results. WetSpass water balance model is widely used for groundwater recharge estimation (Khadri, Pande, & Environment, 2016). WetSpass and MODFLOW were successfully coupled to recognize the characteristics of groundwater.

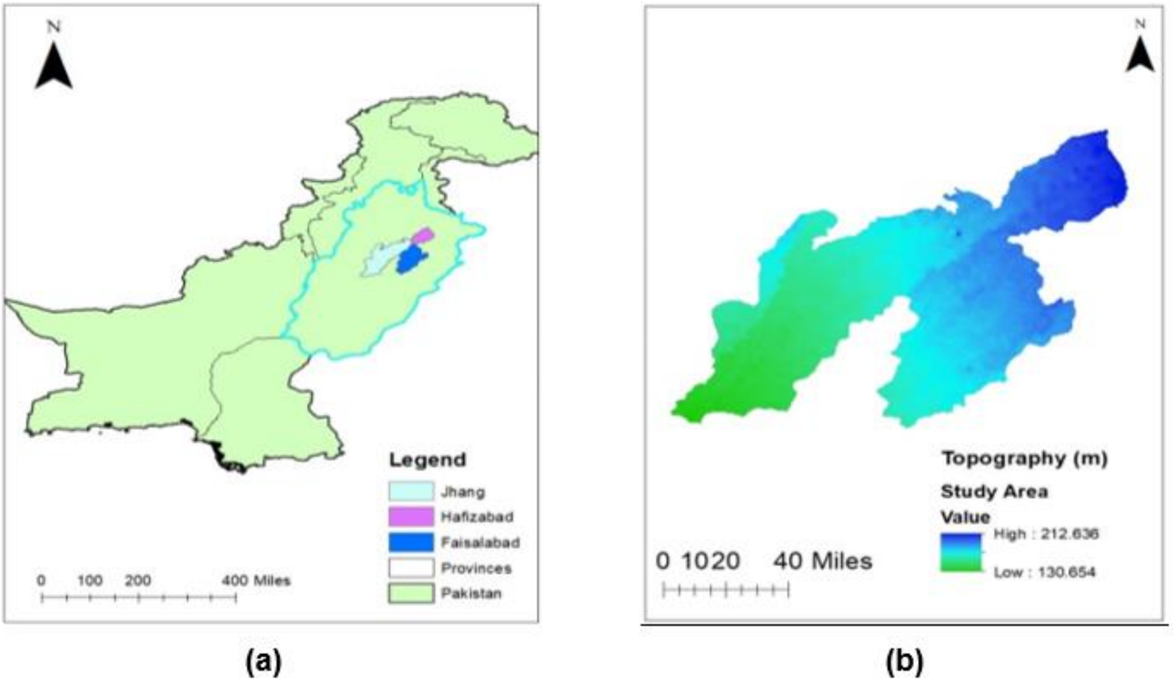
In Rechna Doab surface water is scarce, groundwater is supplemented with crop water to meet agricultural production requirements. It is predicted that as the demand for irrigated water increases daily, so will the need for groundwater in the future to ensure food security. This study was designed for the spatial and temporal assessment of groundwater fluctuation in Rechna Doab. Three different cities were selected and 30 piezometers were installed on the potential recharge zones. MODFLOW was used for the simulation of temporal and spatial distribution of groundwater recharge (Healy, 2010). A groundwater recharge model Wets pass-M is also used in this study. The components of the water balance are distributed spatially based on a variety of factors, including soil texture, land use, slope, groundwater level, and weather (Armanuos, Negm, Yoshimura, & Valeriano, 2016). The ARCGIS software was used to prepare meteorological data, such as precipitation, air temperature, potential evapotranspiration, wind speed, topography, soil, land slope, groundwater level, and land cover/land use, which were all inputs for the model (Chaminé, Carvalho, Teixeira, & Freitas, 2015; Velasco et al., 2013) . Three main future scenarios were developed to replicate the aquifer's projection using MODFLOW-2005. In this study the groundwater flow model MODFLOW-2005 was created and integrated with the groundwater recharge model WetSpass-M to monitor the groundwater level fluctuation and groundwater budget (Basharat, Hashmi, & Opportunities, 2010).

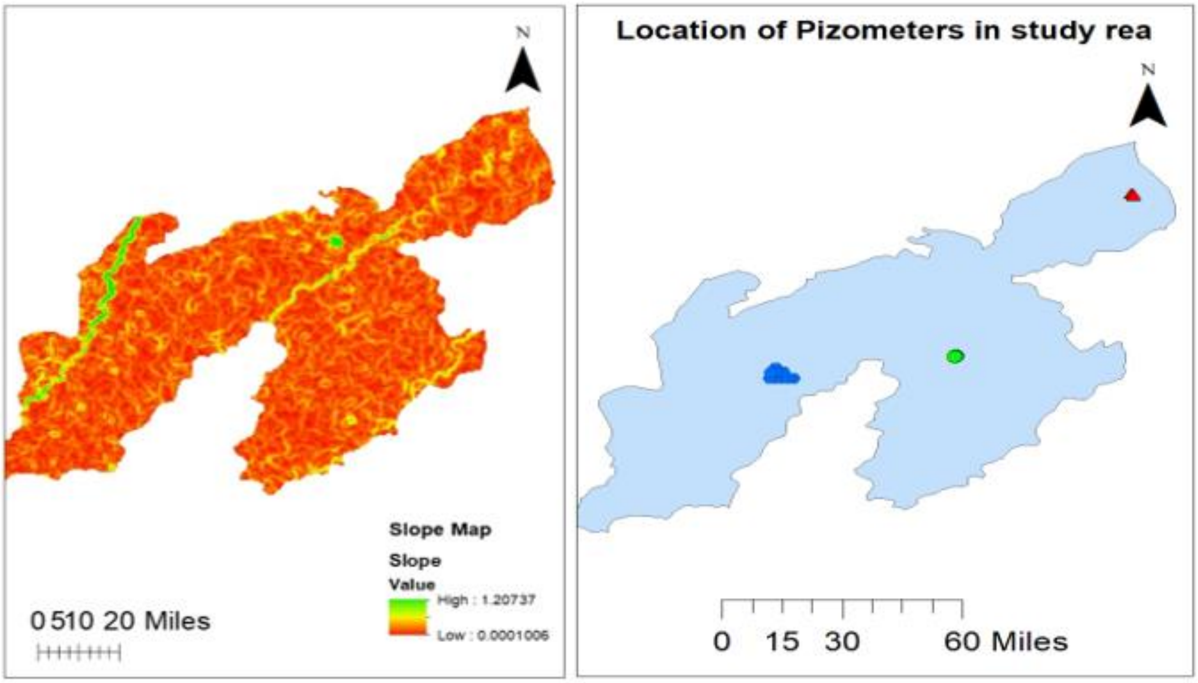
2. MATERIALS AND METHODS

2.1. Study Area

The area in the Rechna Doab is 2.98 million hectares (Mha). This study was conducted in the districts of Hafizabad, Faisalabad, and Jhang in Rechna Doab. Faisalabad is located between the latitude of 31.4504° N and longitude of 73.1350° E and covers an estimated area of 1230 km^2. Jhang is located between the latitude of 31.2781°N and longitude of 72.3317°E and covers an estimated area of 28.27 km^2 and Hafizabad is located between the latitude of 32.071°N and longitude of 73.690°E and covers an estimated area of 2367 km^2.

The Doab's normal slope is 0.38 meter per kilometer. Average annual rainfall of Faisalabad, Hafizabad and Jhang is about 615, 450 and 569 millimeters respectively, mostly falling in the monsoon season, which starts from July and ends in September.





(c) (d)

Figure 1: Characteristics maps of the study area (a) Location Map of Study area (b) Topographic Map of study area (c) Slope Map of Study area (d) Location of Sampling Piezometers in study area

2.2 Climatic Data

The Pakistan Meteorological Department provided meteorological input data for the WetSpass-M model from 2006 to 2020. Summer season starts in the middle of April and ends in the middle of October with temperatures varying from $21^{o}C$ to $50^{o}C$. In winter which is usually considered as a period from October to April, temperature ranges from $15^{o}C$ to $27^{o}C$ and from $7^{o}C$ to $27^{o}C$ during daytime and nighttime, respectively. The average annual precipitation ranges from 341 mm in the south to 1081 mm in the upper land areas of the Doab. Maximum rainfall occurs in July August and September, with maximum values of 120, 40 and 75mm in Faisalabad, Hafizabad and Jhang, respectively.

2.3 Lithology

Sub surface lithology of the soil was determined by collecting soil samples at 30 different locations in study area and with 20cm average sampling depts. Hydrometer method was used to determine the soil texture (Latif, Ahmad, Irrigation, & Drainage, 2009). The results show that most of the soil in the study area was sandy clay loam, clay loam and sandy loam. The soil is relatively homogeneous in some areas, with high percentages of fine sand and silt. The alluvial plain intersects a rock formation in the upper reaches of the

Rachna Doab. The upper 200 meters are made up of a thick arrangement of sand, clay and silt.

2.4 Topography

Elevation data of the study area was taken from Google earth explorer. Topographic map of study area was created in ArcMap with the help of elevation data. The value of the elevation varies from 130m to 212m and the average value of the surface elevation of Faisalabad, Jhang and Hafizabad is 180,158 and 205m respectively.

2.5 Groundwater Data

Groundwater elevation data used for calibration and validation was taken from the piezometers installed by the Punjab Irrigation Department between 2006 and 2020. The department installed 50 piezometers in Faisalabad, 50 piezometers in Hafizabad, and 50 piezometers in Jhang. These piezometers are installed at different locations mostly along the canals to monitor the groundwater table fluctuation around the year. Elevation data was collected twice a year, pre monsoon and post monsoon. This data was used for this model.

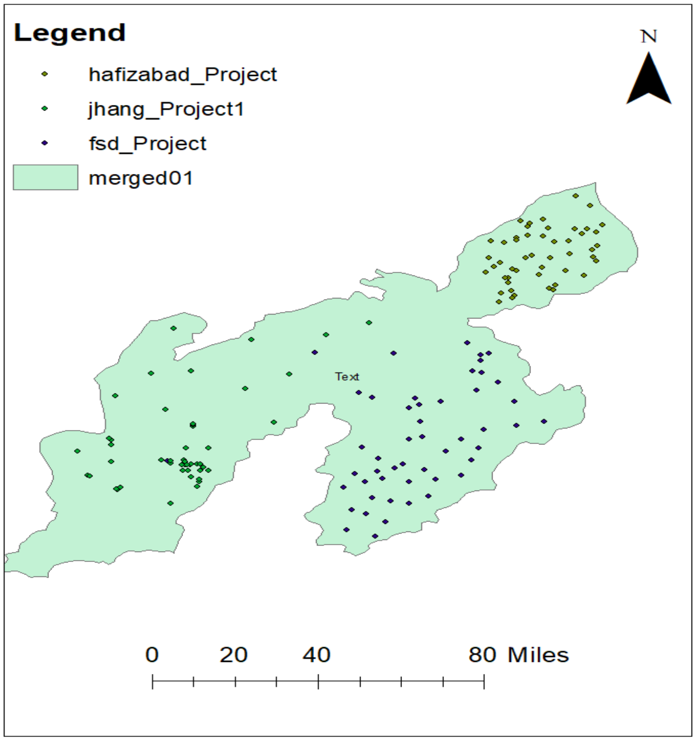


Figure 2: Piezometers Installed by Punjab Irrigation Department

2.6 Groundwater Recharge and Evapotranspiration:

Water balance components as recharge and evapotranspiration can be obtained from WetSpass model in the form of raster data/maps. The model results give yearly data of recharge and evapotranspiration for the period of 2006-2020. Each and every pixel in raster data shows a different value of groundwater recharge and evapotranspiration. This model gives output of water balance components as it is based on water balance equation and it can calculate the groundwater recharge and evapotranspiration (Woldeamlak et al., 2007). The objective of this research was to evaluate and predict the groundwater recharge in the areas of Faisalabad, Hafizabad and Jhang so that the flow of groundwater can be checked and the results are useful for groundwater modeling.

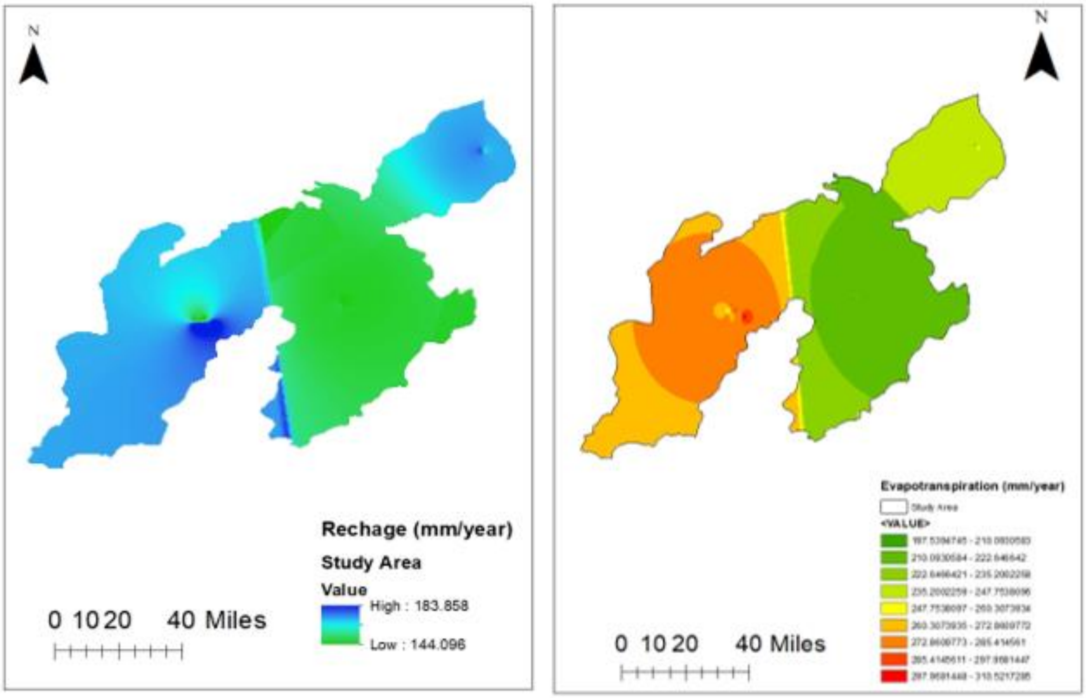


Figure 3: (a) Long-term spatial distributions of annual groundwater recharge (b) Long-term spatial distribution of annual evapotranspiration

The results of WetSpass-M model were arranged at monthly, seasonal and annual scale to estimate and understand the water budget of study area at monthly, seasonal and annual scale. According to the results about 24 percent of total precipitation had been transformed into groundwater recharge. Groundwater recharge in last 15 years for a time period of 2006 to 2020 varies from 117.1 to 184.5.mm/year and the average recharge in last 15 years is about 143.9 mm/year. About 24 percent of total precipitation was transformed into groundwater recharge annually. The groundwater recharge in the year 2020 was simulated with a minimum value of 120 and maximum value of 184.8 mm/year with an average value of 124.8mm/year.

2.7 Groundwater Model Development (Steady State Model Development)

A fully distributed three-dimensional groundwater flow model, MODFLOW-2005, was developed with the help of ModelMuse as a graphical user interface. The formulation of a conceptual model is a very important step in creating a numerical model for a modeling project (Berehanu, Ayenew, Azagegn, & Protection, 2017). ArcGIS was used to prepare the study's subjects, such as the river, irrigation channels, observation wells, and pumping wells, before they were imported into the model. The boundary conditions of the model are represented by these objects.

Model calibration is the most crucial stage in hydrological modeling. In calibration, observation heads data are compared with simulated heads data, making piezometers data quite valuable (Khadri et al., 2016). A calibrated model that works well has strong agreement between simulated and observed data (Awais et al., 2022). Annual mean data from observation wells were used in the creation of the steady state model. For observation heads, the head observation package (HOB) was employed with MODFLOW-2005. ModelMuse received all observation well data in shape file format. Figure 3.24 depicts the location of the piezometers used in the model. The model was calibrated against the last 15year (2006-2020) water level values of these piezometers installed by irrigation department.

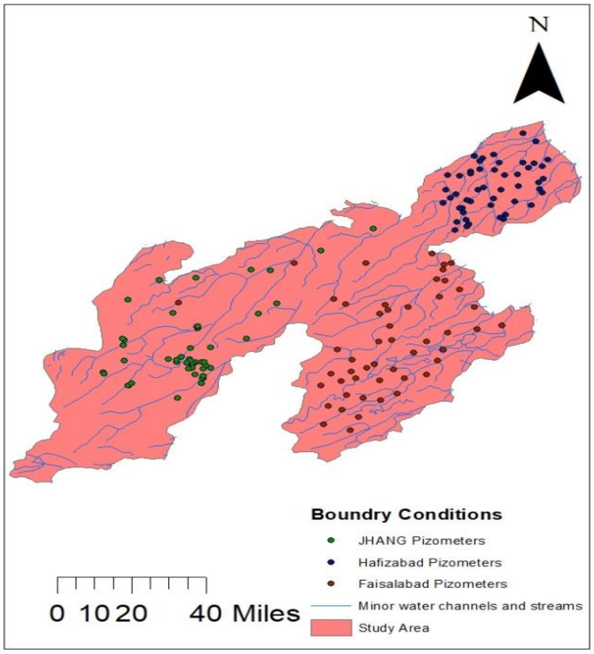


Figure 4: Boundary Conditions of Study Area

2.8 Spatial discretization of model

The process of discretizing a model is breaking it up into a variety of columns, rows, and layers. Effective discretization in modeling influences the accuracy and efficiency of the outcomes. The model's overall area determines the number of rows and columns. The model was discretized into three layers of 100 by 100 m cells for this type of analysis. There were 500 total rows and 1450 total columns in the model. Figure 3.24 depicts the grid used for this model.

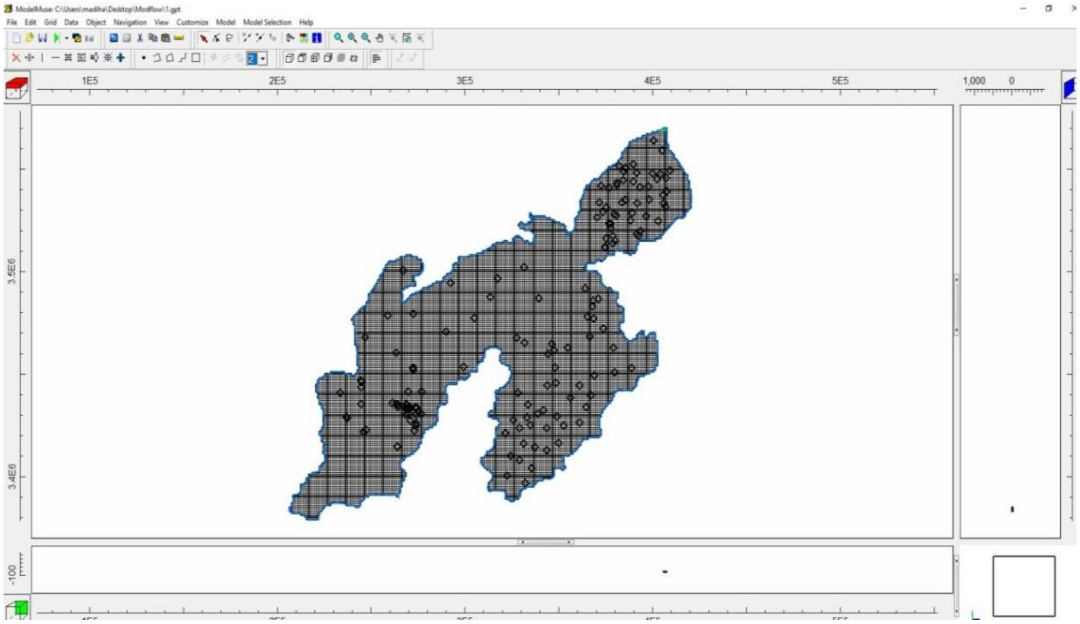


Figure 5: Spatial discretization of model in MODFLOW 2005

2.9 Coupling of Surface Water Model and Groundwater Flow Model

Wetspass model is limited in dealing with groundwater flow and MODFLOW struggles to identify the primary inputs to the groundwater model, namely distributed evapotranspiration and groundwater recharge (Aslam, Arshad, Singh, & Shahid, 2022). That why WetSpass model was used to find the distributed evapotranspiration and groundwater recharge of the study area to use as the input data of MODFLOW. WetSpass simulates various components of water balance equation. MODFLOW is a three dimensional groundwater flow model, it models groundwater recharge, interaction with streams and lakes, drainage water and stream network (Ghouili, Horriche, Zammouri, Benabdallah, & Farhat, 2017). WetSpass-M model results were used as MODFLOW inputs. MODFLOW calculates groundwater hydraulic head and surface water interactions, which are then used in WetSpass. A coupled model was used to examine the current and future hydrology of the Rachna Doab, including water balance, system water budget, and groundwater level (Anderson, Woessner, & Hunt, 2015).

2.10 Model Calibration, validation and sensivity analysis

The model was manually calibrated using the average annual data of 150 piezometers for the last 15years from 2006 to 2020. To create a strong correlation between observed and simulated observation heads, boundary conditions were changed. After the steady state model was calibrated, a transient stage model was created by feeding the model data for time-variant parameters, including recharge, evapotranspiration, hydraulic heads, and pumping rate. In accordance with the time step of each period, the boundary conditions of the model were likewise changed from a steady state to a transient state (Ghouili et al., 2017).

The calibration and validation of the transient state model uses head observation data from 2021 to 2023. The steady state model was validated using observation data from 2021 to 2023. For calibration statistics, MODFLOW supplied well hydrograph data.

Annual Distribution of Groundwater Recharge

Groundwater management cannot be completed without groundwater recharge in this research long term (15 years) groundwater recharge is simulated. According to the results about 24 percent of total precipitation had been transformed into groundwater recharge. Groundwater recharge in last 15 years for a time period of 2006 to 2020 varies from 117.1 to 184.5.mm/year and the average recharge in last 15 years is about 143.9 mm/year.

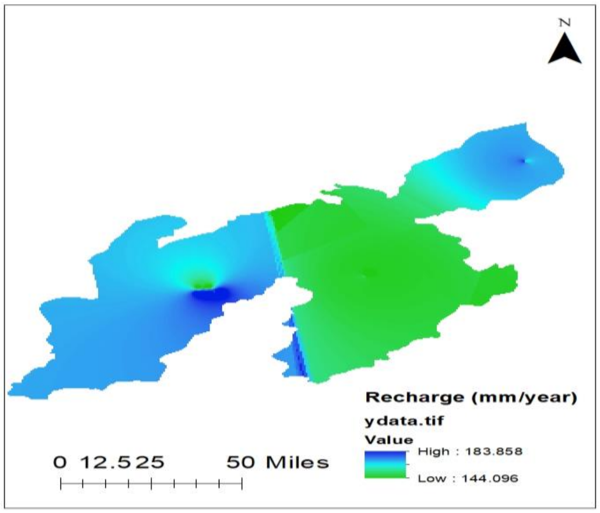


Figure 6: Annual Groundwater Recharge variation

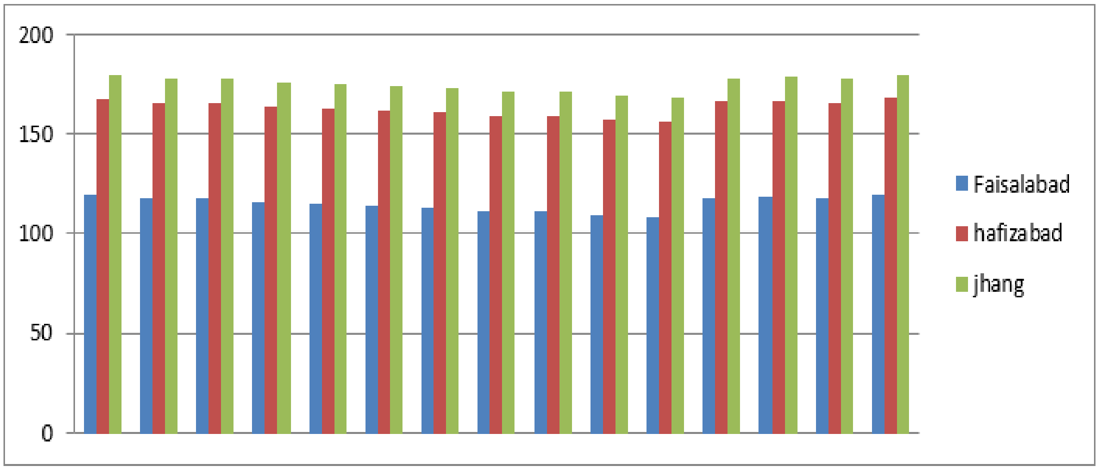


Fig 7: Graphical representation of Annual Simulated Groundwater recharge

Sensitivity analysis for this model was carried out by altering the value of the calibrated model parameters. The primary goal of sensitivity analysis was to identify the model parameter(s) that had the greatest influence on the outcomes of the model It was carried out by altering the calibrated model's values and observing the effects on the model's output (Zhou & Li, 2011).

Table 1: Statistical analysis of field and model data

Parameter	Formula	Calibration	Validation
Mean Error	ME = $\frac{1}{n}\sum_{i=1}^{n}\lvert H_{obs} - H_{sim}\rvert$	-0.01783	0.100805
Mean Absolute Error	MAE = $\frac{1}{n}\sum_{i=1}^{n}\lvert H_{obs} - H_{sim}\rvert$	0.5834	0.3862
Root Mean Suqare Error	RMSE = $\sqrt{\frac{1}{n}\sum_{i=1}^{n}(H_{obs} - H_{sim})_i^2}$	0.0032	0.0035
R^2		0.97	0.98

3. RESULTS

The 25% of the entire precipitation was transformed into groundwater replenishment, according to simulation data. According to the long-term annual groundwater recharge, the value of this groundwater varied from 99.1 mm/year to 218.5 mm/year between 2006 and 2020, with an average of 115.6 mm/year. The minimum recharge was done in 2019 with a value of 118mm/year and maximum recharge was simulated in 2011 with a value of 188mm/year.

The model's recharge simulation in sandy loam soil was observed to be higher than that of loamy soil due to the correlation between soil physical qualities and the distribution of water balance components. However, surface runoff and evapotranspiration were higher in sandy loam soil than in loamy soil.

3.1 Future Scenario Analysis

The calibrated model was run for several scenarios within the research area. The scenarios were created to anticipate potential water shortages and stress on the aquifer in the near future. Developing scenarios are helpful in management strategies and to prevent future issues.

The Groundwater flow model MODFLOW-2005 was used to develop the Future scenarios and to check the response of aquifer on different pumping and recharge rates. The values of groundwater level in 2023 were taken as reference to represent the future possibilities with different recharge and pumping rates. MODFLOW-2005 was used to predict the Hydrodynamic flow of the aquifer up to 2023.

For Scenario-I, the consequences of the pumping rate for next ten years up to 2033 were simulated by following the pumping rates of last 15 years from 2006-2020. A very limited number of piezometers saw their groundwater level rising while the water level was simulated to be falling in many other locations but the decline in groundwater level was not too much at most of the piezometers it was normal or minimal.

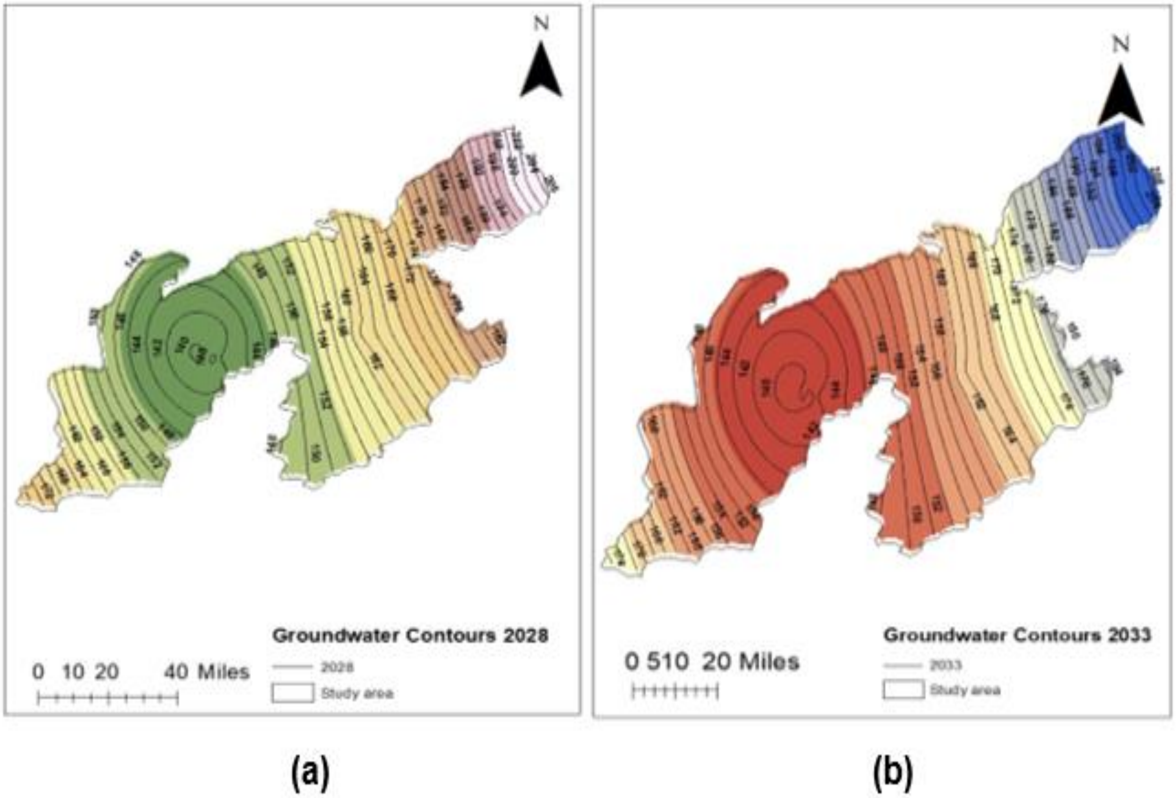


Figure 8: Scenario-I (a) Predicted groundwater level contours for the year 2028 (b) Predicted groundwater level contours for the year 2033

According to the prediction of the model water level at most of the pizometers was declining. These pizometers were installed in areas with potential recharge due to this reason the decline in water table was not too much at all points as these pizometers are near to the watercourse and recharged by the seepage water from watercourse.

A minimal draw down was observed in the upper side of study area and more change is observed in the lower side of study area. The areas where drawdown is more than other areas shows less groundwater recharge from water course through seepage.

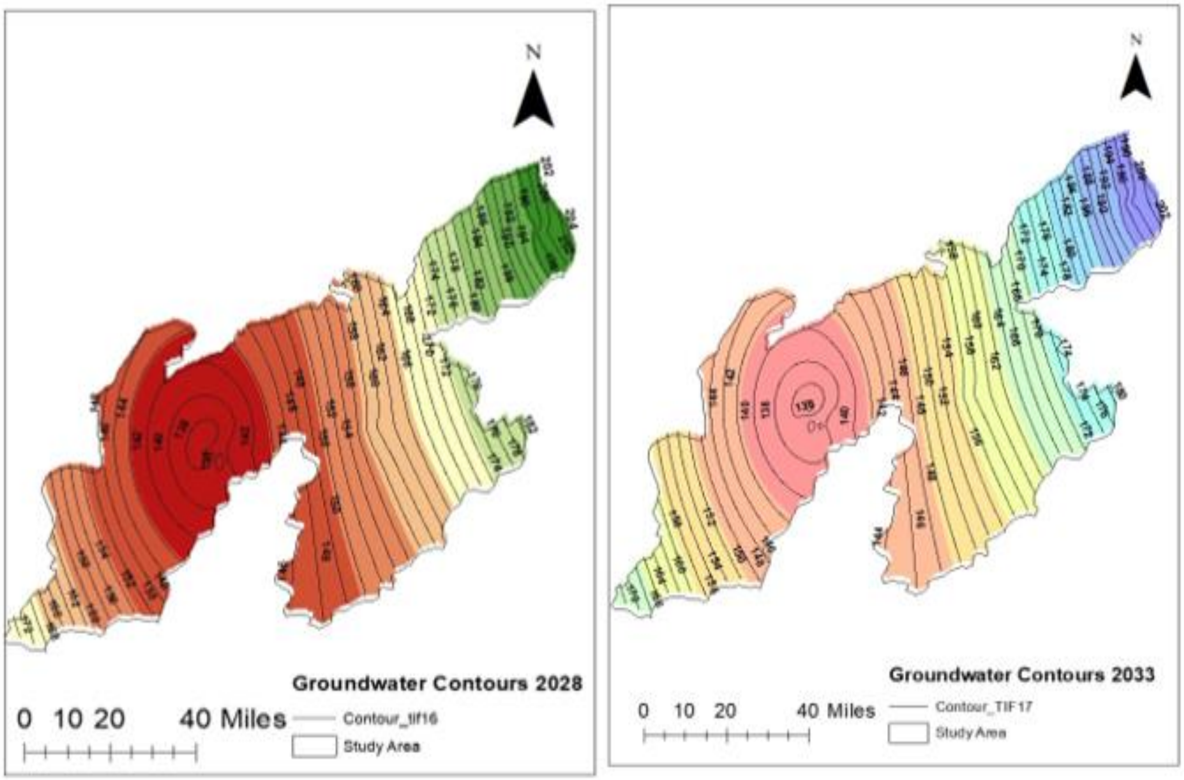
The increase in groundwater abstraction through by pumping is a major source of water scarcity as the rate of pumping is much higher than the rate of groundwater recharge. The numbers of tube wells are increasing day by day, farmers draw water for agricultural uses because they fail to fulfill their needs from canal water.

This creates an alarming situation in future for agricultural production. Declining the groundwater level may also increase the pumping costs as more energy is required to pump water from depth, it decrease the pumping efficiency.

If the significant groundwater abstraction continues for many years it can lead to dry the aquifer in future.

In the second Scenario the future condition of the aquifer was predicted if there is no recharge from watercourse as watercourse stop working.

The results show that water table was declining at all points and there was a major difference in the predicted groundwater level for next ten years.



(a) (b)

Figure 9: Scenario-II (a) Predicted groundwater level contours for the year 2028 (b) Predicted groundwater level contours for the year 2033

The groundwater level varies from 164 to 157m in Faisalabad and from 202 to 194m in Hafizabad. The Fluctuation in groundwater level was from 144 to 133m in Jhang as a maximum and minimum value respectively.

The groundwater level was highly affected in the areas of Jhang and Hafizabad as but in Faisalabad there was a normal decline at some points.

The future behavior of the aquifer was projected in scenario-III by raising the pumping rate by 25%, 50%, 75%, and 100%, respectively, for the next ten years, or 2023–2033.

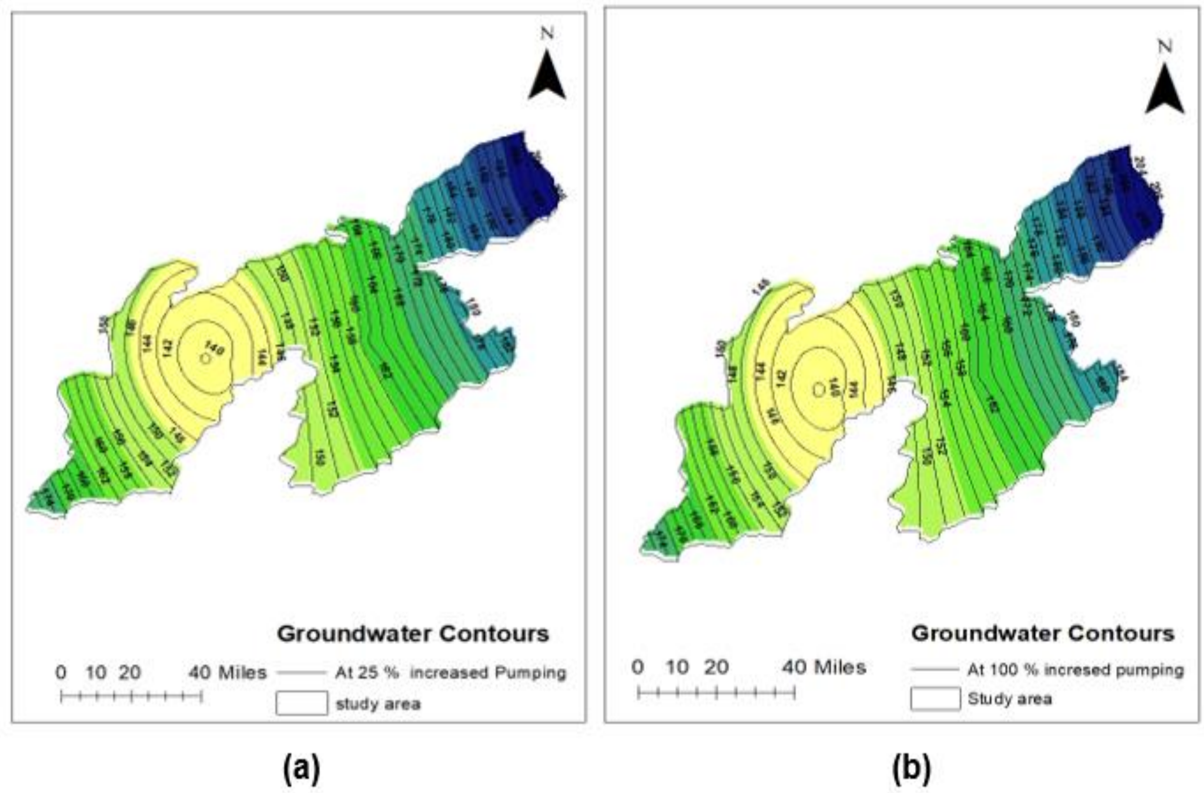


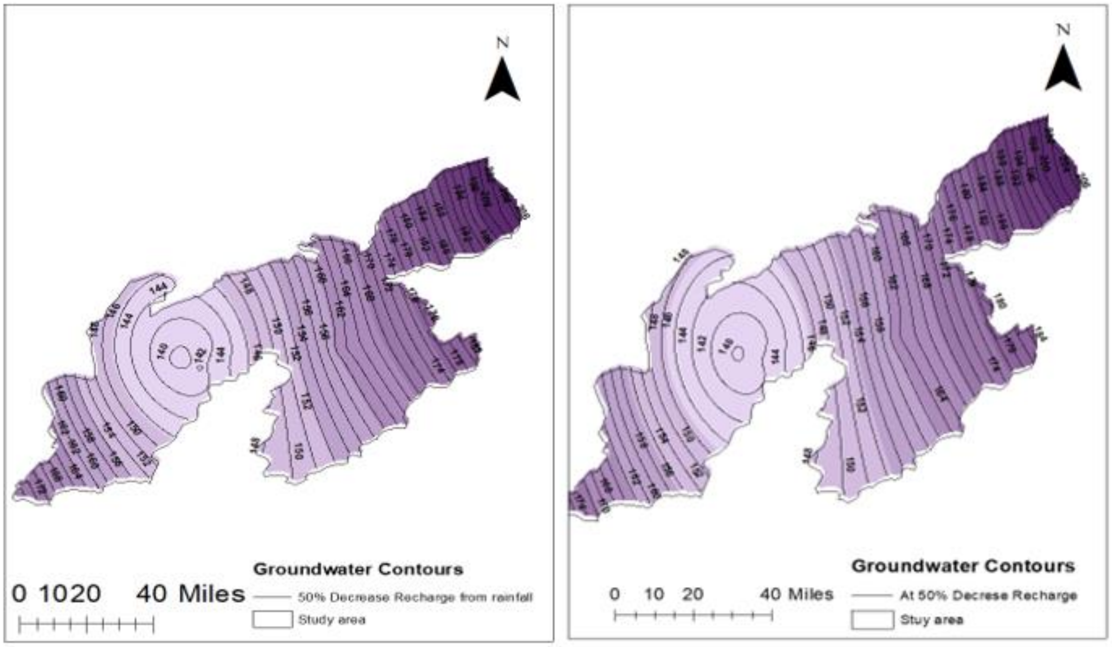
Figure 10: Scenario-III (a) Contours of predicted groundwater level at 25% increased pumping for the year 2033 (b) Contours of predicted groundwater level at 100% increased pumping for the Year 2033

The change in groundwater level by increse in pumping rate by 25% was categorized as normal and moderate decline as the difference in water level was less than 1m at some points but it was more than 1m at other points. but the increse in pumping rate by 50% results in a large decline of water level which is more than 2m at some points.

The high pumping rates as 75% and 100% results in a moderate to high decline at most of the pizometers which is more than 2m, but at some pizometers it was still normal and moderate.

Scenario IV was developed to analyze the impact on the aquifer condition after 2023, the annual groundwater recharge from rivers and rainfall was reduced by 50%and 50% respectively, while maintaining the same pumping trend. The contour lines of groundwater level at 50% less rainfall ranges from 138 to 202m as maximum and minimum value respectively.

In the same way the variation in contour lines for 50% less recharge from river is from 140 to 204m as maximum and minimum value respectively. There is not a significant change in groundwater level at these piezometers due to recharge from watercourse.



(a) (b)

Figure 11: (Scenario- IV) (a) Groundwater Level Contours at 50% Decreased Rainfall (b) Contours of predicted groundwater level at 50% decreased recharge from recharge from the river

This study projected the effects of recharge on the groundwater table under two distinct future scenarios that could arise due to climate change or other unpredictability. The decrease in recharge from the river by 50% results in a normal decline. The results showed that there is more decline in groundwater level in case of 50% decreased recharge from rainfall as compared to the decreased recharge from river.

4. CONCLUSIONS

This study was carried out in a specific region of Rechna Doab, which is located between the Chenab and Ravi rivers. Three districts of Punjab (Faisalabad, Jhang and Hafizabad) were selected for this study. A three-dimensional groundwater flow model MODFLOW-2006 was developed with ModelMuse. ModelMuse is a graphical user interface for the MODFLOW model series from the United States Geological Survey (USGS). Since defining the cells as confined or unconfined is crucial, the finite difference technique is used in this model. The study area comprised three layers, with thicknesses of 8, 32, and 67 meters. First layer of aquifer is from 0 to 8m, the depth of second layer is from 8 to 40m and third layer is 107m deep. Permeability data were used in this study to define the aquifer strata. In the model's development, Layer-1 was designated as unconfined, Layer-2 as convertible, and Layer-3 of the aquifer as is defined as confined. The range of specific yield used for the model was from 0.05 to 0.25m, and specific storage (Ss) varies from 0.0000001 to 0.001 in the model input data. The range of average annual recharge from rainfall is from 0.000321 m/day and 0.000505 m/day, respectively. The model was manually calibrated at steady state condition against the monitored groundwater level. The values of groundwater level in 2006 were used as initial condition for this steady state groundwater model. The UCODE calibration tool was used for the calibration of the monitored groundwater level readings for the year 2006-2020. The validation of the model was done by using two-year data of 30 newly installed piezometers at watercourses in the study area.

It was determined that, on an average annual basis, up to 48% of the total rainfall was transformed into evapotranspiration, 24% into runoff, and the remaining 28% into groundwater recharge. The range of long-term recharge for summer season was 70.1 mm/season to 161.3 mm/season; for winter season it was 45.3 mm/season to 84.5 mm/season. It was observed that maximum recharge occurs in June and July due to maximum rainfall in these months and the minimum recharge was observed in the month of October and November due to less rainfall. Results shows that the minimum monthly recharge was 12.3mm and maximum monthly recharge was 14.9mm.

The results of the MODFLOW simulation, which covered the years 2006 to 2020, indicated that the decline in groundwater table was in normal range in areas near to the river and water bodies while a higher decline was observed in areas at a distance from water bodies. The groundwater recharge from river and watercourse seepage was the cause of this behavior. According to the predicted results of the model in Scenario-I there is minimal change in groundwater table in many locations due to recharge from watercourse and even in some points it could be seen that it was increasing due to less pumping and more recharge from watercourse. In the second Scenario the results indicated the future condition of the groundwater table if watercourse stop working and the pumping rate from the aquifer is same but recharge is not available from the watercourse. The predicted results shows a greater decline in watertable, it means that if there are not any significient ways to recharge the groundwater table itcould create a alarming situation in future by drying the aquifer. The predictions of the Scenario III showed that the decline in groundwater table is as higher as the rate of pumping of groundwater. As the pumping rates are increasing but the rate of recharge is the same. The results of Scenario IV revealed that there is more decline in groundwater level in case of 50% decreased recharge from rainfall as compared to the decreased recharge from river. It can be estimate that the effect of recharge is associated with rainfall.

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