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Predicting discharge potential of upper Thal Doab, Indus basin for irrigation through numerical groundwater flow modeling

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Abstract

Groundwater is playing an important role in sustainability of irrigated agriculture in Pakistan by contributing about 40% in total water resources of the country. To ascertain the present status of the aquifer in the Upper Thal Doab area, a groundwater modeling using Visual MODFLOW 2011.1 has been executed. Steady-state model was calibrated for the year 1984 and transient state model was simulated up to predictive period of 2025. The transient simulation results indicate stability of the aquifer with minor difference between water flowing into and out of the aquifer. During 1984 to 2025 it has been observed that the total water inflows increased from 347.00 to 3029.14 BCM (Billion Cubic Meter) and total discharges from 347.00 to 3029.29 BCM, which shows stability of the total groundwater storages of the aquifer. However, if the pumpage increases with this rate, there are chances that groundwater of the area will deteriorate in future. This study provides a base for timely formation of management strategies for the reasonable utilization and management of groundwater resources in the area.

Keywords: *Groundwater Modeling, Irrigated Agriculture, Thal Doab, Indus Aquifer.*

1. Introduction

Groundwater is the largest source of fresh water lying beneath the ground (Kumar and kumar 2011). Pumping wells on large scale have been installed in the Upper Thal Doab area for irrigation during the last two decades. This trend of groundwater extraction may effects the aquifer. The Pakistan agriculture sector which contributes approximately 25% to the national Gross Domestic Product (GDP) is presently facing number of challenges comprising of population growth, rapid urbanization and water resource reduction (World Bank 2017). Although there is a comprehensive network of irrigation infrastructure, like canals and dams, but the water resources for agriculture are still shorting due to climatic changes, e.g. floods and droughts in recent as well as in coming years. The droughts in recent years have also explored the vulnerability of the Indus basin irrigation system and environmental issues in this region (Ahmad et al. 2003). The situation has encouraged groundwater extraction for irrigation and installation of tubewells has exponentially increased, specifically in the Thal Doab area. The situation demands a thorough evaluation of current status of water resources, especially the groundwater on which the country's agriculture development depends in most of the Indus basin including the Upper Thal Doab in the Punjab plains. Numerical groundwater model plays an important role in estimating groundwater flow pattern and other aquifer characteristics (Abu-El-Sha'r et al. 2007; Zhou and Li 2011).

Toth (1963) used analytical solution for the first time to investigate groundwater flow in hypothetically small basin. Visual MODFLOW (a three-dimensional finite difference groundwater flow model of the United States Geological Survey) has widely been used to model and assess the behavior of groundwater flow systems (Algafar et al. 2011). Integration of groundwater modeling with Geographic Information System (GIS) and remote sensing technology provide an adequate way of analyzing temporal changes with reference to change in depth to groundwater and associated environment (Ashraf and Ahmad 2008; Singhal and Goyal 2011).
This study aims to analyze the groundwater condition in major portion of the Upper Thal Doab and predict future trends in the prevailing conditions. To reach to a conclusive result, latest available groundwater modeling techniques were utilized, taking into consideration the results of previous studies.

2. Study Area Description

The study area covers large portion of the Upper Thal Doab, Punjab, Pakistan located between 70° 46′ 34″ to 72° 14′ 45″ E longitudes and 30° 16′ 29″ to 32° 26′ 32″ N latitudes (Fig 1). The area is bounded from west by the River Indus, from east by the rivers Jhelum and Chenab and the northern and southern ends are bounded by Chashma – Jhelum (CJ) link canal and Taunsa-Punjnad (TP) link canal, respectively. The study area covers districts Bhakkar, Leiah and Jhang fully and Mianwali, Khushab, and Muzaffargarh districts partially. The area pertains to arid region of Punjab and observes hot summer, where the temperature goes to 46^{o}C and cold

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winter up to 2°C. Average annual rainfall is 180 mm, most of which occurs during monsoon season in the months of July and August. The evapotranspiration varies between a minimum value of 56 mm and a maximum value of 227 mm in the month of January and June respectively. The mean average annual temperature remains around 24°C with the maximum average value of 30°C during June and average minimum of 4°C during January. The construction of a network of irrigation canals and installation of tube wells both in public and private sectors during the last few decades has converted major part of this desert into irrigated land. Northern part of Upper Thal Doab is hilly terrain, whereas the lower portion could be divided into desert containing sand dunes and irrigated zone along the rivers and canal system.

The study area is mostly composed of unconsolidated alluvial and Aeolian deposits (Fig 2). The alluvial plain is very thick and the basement rocks are as old as Precambrian. Surficial Aeolian sand forms extensive deposits over the alluvium in central part of the area. The flood plain of the Indus and the Chenab rivers are underlain by thick deposits of sand with rare amount of gravel. Thin lenses of silt and clay occur in the form of inculcation with sand which have limited vertical and lateral extent (Khan et al. 2014). Part of the plain adjacent to river which comes under floodwater during heavy floods is called active flood plain. Depth to water table in most of the area is shallow and is in the range of 0.5 to 9.0 m from ground surface. A geological map at Figure 2 gives the overall geological picture of the study area.

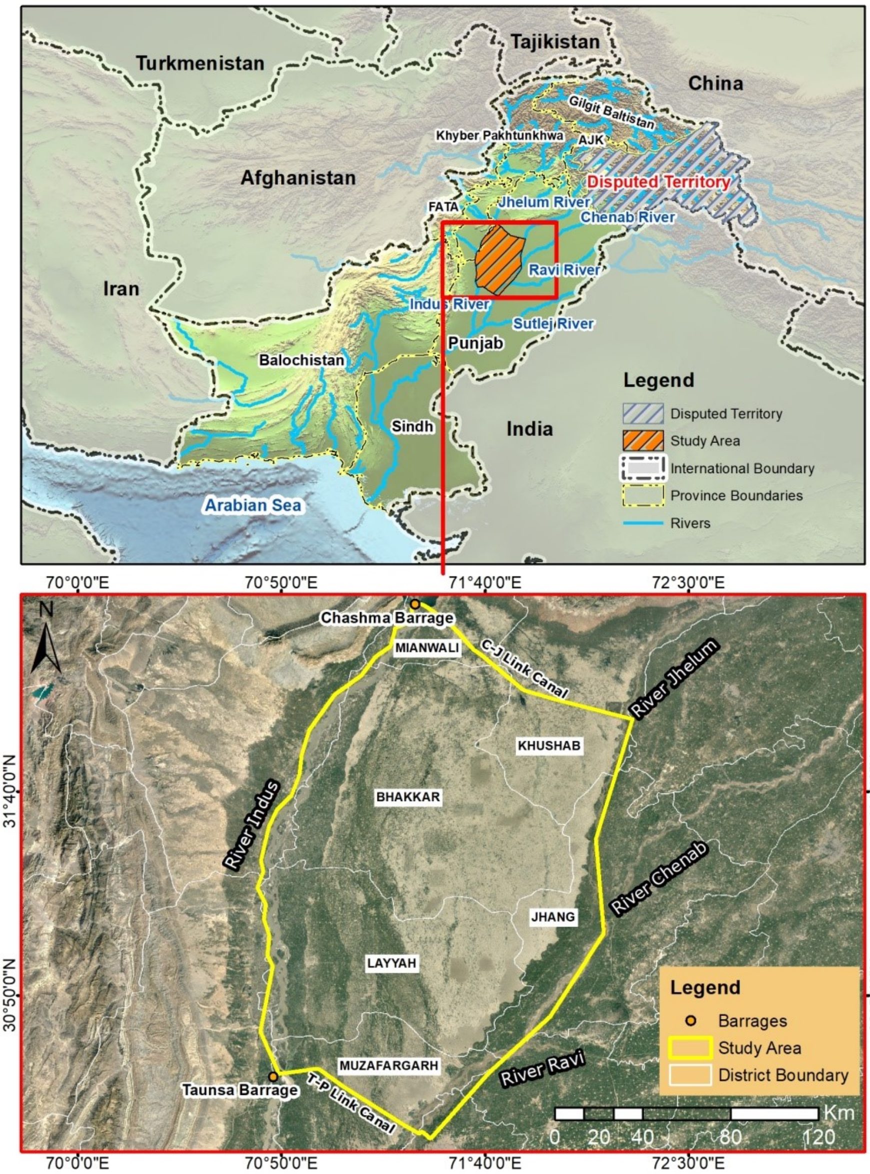

Fig 1. Location map of the study area.

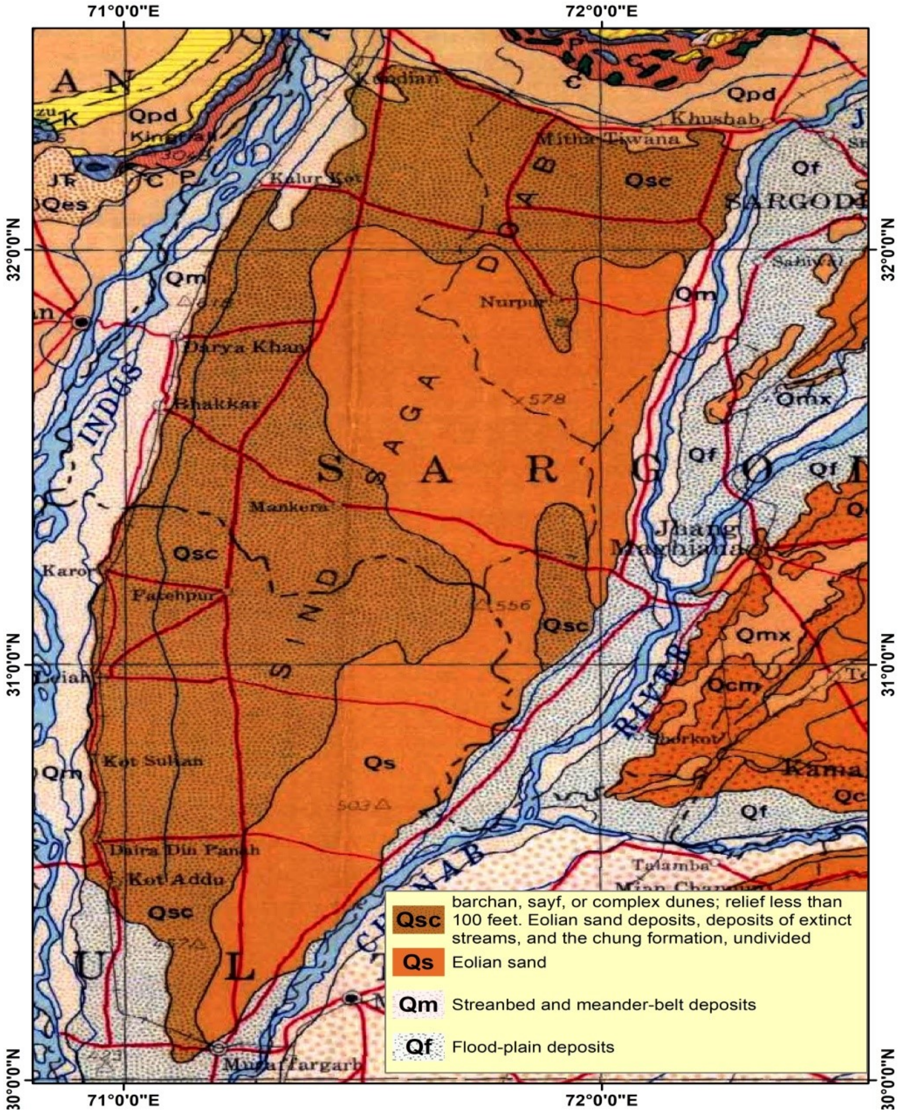

Fig 2. Geological map of study area (extracted from Geological Map of Pakistan on 1:2000,000 scale, published by Geological Survey of Pakistan in 1964).

The Thal Doab aquifer is hydrologically active where the groundwater resource is available in the form of thick alluvium (Shah and Ahmad 2015). The United States Geological Survey (USGS) conducted a study with Water and Power Development Authority (WAPDA), Pakistan in 1961-62 on quality as well as hydraulic characteristics of groundwater (Bennett et al. 1967). The study predicts an average permeability of 0.0033 cfs per square ft in the area. The geological studies concluded that coarse material is on higher side in Thal Doab area (WAPDA 1994). The quality of groundwater up to 200 meters was found generally good (Shamsi and Bilal 1963).

Major source of groundwater recharge in the area is the canal system, i.e., main Thal canal and its distributaries, which flows from north to south. Other sources of recharge include water seepage from Chashma Jhelum (CJ) link canal and Taunsa-Punjnad (TP) link canal forming northern and southern boundaries of the study area, rivers overflow and oxbow-lakes, rainfall and return flow from irrigated wells. The Indus River is feeding Thal Doab through surface water supplies as well as through recharge by its bed and flood plain. The average annual discharge of the Indus River at Kalabagh is about 97 BCM. The high discharges usually occur during summer in the months of July and August owing to monsoon rainfall and snow melting, whereas, low flows are observed during winter season in December.

3. Methodology

3.1. Data Preparation and Analysis

In order to carryout groundwater flow modeling, number of datasets pertaining to observation wells (piezometers), pumping wells and hydraulic conductivity were acquired from WAPDA and PCRWR (Pakistan Council of Research in Water Resources). The climate data pertaining to precipitation, wind speed and daily average temperature was acquired from Pakistan

Meteorological Department (PMD). The lithology, hydraulic conductivity and permeability data was mostly extracted from previous studies and WAPDA data release record. The data was geospatially mapped in a GIS (Geographic Information System) environment using ArcMap software tool to analyze the location of observation wells, pumping wells and altitude contours. Satellite remote sensing images of Landsat TM acquired on 19 February 1993 were also utilized while defining hydraulic conductivity, recharge and specific yield zones.

3.2. Steady-State Modeling

Groundwater flow modeling is an approximation method to solve the partial differential equation pertaining to flow in porous medium. In steady-state flow, the magnitude and direction of flow is constant with time, whereas transient flow takes place when the magnitude and direction of flow changes with time. The groundwater flow of constant density through a porous media is governed by the continuity equation (Eq. 1) (Freeze and Witherspoon 1966).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \quad (1)$$

Where K_{xx}, K_{yy} and K_{zz} are hydraulic conductivity values, h is hydraulic head, W the volumetric flux per unit volume, S_s is specific storage for porous medium and t is time.

In steady-state condition, there is no change in head with respect to time and can be described by three dimensional partial differential equation (Eq. 2).

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)=0 \quad (2)$$

The available data of 31 test wells was utilized for development of hydraulic conductivity zones using Thiessen polygon method (Thiessen 1911). The water level of piezometers and recharge for each zone was entered in the model for steady-state calibration using ArcMap, GIS software, which provides a linking tool for preparation of input files for groundwater model (Jyrkama et al. 2002). The physical boundaries in the form of rivers and canals around the model were considered constant head boundary. During the execution of steady-state model, values of hydraulic conductivity, recharge and boundary conditions were adjusted using trial-and-error procedures, until the calculated head values matched the observed heads. The model was run for 10 years with a single time step to achieve the steady-state condition and calibrations were made using observed hydraulic heads of 1984 in 28 observation wells (Table 1). The model was finally converged to a correct solution and calibration achieved with several runs by modifying the hydraulic conductivity and recharge values. The validation of the steady-state was carried out using hydraulic heads of 1993 in 20 observation wells. The sensitivity of steady-state model was verified by multiplying input parameters like hydraulic conductivity and recharge separately by the factors of 0.2, 0.4, 0.8, 1.2, 1.5, 2.0, 2.5 and 3.0 and then the model was rerun for each factor. The sensitivity process was first carried out for hydraulic conductivity without changing the recharge parameter and the changes in the mean and root mean square of the simulated hydraulic heads were analyzed.

3.3. Transient Modeling

Transient (non-steady) state calibration was used to assess the storage coefficient and analyze the dependability of pre development steady-state calibration parameters (Guvanasen et al. 2005). The model was calibrated in transient state for 1985 using steady state hydraulic heads as initial conditions. The transient model calibration was carried out using trial-and-error procedure by adjusting the specific yield values. The known values of Specific yield (S_y) of pumping wells were used to develop storage zones of the study area. After calibration of transient state, the model was run for the various stress periods up to 2025. The transient conditions were calibrated with known drawdown at observation wells from year 1985 to 1993. Model verification was done by realization of the model from 1994 to 2003 using observed heads of 2003. A good fit between the observed and simulated heads was obtained. Finally the calibrated and verified model was used for predictive simulation up to 2025 to estimate the effect of future stresses and to predict changes in groundwater flow pattern of the area.

The sensitivity of transient state model was tested by uniformly multiplying storage or specific yield by the factors of 0.2, 0.4, 0.8, 1.2, 1.5, 2.0, 2.5 and 3.0 and then the model was rerun for each factor. The corresponding changes in the mean and root mean square of the simulated heads were analyzed. The RMS values decrease with increase in specific yield values and the residual mean increases with respect to increase in specific yield.

4. Results and Discussions

The results of steady-state calibration shows similarity between simulated and observed heads, where the residual mean is 0.17 m, minimum residual is 0.029 m, Root Mean Square Error (RMSE) is 2.482 m and correlation coefficient value is 0.991. Figure 3 shows the results of steady-state calibration in the form of a scatter gram. Those simulated heads which exactly match with the observed heads, falls on the line X=Y and hence the variance is zero. However, those simulated heads which do not exactly match the observed heads show variance of various degrees. The overall variance falls within the 95% confidence interval, i.e where 95% of the total number of data points is expected to occur.

Table 1: List of piezometers and their groundwater levels used for steady-state calibration.

Well Name	Longitude	Latitude	Head values [m]
GTC-17	71° 47' 37.53"E	31° 35' 33.92"N	170.533
GTC-9	72° 8' 49.86"E	31° 43' 57.81"N	161.184
IX-3	71° 1' 26.12"E	30° 34' 15.50"N	162.562
IX-6	71° 22' 42.85"E	31° 25' 24.30"N	159.321
KA-525	70° 53' 14.83"E	30° 44' 57.96"N	137.698
P-272	71° 11' 0.15"E	31° 21' 4"N	133.682
P-296A	70° 53' 45.68"E	31° 15' 17.32"N	148.358
RP-101	71° 55' 49.68"E	30° 57' 49.96"N	135.327
RP-108	71° 53' 48.59"E	30° 52' 46.32"N	135.566
RP-170	71° 52' 58.68"E	30° 49' 17.32"N	135.274
RP-175	71° 43' 44.32"E	30° 40' 13.32"N	129.866
RP-205	71° 49' 36.96"E	30° 43' 54.68"N	132.761
RP-237	71° 46' 52.68"E	30° 47' 6.68"N	134.273
RP-247	71° 36' 0.96"E	30° 43' 39.32"N	136.51
RP-293	71° 39' 43.59"E	30° 52' 30.68"N	142.817
RP-306	71° 35' 7.59"E	30° 35' 11.68"N	127.376
RP-33	72° 1' 37.32"E	31° 6' 13.96"N	141.239
RP-336B	71° 36' 6.32"E	30° 38' 13.96"N	129.996
RP-345	71° 33' 21.96"E	30° 30' 28.68"N	124.86
RP-55A	72° 7' 29.32"E	31° 9' 21.592"N	141.805
RP-60	72° 0' 0.96"E	31° 10' 25.68"N	146.496
VI_B2	71° 27' 53.32"E	32° 12' 14.05"N	187.405
VII-C	71° 34' 51.68"E	32° 0' 47.682"N	172.358
VIII-7	71° 34' 5.96"E	31° 50' 37.68"N	178.117
VIII-9	71° 53' 38.68"E	31° 53' 14.32"N	182.629
X-3	71° 7 '39.96"E	30° 55' 50.68"N	146.317
X-6	71° 24' 28.96"E	30° 54' 50.05"N	143.94
XI-3	71° 1' 32.71"E	30° 34' 0.29"N	134.456

The sensitivity analysis of steady-state model depicts that the groundwater system is sensitive to change in recharge value. The transient-state calibration of the model shows best match between the simulated and observed heads (Fig 4). The calibration shows an average difference of 1.21 m and RMS of 2.471 m between the observed and simulated heads. The sensitivity analyses of transient state model show that the RMS values decrease with increase in specific yield and the residual mean shows an increase trend with respect to increase in specific yield. This depicts that the model is sensitive to specific yield.

The equipotential contours and velocity vectors map of steady-state model in Fig 5a confirm that the water flows follow the true replica of general topography of the area, and the velocity vectors indicate the flows direction towards the rivers and canals along the boundary. This also confirms the general groundwater flow laws that it contributes to river flows through base flow. Further the arrows length of velocity vectors demonstrate the more prospective area for the groundwater exploitation, which mostly occurs along the rivers. The central part of the area shows lesser flows, directing from north to south.

The equipotential surface and velocity vectors map of transient simulation in Fig 5b indicates that the groundwater flows are from the higher to the lower gradients. The velocity vectors depict the dominant and active flow regions. It is found that the eastern, western and southern parts of the area contain dominant velocity vectors with long arrows, indicating the most active region of groundwater flow.

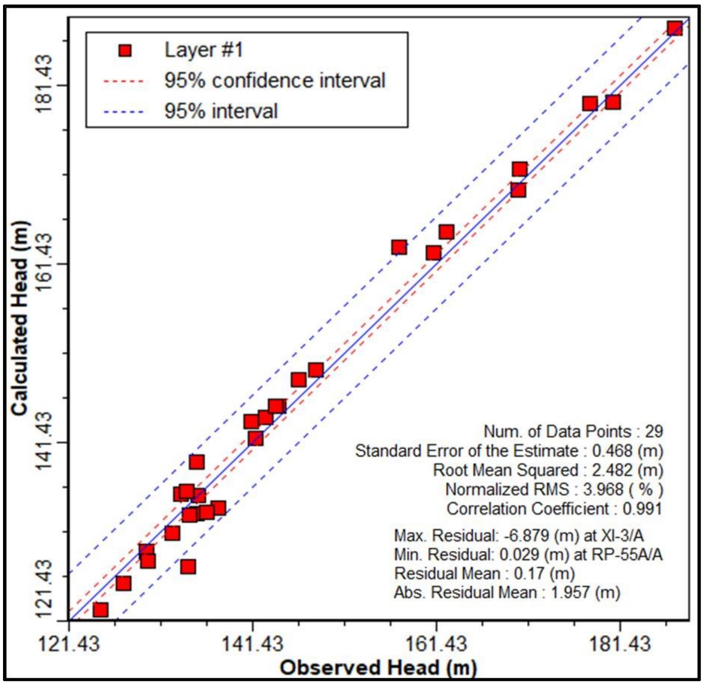

Fig 3. The graph represents results of steady-state calibration in the form of a scatter gram of computed versus observed heads.

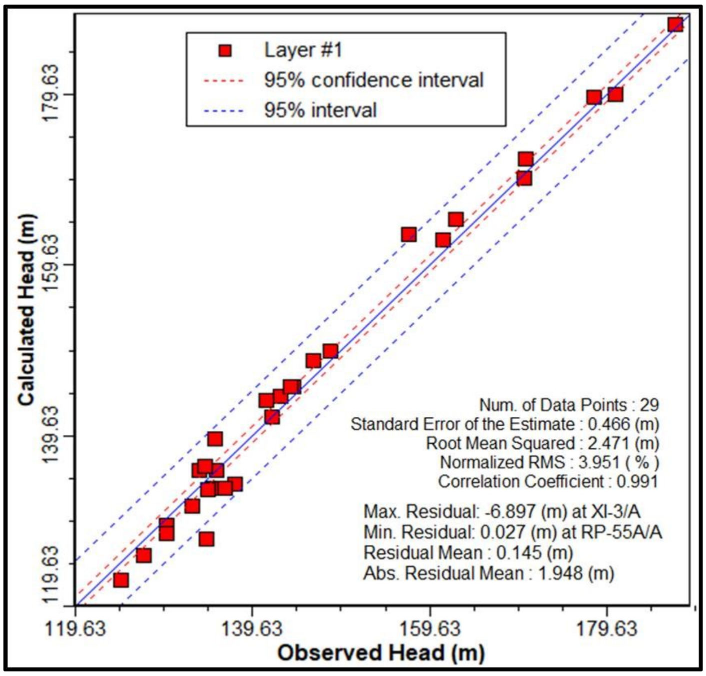

Fig 4. Scatter gram of transient calibration showing calculated verses observed heads. Axis's show model coordinates.

The velocity vectors with shorter dimensions indicate comparatively lesser flows in the central region due to low permeability. The CJ link canal shows more influent character in the upper portion and the TJ link gives effluent character in the lower portion of the model area.

Figure 5b depicts that groundwater flows from northeast to southwest towards the River Indus in the western part, in the central part from north to south and along the eastern border the flows direction is from northwest to southeast, i.e. towards the rivers Jhelum and Chenab. The central part of the modeling area characterizes a low velocity zone, whereas, the southeast portion shows high velocity zone. The total volume of water flowing in through various sources was found to be 18864 BCM and that flowing out of the aquifer through various sources evaluated as 18865 BCM. The prospective zones for the groundwater exploitation occur along the Indus, Jhelum and Chenab rivers. The observed hydraulic heads in the northern portion ranges between 170 m to 190 m, whereas, the simulated heads between 165 m to 185 m with the mean of 172.14 m.

This indicates an increase of 0.9 m in head values over a time span of about 41 years. The observed hydraulic heads in lower part of the area lie in the range of 130 m to 163 m with an average of 138.62 m and the simulated heads between 122 - 163 m with the mean of 136.84 m, which shows an increase of 1.78 m in the head values. The groundwater budget for different stress periods from 1984 (steady-state) to 2025 was evaluated (Fig 6). The analyses specified that during the steady-state period, the groundwater inflows are nearly equal to the outflows. However, the transient simulation from 1991 onward shows little changes due to variations in pumping wells, canal irrigation and variable amount of recharges. Stress period wise response of various water parameters for the transient simulation is given in Table 2.

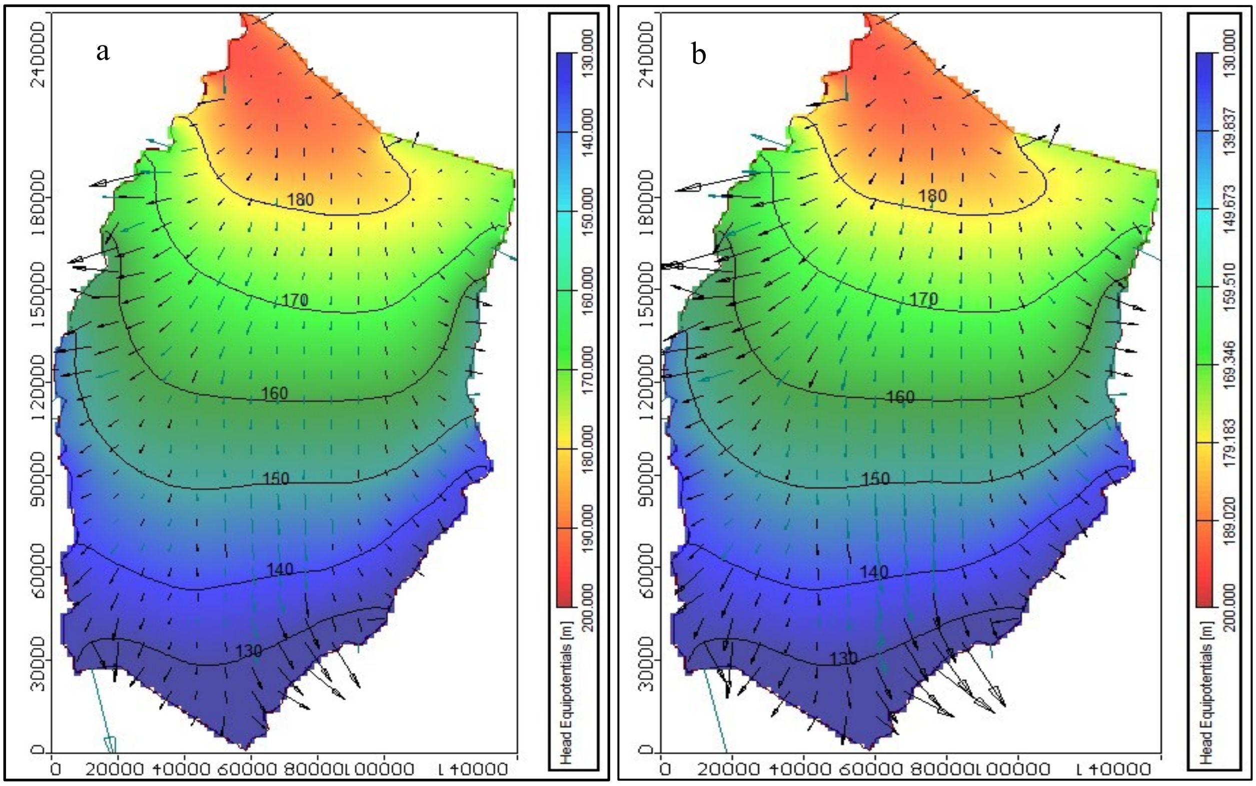

Fig 5. a) Equipotential contours and velocity vectors map of steady-state model, b) Equipotential surface and velocity vectors map of transient state model.

Table 2. Water budget resulted from transient simulation – Depicting total amount of water entering in to the aquifer through various sources and amount of groundwater leaving out the aquifer through various sinks. The ET_0 in the table stands for evapotranspiration.

Year	Storage	Constant Head		Wells	ET_0	Recharge	Total	
	In (BCM)	In (BCM)	Out (BCM)	Out (BCM)	Out (BCM)	In (BCM)	In (BCM)	Out (BCM)
1984	259.00	65.70	336.00	0	10.20	22.00	347.00	347.00
1991	620.94	614.15	1360.70	1.91	21.86	149.28	1384.40	1384.40
1996	686.55	1133.30	2049.30	2.67	23.26	255.00	2075.20	2075.30
2004	715.18	1997.00	3109.20	3.88	24.38	425.07	3137.20	3137.40
2009	720.74	2542.10	3764.50	4.63	25.02	531.14	3793.90	3794.10
2015	723.30	3197.70	4548.40	5.55	25.77	658.42	4579.50	4579.70
2025	724.58	4291.70	5853.00	7.09	27.02	870.57	5886.80	5887.10
Average							3029.14	3029.29

The Table 2 depicts that the total accumulative groundwater inflows and outflows increased from 1991 onward. The groundwater remained in equilibrium till 1991 irrespective of the changes in recharge, evapotranspiration and constant heads. An increased trend in both inflows and outflows was analyzed from 1992 onward. A gradual increase in outflows than inflows was also noted, but it is not significant. The increase in water extraction is mainly due to increase in pumpage for irrigation, which is about 60% of the pumpage in 1991. The change in simulated groundwater recharge shows an exponential increase (Fig 7). If the trend prevails, there is possibility of deterioration of the aquifer in the long run.

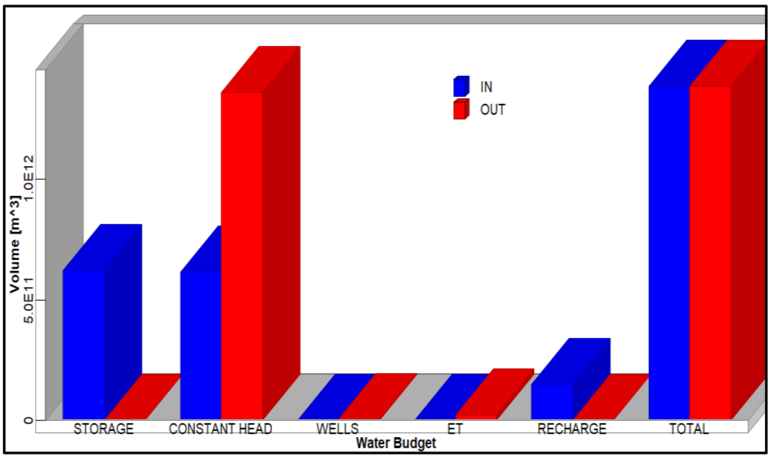

Fig 6. Water budget indicating amount of water entering into and leaving out of the aquifer.

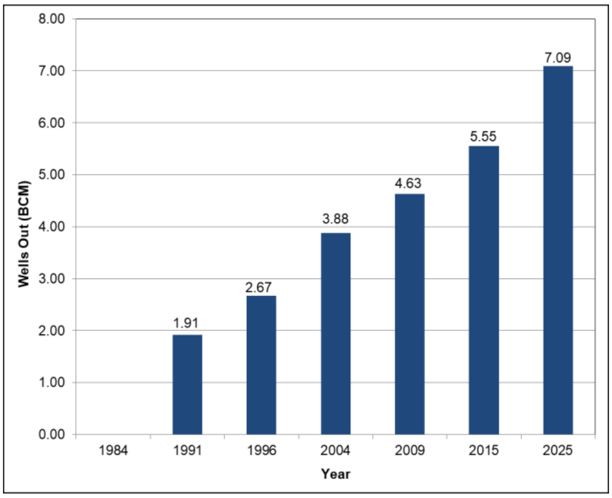

Fig 7. The graph shows increase in groundwater extraction through pumping wells-simulated through transient state modeling.

5. Conclusions

In this study, the groundwater analysis in the Upper Thal Doab was carried out utilizing numerical groundwater flow modeling techniques. Based on the modeling results and available groundwater level data, following have been concluded.

- The results of steady-state calibration shows mean residual of 0.17 m, RMS of 2.482 m and correlation coefficient value of 0.991, and a close agreement between simulated and observed heads.
- The steady state sensitivity analysis depicts that the model is more sensitive to recharge than hydraulic conductivity.
- In the steady state condition, the groundwater flow from northeast to southwest towards the river Indus along the western portion of the area. Whereas, in the central part the flows are mostly from north to south and along the eastern border the flow direction is from northwest to southeast, i.e. towards the Jhelum and the Chenab rivers.
- The mass balance analysis shows that the total volume of water entering into the aquifer through various sources remains equal to total volume of water leaving out through various sinks till 1991, however, lesser increase in outflows than inflows was noted from 1991 onward.

- The aquifer shows stability for the modeling period if existing conditions prevail. In case of increase in pumpage due to installation of water wells on large scale, deterioration of groundwater aquifers of the area may take place.

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