



# Predicting behaviour of the Indus basin aquifer susceptible to degraded environment in the Punjab province, Pakistan

Mussarat Jabeen<sup>1</sup> · Zulfiqar Ahmad<sup>2</sup> · Arshad Ashraf<sup>3</sup>

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## Abstract

Rapid changes in the irrigated system due to climate change and drastic growth in urbanization and industrialization have raised serious concerns related to available groundwater resources of the Indus basin on which millions of people depend upon for their sustenance. Under the prevailing scenario, three-dimensional numerical groundwater flow model Visual MODFLOW has been used to evaluate the regional groundwater flow from the steady-state period of 1987 (used as a base to run the model for several simulation periods) up to the predictive period of 2030 for sustainable water resource management in the Indus plain of Pakistan. The steady-state calibration of the model indicated a close agreement between the simulated and the observed heads as indicative from the residual mean value of 0.10 m and an absolute residual mean of 0.47 m. The velocity vectors of the groundwater flow indicate that in most parts of the study area groundwater is discharged into the Jhelum and Chenab rivers. In the transient-state condition, groundwater levels indicated a rising trend till 1989, but as the irrigated area tends to increase continuously, the heads started to drop from year 1991 onward at an average rate of 0.45 m/year. The Bari Doab in the south appears to be more under stress than the Rechna and the Lower Chaj Doabs because of the overexploitation of groundwater, low flows in the Ravi River and less recharge from rainfall. The negative impacts of environment changes on the underlying aquifer could be minimized through long-term monitoring of the groundwater system and adoption of integrated water resource management approach in future.

**Keywords** Aquifer depletion · Groundwater system · Indus basin · Numerical modelling · Punjab

## Introduction

Groundwater management is facing challenges of depletion in groundwater levels, quantity and quality (Yu et al. 2013; Mukherjee 2018). The tendency of groundwater use has been increased many folds because of growing trends in urbanization, industrialization, extension in agriculture activities and climate change (e.g. drought condition) in the last several decades in the Indus basin (Laghari et al. 2012; Sadaf et al. 2019; Memon et al. 2020). The groundwater pumping through water wells is preferred for irrigation

because it adds flexibility in meeting crop water requirements in the Indus basin (Ashraf et al. 2018). The Indus basin covers a gross command area of about 16 million ha containing an extensive unconfined aquifer on which millions of people living rely upon for their survival and livelihood. (Qureshi 2011; FAO 2012; Macdonald et al. 2016). Over 60% of irrigation water at the farm gate in Pakistan is being met from groundwater (Qureshi et al. 2003). Groundwater has played a major role in increasing the overall cropping intensity in Pakistan, i.e. from about 63% in 1947 to 150% in 2015 (Khan et al. 2016). Although groundwater is utilized to supplement the canal irrigation supplies during water stress conditions, in many cases such situation results in depletion of underlying aquifers (Bhutta et al. 2000; World Bank 2006; Ashraf and Ahmad 2008; Jabeen et al. 2019). The number of water wells has been increased from 0.088 million in 1970 to over a million in Punjab province only (PDS 2012). Annual pumpage has already surpassed the safe yields resulted in declining of groundwater levels in several parts of the region (Khan et al. 2016).

✉ Arshad Ashraf  
mashr22@yahoo.com

<sup>1</sup> Department of Earth Sciences, Quaid-i-Azam University, Islamabad, Pakistan

<sup>2</sup> University of Wah, Wah, Pakistan

<sup>3</sup> National Agricultural Research Centre (NARC), Park Road, Islamabad, Pakistan

Groundwater models are representation of reality and, if properly constructed, can lead to a valuable predictive tool for the management of groundwater resources (Wang and Anderson 1982; Chiang and Kinzelbach 2001). The numerical modelling approach in groundwater hydrology is usually adopted to study the behaviour of groundwater flow regime under the variable surface and subsurface conditions of an aquifer (Middlemis 2000; Elkrail 2004; Ökten and Yazicigil 2005; Ahmad et al. 2010; Anderson et al. 2015). As irrigation developments in the area have been continuously increasing, therefore, the surface irrigation system alone could not meet the future needs of the area. Hence, a proper understanding of the groundwater system is prerequisite for future water resource management and groundwater development in this region.

The present study is focused on evaluating regional characteristics of the Indus Basin aquifer regime adopting three-dimensional numerical modelling approach for sustainable water resource management in the Punjab province of Pakistan. The Visual MODFLOW was used to study the long-term behaviour of groundwater flow from the steady-state period of 1987 to the predictive period of 2030.

### Description of the study area

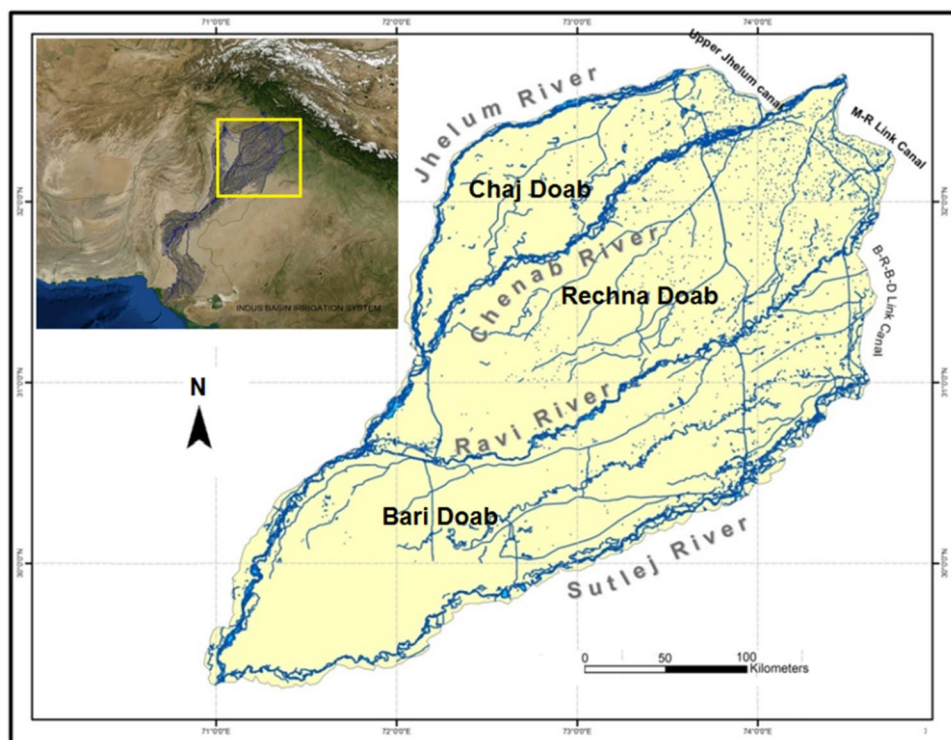
The study area stretches over 75,040 km<sup>2</sup> between 71°–75° E longitudes and 29°–33° N latitudes in The Indus basin plain of Punjab province, Pakistan (Fig. 1). It comprises of three major Doabs (a local term used for lands between

two rivers), i.e. Rechna Doab, Chaj Doab and Bari Doab formed by the rivers Jhelum, Chenab and Sutlej containing 20 districts. On the eastern side, three link canals are Upper Jhelum canal, M. R. link canal and B. R. B. D. link canal. The climate is arid to semi-arid with mean annual rainfall ranging from < 100 mm in parts of the Lower Indus basin to > 700 mm near the foothills of the Upper Indus basin. Two-thirds of this rainfall occurs during monsoon period (July–September). Temperature ranges from – 2 to 45 °C and occasionally reaches to 50 °C during the summer. Irrigated agriculture is the main land use of the area (Fig. 2). The summer crops include cotton, rice, fodder and maize, while winter crops include wheat and fodder, besides sugarcane and fruits are grown as perennial crops. The soils are generally calcareous silt loams having good porosity and permeability. The clayey soils exist in lenses and in minor patches, where waterlogged and saline areas are found in the localized perched conditions.

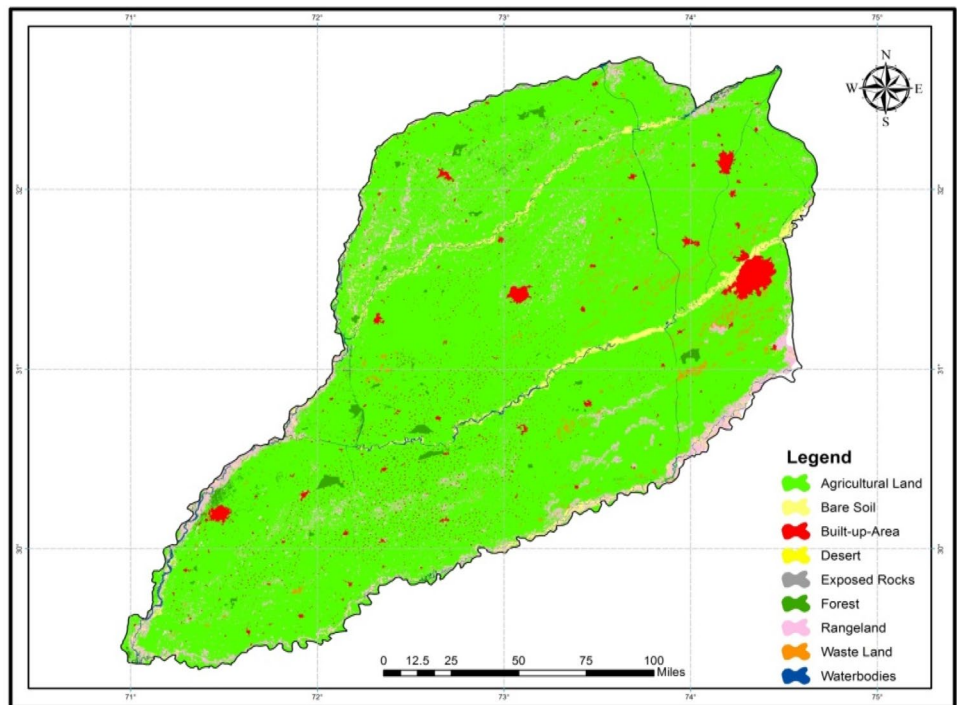
### Hydrogeological setup

The study area is a part of the Indo-Gangetic plain (Kidwai and Swarzenski 1964) and underlain by Punjab geosyncline characterized by the concurrent occurrence of sedimentation and subsidence. The sedimentation formed several-kilometer-thick deposits of Quaternary alluvial fills that are mostly heterogeneous. The unconsolidated sediments consist of a complex matrix of sand, silt, gravels and clay in which a fair transmissive aquifer is present (WAPDA 1982). The Punjab

**Fig. 1** Major rivers and canal network in the study area in Pakistan



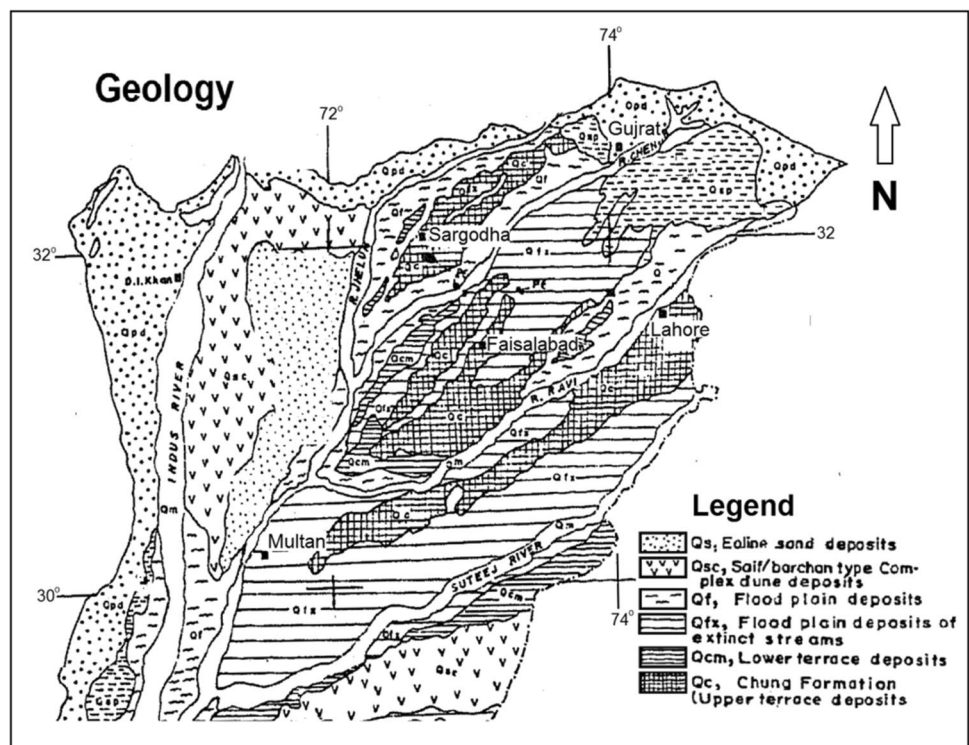
**Fig. 2** Land use/cover distribution in the study area



plain has low relief with a low slope toward the south-west, i.e. the direction of surface flows, consisting of old river paths and paleo-channels. The ancestral tributaries of the Indus River deposited the Quaternary alluvial sediments during constantly shifting courses. The micro-geomorphology is characterized by different flood plains and bar uplands

exhibiting changes in the distribution of lithology in the area (Fig. 3). The surface runoff and rainfall seep through the sandy bar deposits are responsible for recharging the underlying aquifer. The Quaternary alluvium is assumed to overlay semi-consolidated tertiary metamorphic rocks and igneous rocks of Precambrian age (WAPDA 1980; Wayne

**Fig. 3** Geomorphological and geological setup of the study area (from Kazmi 1966)





and William 2000) exposed in the form of Kirana Hills on the north-eastern margin of the Punjab Platform (Hasany et al. 2007). The generalized lithostratigraphy of the area established on the basis of seismic and drilling studies is shown in Fig. 4. Horizontal hydraulic conductivity differs from 30 to 60 m/day with a specific yield of 13%. Water

quality mainly differs from one place to another. The aquifer is highly transmissive with good water-holding capacity and yield. The groundwater exists under unconfined to locally semi-confined conditions in the shallow aquifer, whereas it occurs under the semi-confined conditions in deeper layers. The water table usually varies within 6 m depth.

**Fig. 4** Stratigraphy of the study area

Age	Formation	Thickness (m)	Lithology	Description
	Alluvium	39		
MIOCENE PLIOCENE	Siwalik	430		Sandstone Shale Siltstone
	Habib Rahi	49		Limestone
EOCENE	Ghazij	250		Sandstone Shale Limestone
	Ranikot	30		Sandstone Shale
CRETACEOUS	Goru	900		Sandstone Shale Limestone Marl
	Sember	150		
JURASSIC	Chiltan/ Samanasuk	300		Shale Limestone Marl
	Shinawari	200		Shale Limestone Marl
	Datta	80		Sandstone Shale
PERMAIN	Warcha/Dandot	110		Shale Conglomerate
	Tobra	60		Sandstone Shale
CAMBRIAN	Baghanwala	120		Sandstone Shale Silt
	Jutana	70		Dolomite Shale
	Kussak	150		Sandstone Shale Dolomite
	Khewra	150		Sandstone Shale Dolomite
INFRA CAMBRAIN	Salt Range	210		Shale Sandstone Dolomite Salt
	Basement			

## Materials and methods

### Data used

The climate data (temperature, rainfall), discharge data of major rivers and canal irrigation network were acquired from various sources like Pakistan Meteorological department (PMD), Water and Power Development Authority (WAPDA) and Punjab irrigation department from 1980 onward. The groundwater data like locations of tube wells/piezometers, water levels and withdrawals were collected from SCARP monitoring organization, WAPDA and groundwater-monitoring cell of the irrigation department, Lahore. The hydrogeological and lithological log data of the study area were collected from previously published reports and literature (e.g. Kidwai 1962; Kidwai and Swarzenski 1964; Ibrahim et al. 1972; WAPDA 1980, 1982) for the determination of the aquifer properties like hydraulic conductivity, transmissivity and specific storage. The lithological logs of 150 exploratory wells were used to examine and to determine the thicknesses of the individual permeable geological layer, which further used to evaluate the hydraulic conductivity ( $k$ ) with the relationship of  $k = T/b$ , where  $T$  is the transmissivity and  $b$  the thickness of the individual layer.

### Setup of numerical ground flow model

Visual MODFLOW Pro 4.0 developed by the US Geological Survey (MacDonald and Harbaugh 1984) was used to simulate three-dimensional groundwater flow through a porous medium solving the governing equations for the steady state and transient flow. Visual MODFLOW was selected for groundwater flow modelling because it (1) simulates 3-D saturated flow, (2) is compatible with other particle tracking and solute transport computer codes that are readily available, (3) is capable of calculating accurate sensitivities. The discrete variables (e.g. hydraulic head inflow models, concentration in transport models) of the model are determined at nodes in the model domain, determined by a grid (Ahmad and Serrano 2001; Ahmad et al. 2010).

According to equation of continuity, the sum of all flows into and out of the cell must be equal to the rate of change of storage within the cell. With the assumption that the density of groundwater being constant, the continuity equation gives the balance of flow for a cell. The groundwater flow equation can be derived by combining the equation of continuity with that of Darcy’s law (Anderson 2015).

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} = 0 \tag{1}$$

$$\frac{\partial}{\partial x} \left( -K \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( -K \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( -K \frac{\partial h}{\partial z} \right) = 0 \tag{2}$$

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{\partial^2 h}{\partial z^2} = 0 \tag{3}$$

$$\frac{\partial}{\partial x} \left( K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( K_{zz} \frac{\partial h}{\partial z} \right) - W = S_x \frac{\partial h}{\partial t} \tag{4}$$

where  $K_{xx}$ ,  $K_{yy}$  and  $K_{zz}$  are hydraulic conductivities along  $x$ ,  $y$  and  $z$  axis,  $W$  is volumetric flux per unit volume representing sources and/or sink of water,  $S_x$  is specific storage of the porous material. Equation (4) depicts the groundwater flow under non-equilibrium condition in heterogeneous and isotropic medium.

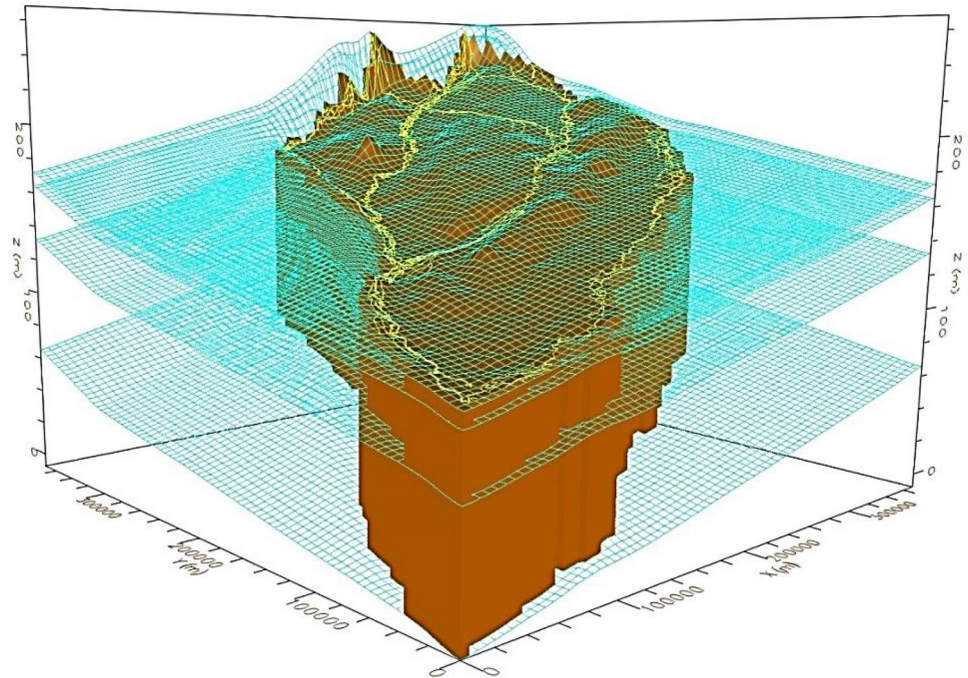
The rivers (Jhelum, Chenab and Sutlej) were treated as the constant head boundaries. The Jhelum River is the uppermost boundary, whereas the Sutlej River in the south forms the lowermost boundary of the model domain. In the west, the rivers Jhelum and Chenab, and in the east three canals mark the boundaries of the model.

Besides, the recharge components of groundwater are canal irrigation supplies, river flows, return flow of water wells pumpage, rainfall, groundwater inflows, while discharge components are evapotranspiration, water wells pumpage, drains and outflows to the rivers. The recharge values determined by various sources (NESPAC 1993; Nazir 1995) were used as initial conditions in the model. It is well known fact that about 8% of the annual rainfall is considered to recharge groundwater in the northern Punjab area. However, recharge from the return flow of groundwater has been estimated over 20%, while as per previous reports, about 18% of unlined canals water tends to seep through its beds, out of which only 80% recharges the groundwater (Akhter and Ahmad 2001).

The spatial domain represented in the model consists of 82 rows and 72 columns (total of 5904 cells in each layer) with a spacing of 1000–2000 m in both  $x$  and  $y$  directions, respectively. The model consists of three layers in which the first layer (thickness 26 m) is mainly composed of sand, the second layer (thickness 32 m) of gravel and the third layer (thickness 67 m) of gravel with sand. Clay and silt are also present in the form of thin lenses in these layers. All the layers’ thicknesses were evaluated on the basis of the groundwater elevation above mean sea level (AMSL) with respect to vertical depth of the layers. The area lying out of the study domain was treated as an inactive zone. The three-layered gridded model is shown in a three-dimensional view in Fig. 5.

Individual data point comprised of hydraulic conductivities of 150 water wells were used to define and delineate

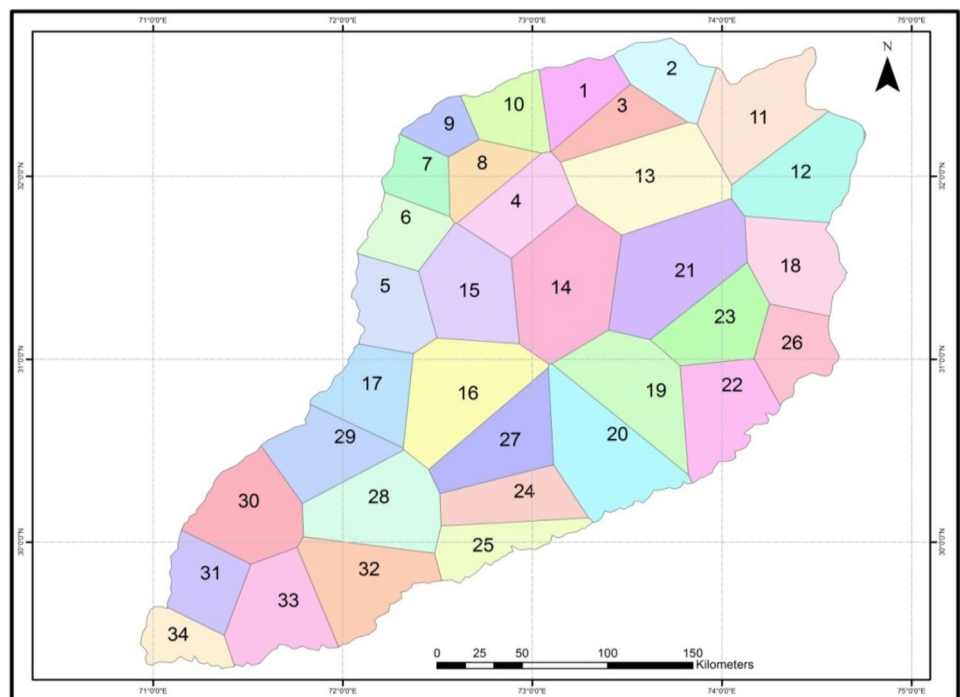
**Fig. 5** Representation of the three-layer gridded model of the study area



proximal regions around these points in order to construct the Thiessen polygons of hydraulic conductivities (Theissen 1911). The vertical hydraulic conductivity of the material was assumed 1/10th of the horizontal conductivity of materials. As such thirty-four hydraulic conductivity zones

emerged in the model domain as shown in Fig. 6. The hydraulic conductivity values of these zones are given in Table 1. Based on the similar methodology for the lithology and the recharge characteristics of the topsoil, 20 recharge zones of the study area were delineated.

**Fig. 6** Hydraulic conductivity zonation of the study area



**Table 1** Details of hydraulic conductivity values determined in the model domain

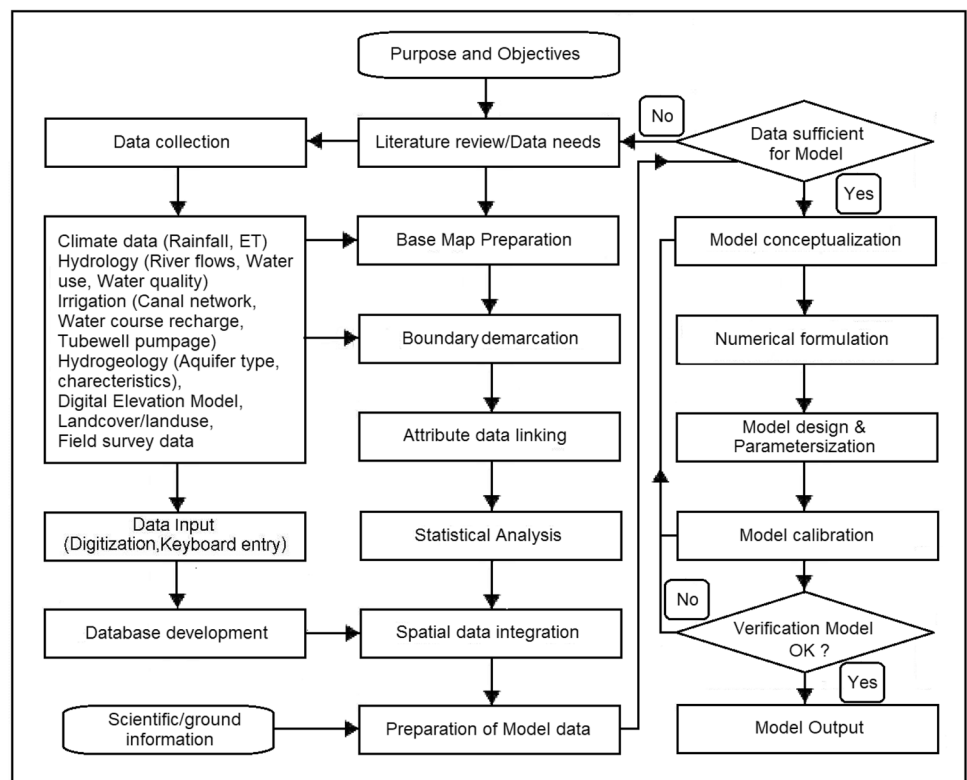
Zone#	Hydraulic conductivity k (m/sec)	Zone#	Hydraulic conductivity k (m/sec)
1	5.49E-04	18	1.40E-04
2	6.40E-04	19	2.74E+00
3	4.57E-04	20	5.03E-01
4	9.95E-04	21	5.03E-01
5	1.37E-03	22	2.40E+00
6	8.84E-04	23	2.30E+00
7	7.32E-04	24	1.95E+00
8	9.75E-04	25	4.78E-01
9	7.32E-04	26	1.04E+00
10	1.10E-03	27	9.10E-01
11	1.42E-04	28	2.34E+00
12	2.89E-05	29	1.07E+00
13	8.68E-05	30	1.99E+00
14	1.10E-04	31	2.96E+00
15	6.94E-05	32	1.23E+00
16	1.27E-04	33	7.52E-01
17	1.56E-04	34	9.90E-01

**Model calibration**

The model was calibrated for steady-state condition using the hydraulic head data of 141 observation wells of 1987

period as at that time groundwater levels appeared to be in the equilibrium condition. Parameter Estimation (PEST) program (Doherty 1995), embedded in Visual MODFLOW, was used to automate the model calibration process. In a steady-state condition, the amount of water flows into the groundwater system equals the amount flows out of the system. The calibrated heads obtained during steady-state modelling were used as input to execute transient-state modelling. The transient state calibration was carried out to monitor the effect of storage parameters, i.e. specific yield on the equipotential surface and to investigate the effect of groundwater pumping. During transient state modelling, groundwater flow was simulated between 1987 and 2016 and then further predicted to year 2030. Transient flow occurs when the magnitude and direction of the flow changes with time. There were thirty-three specific yield zones configured based on field data and hydrogeological setup. During unsteady-state calibration, values of specific yield and recharge have been adjusted to obtain a perfect fit of data points between the observed and simulated heads of the model. The methodology adopted for numerical modelling of groundwater flow is shown in Fig. 7. Sensitivity analysis was performed to check the model sensitivity to input parameters like hydraulic conductivity, specific yield and recharge by multiplying the parameter values with some factor values and then model was rerun to get the results.

**Fig. 7** Methodology in flow-chart followed in the present study





## Results and discussion

### Analysis of steady-state groundwater flow

The steady-state calibration of the model exhibited a close agreement between the simulated and the observed heads as indicative from the residual mean value of 0.1 m and an absolute residual mean of 0.47 m (Fig. 8). The steady-state model indicated groundwater flow towards the south-west direction. The hydraulic heads ranging between 100 m and 260 m in the model domain tend to decrease as the elevation of the ground surface, i.e. from north–east to south–west. The velocity vectors in the top first layer showed greater magnitude in the south-west, while the lowest velocity magnitude was observed in the north-east of the model domain (Fig. 9). In the second layer, velocity magnitude was higher below the centre of the study area, while the lowest velocity was evident in the north of the area. In the third layer, highest velocity was observed in the centre of the model domain, while the lowest magnitude in the north and some eastern parts of the study area. Sensitivity analysis carried out of the model indicated that the model was sensitive to recharge.

### Analysis of transient state simulation

The transient flow model simulated the groundwater flow between 1987 and 2016 and onward to predict the behaviour

of equipotential surface of year 2030. The calibrated heads exhibited a reasonable agreement with the observed heads (Fig. 8) both for the steady-state and transient conditions. Initially, the heads started to rise till 1989 but as the irrigated area increased continuously and consequently the outtake of water from the aquifer had also increased, the heads started to drop since 1991 at a rate of 0.45 m/year. A similar situation of decline in groundwater levels had been observed in the Indus plain by World Bank (2006) and Qureshi (2011). According to Qureshi (2011), extensive groundwater use in the Indus basin led to an annual decline of 1.5 m in the water table, as a result of which aquifer started to drain faster than the natural recharge process (Laghari et al. 2012). Groundwater withdrawals more than the aquifer replenishment often result in declining of groundwater levels (Chandra 2018). According to Qureshi (2014), farmers had started installing private wells of smaller capacities (28 L/sec) after realizing the initial benefits of increasing cropping yields through groundwater use during the 1980s; since then, these wells grew in numbers at a rate of about 9.6% per annum. During transient-state condition, the changing stresses such as increased pumping had affected slightly the equipotential surface. Hence, the river base flow responded drastically to those changes, especially during dry periods. Increased pumping induced more recharge from the rivers into the aquifer and decreased the base flow consequently reducing the total river discharge.

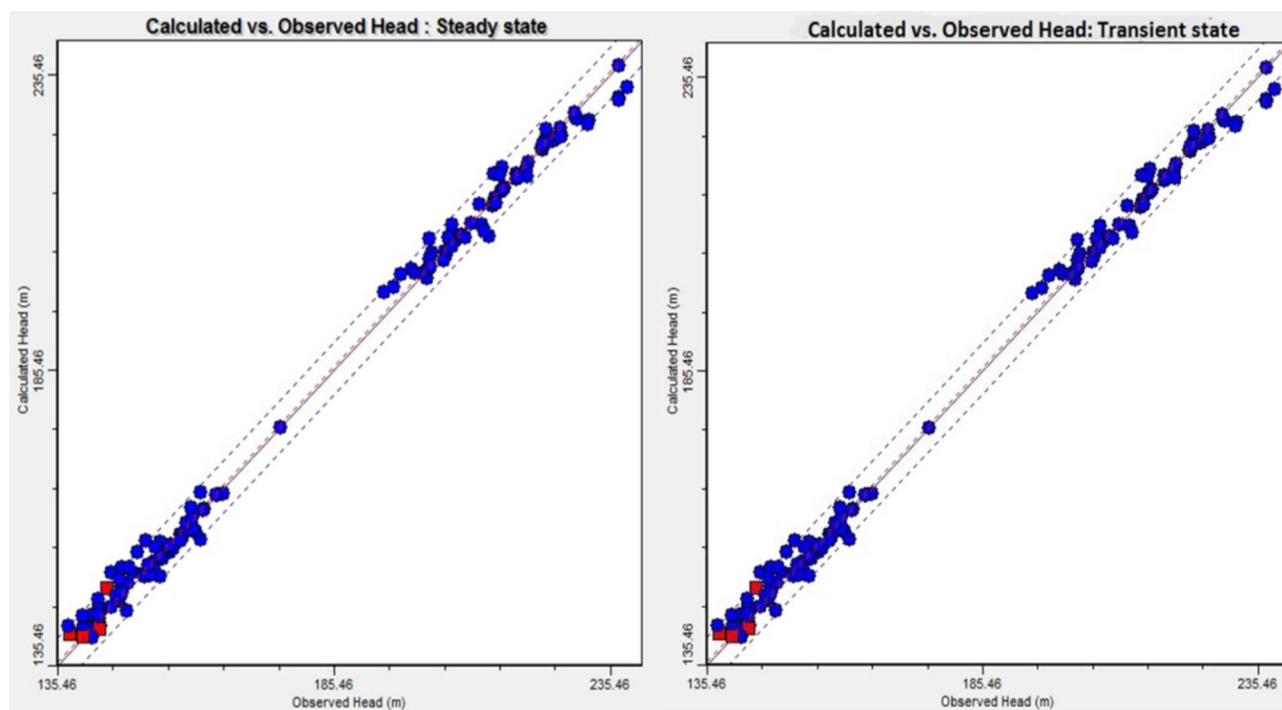
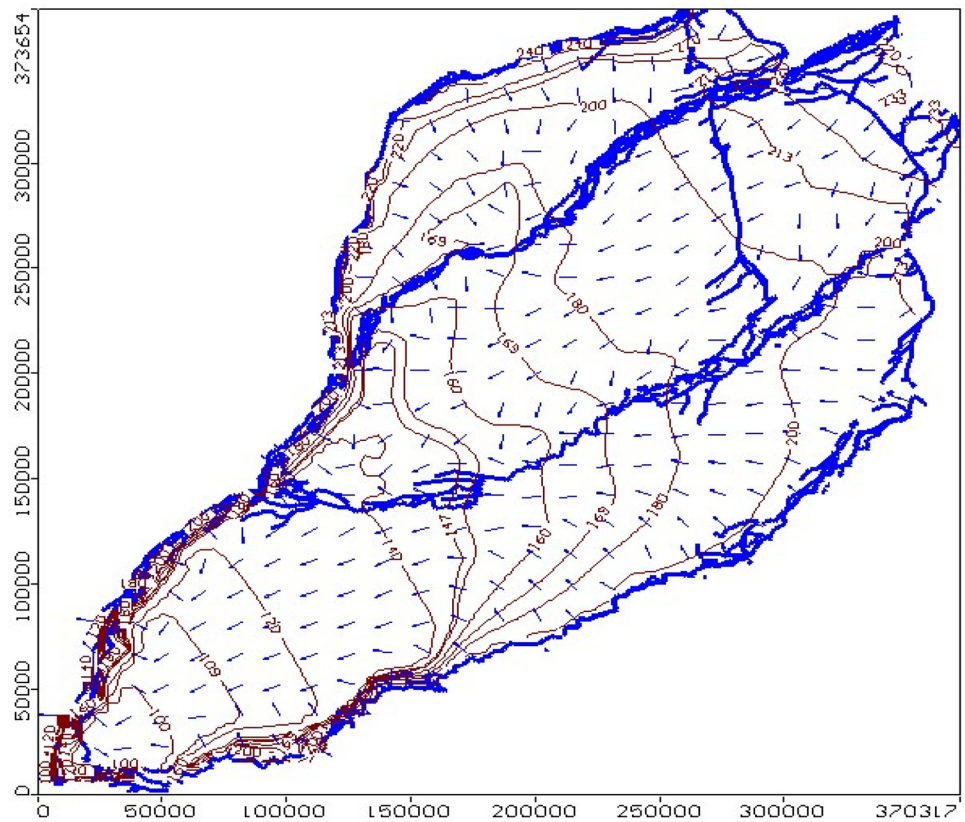


Fig. 8 Scatter plots of steady-state and transient-state calibrations



**Fig. 9** Steady-state calibrated equipotential map of the study area (Top layer)



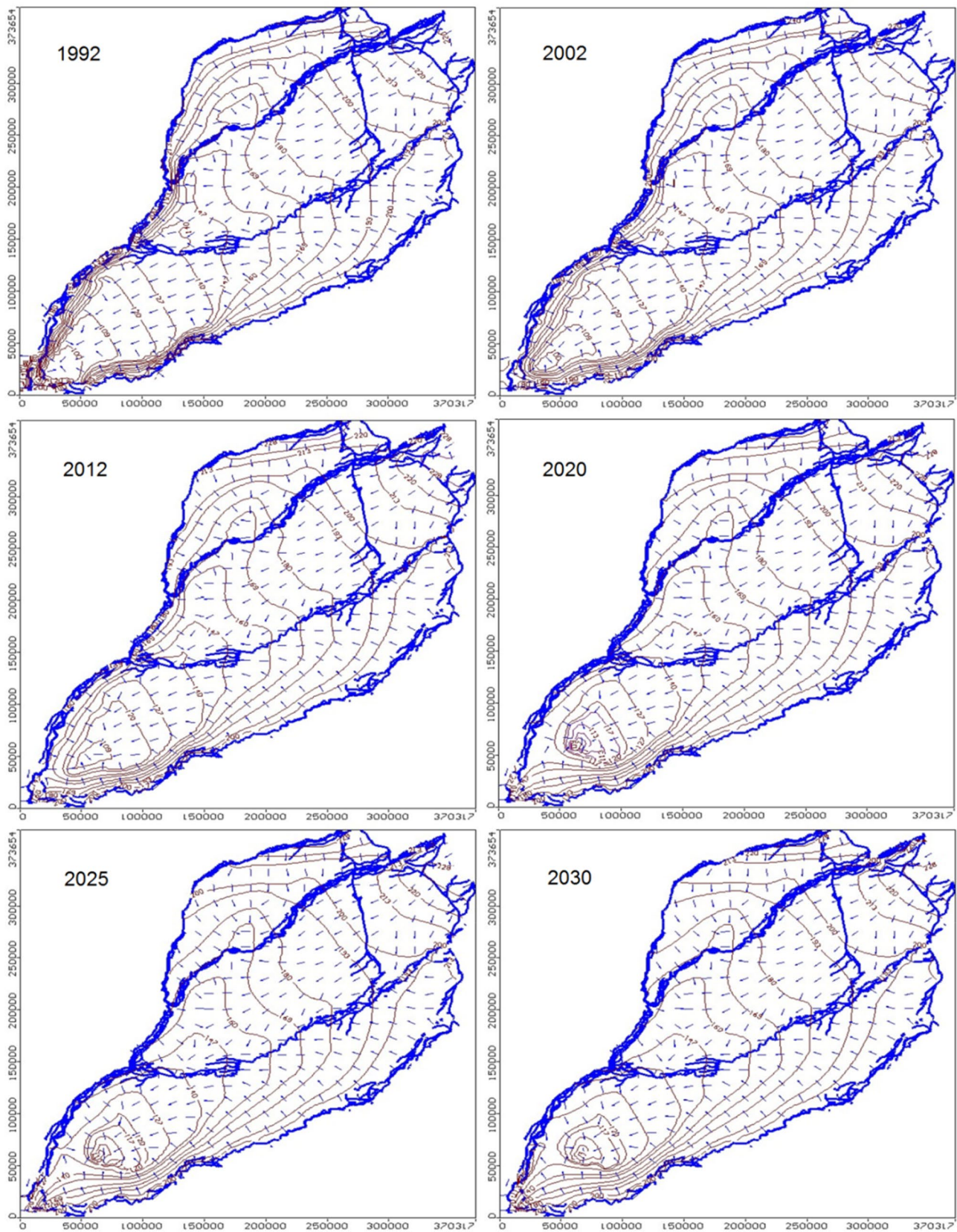
The flow direction in the Chaj Doab was from the upper Jhelum link canal and the Chenab River to the groundwater system. In the Rechna Doab, the groundwater flow direction was from the M. R. link canal to the groundwater system, whereas in the lower parts of the Doab, the flow was from the groundwater system to the Ravi River, and in the extreme lower parts, from the rivers to the groundwater system. A small cone of depression appeared in the lower Rechna Doab during 1992. In Bari Doab, the direction of flow was from the Sutlej River to the groundwater system and then towards the Ravi River. Large variations in the heads were observed under a higher lateral gradient in the north-eastern part due to the presence of shallow piedmont deposits underneath the area. In the year 2002, the cone of depression appeared in south-west of the Bari Doab, which grew bigger during the years between 2007 and 2012. The cone of depression tends to expand further and shifted towards the north-east from 2012 onward to predictive year in 2030 (Fig. 10). The resultant situation has been considered to happen significantly under the influence of large extraction of groundwater to meet the growing water demand for irrigation and urban use in the Indus plain. During transient flow conditions, some of the rivers tend to behave as effluent (gaining) and some as influent (losing). For example, the Jhelum River behaves as an influent stream, while the Chenab River behaves as an effluent stream in the upper and bottom reaches and as

an influent stream in the middle reaches. The Sutlej River at the extreme end of the modelling domain appears to act as an influent stream, whereas the Ravi River behaves as an effluent gaining stream. The water table elevation is higher in the vicinity of the Ravi River; therefore, water flows from groundwater to the river through river bedding.

### Groundwater depletion in different Doabs

Mean water table exhibited an overall declining trend in the Chaj Doab from 2004 onward. The decline in water table was high in the central Chaj Doab (i.e. 1.7 m) during the 1984–2009 period likely due to more dependency on the groundwater for irrigation use, which was increased since the occurrence of the last drought (1999–2003) in this region. A head drop of about 3 m was predicted in the Lower Chaj Doab during 1984–2030 period. This situation is likely to occur here due to more groundwater pumping than recharge. However, Chaj Doab in the north appears to be more stable than the other doabs of the study area due to its smaller area, higher recharge intake from the adjoining rivers, Mangla dam and hill-torrent flows originating from the sub-Himalayan Mountains in the northeast.

The groundwater levels indicated a mean decline of about 2.8 m in the Upper and the Lower Rechna Doabs, whereas decline in water table was over 2.7 m in the Bari



**Fig. 10** Transient state equipotential maps indicating development cone depression in the southwest of the study area



Doab located in the southern part of the study area. It was envisaged that the lowering in water table was higher both in the upper and lower parts of the Doabs, whereas it was least in the central Doab during 1984–2030 period. In the central Doab, the seepage from the irrigations system appears more intensive than the groundwater pumpage from the water wells. The aquifer underlying the Upper Bari Doab had shown stress condition likely due to excessive pumpage and reduction in recharge owing to drastic growth in urbanization in Lahore city coupled with low flows in the Ravi River (Khan et al. 2016). However, the excess water during occasional floods spills over on the flood plains through river banks and considerable percolation occurs. The depletion of groundwater in the Lower Bari Doab is likely due to more dependence on groundwater to fulfil irrigation requirements (Basharat and Tariq 2013). Besides overexploitation of groundwater, reduction in canal command area resulting in low natural recharge and changing rainfall pattern are other causes of aquifer depletion. The water table had shown depletion at an average rate of about 0.38, 0.24 and 0.18 m/year in Multan, Lodhran and Khanewal districts in the Lower Bari Doab, respectively, during 2005–2015 periods. The safe yields of about 8.7 billion cubic meter (BCM) per million hectares (Mha) and 7.7 BCM per Mha have been evaluated in the Chaj and the Rechna Doabs, and lowest of about 4.5 BCM per Mha in the Bari Doab due to controlled surface water flows in the Eastern Rivers (the Sutlej and the Ravi) and low rainfall (Khan et al. 2016).

## Conclusion

In the present study, a three-dimensional numerical modelling approach using Visual MODFLOW was adopted to study the long-term behaviour of groundwater flow for sustainable water resource management in the Indus basin of Pakistan. The steady-state calibration of the model indicated a residual mean value of 0.10 m and an absolute residual mean of 0.47 m between the simulated and the observed heads of the model domain. In the transient-state condition, the groundwater levels indicated a rising trend till 1989, but as the irrigated area increased continuously, the heads started dropping from the year 1991 at an average rate of 0.45 m/year. The velocity vectors of the groundwater flow indicate that in most parts of the study area, groundwater is discharged into the Jhelum and the Chenab rivers. Because of overexploitation of groundwater and less recharge from the Ravi River flows and rainfall, the Bari Doab in the south appears to be more under stress than the Rechna and the Lower Chaj Doabs. The Chaj Doab in the north has shown more stable condition than the other Doabs of the study area as much as due to receiving higher recharge from the adjoining rivers, Mangla dam and hill-torrents flows comparatively

than the groundwater withdrawals. Artificial recharging techniques like floodwater spreading and ponding through rainwater harvesting may be adopted in highly depleted areas. Long-term groundwater monitoring and controlled pumping under a proper groundwater management program could minimize any detrimental impacts on the underlying aquifers in the highly stressed groundwater regimes.

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