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ORIGINAL PAPER

A spatio-temporal three-dimensional conceptualization and simulation of Dera Ismail Khan alluvial aquifer in visual MODFLOW: a case study from Pakistan

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Abstract Dera Ismail Khan (DIK) is situated in the Lower Indus Basin of Pakistan. The land use has been changed in the canal command area due to irrigation activities near the Indus River. To check the current status and predict the groundwater levels in the area, the unconfined aquifer has been simulated in Visual MODFLOW for a period of 35 years, i.e., from 1985 to 2020. The 2900-km^2 area has been modeled with a grid of 500 by 500 m and the depth set to 100 m. The aquifer in the study area has been divided vertically and laterally into three and ten zones, respectively, for the characterization. Water wells and streams were used as the sinks and hydrologic boundaries, respectively. The model was successfully calibrated in steady and the non-steady state. The simulation revealed that the whole simulation can be divided into two phases, i.e., before and after the construction of the Chashma Right Bank Canal (CRBC), whereas the results were summarized in the form of water table depth maps and groundwater budget calculations. To determine the groundwater sustainability, a conjunctive use scenario has been employed to simulate the aquifer dynamics till 2020. The simulation revealed incremental drawdowns till the end.

Keywords Visual MODFLOW · DIK · Water table depth (WTD) · Indus River

Introduction

Visual MODFLOW aids in the understanding of flow, transport of solutes, and water budgets in the groundwater system for effective management. The earliest analytical solutions for hypothetical groundwater flow systems has been elaborated in 1960s by the help of recharge and discharge areas, groundwater level fluctuations, surface topography, hydrochemistry, environmental isotopes, vegetations, and surface water. (Toth 1963, 1970, 1971, 1972). The steady state models were first simulated for steady state modeling of hypothetically layered aquifers putting the concepts of three-dimensional aquifer heterogeneity and anisotropy in the groundwater basins (Freeze and Witherspoon 1966, 1967, 1968). The transient model was initiated to determine the impacts of infiltration on the water table rise and base flow hydrographs leading to the prediction of maximum yield, pumping pattern, and recharge and discharge conditions (Freeze 1971). Following these hypothetical studies, a large-scale aquifer simulation program has been initiated during 1978 to 1995 by the name of Regional Aquifer System Analysis (RASA) program of US Geological Survey (Sun and Johnson 1994). The computer modeling techniques used in most cases were the USGS 3D finite difference model (Trescott 1975) and the USGS MODLFOW (McDonald and Harbaugh 1988). A listing of 1105 reports was published from RASA program in USGS Professional Paper numbered from Sun et al. (1997). The Netherlands has also contributed in broadening the concepts and methodologies in hydrological

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system analysis (Engelen and Jones 1986; Engelen and Kloosterman 1996). In China, several regional groundwater models have been constructed in recent years (Shao et al. 2009; Hou and Zhang 2008; Wang et al. 2009, 2010).

MODFLOW evolved with time in response to its widespread usage in industry. Three generations of MODFLOW can be found, i.e., 1988, 2000, and 2005 (Harbaugh et al. 2000; Harbaugh 2005; Barlow and Harbaugh 2006). Several Windows-based graphic user interfaces for MODFLOW have been developed such as Processing Modflow (Chiang and Kinzelbach 2001). Visual Modflow (Waterloo Hydrogeological 2001). Groundwater Modeling Systems (GMS) (Brigham Young University, Environmental Modeling Research Brigham Young and Environmental Modeling Research 2000). and Groundwater Vista (Rumbaugh and Rumbaugh 2005).

An exponential growth of application of numerical model flow study has been witnessed in the last 20 years in the world. The numerical models are used at various scales and for different purposes such as water management (Al-Salamah et al. 2011), surface water and groundwater interactions (Hunt et al. 2003). contaminant transport (Al-Thani et al. 2004; Halford et al. 2010), aquifer response determination (Clemo 2005). recharge study (Korkmaz 2013; Anderson et al. 2002; Jyrkama et al. 2002). and well head protection (Ahmad et al. 2010; Bolster et al. 2001).

In this study, a model has been constructed in visual MODFLOW 4.0 which uses the finite difference technique to simulate heads at a block centered nodal grid. A three-layered finite difference grid of 186 columns and 182 rows was overlaid on the study area with a constant node spacing of 500 × 500 m in both *x*- and *y*-axes. The model was run initially with constant head and stream boundaries, but finally, the model settled down with the stream boundaries for the Indus River, Takwarrah Nala, and Sheikh Haider Zaman Nala (Fig. 1). Various hydraulic parameters including hydraulic conductivity (*K*), initial heads, recharge, porosity, specific storage (S_s), specific yield (S_y), and top and bottom elevation of aquifers are incorporated in the model.

Dera Ismail Khan (DIK) is the southernmost district of Khyber Pakhtunkhwa, lying between 31° 15′ and 32° 32′ north latitudes and 70° 11′ and 71° 20′ east longitudes (Fig. 1). The DIK town is situated along the west bank of the Indus River. The study area is the Chashma Right Bank Canal (CRBC) stage-II command area, which is situated between the Indus River and the CRBC covering an area of 2900 km$^{2.}$ The Indus River forms the eastern boundary of the model. The water from the Indus River is diverted in the form of canals for the irrigation purposes. Takwarrah Nala is a branch of Tank Zam having perennial flows. Another stream Gomal Zam is a major command having perennial flows. Sheikh Haider Zaman Nala is the southeastern boundary of the model and has a negligible perennial discharge. DIK's western boundary is surrounded by the mountains and hills of South Waziristan Agency and tribal area. The highest region lies toward north in the Sulaiman range about 3500 m above mean sea level and the lowest point lies in the south near the Indus River and is approximately 152 m high above mean sea level.

The DIK district lies in the domain of hot semi-arid climate. The model is divided into two zones by the CRBC into canal command and non-canal command. The study area consists of three broad hydrogeological zones: (1) the gravels and boulders of the alluvial fan deposits, (2) the silty clay series of the piedmont plain, and (3) the Punjab-type sand deposits of the active and abandoned flood plains along the Indus (Hood 1970). In the central, western, and northern regions of the area, the fill consists of sediments conveyed by the streams and rivers from the consolidated rocks surrounding the basin to the west. These deposits have extended to the east, where they interfinger with the Punjab-type sand deposits (Malik 1985; Fig. 2). The residents of the study area utilize two sources of water: the surface water and the groundwater. The surface water resources consist of the Indus River, streams, and the ponds storing the rain water. The

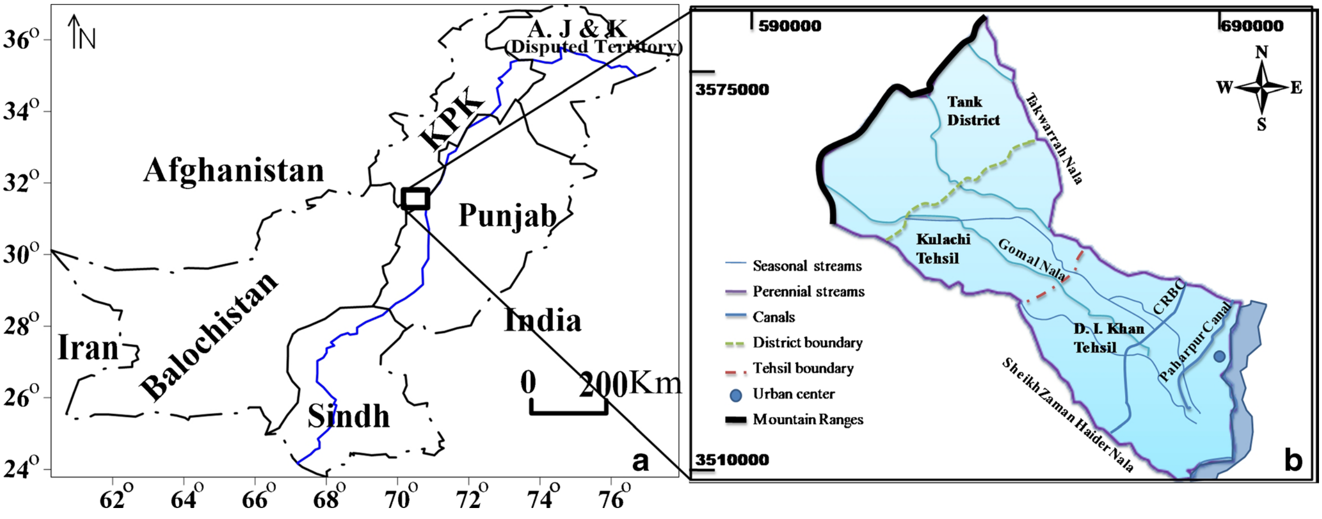

Fig. 1 Location map of the DIK area showing the modeled area with all of the distinctive boundaries

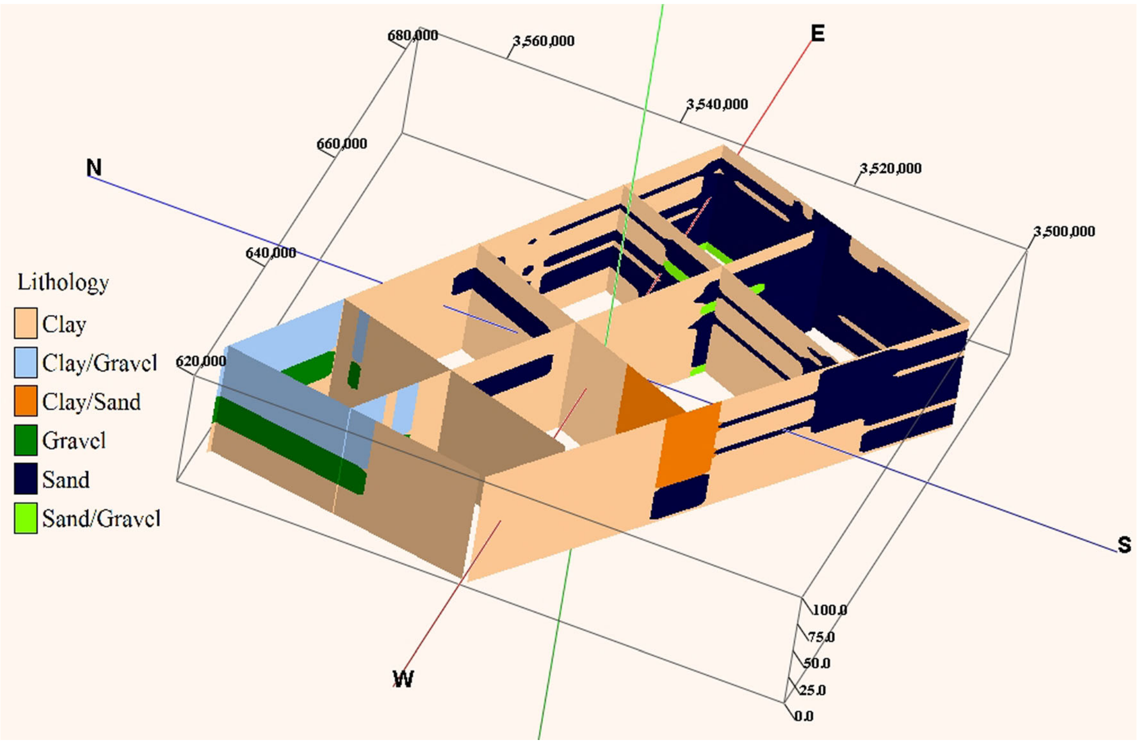

Fig. 2 The fence diagram of the DIK modeled area showing the variation in subsurface rock assemblages

two main diversions that drain the modeled area are the CRBC and the Paharpur canals. The CRBC command area located in the Indus basin receives its water from the Indus River at Chashma Barrage and irrigates an area of 0.470 million acres of the DIK (Ahmed 1972). This canal was completed in three stages, i.e., in 1987, 1992, and 2002.

To predict the situation of groundwater levels in this area, a numerical model integrated in a Geographic Information System (GIS) has been simulated for 30 years, i.e., from 1985 to 2020. The most important tasks undertaken were to conceptualize the natural system of the subsurface aquifer system and then the simulation to predict the groundwater level changes in the longer term, i.e., 2020. This model will work as a tool for understanding the interaction between the surface and the groundwater and take necessary measures to prevent the deteriorating effects on land and water resources of the study area (Katpatal et al. 2014). Further, this model may be integrated with the climate change models to simulate the long-term effects for the future research. Consequently, it will provide a baseline for the understanding of future groundwater flow modeling and the problem solution regarding the well head protection, water logging status determination, and the determination of optimum well discharges in the resembling set of conditions.

Methodology

The methodology followed for the current study involved software Visual MODFLOW 4.0 with standard procedures, adopted from Anderson and Woessner (1992). Visual MODFLOW uses MODFLOW 2000 to describe groundwater flow of constant density under non-equilibrium conditions in a heterogeneous and anisotropic medium according to the following equation:

$$\frac{\partial}{\partial x}\left(K_{XX}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial y}\left(K_{YY}\frac{\partial h}{\partial t}\right)+\frac{\partial}{\partial z}\left(K_{ZZ}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \qquad (1)$$

where K_{XX}, K_{YY}, and K_{ZZ} are the hydraulic conductivity along the x, y, and z coordinate axes (Lt^{-1}); h is the potentiometric head (L); W is a volumetric flux per unit volume and represents sources and/or sinks of water (t^{-1}); S_S is the specific storage of the porous material (L^{-1}); and t is the time (t). In general, S_S, K_{XX}, K_{YY}, and K_{ZZ} may be functions of space ($S_s = S_s\ (x,y,z)$, $K_{XX} = K_{XX}\ (x,y,z)$, etc.) and W may be a function of space and time ($W = W(x,y,z,t)$).

Initially, data from Public Health Engineering Department (PHED) and Water and Power Development Authority (WAPDA) were obtained. Most of the details of the field conditions are also addressed during the number of field works made in the area. On the basis of the data and the relevant research, a conceptual model is prepared (Figs. 2 and 3). The hydrogeological system of the study area is modeled as multi-layered unconfined aquifer with variable thickness gently sloping from mountain regions in NNW to Indus River in SSE (Fig. 3). Based on the subsurface depositional unit correlations and the pump screen settings in Fig. 3, the model is divided into three layers (Table 1). Initial data of aquifer layer dimensions, i.e., elevations and lateral extents, have been

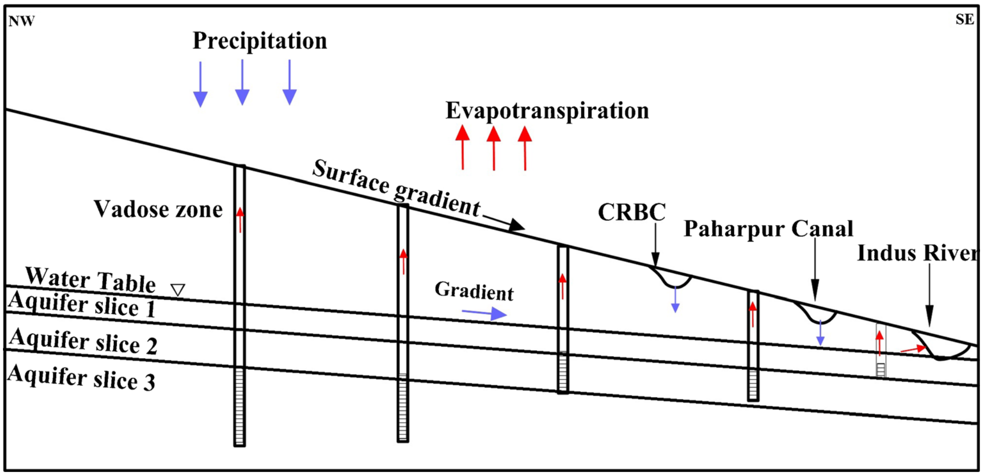

Fig. 3 The conceptual model of the simulated area showing slices of aquifer on the basis of various groundwater tapping depths and general conditions of flow in DIK. The *blue* and *red arrows* mark the volume of water moving in and out of the system

imported in the digitized vector format prepared in Global Mapper 7.0 and Rockworks 2002 (Fig. 4).

The boundaries are assigned in the software by digitizing and attributing pertaining to the flows, channel widths, stages, and vertical hydraulic conductivities. The area has been subdivided into a three-layered finite difference grid of 186 columns and 182 rows with a constant node spacing of 500 × 500 m both in *x*- and *y*-axes. The model was run initially with constant head and stream boundaries, but finally, the model settled down with the stream boundaries for the Indus River, Takwarrah Nala, and Sheikh Haider Zaman Nala. The CRBC canal has also been modeled as a stream boundary after the 1987. Subsequently, ten test wells data obtained from the previous reports of Naqvi (1977) and Malik (1985) were used to interpolate the properties of the modeled area, e.g., hydraulic conductivities, specific yield, recharge, and porosity, using Theissen polygon method (Theissen 1911).

The precipitation, river flows, canals, and irrigation practices were considered as the recharge source in the study area. Using the data of annual precipitation of the DIK meteorological station from Naqvi (1977) and Malik (1985). the recharge was calculated. The rest of the recharge is through the infiltration from the Indus River, CRBC, and other perennial streams. Discharge components include the evapotranspiration and the pumping wells data that are incorporated in this model. The evapotranspiration and pumping wells data have been acquired from the previous literature (Naqvi 1977; Malik 1985) and measured the recent discharge data of selective wells in the study area. The recharge in this model is taken for the rainfall (Kijne 1996) whereas the recharge from the canals and rivers is addressed separately in the stream boundaries (Fig. 4). A conjunctive use scenario has been simulated such as the usage of canal water and the groundwater to predict the groundwater balance in the study area.

After importing and assigning the respective features in the software, the model has been simulated and calibrated in steady state in 1985 by modifying the hydraulic conductivities and recharge values in a single time step during several runs

Table 1 Hydraulic conductivity zonation in the three-layered aquifer model

Layers	1			2			3			
Properties		*K* (m/s)	S_y	*POR*	*K* (m/s)	S_y	*POR*	*K* (m/s)	S_s	*POR*
ZONATION	Zone 1	1.30×10^{-5}	0.15	0.3	2.02×10^{-5}	0.15	0.32	3.20×10^{-5}	1.20×10^{-4}	0.35
	Zone 2	1.00×10^{-5}	0.13	0.33	1.20×10^{-5}	0.13	0.34	1.50×10^{-5}	1.00×10^{-4}	0.35
	Zone 3	1.03×10^{-6}	0.07	0.37	1.50×10^{-6}	0.05	0.36	2.00×10^{-6}	2.50×10^{-3}	0.38
	Zone 4	5.00×10^{-7}	0.01	0.4	3.00×10^{-7}	0.02	0.403	1.00×10^{-7}	2.50×10^{-2}	0.412
	Zone 5	1.51×10^{-5}	0.16	0.31	2.76×10^{-5}	0.17	0.32	3.90×10^{-5}	1.00×10^{-3}	0.31
	Zone 6	3.20×10^{-5}	0.19	0.3	2.40×10^{-5}	0.17	0.33	3.00×10^{-5}	2.00×10^{-4}	3.60×10^{-1}
	Zone 7	1.30E-05	0.15	0.34	1.50×10^{-5}	0.15	0.36	2.00×10^{-5}	1.20×10^{-4}	3.90×10^{-1}
	Zone 8	1.50×10^{-6}	0.09	0.39	1.70×10^{-6}	0.09	0.4	1.00×10^{-5}	1.70×10^{-3}	3.70×10^{-1}
	Zone 9	2.00×10^{-6}	0.03	0.41	3.70×10^{-6}	0.03	0.405	3.50×10^{-6}	2.70×10^{-2}	4.32×10^{-1}
	Zone 10	1.21×10^{-5}	0.15	0.31	3.00×10^{-5}	0.16	0.3	3.31×10^{-5}	1.10×10^{-3}	2.90×10^{-1}

The *K*, S_y, and *POR* describes the hydraulic conductivity, specific yield, and porosity

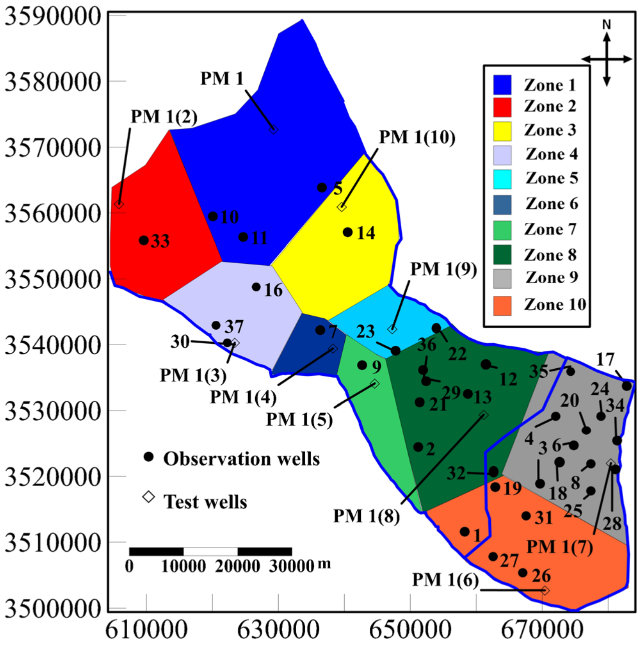

Fig. 4 Location ofwater wells used to establish the subsurface depositional unit correlation, calibration points for hydraulic heads in steady state

(Thangarajan 2004). The parameter estimation and testing (PEST) has been used to manage the calibration with the minimum and maximum ranges of 30 hydraulic conductivities and recharge values as described by Hill (1998). Later on, on the basis of successful calibration, the sensitivity analysis is performed. The sensitivity of the model was tested by uniformly multiplying recharge and hydraulic conductivity by the factors of 0.2, 0.4, 0.8, 1.2, 1.5, 2.0, 2.5, and 3.0 throughout the model's interior nodes, and then the model was rerun. The process is to be carried individually with one parameter and later with the other. First, the analysis was carried out for hydraulic conductivities by multiplying with the pre-defined factors and observed the changes in the mean, root mean square, and standard deviation of the simulated hydraulic heads. Following the sensitivity analysis, the transient calibration has been carried out to define the storage coefficients and to test the reliability of parameters (Guvanasen et al. 1998; Akhter 2002). The transient state model has been calibrated using water levels and drawdowns measured in ten test wells over a 6-month period of the Rabi season (agricultural crops sown in winter and harvested in the spring) from April 15, 1985 to September 15, 1985 using steady state hydraulic heads as the initial condition. Therefore, the PEST has been utilized to assess the automatic parameter estimation by calibrating it with the specific yield and specific storage (Table 1).

The steady state model was further enhanced for transient conditions and simulated for 25 years more up to 2020. The results thus acquired by the simulations were compared in different maps such as equipotential maps and water table depth maps. The modeling results have been summarized by analyzing the drawdown, water table depth calculated maps, and the analysis of the water balance in the model exported and interpolated in software Surfer 7.

Results and discussion

The successful calibration between the observed and the calculated hydraulic head values led to the steady state model of the groundwater flow in DIK. The root-mean-square (RMS) for the correlation is 0.65 with correlation coefficient 1.0 and mean residual around 0.055 m (Fig. 5). The model was simulated with all the boundaries set to stream package of the Visual MODFLOW.

The equipotential map of the year 1985 shows a general gradient from northwest to southeast, i.e., from the mountain ranges of the west to the Indus River (Fig. 6). An overall head drop of 110 m is observed with a higher value of 260 m in the extreme northwest to 150 m in the extreme southeast. The main recharge tends to exist from the western rivers of Gomal Zam and Tank Zam. The results have been matched with the previous equipotential map of the study area to reach the final conclusion (Naqvi 1977; Malik 1985).

The sensitivity analysis has been carried out for hydraulic conductivities, recharge, and specific yield by multiplying with the pre-defined factors and observed the changes in the mean, root-mean-square, and standard deviation of the simulated hydraulic heads (Thangarajan 2004). The results of the analysis show that model is more sensitive to recharge as compared to hydraulic conductivity in the steady state. The calibration in the transient state has been followed by the sensitivity analysis for the specific yield, and model has been found to be less sensitive.

The results of the simulation are summarized in Fig. 7. The water table depth maps show that there is a continuous drawdown in the groundwater table from 1985 to 1995 (Fig. 7a–c). Initially, there is a sharp decline in water table; however, after 1995, i.e., the time of inception of CRBC, there was

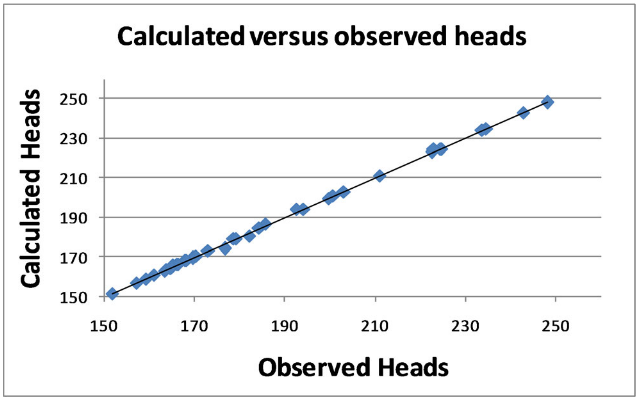

Fig. 5 The steady state calibration results of the DIK groundwater flow model

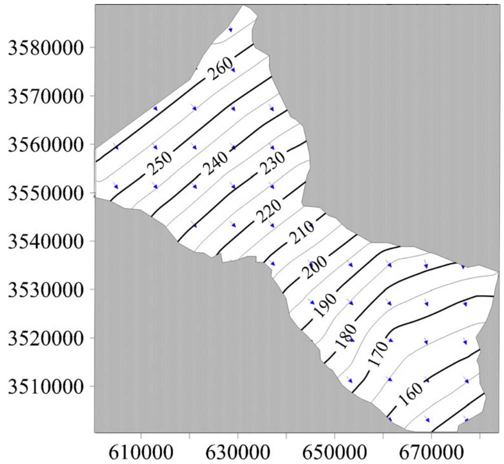

Fig. 6 The steady state equipotential map of the DIKalluvial aquifer after calibration and sensitivity analysis

stabilization of water table hence leading to a gradual decline (Fig. 7). This change may be attributed to the CRBC and irrigation activities. According to Kijne (1996) and Qureshi (2008). there is a rise of water tables in the canal command areas of Pakistan. However, in this simulation, it is clearly visible that a long-term pumping of the groundwater will affect the wells and there will be a decline of water table depths in the aquifers in the order of tens of meters till 2020.

The drawdowns calculated in the ten zones have been used to assess the potential of aquifers for the future exploitation in hypothetical observation wells corresponding to the zones of the model (Fig. 8). It has been found that the 35 years of drawdown simulation curves can easily be divided into two phases, i.e., before CRBC from 1985 to 1995 and after CRBC from 1995 to 2020. The predictive period is from 2013 to 2020. In pre-CRBC phase, the drawdown curves show a moderate steep rise in the curve and may be attributed to the initial stress conditions in the area. The post-CRBC phase shows a gentle gradient of drawdown curves that is the result of the stable situation. In predictive period, it can be found that there is again a change in the situation as the drawdown curves are

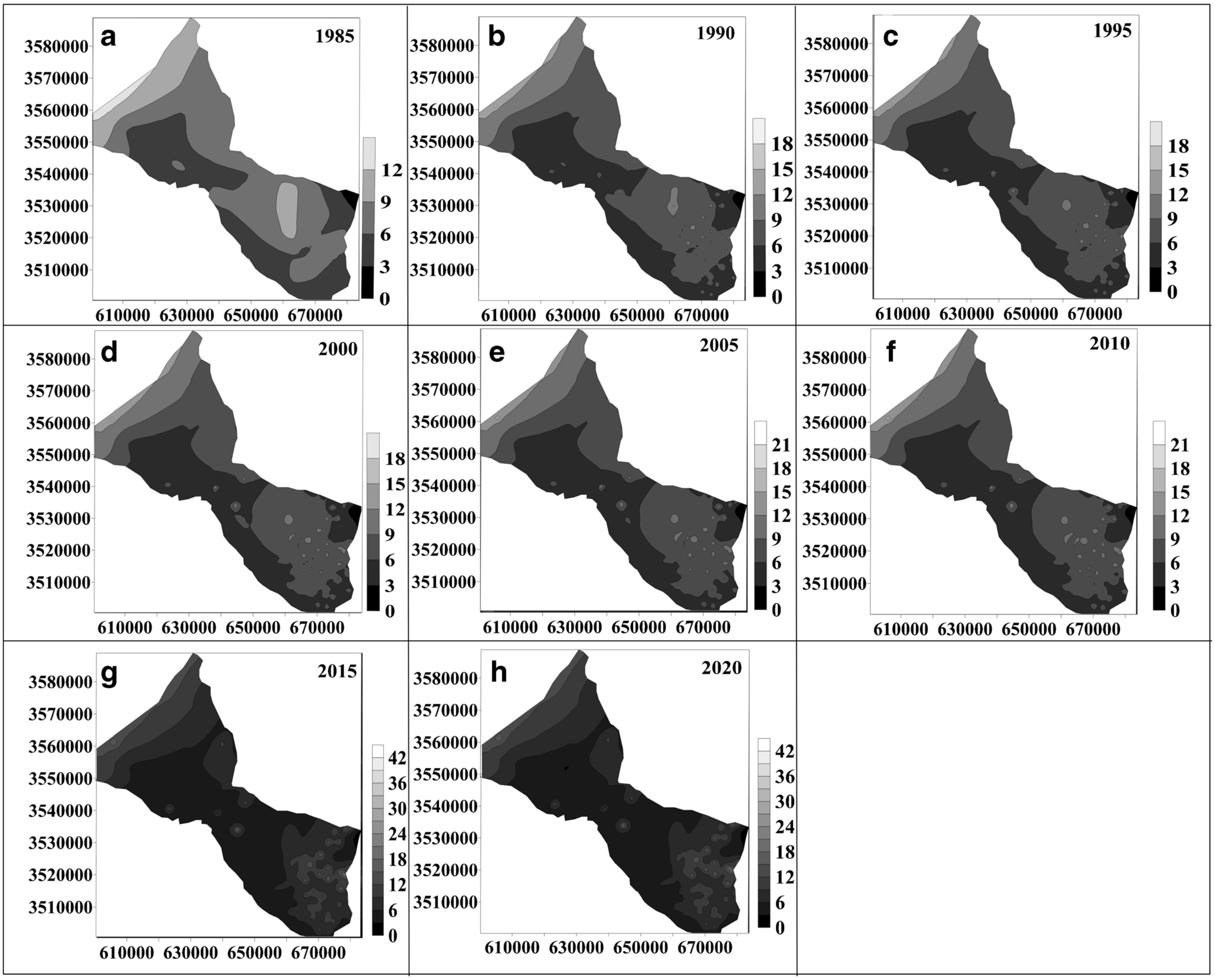

Fig. 7 The water table depth maps of the years 1985, 1990, 1995, 2000, 2005, 2010, 2015, and 2020 (**a**–**h**), showing the changes in the water table depth

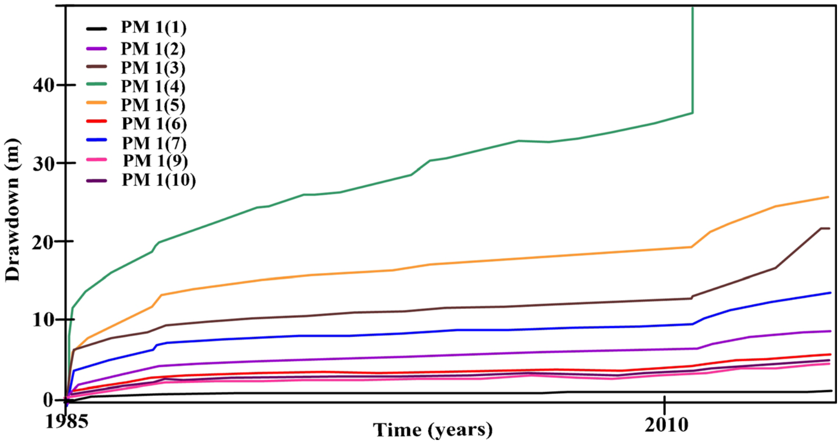

Fig. 8 The drawdowns calculated during the complete simulation of the model for 30 years. The general trend of drawdowns show an increase in the extraction of groundwater; however, the well PM 1(4) is showing a variation in the general trend because of its location in a low-conductivity zone

gaining the higher angles and continue to rise till 2020. In general, the drawdowns tend to descend in order from PM 1 (8) (water well dried up during the early stage of pumping), (4), (5), (3), (7), (2), (6), (10), (9), and (1). The drawdowns are lesser than 5 m in five wells that are located in areas near the western and eastern parts of the model (Fig. 5). These zones are prospective zones for the exploitation of groundwater in the future till 2020.

The construction of CRBC in 1987 has divided the whole region into two parts, i.e., the western bank and the eastern bank area. Based upon the concepts of the regional flows, it obliterated the whole groundwater flow system (Toth 1970). The groundwater movement shows that the western side of the CRBC is an effluent part whereas the eastern bank is an influent part in most of the cases. The central zone lies adjacent to the west bank of the CRBC. So the sensitivity of this zone to

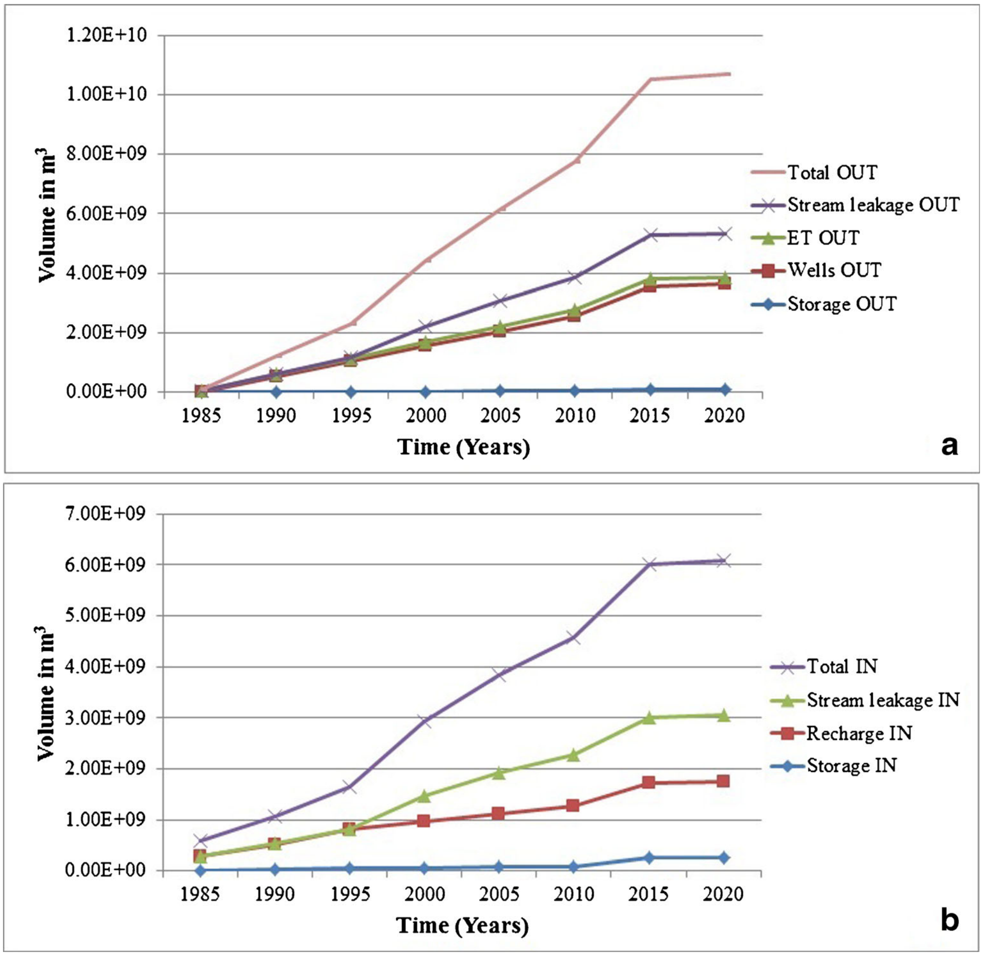

Fig. 9 The groundwater budget analysis of the DIK groundwater flow model simulation

the pumping is an obvious one due to the drainage of groundwater in that direction.

Following the drawdown analysis, the groundwater budget in the study area has been analyzed and divided into two characteristic temporal zones, i.e., pre- and post-CRBC as described earlier. In pre-CRBC conditions, the graphs for the groundwater balance show a moderate rise in the curves for the storage, recharge, stream leakage, evapotranspiration, and well discharge (Fig. 9). The storage out shows a constant trend as compared to the storage in that shows a small rise after 2010, i.e., the prediction period. The evapotranspiration is found to be greater than the well discharges. The curves of stream leakage in and out comparison revealed that most of the streams have an influent as well as effluent character. On the basis of groundwater budget analysis of the system, it can be inferred that the water moving into the system, i.e., recharge, is lesser than the discharge, i.e., water moving out of the system (Fig. 9). In the previous studies of the groundwater budgets, it has been reported that the CRBC command area is having more of the recharge, whereas this study revealed a lesser recharge (Qadir et al. 2014) owing to a larger area where there is less calculated recharge as compared to the discharge.

With the technological and demographic changes, it is pertinent that all the groundwater basins of Pakistan have to be modeled for the better understanding and management in the forecoming era of climatic changes and uncertainities to ensure the sustainability of aquifers and food security in this area.

Conclusions

The simulation results confirmed the nature of most of the streams to be of influent character toward northwest. The northwestern part of the region is attributed to be the recharge area, whereas the southeastern part consists of the effluent nature of streams in this model. The recharge rate is much less than the combined rate of extraction and natural discharge. The central part of the modeling represents a low-velocity zone, and a moderate-velocity zone lies in the extreme southeast.

Two temporal phases of groundwater flow are found, i.e., the pre-CRBC, a sharp increase in water level decline, and post-CRBC, showing a gradual decline due to an added recharge in the command area. The simulation also revealed that at present extraction rates, the maximum groundwater decline will be found in the central low-velocity zone, i.e., located on the west bank of the CRBC that has an influent nature. The prospective zones for the groundwater exploitation in the study area exist near the Indus River and near the western mountain ranges. The transition zone between the piedmont and the floodplain deposits lying away from the canal command area toward west is sensitive to the pumping. The prediction results prove the affordability of the short-term increase in groundwater extraction in the DIK aquifer mostly in the northwestern and southeastern extremities.

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