



Monitoring regional groundwater flow and contaminant transport in Southern Punjab, Pakistan, using numerical modeling approach

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Abstract

A three-dimensional groundwater flow model was developed using Visual MODFLOW to characterize the groundwater regime and simulate groundwater flow behavior in Multan District of Pakistan from 1962 to 2015. The multi-layered model was calibrated in which arsenic concentration was used as a point source for solute transport modeling in the flow domain. The model calibration indicated a close agreement between the simulated and observed head values achieving residual mean value of 0.1 m and a correlation coefficient (R) value of 0.9 during the steady-state condition. The study revealed a gradual rise in groundwater levels from 1972, i.e., at a rate of about 0.08 m/year followed by a gradual decline after 1990 at a rate of about 0.39 m/year likely due to overexploitation of groundwater. The other reasons of depletion of the aquifer may include lesser natural recharge due to reduction in canal command area and increasing water demand and pumpage due to growing urban/rural development. The findings of contaminant transport modeling depicted flow path representation of arsenic movement mostly towards the rivers in the model domain. Overexploitation of groundwater needs to be controlled for effective development of groundwater resource, and proper purifying/filtering techniques have to be adopted to ensure safe groundwater use in the area.

Keywords Groundwater modeling · Contaminant transport · Arsenic · Punjab · Indus Basin

Introduction

Over one third of the world's population is estimated to use groundwater for drinking purposes (UNEP 1999). Irrigation through tubewells is an important sector of groundwater use in the Indus Basin, which adds flexibility of water supplies to match the crop water requirements (Ashraf et al. 2018). Groundwater management is a major challenge in the Indus Basin, where groundwater flows and water quality vary with time and space

(Yu et al. 2013). In recent decades, the global water supplies contaminated with arsenic have come to the front position in policy decisions (Morgen et al. 2014). A number of studies have been conducted in different countries to find health effects of arsenic-contaminated drinking water, e.g., in the USA (James et al. 2015), in Bangladesh (Mushtaq 2004; Rahman et al. 2007), in India (Mukherjee et al. 2007), in Iran (Mehrdadi et al. 2009; Baghvand et al. 2010; Nasrabadi et al. 2015), and in Pakistan (Kazi et al. 2009; Gilani et al. 2013; Abbas and Cheema 2015; Bibi et al. 2015). A high arsenic level is generally associated with various types of cancers, nervous system disorders, cardiovascular problems, kidney and liver diseases, diabetes, and respiratory problems (ATSDR 2007). More than 100 million people are exposed every day to arsenic-contaminated drinking water in Bangladesh, Cambodia, China, India, Myanmar, Nepal, Pakistan, and Vietnam (Stanford News 2010).

The groundwater arsenic concentrations are spatially variable and are an emerging peril in several parts of Pakistan (Toor and Tahir 2009; Shakoor et al. 2015; Alamgir et al. 2016; Rasool et al. 2016). According to Kahlowan et al. (2003), the water resources of Pakistan are facing arsenic, nitrate, fluoride, and bacteriological contaminations. According to WHO guideline, the arsenic in drinking water must be below

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10 $\mu\text{g/L}$ or parts per billion (ppb) (WHO 1998) but the maximum permissible limit for arsenic is 50 $\mu\text{g/L}$ as per the National Drinking Water Quality Standards (NDWQS) of Pakistan (NDWQS 2010). A study carried out in Punjab showed that 20% of the population is exposed to arsenic contamination of 10 ppb and nearly 3% to arsenic contamination of 150 ppb in drinking water (Kahlowan et al. 2002). Southern Punjab showed the highest arsenic contamination in the groundwater of district Multan. A good knowledge of the problem and analysis of various hydrological components of the system is thus vital for better management of groundwater resource.

Groundwater models are the simple representation of reality and, if properly constructed, can be used as a valuable predictive tool for management of groundwater resources. A suitable model not only helps in evaluation of water resources but also supports

their management through provision of alternative solutions. Three-dimensional numerical modeling provides base for monitoring present and future groundwater flow behavior and simulating contaminant transport in an aquifer (Ahmad and Khawaja 1999; Chiang and Kinzelbach 2001; Ökten and Yazicigil 2005; Ahmad et al. 2010; Anderson et al. 2015). In the present study, numerical modeling using Visual MODFLOW and advective-dispersive transport code (MT3D) has been applied in order to understand the behavior of groundwater flow and arsenic transport in the aquifer system of Multan District of Pakistan.

Description of the study area

The study area of Multan District lies within longitudes 71° 12' to 72° E and latitudes 29° 24' to 30° 48' N covering an area

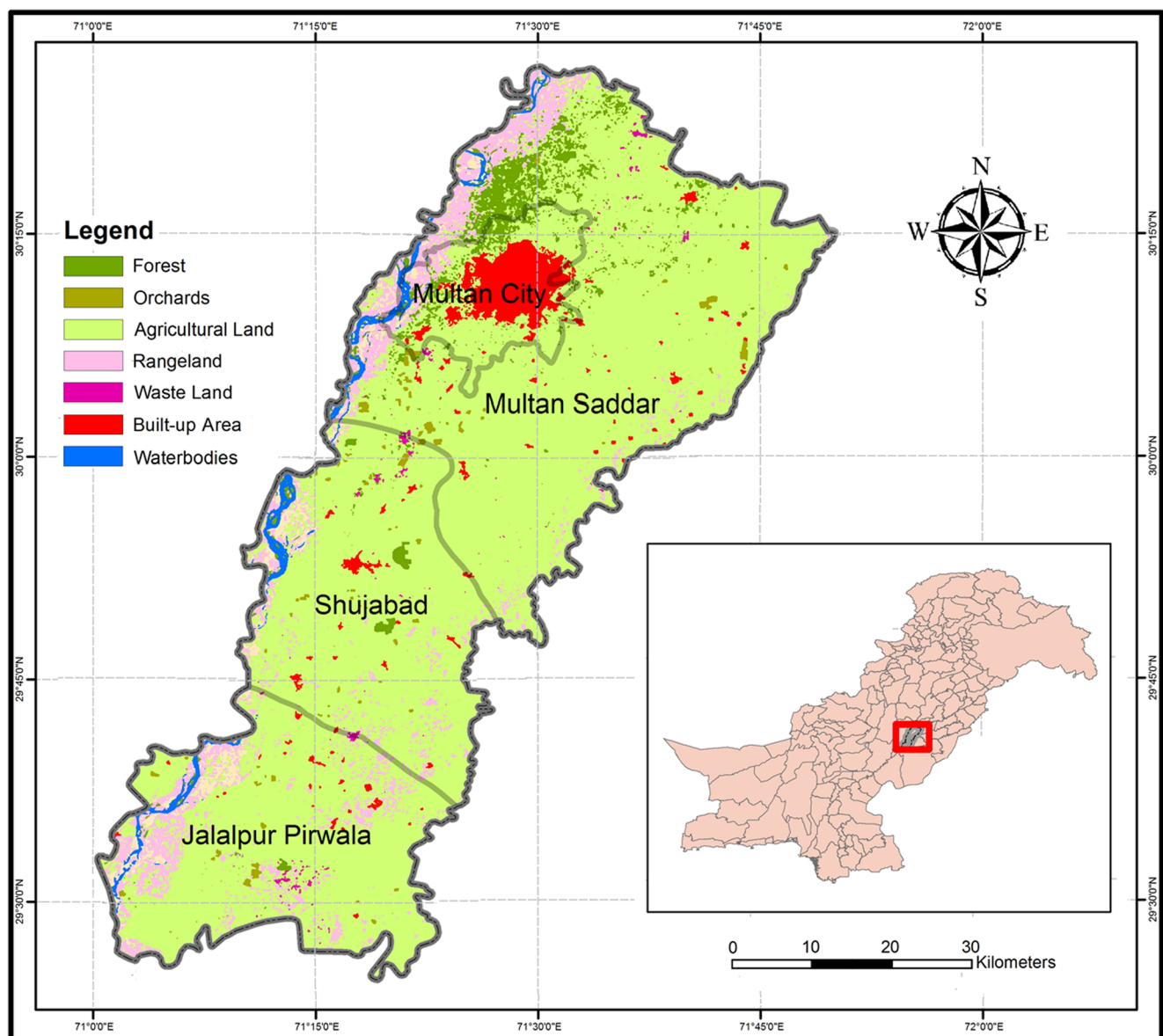
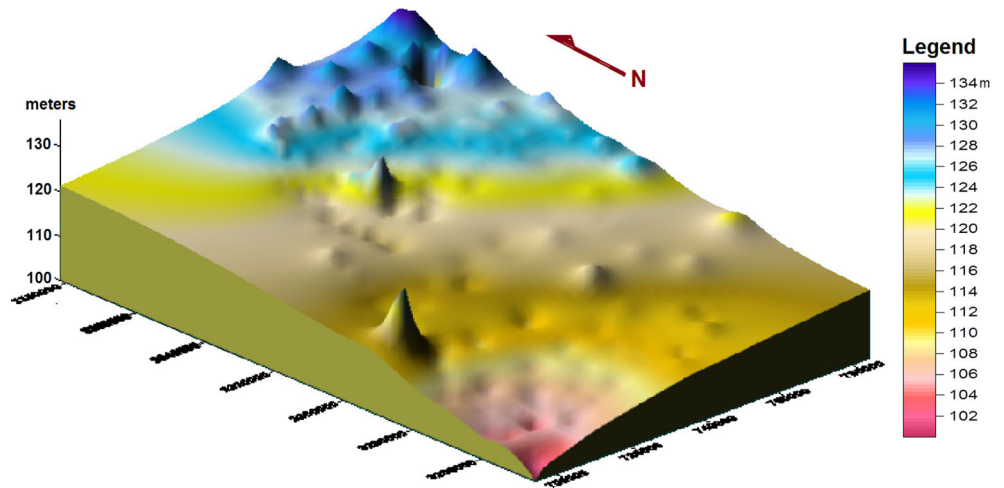


Fig. 1 Location map indicating land use/land cover distribution in the study area

Fig. 2 General topography and relief trend in the study area



of about 3721 km² in the Southern Punjab Plain of Pakistan (Fig. 1). It is located in Bari Doab (“Doab” is a local term used for the area surrounded by two rivers) within an elevation range of 100–136 m above mean sea level with a mean slope towards southwest direction (Fig. 2). The Chenab River flowing in the west of Multan City is a major source of water supply and groundwater recharge in the area. Climate is mainly arid subtropical continental with the mean annual rainfall of 200–300 mm. The mean daily maximum temperature during

summer is 41–42 °C, while in winter, the mean daily minimum temperature is 6 °C with occasional cold spells. Canal-irrigated cropping is the main land use in the area (Fig. 1). Built-up land, some forest cover, and orchards are mostly concentrated in the northwest and in scattered form within agriculture land throughout the study area. Patches of waste land (i.e., waterlogged and saline areas) are found where groundwater exists in localized perched condition.

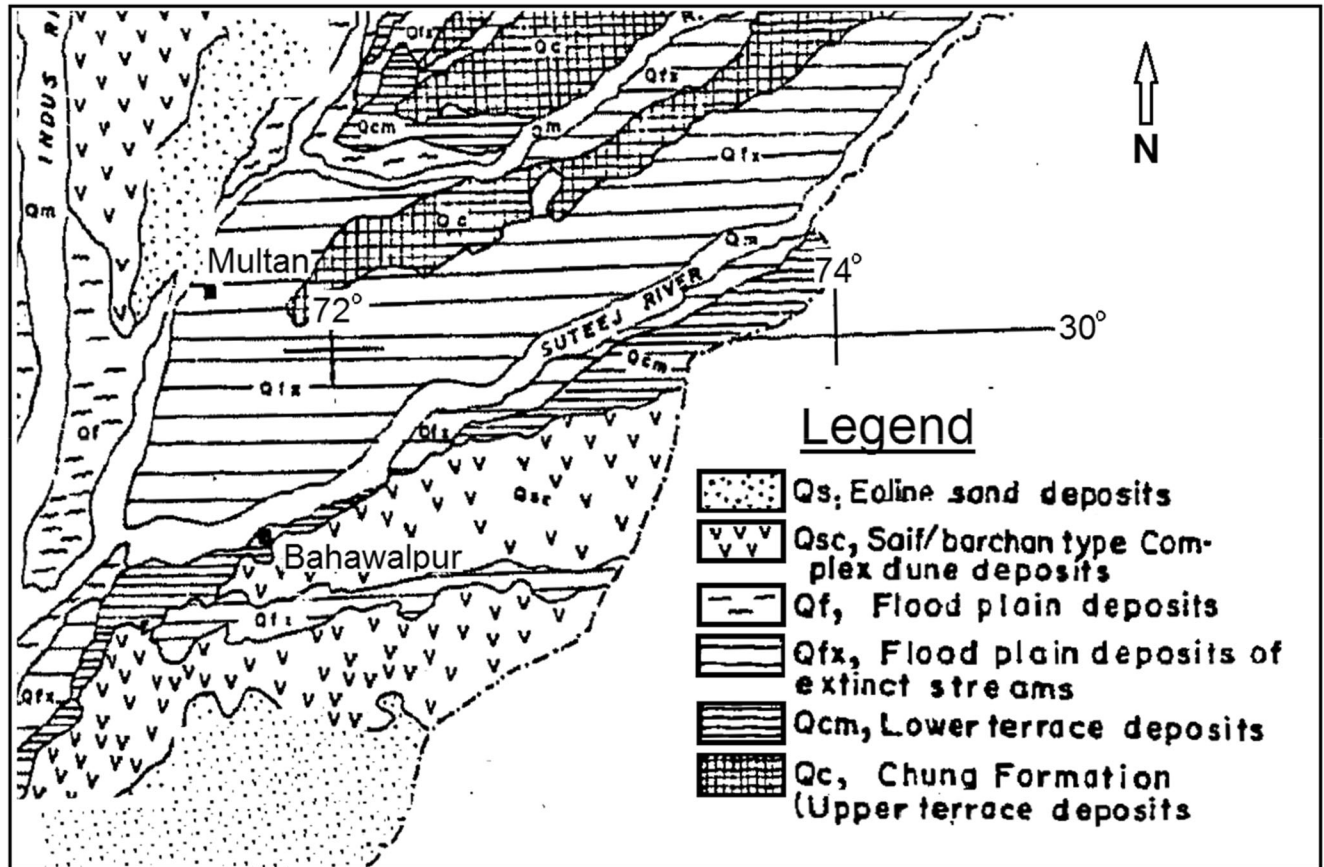
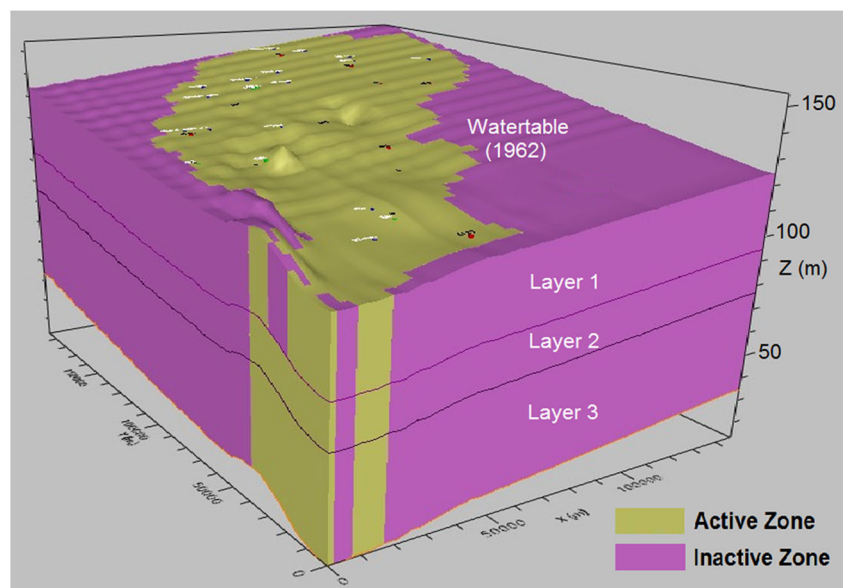


Fig. 3 Geological distribution of the Southern Punjab Plain (from Kazni 1966)

Table 1 Net annual areal recharge in the study area

Parameter	$\text{m}^3 \times 10^6$	mm/year
Canal recharge (80% of the canal seepage)	2131.49	207.8
Recharge from the return flow of pumpage	279.90	27.3
Rainfall recharge	101.84	9.9
Total recharge (IN)	2513.24	245.0
Total discharge mainly from pumpage (OUT)	2618.99	255.3
Net recharge (IN–OUT)	–105.76	–10.3

The study area lies in the Punjab Plain which is a part of the Indo-Gangetic Plain (Kidwai and Swarzenski 1964) and dry Punjab geosyncline in which sedimentation and subsidence are taking place concomitantly. In this vast geosyncline, the Quaternary alluvium presumably overlies semi-consolidated tertiary metamorphic rocks and igneous rocks of Precambrian age (WAPDA 1980; Wayne and William 2000). On the basis of geology, the area is divided into three parts, i.e., Quaternary alluvial complex, unidentified unit, and Precambrian basement rocks. Quaternary alluvial sediments were deposited by the ancestral tributaries of the Indus River during constantly shifting courses. The alluvial complex consists mainly of unconsolidated sand and silt, with minor amounts of clay and gravel, in which a fairly thick and transmissive aquifer is present in unconfined condition (WAPDA 1982). From the point of micro-geomorphology, the area can be classified into different flood plains and bar uplands that exhibit changes in lithology due to different modes of depositional environment (Fig. 3). The dominant soils are calcareous silt loams having good porosity and permeability, whereas clayey soils exist in minor patches. Average water table depth varies between 1 and 6 m.

Fig. 4 Conceptualization of the three-dimensional multi-layered numerical model

Material and methods

Numerical modeling of groundwater flow

MODFLOW is a well-known example of a general finite difference groundwater flow model. It is developed by the US Geological Survey as a modular and extensible simulation tool for modeling groundwater flow (McDonald and Harbaugh 1984). In the present study, Visual MODFLOW Pro (version 4.0) and the three-dimensional advective-dispersive transport code MT3D were used for numerical groundwater flow modeling and contaminant transport in the Multan area. The groundwater data since the 1960s had been acquired from the Water and Power Development Authority (WAPDA), and the model was calibrated using the hydraulic head data of 1962 as at that time, groundwater levels appeared to be in equilibrium condition (WAPDA 1980, 1982). The main sources of groundwater recharge in the area are seepage from canals, distributaries, minors, watercourses, field applications, return flow of groundwater pumpage, and rainfall. Aquifer discharge sources are groundwater pumpage from tubewells, evapotranspiration, outflows to the rivers, and drains. The net recharge to the groundwater flow model has been estimated using a simple water balance model as expressed in the following:

$$Q_r = Q_{mc} + Q_{dm} + Q_{wf} + Q_{riv} + Q_{rf} + Q_{rtw} - [Q_{et} + Q_{tw} + Q_{dr}] \quad (1)$$

where Q_r is the net recharge to the aquifer, Q_{mc} is the recharge from main and link canals, Q_{dm} is the recharge from distributary/minors, Q_{wf} is the recharge from watercourses and irrigated fields, Q_{riv} is the recharge/discharge from rivers, Q_{rf} is

the recharge from rainfall, Q_{rtw} is the recharge from return flow of tubewell pumpage, Q_{et} is the discharge by evapotranspiration, Q_{tw} is the pumpage from tubewells, and Q_{dr} is the discharge from drains. The values of recharge from various sources were maintained according to the specified limits of WAPDA and irrigation department (NESPAK 1993). According to Akhter and Ahmad (2001), 18% of canal discharge is lost as seepages and 80% of this seepage is percolated to recharge the groundwater (Table 1). The total annual recharge estimated from various sources for the year 1962 was 245 mm/year, while the total discharge was 255.3 mm/year. The recharge estimates were used in the numerical model as initial conditions during the calibration process. The calibrated head values of steady-state model were used as an input for transient-state modeling to predict future changes in head values from the year 2010 to 2015 in the model domain.

Model design

The model grid consists of 60 rows and 20 columns (total of 1200 cells in each layer) with a variable spacing of 1000 m to 2000 m in both x and y directions, respectively. The active zone of the model covers an area of about 3721 km² (Fig. 4). The Chenab River was treated as the western constant head boundary and the Sutlej River as the southern constant head

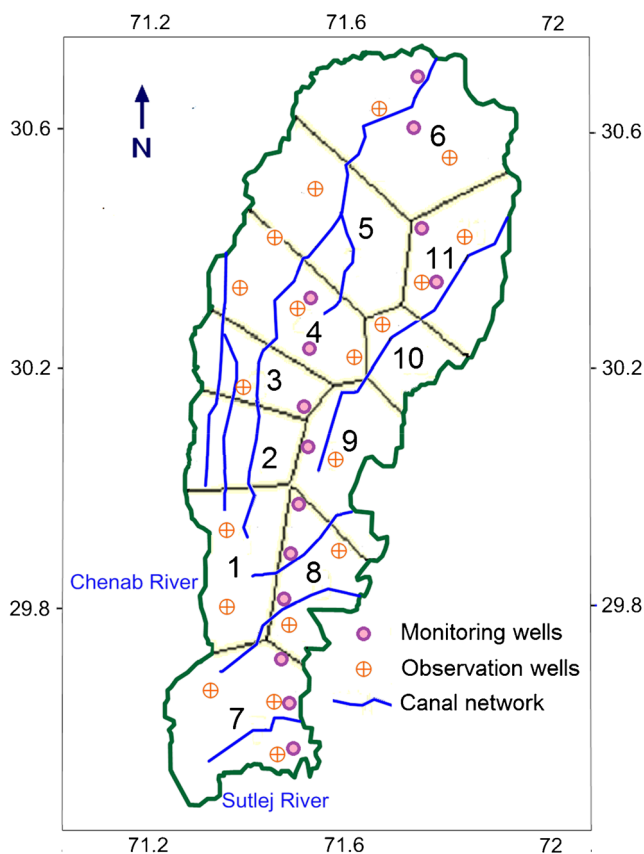


Fig. 5 Zonation of hydraulic conductivity and specific yield

Table 2 Hydraulic conductivity (K) values (m/day) in various zones of 3 layers

Zone	Layer 1	Layer 2	Layer 3
1	27.4	30.0	30.0
2	92.7	150.0	64.2
3	147.3	150.0	101.2
4	141.7	150.0	130.6
5	130.1	150.0	150.0
6	37.6	40.0	45.6
7	118.1	41.7	30.0
8	139.0	150.0	150.0
9	145.9	191.5	25.7
10	56.7	30.0	156.7
11	118.0	41.7	30.0

boundary. The aquifer in the study area was divided into three layers based on the lithological data of WAPDA (1982). The first layer consists of sand from the ground surface to 30 m depth, the second layer contains gravel and sand with some clay lenses from 30 to 48 m depth (thickness 18 m), and the third layer consists mainly of gravel with sand and silt within 48–90 m depth (thickness 42 m). Different hydraulic parameters were calculated using the hydrogeological data of WAPDA (1980). The area was divided into 11 zones of hydraulic conductivity and specific yield using the Thiessen polygon method (Fig. 5). The hydraulic conductivity (K) values were estimated within the 27.4–147.3 m/day range in layer 1, within 30–191.5 m/day in layer 2, and between 25.7 and 156.7 m/day in layer 3 (Table 2). Vertical hydraulic conductivity values were assumed to be 1/10th of the horizontal conductivity values (Akhter and Ahmad 2001). Specific yield (SY) values derived from the bore log data ranged within 0.15–0.25 in layers 1 and 2 and between 0.14 and 0.25 in layer 3 (Table 3). For steady- and transient-state calibration, head values of 19 observation wells were used (Fig. 5). Arsenic concentration data of 14 monitoring wells were used for executing contaminant transport modeling assuming point

Table 3 Specific yield (SY) values in the various zones of 3 layers

Zone	Layer 1	Layer 2	Layer 3
1	0.15	0.15	0.15
2	0.20	0.25	0.18
3	0.25	0.25	0.21
4	0.24	0.25	0.23
5	0.24	0.25	0.25
6	0.15	0.15	0.18
7	0.20	0.16	0.15
8	0.24	0.25	0.25
9	0.21	0.25	0.14
10	0.17	0.15	0.24
11	0.20	0.16	0.15

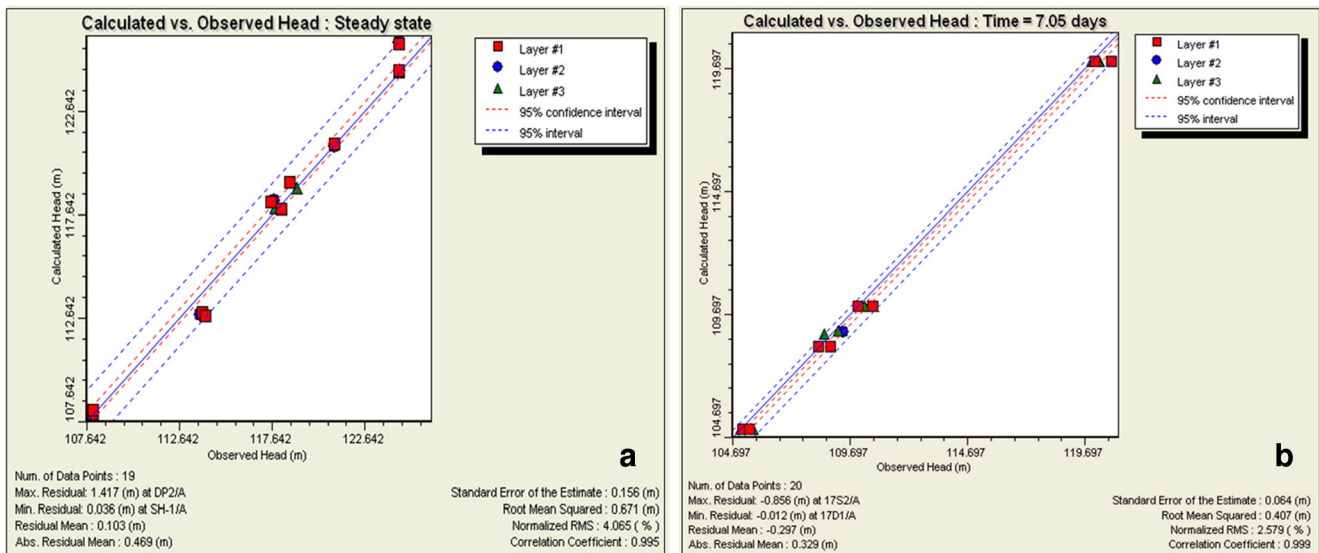


Fig. 6 a Steady-state calibration (1962). b Non-steady-state calibrations

sources of arsenic pollution, i.e., from highly localized pockets.

Arsenic transport

The groundwater arsenic is mostly found in terms of arsenite (AsO_3^{3-}) and arsenate (AsO_4^{3-}) oxyanionic forms (Flora et al. 2009). The naturally occurring groundwater arsenic areas are mostly found either in closed basins of arid and semi-arid areas or in alluvium-derived, strongly reducing aquifers. Both environments have geologically young sediments, and the groundwater flow is very slow in these low-lying flat areas. The arsenic released from the sedimentary layers after burial is accumulated in the groundwater of these poorly flushed aquifers (Smedley and Kinniburgh 2002).

Arsenic is found in comparatively unweathered alluvial deposits resulting from igneous and metamorphic rocks in the Himalayas and related young mountain chains (Brammer and Ravenscroft 2009). However, there are anthropogenic sources; e.g., arsenic is mainly emitted by the copper producing industries, but also during lead and zinc production, and toxic waste generation from the urban land use.

The solute transport model MT3D is a comprehensive three-dimensional numerical model for simulating solute transport in complex hydrogeologic settings. It is capable of modeling advection in complex steady-state and transient flow fields, anisotropic dispersion, first-order decay and production reactions, and linear and non-linear sorption. Output from steady-state or transient-state MODFLOW simulations is used in MODPATH to compute paths for imaginary

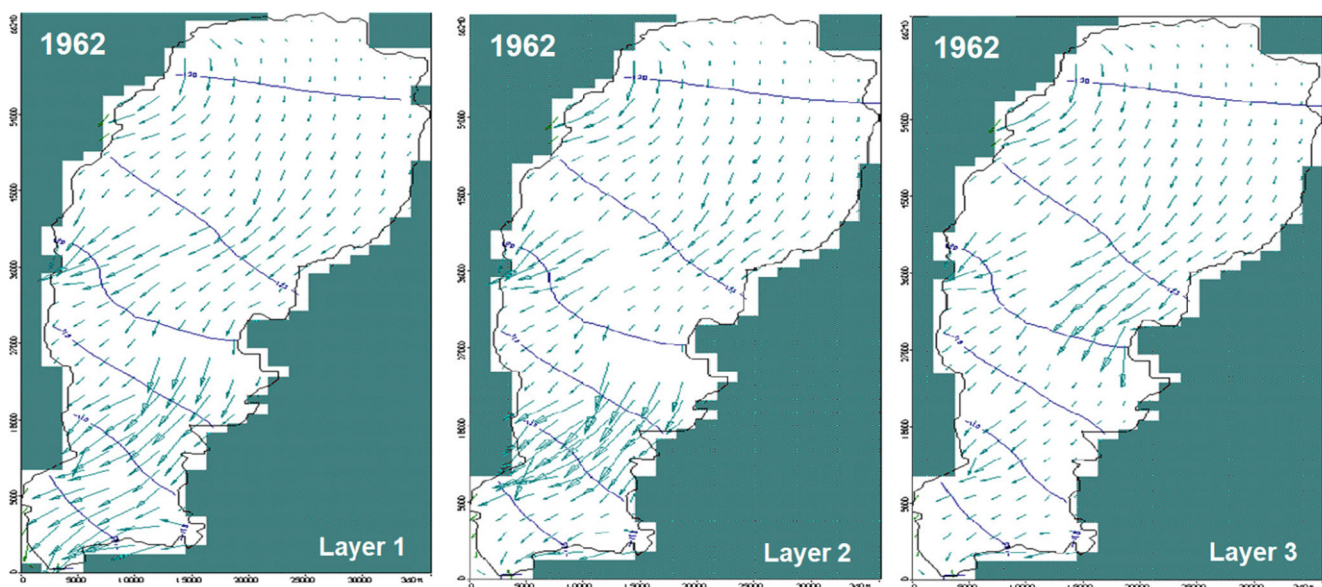


Fig. 7 Steady-state map of velocity magnitude in layers 1–3 (1962)

particles of water moving through the simulated groundwater system. The equations of particle tracking method in MODPATH have been documented by various researchers (e.g., Anderson et al. 2015; Langevin et al. 2017; Winston et al. 2018). The calibrated transient-state model data was used in MODPATH for the particle tracking of arsenic point source, i.e., flow path determination and representation. Forward tracking of the particles is used for determining the possible path and rate of flow of the particles. On the other hand, backward tracking is useful for determining the possible route of the particles and/or source of the contamination in the groundwater regime. For MT3D run, the porosity value of 0.2 was assumed, as sand is the dominant subsurface material in the area. The apparent longitudinal dispersivity (α_L) value of 13.5 m was estimated, which was assumed to be constant

for all the cells. The transverse horizontal dispersivity and transverse vertical dispersivity were assumed to be 10% and 1% of the longitudinal dispersivity, respectively. The molecular diffusion value used in MT3D was $1.0 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$.

Results and discussion

Steady-state modeling

Calibration of the steady-state model was performed using 1962 hydrologic conditions when according to the source data of WAPDA, groundwater levels were nearly in equilibrium condition. The model was calibrated using the automated parameter estimation (PEST) program (Doherty 1995)

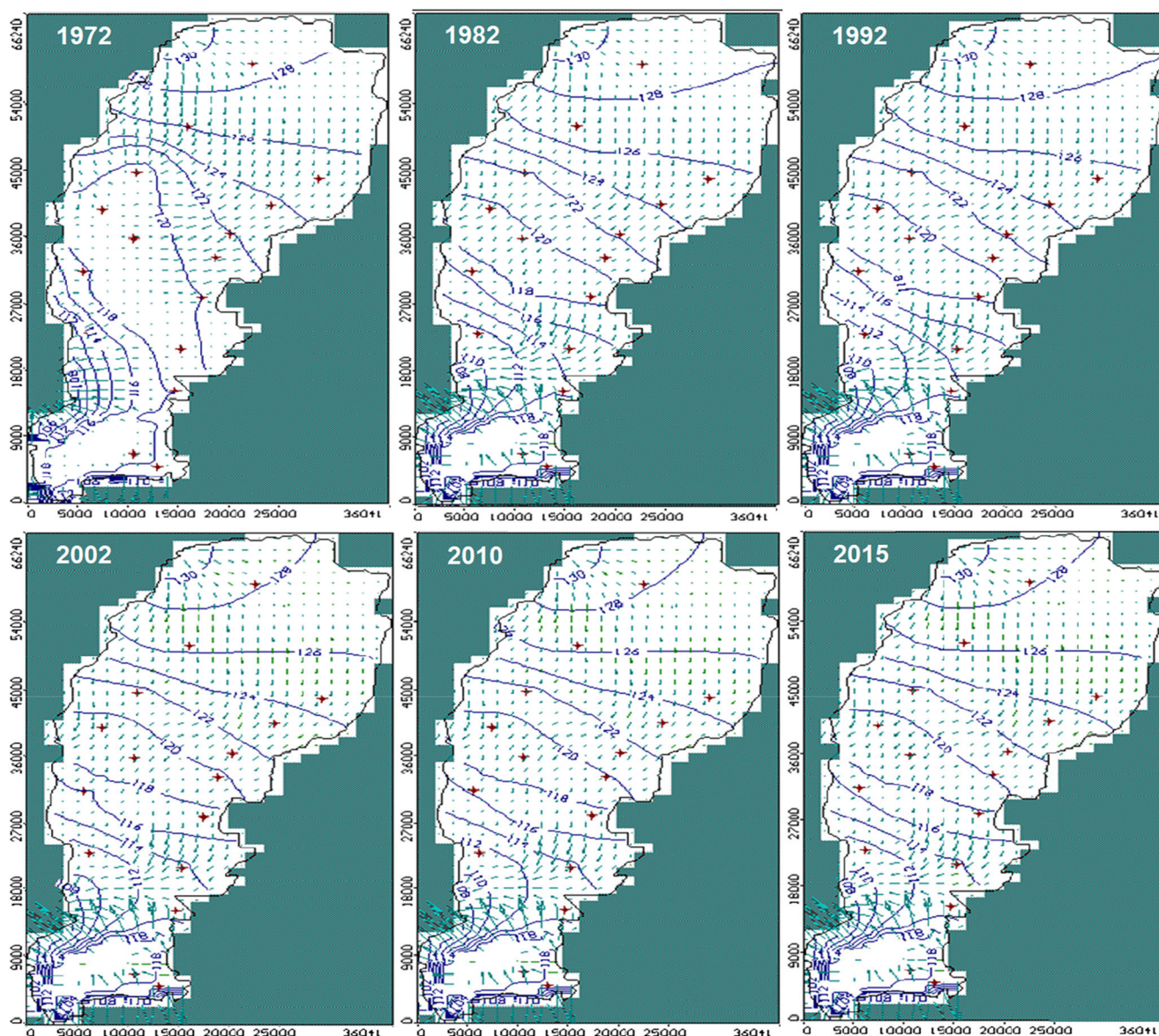


Fig. 8 Equipotential maps of various stress periods from 1972 to 2015 (15 wells are operating with variable discharge rates)

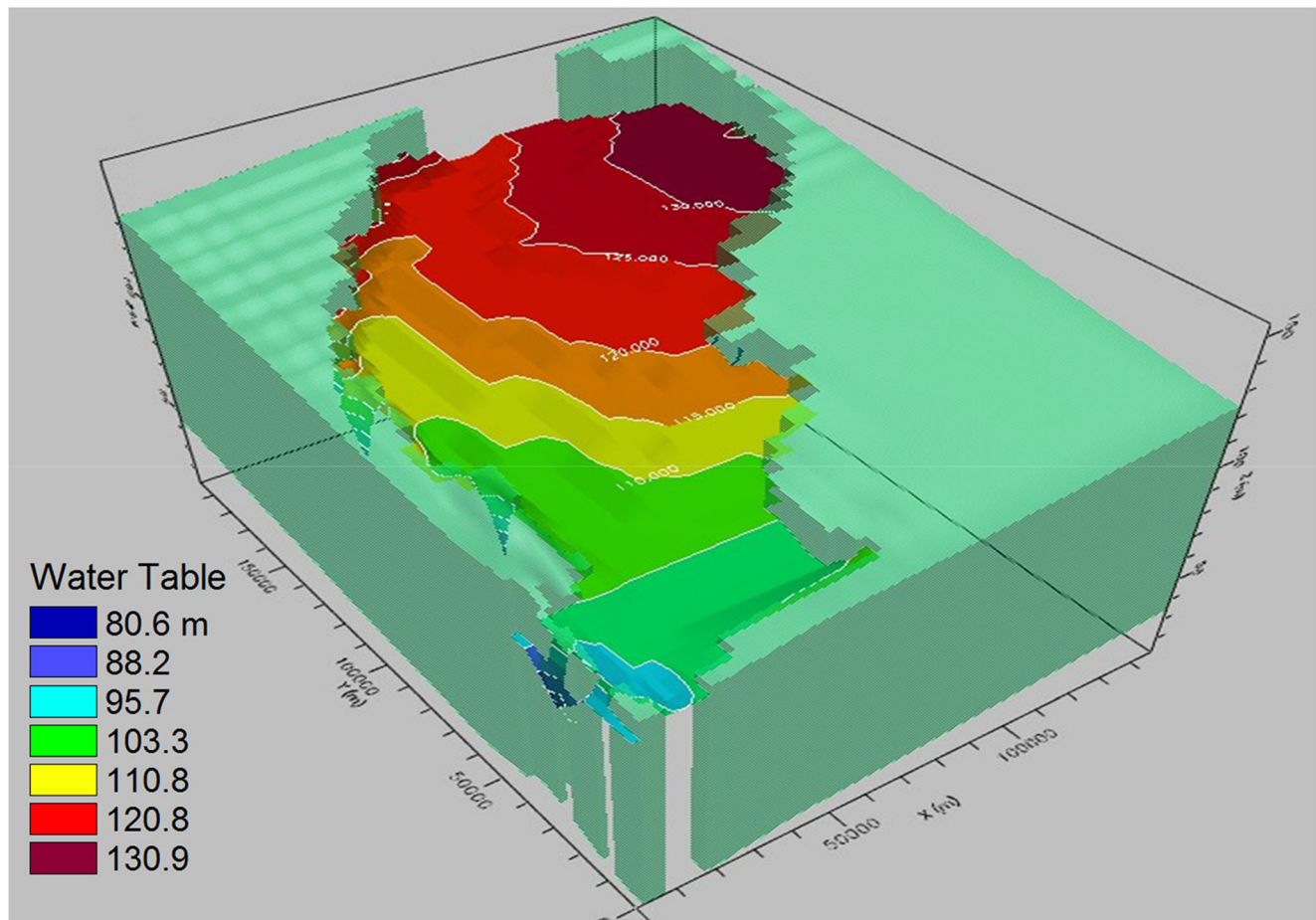


Fig. 9 Three-dimensional representation of the equipotential map of the model domain

embedded in Visual MODFLOW. The model was calibrated in both steady state and non-steady state successfully (Fig. 6). The groundwater heads of June 1962 (pre-monsoon) were used as an initial condition for steady-state simulation. Recharge from rainfall and canals was considered in the initial data input. The initial parameters were adjusted in the automated calibration by PEST. In the steady-state calibration, the residual mean was 0.1 m, and the correlation coefficient (R) was 0.99, indicating a reasonable agreement between the simulated and observed head values.

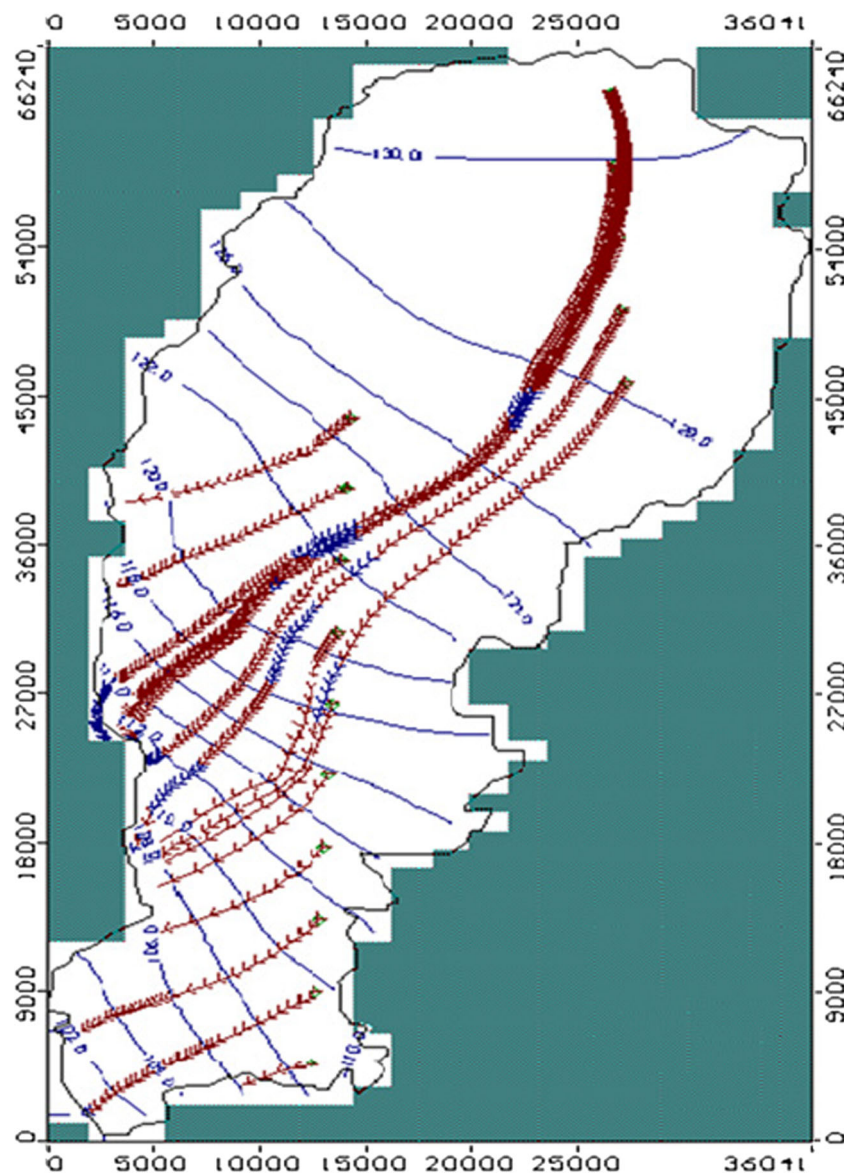
The equipotential map of the steady-state simulation shows groundwater flow towards the southwest direction following the topographic relief of the area (Fig. 7). Total annual inflows during the steady-state condition were around 632 million m^3 (MCM) in which 13.2% was contributed by constant head boundaries. Hydraulic heads fall in the range of 90–130.9 m above mean sea level. The direction of velocity vectors points the groundwater flow towards the constant head boundaries in the west and south of the model domain. The magnitude of velocity vectors was highest in the southern part of the model area, while it was lowest in the northeastern part of the area. In the second layer, velocity magnitude was highest below the center of the study area, while lowest velocity was observed in

the north of the area. In the third layer, highest velocity was evident in the eastern center of the study domain, while lowest in the north and northeastern parts of the domain (Fig. 7).

Transient-state simulation

Transient modeling, often referred as time dependent, non-steady, or non-equilibrium, was conducted using the initial conditions of the already calibrated head in the steady-state simulation. The specific yield of the aquifer regime was considered during transient-state modeling. Higher drawdown due to tubewell pumpage was observed in the southwestern and eastern parts of the study area. The simulated equipotential maps of various stress periods from 1972 to 2015 (layer 1) are shown in Fig. 8. The velocity of groundwater flow is pronounced in layer 1 representing the upper unconfined aquifer because of the direct effect of the surficial recharge. From 1972 to 1982, a gradual rise in groundwater levels at a rate of about 0.08 m/year was observed, which appears to sustain for few years, then a gradual decline in the levels was noticed after 1990 at a rate of about 0.39 m/year. The declining trend in groundwater indicates that the aquifer is over pumped and abstraction rates are higher than recharge. The head varied

Fig. 10 Flow path representation of arsenic point source concentrations after the 360-day simulation (forward tracking) in the study area



from 85 m in the southwest to more than 130 m in the north-west during these stress periods. The overall pattern of the groundwater flow was found similar in most of the central and northern half of the study area. The three-dimensional equipotential map of the model is shown in Fig. 9.

Particle streamlines

A three-dimensional particle tracking function of the MT3D model was used to compute the streamlines and position of the particle at a specified point in time. Both forward tracking and backward tracking were executed. The concept of particle tracking is adopted here for the evaluation of flow paths of the groundwater in the target aquifer regime. Arsenic concentration data of 14 monitoring wells ranging in values between 52 and 328 $\mu\text{g/L}$ were used in the particle tracking mode of

the model. The particles had been added in the model, and the release time was assigned for forward and backward tracking. The particle streamlines after 360 days of simulation period depicted the pollutant movement towards the river boundary in the southwest of study area (Fig. 10). The decrease in the rate of flow of particles during the simulation period indicates a decline in the pollutant concentration. The loss of mass generation takes place due to adsorption and the biokinetics of mass dissolved/suspended in the moving water (Mirbagheri et al. 2016). According to Bibi et al. (2015), the pedogenesis and weathering of parent rocks are natural sources of arsenic poisoning in soils that ultimately contaminate the groundwater in the Indus Basin. However, relatively higher concentrations within urban land use are due to anthropogenic activities related to disposal of industrial and municipal wastes. Khalid et al. (2013) also highlighted the leachate percolation

from the landfill sites in cities like Lahore. Höhn et al. (2006) studied the chemical processes controlling arsenic mobility through injecting a solution of groundwater with dissolved arsenic in a well. According to their results, the mobility of trace amounts of arsenic can be affected by chemical reactions between nitrate, iron, and oxygen. In addition to forward tracking of the particles, backward tracking was also executed on the concentration wells to determine the source of the contaminants on that point.

Conclusions

In the present study, groundwater flow behavior and arsenic transport were studied in Multan District, Southern Punjab Plain of Pakistan, using numerical modeling techniques. The model indicated a close relationship between the simulated and observed head values, achieving a residual mean value of 0.1 m and a correlation coefficient value of 0.9 during the steady-state calibration. A gradual rise in groundwater levels was observed from 1972, i.e., at a rate of about 0.08 m/year followed by a gradual decline after 1990 at a rate of about 0.39 m/year likely due to overexploitation of groundwater. A similar situation of decline in groundwater levels had been observed in the nearby Thal Doab since 1990 by Rehman et al. (2018), in the Chaj Doab since 1999 by Ashraf et al. (2018), and overall, in the Indus Plain by World Bank (2006) and Qureshi (2011). The continuous decline in water table due to overdrafting of the groundwater regime indicates that annual groundwater budget could not be adequately balanced. The other reasons of depletion of the aquifer may include lesser natural recharge due to reduction in the canal command area and increasing water demand and pumpage due to growing urban/rural development. Forward tracking of arsenic contamination depicted pollutant movement towards the rivers. The groundwater needs to be managed properly, and overexploitation should be controlled for effective development of groundwater resources in the area. Because of the severe health effects of the arsenic, groundwater should be used very carefully after adopting proper purifying/filtering techniques.

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