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Water budget study for groundwater recharge in Indus River Basin, Punjab (Pakistan)

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ABSTRACT

Assessing groundwater recharge is crucial for managing and governing water resources in any region. Indus River Basin (IRB) is an area that relies heavily on canal and groundwater irrigation. The replenishment of groundwater is largely dependent on surface water supplies. The purpose of this research is to determine the amount of groundwater recharge from various sources in Rachna Doab. The study employed the water budget method to calculate seasonal groundwater recharge during the Rabi (October–March) and Kharif (April–September) (Summer) periods from 2005 to 2011. The main components of the recharge were rainfall, water conveyed through channels, and irrigation water applied to cultivated fields. Conversely, the extraction of water from private and public tube wells was the discharge component of the study. Groundwater levels increased during the Kharif season but decreased during the Rabi season. Average recharge contribution from rainfall was 45 and 14% during the Kharif and Rabi seasons, respectively. The total annual recharge from watercourses and irrigation fields was estimated to be approximately 33% of the total recharge. Rainfall was the most significant source of long-term seasonal recharge, followed by watercourses and irrigation fields. In general, the average depletion of the reservoir was 94 million cubic meters per season.

Key words: groundwater, Indus River Basin, recharge, water balance method, water budget

HIGHLIGHTS

- Contribution to groundwater recharge from different sources in Rachna Doab is estimated using water budget method for 2005–2011.
- Rainfall contributes to groundwater recharge, i.e., 45% during the Kharif season and 14% during the Rabi season.
- Water courses and field irrigation contribute an average of 33% of total recharge.
- The groundwater reservoir in the study area is depleted at a rate of 94 MCM per season due to more pumping than recharge.

INTRODUCTION

Water is an essential and limited natural resource, and groundwater plays a crucial role in the livelihoods and health of people. In Pakistan, particularly in arid and semi-arid regions, groundwater is extensively used in domestic, agricultural, and industrial sectors. Agriculture is a significant contributor to Pakistan's economy, with Punjab, the most populous province, contributing over 20% (Hassan & Hassan 2017; Zakir-Hassan *et al.* 2022; Zakir *et al.* 2023) of the agriculture Gross Domestic Product (GDP). Punjab is known as 'The Land of Five Rivers,' with Sutlej, Ravi, Chenab, Jhelum, and Indus rivers flowing from East to West. The area between two neighboring rivers is referred to as a Doab. Groundwater depletion in Rachna Doab has led to an increase in the depth to the groundwater table (Hassan & Bhutta 1996). Over-extraction of groundwater has caused a decline in the water table and compromised its quality (Qureshi *et al.* 2010). During crop irrigation, water loss occurs, a portion of which contributes to groundwater recharge (Anderson *et al.* 2015).

The irrigation system in the Indus Basin of Pakistan is encountering numerous operational issues resulting in significant water loss during conveyance and crop irrigation (Ahmad & Majeed 2001). Groundwater recharge occurs via several water sources such as rainfall, seepage from canals and distributaries, river recharge, and irrigation losses. Public and private pumping systems maintain a balance in the recharged aquifer. In Punjab, the area under irrigation through tubewells has increased compared to other provinces, rising from 9.4 million hectares to 9.92 million hectares between 1996 and 1997 and between 1999 and 2000 (Pakistan Statistical Year Book 2001). Groundwater has become the major source of crop water requirements, accounting for over 50% of the total (Zakir-Hassan *et al.* 2022). However, during the drought or when the water table is deep and shallow, the groundwater share can increase to 80%. When large amounts of groundwater containing high levels of sodium carbonate are extracted, it leads to salinization effects (Shafique *et al.* 2002).

The proper estimation of groundwater recharge is essential for effective hydrological management and sustainability. Thus, this study aims to determine the contribution of various sources to the recharge of groundwater in irrigated fields.

MATERIALS AND METHODS

Study area

This study has been conducted on groundwater modeling in Faisalabad and Chiniot districts of Faisalabad Irrigation Zone, Punjab, Pakistan, aimed at planning sustainable well fields. The study area spans an area of 1,944 km^2 between latitude 31.24°N and 31.56°N and longitude 72.39°E and 73.18°E and is located in the central part of Rachna Doab. The study area is depicted in Figure 1 and is bounded by the River Chenab in the North-West and Faisalabad region in the South-East.

The research was conducted in an area with an arid climate that is comparable to that of Faisalabad, characterized by hot summers and cold winters. The primary economic activity in the region is agriculture, with two crop seasons – Kharif and Rabi – being observed. The Kharif season runs from April 16 to October 15 and coincides with the monsoon season. During this period, crops such as cotton, rice, sugarcane, and maize are grown. On the other hand, the Rabi season runs from October 16 to April 15, and it is drier. Wheat is the primary crop grown during this season (Ahmad 2002).

The project area is comprised of two main regions, namely the Kirnana Hill and Alluvial Plains. The northern portion of the project area, near Chiniot, features a group of bed rocks that rise suddenly to a height of 330 m (1,000 ft) above the surrounding plains. In most of the study areas, the bed rocks are underlain by alluvium. The alluvium is composed of sand, silt, clay, and gravel that were deposited by the present and ancestral tributaries of the Indus River. Pebbles of siltstone and '*kankar*' are embedded in silty and clayey sand at different depths of strata. The aquifer is unconfined, with a thickness ranging from 100 to 300 m (Jehangir *et al.* 2002), and is primarily composed of the aforementioned materials.

Water budget method

Different methods are used to estimate net groundwater recharge and changes in storage, such as water balance/ water budget, specific yield, and groundwater flocculation methods. The present study employs the water budget technique to estimate groundwater recharge and changes in storage (Hassan & Bhutta 1996). The water budget technique subtracts all discharge components from the sum of all recharge components to estimate sustainable pumpage (Njamnsi & Mbue 2009), change in aquifer potential (Chen *et al.* 2005), and groundwater recharge and storage (Keller & Jaimes 1998; Healy & Cook 2002; Moon *et al.* 2004; Ruud *et al.* 2004; Arshad & Choudhry 2005; Risser 2008). The present study employs an already established regional lumped method/model of determining the water budget in terms of change in water storage based on the inflows and outflows for the study area (Hassan & Bhutta 1996). It is worth mentioning that the results obtained from the model in the previous study were validated with the results obtained from a specific yield method as well. The results obtained from the developed model agreed with the results obtained from the specific yield method using actual observed groundwater level data (for the period of 1960–1990) (Hassan & Bhutta 1996). Therefore, this methodology has been utilized for the same study area to estimate the current water balance accordingly. The water budgeting technique is represented mathematically by Equation (1) and so on. The groundwater budget of an aquifer is

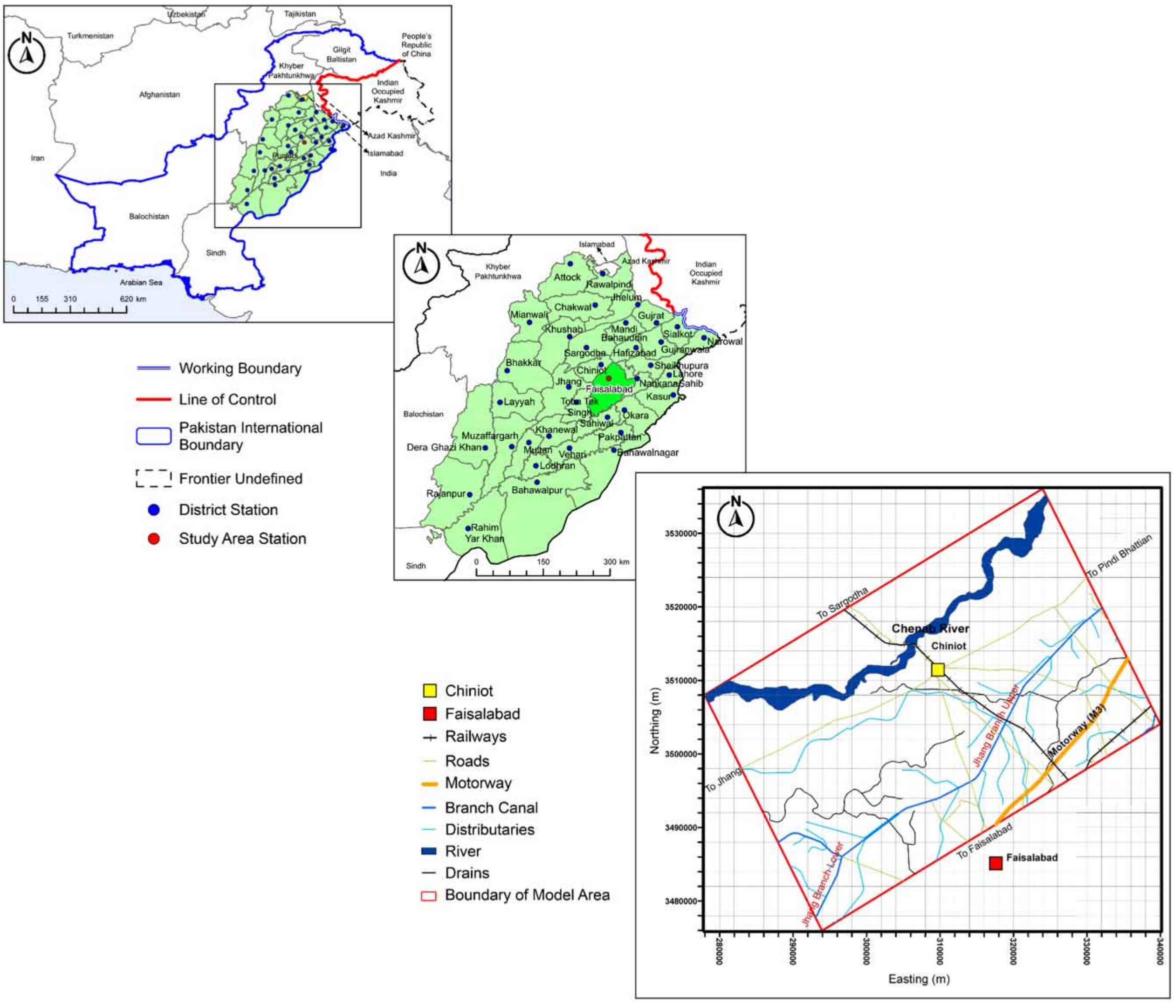

Figure 1 | Location and boundaries of the study area, i.e., Faisalabad, Pakistan.

defined by the inflow (recharge) and outflow (discharge) in a system.

$$\Delta S = I - O \tag{1}$$

where I represents inflow, O is outflow from the system, and ΔS is the change in water storage.

By breaking down the above equation in recharge (inflows) and discharge (outflows) components for our study area, it can be rewritten as:

$$Q_{\text{net}} = (R_{\text{rf}} + R_{\text{c}} + R_{\text{wc}} + R_{\text{fi}} + G_{\text{in}}) - (ET + D_{\text{W}} + G_{\text{out}} + F_{\text{d}}) \tag{2}$$

where Q_{net} represents net recharge (change in storage), R_{rf} represents recharge from rainfall, R_{c} represents recharge from canals, R_{wc} represents recharge from water courses, R_{fi} represents recharge from field irrigation, G_{in} represents groundwater entering into the study area system, ET represents evapotranspiration, D_{W} represents discharge from public and private tubewells, G_{out} represents groundwater outgoing from the area system, and F_{d} represents flow to the drains.

For the regional water balance study, the lateral inflow and out flows to and from the system were considered non-significant (Hassan & Bhutta 1996)

$$Q_{\text{net}} = (R_{\text{rf}} + R_{\text{c}} + R_{\text{wc}} + R_{\text{fi}}) - (\text{ET} + D_{\text{W}} + F_{\text{d}}) \tag{3}$$

The net recharge/change in storage in the study area can be estimated by substituting recharge and discharge components in Equation (3). Groundwater recharge in Rachna Doab was estimated by using the water balance method (Zakir-Hassan 1993; Hassan & Bhutta 1996; Sajil Kumar *et al.* 2021). Components of data collection and data analysis of recharging and discharging are described in the proceeding section. Different components of the water balance equation were estimated as follows:

Recharge from rainfall (R_{rf})

The natural recharge of an aquifer due to precipitation depends on various factors, including the type of precipitation, climatic conditions, soil moisture before and after rainfall, duration and intensity of rainfall, topography, soil properties, cropping intensity, and pattern. For the current study, rainfall data from the Pakistan Meteorological Department were collected for the period between 1996 and 2011. The data were analyzed on a seasonal basis and used to fit into the water balance study of the study area. Isohyetal trends, as reported by WAPDA in 1962, were used to estimate the distribution of seasonal rainfall in different parts of the study area.

The study area comprises 3,720 km^2, which was divided into 930 cells comprising 30 rows and 31 columns. In addition, the present study estimated the water budgeting of the whole study area as a unit entity. In order to estimate rainfall and recharge, an isohyetal map of long-term rainfall records was utilized, and counter maps were created using ArcGIS 9.3 and Surfer Pro 8.0 through Kriging. From the isohyetal map, a ratio factor was computed for each cell. The data of rainfall in each cell, which was calculated through contours, were multiplied by the ratio factor of that cell. It was assumed that 30% of total rainfall seeps into the ground through deep percolation, and 90% of this percolation was considered as recharge. A uniform recharge factor was employed in the study.

Recharge from the irrigation system

The canal irrigation network in Pakistan is known for its large canals and distributaries, making it a unique system worldwide. The study area falls within the Indus Basin Irrigation System, situated in the Rachna Doab region (the area between the Chenab and Ravi rivers) in the Faisalabad Irrigation Zone. The Jhang Branch Canal (JBC) and its tributaries, which receive water from the Chenab River through the Lower Chenab Canal (LCC), irrigate a significant part of the study area. The LCC was established as a perennial canal in 1892. Discharge information for canals, distributaries, and minors entering the study area was obtained from the Program Monitoring and Implementation Unit (PMIU) of the Irrigation Department Lahore and the Irrigation Zone Faisalabad.

The estimation of groundwater recharge from the irrigation system has been conducted in three stages, which includes recharge from Jhang Branch Canal, recharge from distributaries and minors, and recharge from watercourses and irrigated fields. The unlined channels play a vital role in the groundwater recharge process. The seepage loss from these channels depends on the geometry of the canal, aquifer characteristics, canal discharge, and depth to water table. To calculate canal losses in various doabs, WAPDA (Khan 1978) developed an empirical relationship. Equation (4) represents the equation for canal losses in Rachna and Chaj Doabs.

$$S = cQ^m \tag{4}$$

where S is the seepage loss per canal miles in cubic feet per second per million square feet of wetted area (cfs/msf), Q is canal discharge in cfs, and c and m are exponential and were estimated as 0.03 and 0.71, respectively. This empirical relation does not consider the variation in aquifer characteristics and depth to water table below full supply level (FSL) in the canal. Volume of seepage and groundwater recharge from irrigation systems for all seasons was calculated.

Recharge from JBC (R_c)

The primary canal that traverses the research location is Jhang Branch. The seepage from JBC was evaluated utilizing Equation (3), and it is estimated that 75% of canal seepage contributes to recharge (Khan 1978). Excel spreadsheets were established to calculate the cell-wise seepage and recharge for all seasons. The seasonal values for recharge from the canal (R_c) have been included in the next section, which outlines the seasonal groundwater balance sheet. The length of JBC for each cell was calculated using ArcMap GIS 9.3.

Recharge from distributaries/minors

The study did not have access to data on seepage from distributaries and minors. Therefore, it was assumed that 8% of their discharge is lost through seepage. This assumption was based on the fact that the efficiency of the irrigation system has increased to over 80% due to lining. The lengths of the distributaries and minors were used to calculate the seepage losses using the equation mentioned above. These losses were expressed in cfs and the percentage of seasonal losses was distributed over the three reaches of each section. It was assumed that 60% of the loss occurs in the first reach, 30% in the second reach, and 10% in the third reach. The constant seepage losses were converted into groundwater contribution, which is assumed to be 75% of the loss rate according to WAPDA (Khan 1978). This value is flexible and has been used in the process.

To calculate cell-wise distributary losses, the length of a particular cell was divided by the total length of the reach where the cell is located, and then multiplied by the distributary losses in that reach. These losses refer to the losses from the irrigation system within the cell.

Recharge from watercourse (R_{wc}) and field irrigation (R_{if})

Most of the watercourses are unlined and they were not maintained by farmers. Recharge from watercourses and the field irrigation were estimated by using the following procedure. Firstly, total available irrigation water rates at head of watercourses of distributaries and minors have been calculated by subtracting distributaries/minors' losses through seepage from distributaries/minor discharge flow. It is assumed that 25% of total flow in water courses is lost through seepage. 60% of water course seepage losses are assumed into groundwater recharge. Water after watercourses losses (seepage) is available for irrigation field. It is assumed that 30% of field irrigation water is lost through deep percolation (Marc *et al.* 2015) and 90% of the deep percolation is assumed as a recharge.

The total available irrigation discharge rates of all the outlets along a distributary were first calculated by multiplying the seasonal head delivery discharge rates with the average loss fraction of the distributary under consideration. Next, the available irrigation discharge rate at each outlet was calculated as the ratio of the design discharge of the outlet in question and the total design capacity of all the outlets in that distributary/minor, multiplied with seasonal head delivery discharge.

The following step involves determining the percentage of active cell area occupied by each outlet's gross area. Although the canal command area (CCA) was known as a percentage of gross area for each outlet, there was no data available cell area wise. As a result, it was assumed that the irrigation water was uniformly distributed over the gross area of each outlet, resulting in a uniform depth in all cell areas within the gross area of that outlet. This uniform contribution accounted for irrigation recharge (Stevick *et al.* 2005). These percentages varied for each active cell area but remained constant over the various seasons. In this way, seasonal discharge rates for field irrigation were estimated. The head delivery discharges of all outlets are the basic data, and the transform function used in the turning process converts the available discharge into recharge. The previous section presents the estimated seasonal recharges from watercourses and field irrigation.

Groundwater recharge and discharge by tubewells (D_w)

The hydraulic system is balanced by recharge and discharge component. Groundwater is pumped by tubewells. There are two types of tubewells in the study area.

(i) Private tubewells (farmers' wells)
(ii) Public wells (WASA & JICA well fields)

Groundwater draft (discharge) by tubewells has been estimated by applying the unit draft method recommended by Central Groundwater Board Faridabad, India (2009). The unit draft method is used to estimate the quantity of water withdrawn by some source. In this method, unit draft by a single source is multiplied by all such sources present in the study area. For example, a well is a draft source and if more than a number of wells are present in an area. Total draft is estimated by taking discharge rate, utilization factor, operation hours, and days. The product of discharge rate and operation hour and days is total draft by one well for a season. Multiply the number of wells with draft by one well to calculate total draft in an area.

Discharge and recharge by farmers' tubewells

Due to insufficient canal water supply to meet the water requirements of crops, farmers have resorted to installing private tubewells. Factors that determine the installation of tubewells include the farm size, energy source, availability of canal water, climatic conditions, soil characteristics, crop pattern, and financial condition of the farmer. Groundwater discharge is a critical component of the water balance equation and is essential for groundwater management in the future. However, there is no agency that maintains data on tubewells, and no check and balance on their installation by farmers. Consequently, the number of tubewells is increasing every year. According to Punjab Development Statistics (Bureau of Statistics 2011), there are more than 0.941 million private tubewells in Punjab with a discharge capacity ranging from 0.75 to 1.25 cfs.

The data on private tubewells in the study area were collected from multiple sources, including annual reports of Punjab Development Statistics and the Punjab Agriculture Department in Thokar Niaz Beg, Lahore (Bureau of Statistics 2007, 2008, 2009, 2010). They used Arc GIS 9.3 to distribute the tubewells by cell and calculated cell-wise pumpage using the unit draft method in Microsoft Excel. To verify the data, the researchers conducted field surveys for some of the tubewells. They estimated the seasonal discharge rate for each cell by assuming a discharge capacity of 0.75 cfs for each tubewell and an operation factor of 25%.

Private tubewells used by farmers are considered to have less impact on the groundwater system compared to the well fields used for public water supply by the Water and Sanitation Agency (WASA). This is because the pumped water from private tubewells is primarily used for irrigation purposes and the resulting discharge is considered as return flow. However, it has been observed that 15% of the tubewell discharge is lost due to underground seepage, and out of this seepage, 60% is assumed to contribute to groundwater recharge.

Discharge by public tubewells

The urban areas of Faisalabad, Pakistan require groundwater for industrial and domestic purposes and public tubewells have been installed for this purpose. To supply groundwater, WASA, Faisalabad installed 29 tubewells in the Chiniot area on the right side of JBC in 1992. This was necessary as the groundwater in the vicinity of Faisalabad was brackish. Information regarding WASA's old well field was obtained from WASA, Faisalabad. In addition, in 2012, WASA, in collaboration with JICA, installed 25 new tubewells with a discharge capacity of 2 cfs along the left bank of JBC from reduced distance (RD) 225 to 280 along the canal (RD is a measure of canal running length, i.e., 1 RD = 1,000 ft). Similarly, Faisalabad Development Authority (FDA) has planned to install five new tubewells with a capacity of 2 cfs each along JBC at RD 209-216. The net groundwater recharge was calculated by adding recharges from various sources such as rainfall, canal, distributaries/minors, watercourses and field irrigation and return from private tubewells. The groundwater abstraction was calculated by combining the abstraction sources including private tubewells and public well fields. Equation (2) was used to determine the change in storage and net recharge in the aquifer. The extraction of groundwater by public tubewells has a different impact on the groundwater system than that of farmers' tubewells, which is primarily used for irrigation purposes.

RESULTS AND DISCUSSIONS

For the assessment of net groundwater recharge, results of various components including rainfall, groundwater level, and groundwater pumpage were assessed, and conclusions were drawn.

Rainfall

Groundwater recharge is influenced by rainfall, which has a significant impact. The variation in monthly minimum and maximum temperatures and rainfall between 1996 and 2011 is displayed in Figure 2. The graph demonstrates that the majority (70%) of the total rainfall occurs in July and August during the monsoon season, while the lowest rainfall occurs in January and February, which are part of the Rabi season. As a result, groundwater levels rise during the monsoon season due to increased recharge from rainfall and decrease during the Rabi season. The annual average rainfall in Faisalabad varies between 360 and 380 mm, which is consistent with previous research (Khan 1978; Hassan & Bhutta 1996). The data show that there is spatial and temporal (monthly and yearly) variation in rainfall. Rainfall within the range of 350–400 mm occurs every 2–3 years, while rainfall above 400 mm is only observed once every 5 years.

Groundwater levels

Groundwater level measurement is essential in evaluating the potential of aquifers. Temporal and spatial monitoring of groundwater levels assists in the management of groundwater and the determination of recharge and discharge rates in the aquifer (Armbruster & Leibundgut 2001; Healy & Cook 2002). The primary purposes of measuring water levels include: (i) understanding the groundwater regime, (ii) estimating annual recharge and

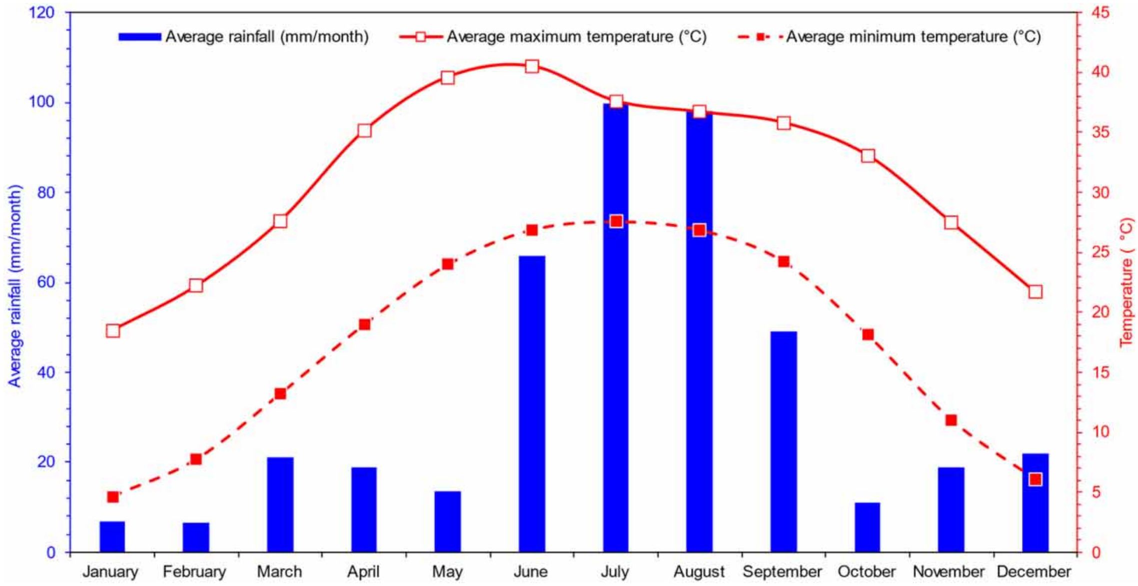

Figure 2 | Profile of temperature and rainfall of Faisalabad, Pakistan for the period of 1996–2011. Data source: Pakistan Meteorological Department (PMD).

discharge rates, (iii) computing the availability of groundwater resources, and (iv) identifying and quantifying the long-term effects of pumping.

To monitor seasonal variations in water levels in the Rachna Doab area, a number of observation wells have been installed. The study area comprises 65 observation wells that have been installed and monitored by various organizations such as SCARP Monitoring Organization (SMO-WAPDA), Directorate of Land Reclamation (DLR), WASA, Faisalabad, and Irrigation Research Institute (IRI). The data on groundwater levels are collected twice a year, before and after monsoon periods. The collected data have been analyzed for frequency, distribution, consistency, and reliability. The locations of the observation wells have been plotted on a map using ArcGIS 9.3 software (shown in Figure 3) and hydrographs for the periods from 2005 to 2011 have been prepared and depicted in Figure 4.

The hydrographs displaying the groundwater elevation between 2005 and 2011 reveal temporal and spatial changes in the recharge and discharge rate of groundwater. A decline in water level during the Rabi season and an increase during the Kharif season were noted, which may be attributed to lower rainfall during the Rabi season and higher water extraction by farmers to cater to crop water requirements. The majority of the rainfall was observed in the monsoon season, specifically from June to August. Observation wells located close to canals and rivers demonstrated higher water levels, suggesting recharge from these sources. Continual decrease in the groundwater levels of observation wells situated near old WASA well fields indicates a higher discharge rate than recharge rate. In the old WASA well field, an average of 0.9 m of water level has been declining.

Groundwater pumpage

Groundwater discharge is a crucial factor that affects the water balance equation and is important in groundwater management and modeling studies for future planning. The study estimates the amount of groundwater abstraction by private and public tubewells. The JICA and WASA Faisalabad (JICA 2019) installed 29 tubewells in the Chiniot area on the right side of JBC at a depth of 400–450 ft with 4 cfs discharging capacity to supply groundwater, as the water in the vicinity of Faisalabad is brackish, and they commenced operations in 1993. The distance between two consecutive tube wells was kept at 400 m, and the seasonal average estimated discharge of the well field is 33.86 million cubic meters (MCM) in Kharif and 32.76 MCM in Rabi season. Table 1 provides a summary of the estimated pumpage through private and public tubewells in the study area for the period from 2005 to 2011.

The primary sources of groundwater stress in the study area, as shown in Table 1, are the pumpage from the existing WASA well field and the private farmer tubewells, which are increasing each year. After conducting field visits and analyzing data obtained from the Agriculture Department, it was discovered that the number of

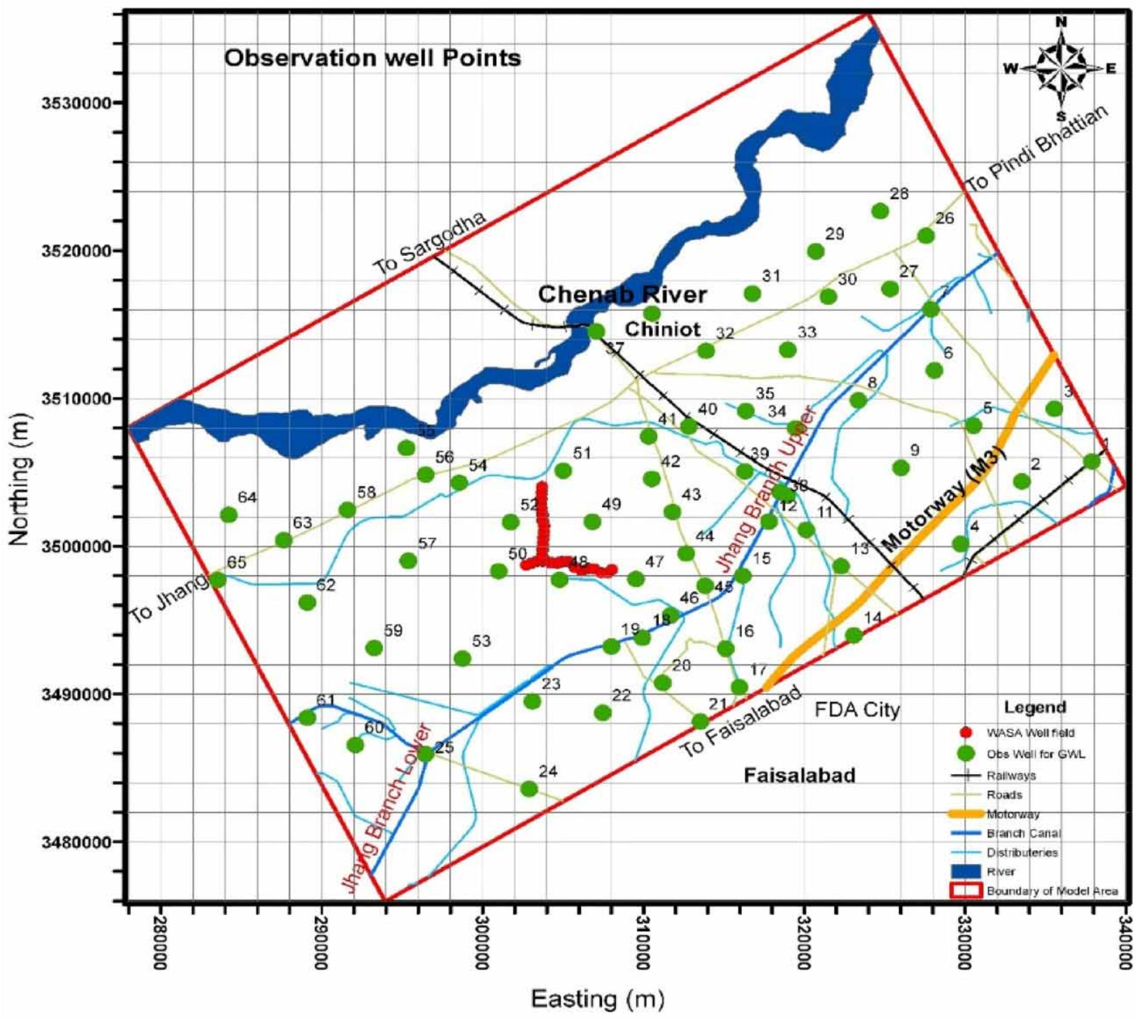

Figure 3 | Location of the observation wells installed in the study area, i.e., Faisalabad, Pakistan.

private tubewells is higher in areas where the groundwater quality is fresh, while the number is lower in areas with brackish water. The data also indicate an annual increase of 2–3% in private tubewells. While the water availability from canals is expected to remain stable, the abstraction of groundwater for agriculture is anticipated to increase. Furthermore, some of the groundwater extracted by private tubewells is said to be returned to the aquifer.

JICA has recently installed tubewells on the left bank of Jhang Branch to fulfill a daily pumping requirement of 91,000 m^3. A feasibility study was conducted to determine the available safe yield of the aquifer, which was mainly based on recharge from JBC. The study found that the operation of new well fields would impact the old well field, leading to an enlarged sink area and increased depth of the sink. This is because the canal seepage, which is a recharge source for the existing well field, will not be available. As the study area is primarily agricultural land, the impact of well fields on the environment is unfavorable to farmers. A socio-economic and environmental impact analysis was conducted, indicating that the construction and operational costs of private tubewells have increased and will continue to increase due to the lowering of the depth to the water table. This has a negative effect on farmers who cultivate food and fibers for the people of Pakistan.

Groundwater recharge

Main recharges sources in the study area are rainfall, canal seepage, and field irrigation. Data regarding rainfall, seepage from canals, distributaries and minors, and field irrigation were analyzed to find out groundwater recharges from these sources. Seasonal groundwater recharge from rainfall, irrigation network (canal seepage), field irrigation and return from farmer tubewells are tabulated in Table 2.

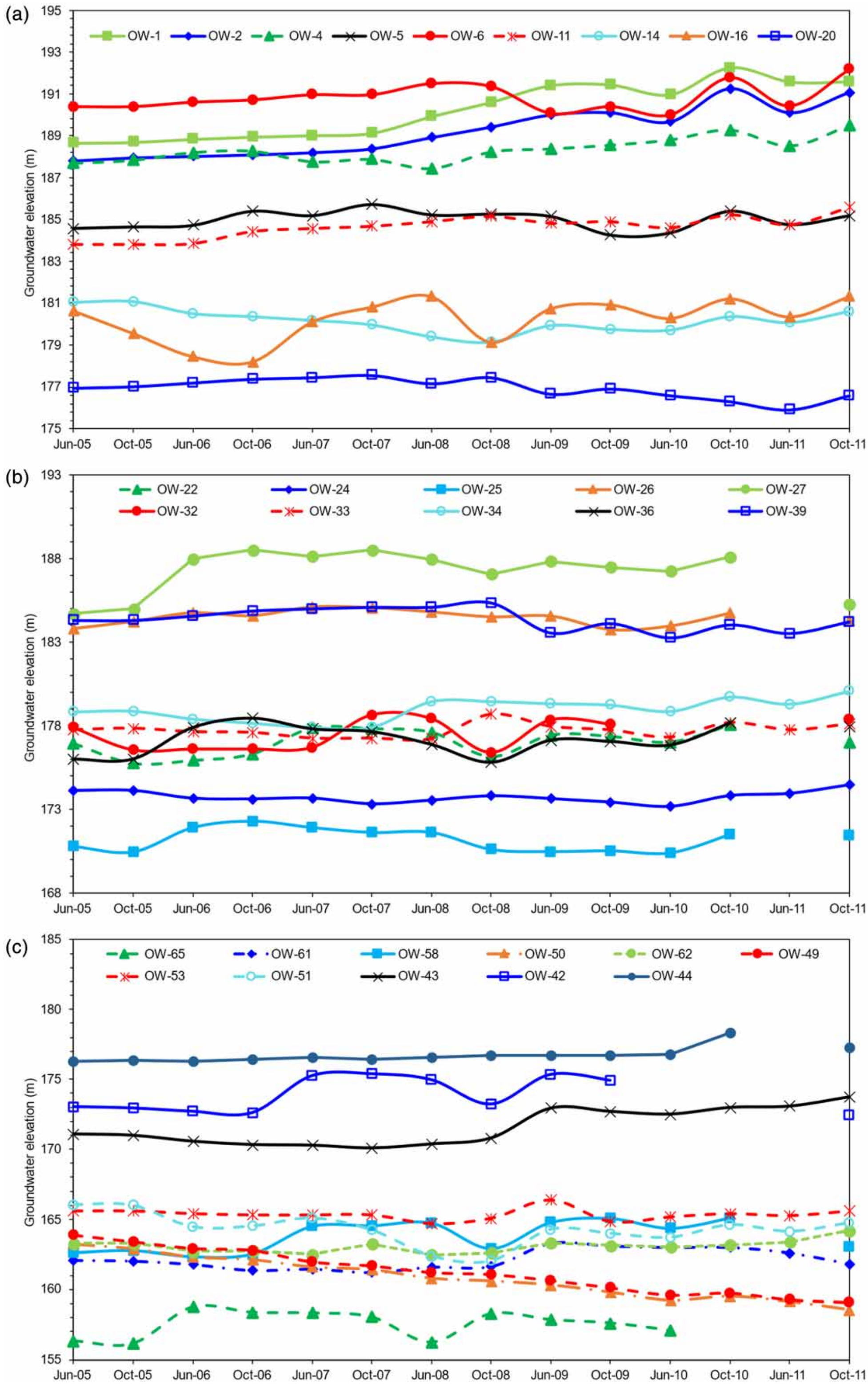

Figure 4 | Hydrograph groundwater elevation (in meters) of observation wells for the period of 2005–2011, divided into three groups (a–c) for clarity.

It has been observed that 70% of the total rainfall occurs in the Kharif seasons. This indicates that groundwater recharge is more in kharif season than that of Rabi season. Results show that recharge from rainfall is directly linked to rainfall rate. The study area contains a major irrigation network system. It consists of the main JBC, its distributaries/minors and water courses. The reach length of JBC from RD 143 to RD 308 runs through the

Table 1 | Seasonal groundwater pumpage by public and private tubewells for the period of 2005–2011 in the study area

Sr. #	Season	No. of private tubewells	Pumpage by private tubewells (million cubic meter)	No. of WASA tubewells	Pumpage by WASA old well field (million cubic meter)	Total pumpage by tubewells (million cubic meter)
1	Kharif-2005	4,749	398.63	29	33.86	432.49
2	Rabi (2005–2006)	4,749	396.45	29	32.76	429.21
3	Kharif-2006	4,856	407.60	29	33.86	441.46
4	Rabi (2006–2007)	4,856	405.37	29	32.76	438.13
5	Kharif-2007	4,965	416.77	29	33.86	450.63
6	Rabi (2007–2008)	4,965	414.49	29	32.76	447.25
7	Kharif-2008	5,077	426.14	29	33.86	460
8	Rabi (2008–2009)	5,077	423.81	29	32.76	456.57
9	Kharif-2009	5,189	435.52	29	33.86	469.38
10	Rabi (2009–2010)	5,189	433.14	29	32.76	465.9
11	Kharif-2010	5,303	445.10	29	33.86	478.96
12	Rabi (2010–2011)	5,303	442.67	29	32.76	475.43
13	Kharif-2011	5,420	454.89	29	33.86	488.75

Table 2 | Seasonal groundwater balance sheet for the period of 2005–2011 for the study area

		Recharge by different sources (million cubic meter)							
Sr. No	Seasons	Rainfall	Main canal	Disty/ Minors	Water courses/ irrigation field	Irrigation tubewell	Total recharge (million cubic meter)	Discharge by tubewells (million cubic meter)	Net balance (million cubic meter)
1	Kharif 2005	182.96	89.61	0.0031	120.53	36.00	428.97	432.49	−3.52
2	Rabi 2005–2006	28.18	71.44	0.0029	102.25	36.00	237.55	429.21	−191.66
3	Kharif 2006	163.90	89.34	0.0032	131.15	37.00	421.08	441.46	−20.38
4	Rabi 2006–2007	70.82	72.01	0.0030	107.32	36.00	286.63	438.13	−151.5
5	Kharif 2007	143.91	91.56	0.0032	132.59	38.00	405.58	447.25	−41.67
6	Rabi 2007–2008	39.59	70.13	0.0029	101.52	37.00	248.54	450.63	−202.09
7	Kharif 2008	282.99	88.66	0.0032	130.32	38.00	540.32	460	80.32
8	Rabi 2008–2009	33.13	59.72	0.0028	87.24	38.00	218.24	456.57	−238.33
9	Kharif 2009	176.49	86.48	0.0031	124.77	39.00	426.94	469.38	−42.44
10	Rabi 2009–2010	14.39	65.70	0.0028	92.24	39.00	211.31	465.9	−254.59
11	Kharif 2010	286.19	80.24	0.0030	116.43	40.00	522.92	478.96	43.96
12	Rabi 2010–2011	26.07	71.90	0.0029	101.46	40.00	239.27	475.43	−236.16
13	Kharif 2011	277.07	86.79	0.0030	115.05	41.00	519.86	488.75	31.11
	Avg	**133**	**79**	**0.0030**	**113**	**38**	**362**	**456**	**− 94**

study area. Seepage from this network recharges the groundwater reservoir. Recharge from canal seepage plays a pivotal role for groundwater potential in the study area.

Based on estimates, the average recharge from the main JBC during Kharif is approximately 85 MCM, while during Rabi it is less, around 70.0 MCM. This is due to the JBC being closed for 1 month in January during Rabi. The main canal contributes about 24% of the total recharge, while water courses and field irrigation contribute about 33%. The abstraction of groundwater through tubewells accounts for approximately 11% of the total recharge.

Throughout the study area, it was observed that there is a distributed irrigation network that not only provides surface water for crops but also helps in the recharge of groundwater. The quality of canal water is suitable for irrigation purposes, and it is less expensive to irrigate crops from surface water supply than from pumped water. However, in the study area, the availability of canal water is insufficient to meet the crop's requirements, which is why private tubewells were installed to ensure maximum crop production. Table 2 represents the estimated net groundwater balance using the water budget/water balance method, and it also elaborates on the recharge and discharge from all the components.

The primary sources of seasonal recharge in the area are rainfall, water courses, and irrigation fields. However, the reservoir is experiencing a depletion rate of 94 MCM per season on average. Table 2 shows some positive values of net change in storage during the Kharif season, indicating a rise in the water table in the aquifer. This can be attributed to the increased rainfall during that season, as depicted in Figure 5. Additionally, the study has found that the depletion rate of groundwater storage is lower in the Kharif season than in the Rabi season.

The main sources of stress on the aquifer in the model area are the pumpage by the existing well field of WASA, the new well field of JICA, and the pumpage by private farmer tubewells that are increasing annually. It is observed that the impact of farmer tubewells is distributed uniformly over the entire study area, as they are scattered throughout. The existing WASA well field is putting intense stress on the groundwater reservoir, resulting in a significant depletion of groundwater. The contributions of seasonal recharge to groundwater from rainfall, watercourse/irrigation fields, and main canals are 41, 35, and 24%, respectively, of the total recharge to the groundwater reservoir, as depicted in Figure 6(a). The overall pumpage of groundwater is greater than the recharge, as shown in Figure 6(b).

Aquifers have a tendency to reach a state of equilibrium if there is no significant change in the inflow and outflow components for an extended period of time. The net change in storage per unit of time is equal to all the flows into or out of the cell. When there is a positive net change in storage, the water table rises, while when there is a negative net change in storage, the water table falls. When there is zero net change in storage, the water table neither increases nor decreases. The outcomes presented in Table 2 reveal that there are only a few years with a positive balance. Negative balance, on the other hand, indicates that net discharge is higher than net recharge. Furthermore, it has been noted that more than 80% of the negative recharge occurs during the Rabi seasons, as the recharge rate is lower (50%) than during the Kharif season.

CONCLUSIONS

This study aimed to explore the contribution of various sources to the recharge of groundwater in irrigated fields in the Rachna Doab, Indus River Basin, Pakistan. The study findings show that groundwater levels vary

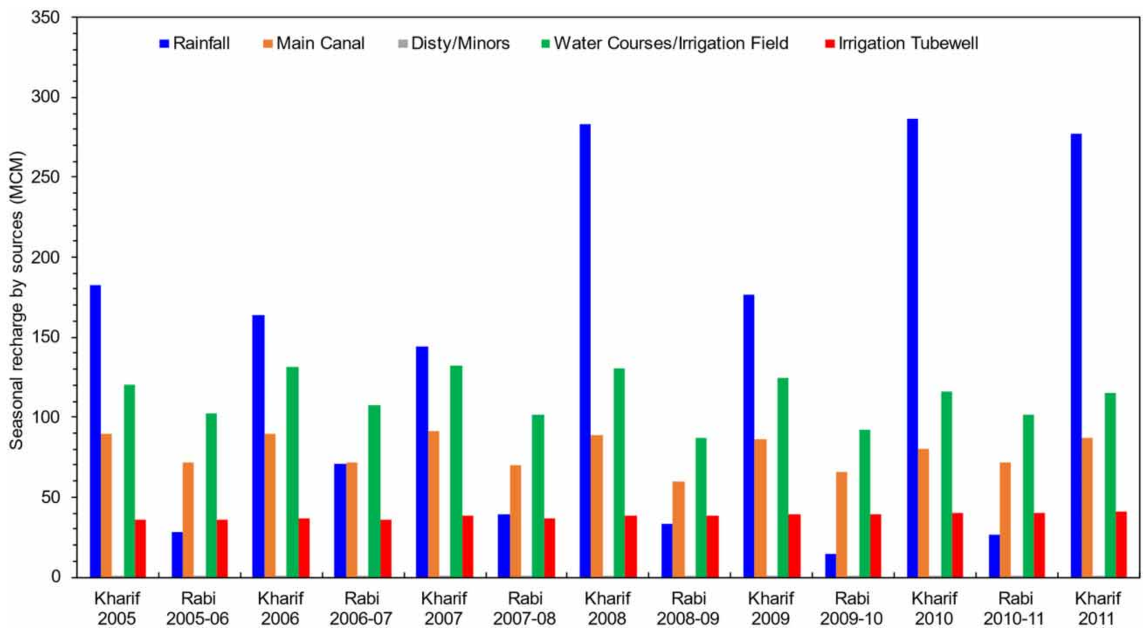

Figure 5 | Seasonal groundwater recharge by different sources for the period of 2005–2011 in the study area.

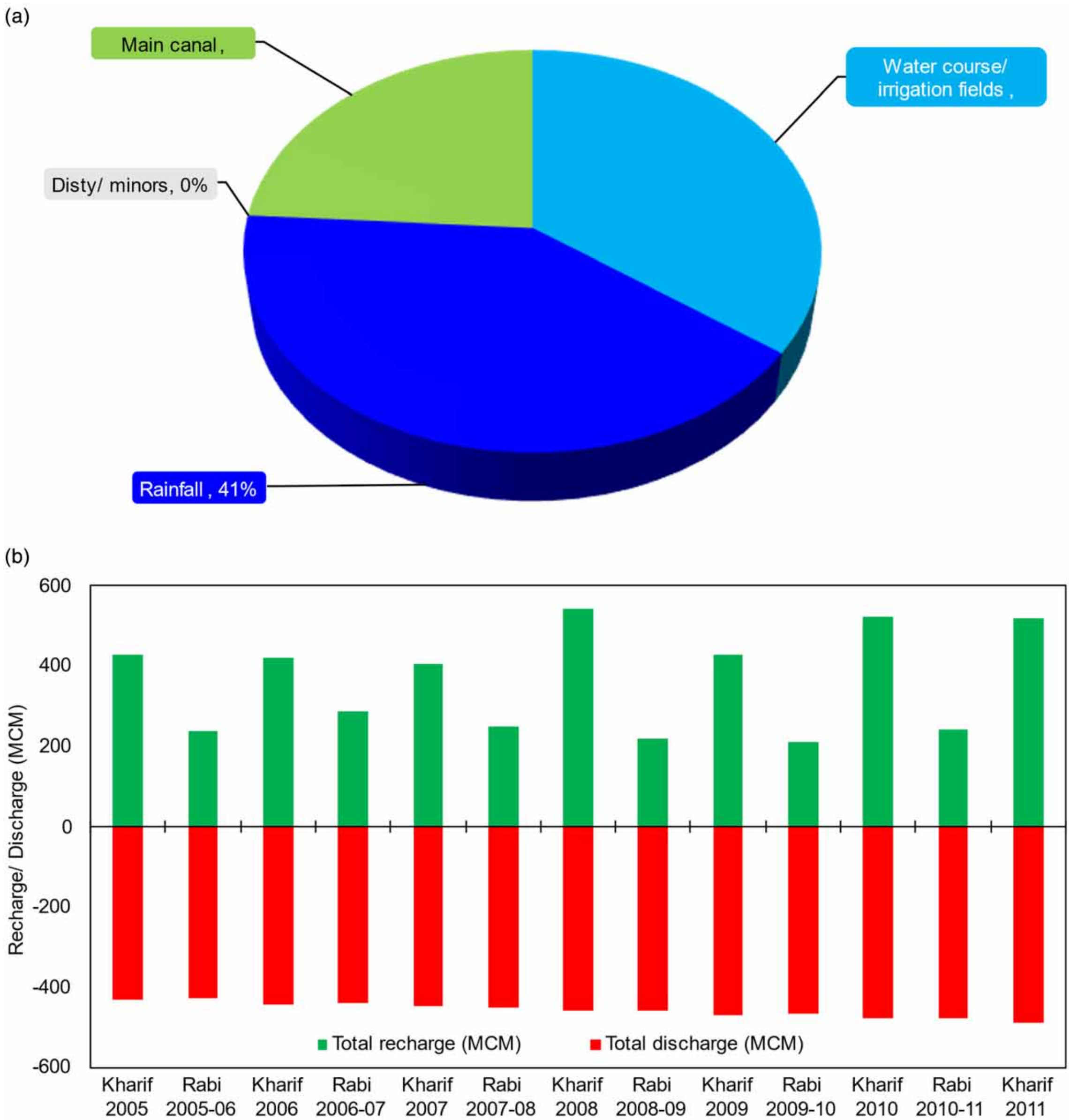

Figure 6 | Profile of (a) percentage contribution of recharge from different sources, and (b) water balance of the total seasonal recharge and discharge for the period of 2005–2011 in the study area.

considerably in both time and space. During wet seasons, water levels increase, while they decrease during dry seasons. Rainfall, water courses/irrigation fields, and main canals all play a significant role in recharging groundwater, with variability across time and location. The average seasonal recharge contributions from rainfall, water courses/irrigation fields, and main canals are 41, 35, and 24%, respectively. Hydrographs indicate that the River Chenab and JBC contribute significantly to recharge in the underlying aquifer, as they exhibit higher groundwater potential head. Groundwater pumpage rates, particularly in existing well fields, exceed recharge rates in the aquifer. The study concludes that the installation and operation of new well fields are unsustainable in the study area since excessive pumpage will further deplete the groundwater reservoir, which is already depleting at a rate of 94 MCM per season. Rainfall is the primary source of recharge in the study region, and overall, groundwater pumpage exceeds recharge.

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AUTHOR CONTRIBUTIONS

G.Z.-H. conceptualized the whole article; S.A., G.S. and F.R.H. developed the methodology; G.Z.-H., and H.A. rendered support in software; S.A., G.S., and F.R.H. validated the article; F.R.H. and H.A. worked on formal analysis; G.Z.-H. and M.S. investigated the data; G.Z.-H. and M.S. brought the resources; G.Z.-H rendered support in data curation; G.Z.-H., S.A., and G.S. wrote the original draft; H.A. and M.S. wrote the review and edited the article; H.A. and M.S. focused on visualization; G.Z.-H. supervised the work; G.Z.-H. administered the project; G.Z.-H. and M.S. conducted funding acquisition. All authors contributed to the article and approved the submitted version.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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