

Chapter 9

Groundwater Irrigated Agriculture Evolution in Central Punjab, Pakistan



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Abstract Irrigation water for agriculture in Pakistan is an issue due to a significant difference between rainfall and crop water needs. Irrigation water is either coming from snowmelt and rainfall in the northern mountains, or being pumped from groundwater. Canal water is limited, and water distribution using the warabandi system, a fixed canal water rotation system among water users on a particular irrigation channel, is not adequate and flexible. The result is overdependence on groundwater, which has impaired crop growth, notably in regions of bad groundwater quality.

The history of groundwater use is not very old in Punjab, Pakistan. By the end of 1990s, canal irrigation was dominant, which was then surpassed by groundwater at the start of 1990s. Since then the groundwater development has expanded exponentially, and recently the groundwater share in irrigated agriculture of the country is about 50%. By the end of 2013, more than one million tubewells are operational in the country and most of them are located in the Punjab province. The consequence is a drop of groundwater level in majority canal commands including the lower Chenab canal irrigation system. Evapotranspiration is the major outflow from the water balance in the region. Cultivation of high delta crops during kharif seasons including rice, cotton and sugarcane are responsible, which is triggered by elevated temperatures. During rabi seasons, wheat is the single major crop all over the lower Chenab canal with its coverage on more than 50% area. The overall recharge results showed that rainfall is the major inflow during kharif seasons, while during rabi canal

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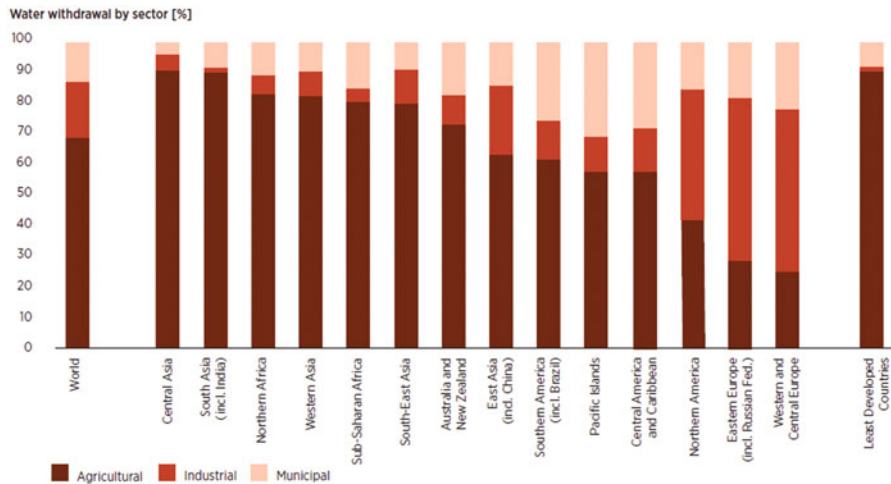
seepage dominates all other recharge sources. During kharif, the other major sources of recharge are field percolations, canal seepage, watercourse losses and distributary losses. Rainfall recharge, field percolation, watercourse losses and distributary losses are considered major recharge sources during rabi seasons.

Keywords Groundwater · Recharge · Remote sensing · Modelling · Kharif · Rabi · Climate change · Punjab · Pakistan

9.1 Introduction

9.1.1 Groundwater for Agriculture Worldwide

Irrigated agriculture is the largest consumer of groundwater resource accounting for about 70% of the global fresh water abstraction and 90% of consumptive water use (FAO 2010; Döll 2009). According to Llamas and Martinez-Santos (2005), during the last 20–30 years, there is a boom in the utilization of groundwater resources for irrigation in areas subject to extended dry seasons and/or regular droughts. Globally, an area of about 300 million ha (Mha) is under irrigation and 38% of this land are equipped for irrigation with groundwater amounting to 545 km³/year (Siebert et al. 2010). Extended groundwater use is not only restricted to semi-arid regions, but also occurs in many humid areas (Fig. 9.1). It is envisaged that groundwater use for irrigated agriculture will continue to expand due to many possible reasons including:



Source: FAO AQUASTAT (<http://www.fao.org/nr/water/aquastat/main/index.stm>, accessed in 2011).

Fig. 9.1 Water withdrawal by sector in different world regions (2005). Agricultural water use is highest in South Asia, nearly 90%, followed by least developed world countries

(a) it is usually found close to point of use, (b) it can be developed quickly by individual private investment at low capital cost, (c) it is available directly for crop needs, (d) it is suited to pressurized irrigation and, (e) it has permitted irrigated agriculture outside of canal command regions (Shah et al. 2007).

Groundwater use has been the crux of the green revolution in agriculture across many Asian nations. Currently, the nations with highest groundwater use are India (39 Mha), China (19 Mha) and USA (17 Mha) (Siebert et al. 2010; Madramootoo 2012). Groundwater use in developing countries is likely to continue and the pressure on groundwater resources over next 25 years in Asia will come from demographic increase, agriculture and increasing water demand per capita, industrial activity and energy demand. It is predicted that the world population will increase from 6.9 billion in 2010 to 8.3 billion in 2030 and to 9.1 billion in 2050, most of which will occur in Asia (Christmann et al. 2009; UNDESA 2009). This increase in population will expand food demand by 50% in 2030 and by 70% in 2050. Nevertheless, Ayars et al. (2006) reported that future scenarios predict a worldwide fresh irrigation water scarcity which is even higher in arid and semi-arid regions. This fact emphasizes that the role of water should be properly regarded as socio-economic and life sustaining commodity demanding management procedures and be implemented through water conservation and resource assessment and reuse (UNCED 2002). Otherwise, poor management of groundwater resources will nullify the social gains made so far (Mukherji and Shah 2005).

9.1.2 Development of Groundwater Use in Pakistan

The Indus Basin Irrigation System (IBIS) of Pakistan was designed about a century ago and is one of the largest contiguous irrigation systems in the world. Its design objectives were to prevent crop failure, avoid famine and expand settlement opportunities (Jurriens and Mollinga 1996) by constructing reservoirs, barrages and main canals which are now serving an area of 16 Mha with some 172 billion m³ of river water flow per year (Aslam and Prathapar 2006). The IBIS is supported by the basin of the Indus river and its tributaries including the Kabul, Jehlum, Chenab, Ravi and Satluj rivers. The irrigation system is comprised of three major storage reservoirs, 19 barrages, 12 link canals, 45 major irrigation canal commands and over 120,000 field water channels. The total canal length is about 60,000 km, with additional 1.8 million km comprising of watercourses, farm channels and field ditches (COMSATS 2003). The rivers of IBIS have glaciated headwaters and snowfields that provide about 50–80% of surface water flow out of the total volume of 137×10^9 m³. The remaining volume is due to monsoon runoff. It is estimated that effective rainfall contributes about 200–300 mm in total crop water availability in the north of the country and some 50 mm in the south (Qureshi et al. 2010).

The IBIS was designed for an annual cropping intensity (ratio of effective crop area harvested to the physical area) of about 75% with the intention of spreading the irrigation water over large areas to expand settlement opportunities (Qureshi et al.

2010), and has grown up to 200% (Kazmi et al. 2012) because more than one crop cycle per year has become possible. Also many canals have lost their design capacity over time due to siltation and erosion of their banks (Badruddin 1996). The result is further limitation of canal water availability per unit of irrigated land (Sarwar 2000).

Huge crop yield losses, land degradation and social instability were observed during the 1970s due to inadequacy, inequity and unreliability of surface water supplies, which resulted in large scale migration of populations from rural areas to cities (Postel 2003). Nevertheless, large farming communities also came forward to rescue themselves against this situation and huge investment is made to extract groundwater by installing agricultural wells for crops. The government also helped farmers by subsidizing the power supply after realizing the benefits of groundwater irrigation for expansion of irrigated areas and to maintain higher crop production levels. In the early days, open wells, Persian wheels, karezes, hand pumps and reciprocating pumps were used for groundwater abstraction. Introduction of indigenous small diesel engines and subsidized energy supply caused a dramatic increase in the number of private tubewells (i.e. individual farmer owned) in the country. By the end of the 1990s, canal irrigation dominated the irrigated agriculture in the country, but in the early 1990s, groundwater irrigation had surpassed canal irrigation (Van der Velde and Kijne 1992). According to Chaudhary et al. (2002), more than 50% of irrigated lands in the country are irrigated by groundwater wells. More than 70% of the farmers in the Punjab province depend directly or indirectly on groundwater for agriculture (Qureshi et al. 2003). About 80% of total tubewells in the country are private owned. According to some estimates, the investment in the private tubewells is of the order of Rs. 25 billion (US\$ 400 million) whereas, the annual benefits are of the order of Rs. 150 billion (US\$ 2.3 billion) in the form of agricultural production (Shah 2003; Qureshi et al. 2010). According to Government of Pakistan, on average, every fourth farming family owns a tubewell and a large proportion of farmers without tubewell ownership purchase water through local groundwater markets (Government of Pakistan (GOP) 2000). Figure 9.2 depicts the development and distribution of tubewells in each province of Pakistan.

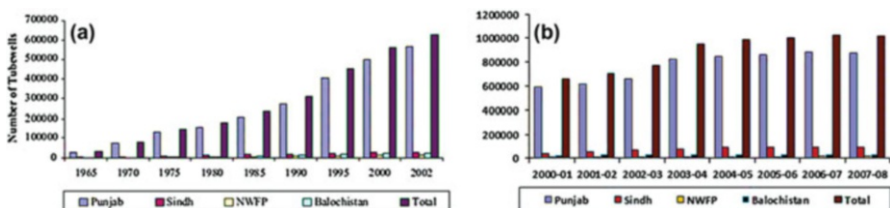


Fig. 9.2 Number of tubewells in Pakistan (a) Qureshi et al. (2010), (b) Agricultural Statistics of Pakistan (2008–2009). The data show that over the years, the growth of tubewells have been exponential in Pakistan particularly in the province of Punjab

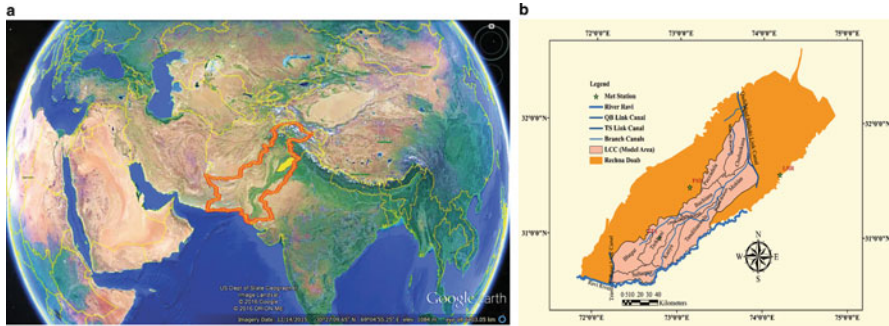


Fig. 9.3 Location of lower Chenab canal irrigation system in Rechna Doab, Punjab, Pakistan. Lower Chenab canal irrigation system is subdivided into ten irrigation subdivisions, a smallest administrative unit for better irrigation management

9.1.3 Study Site

Lower Chenab canal irrigation system, Punjab, Pakistan has been chosen as the study region (Fig. 9.3). The lower Chenab canal irrigation system originates at the Khanki headworks which distribute water to its eastern and western parts through seven branch canals. This irrigation system was designed in 1892–1898 and its command area lies in Rechna Doab which comprises of the land mass between rivers Ravi and Chenab.

The location of the area is between latitude $30^{\circ} 36'$ and $32^{\circ} 09'$ N and longitude $72^{\circ} 14'$ and $77^{\circ} 44'$ E. The present study mainly focuses on the eastern part of lower Chenab canal irrigation system. Two link canals namely Qadirabad-Balloki and Trimu-Sidhnai flow from north to south and fall into river Ravi. Major part of lower Chenab canal irrigation system (east) lies in the districts of Faisalabad and Toba Tek Singh. Administratively, the entire study area is split into ten irrigation subdivisions: Sagar, Chuharkana, Paccadala, Mohlan, Buchiana, Tandlianwala, Kanya, Tarkhani, Bhagat and Sultanpur. Irrigation subdivision is considered as the smallest management unit of the irrigation system. The structuring of these irrigation subdivisions ensures the equitable distribution of canal water among different consumers.

9.1.3.1 History of Groundwater Use in Lower Chenab Canal Irrigation System

Punjab province of Pakistan is called ‘the land of five rivers’ and covers an area of about 127,000 km². These rivers include Indus, Jhelum, Chenab, Ravi and Sutlej from west to east. The land between any two rivers is known as ‘doab’. These doabs include Thal (between rivers Indus and Jhelum), Chaj (between rivers Chenab and Jhelum), Rechna (between rivers Chenab and Ravi) and Bari (between rivers Ravi

and Sutlej) and the plains of these doabs have been formed by alluvial deposits and are very fertile. During the 1900s, during the rule of British over the subcontinent, an extensive network of irrigation canal was constructed in order to develop the barren land and to utilize the water of these five rivers. These practices paid off the investment of millions of rupees for construction of canals and headworks within a few years as the area converted into lush green fields (Hassan and Bhutta 1996). The period of prosperity proved very short as intensive irrigation application coupled with poor subsurface drainage resulted in a gradual increase of groundwater. By the late 1930s and early 1940s, several million acres of land had been affected by waterlogging and salinization, both of which were spreading alarmingly every year (Malmberg 1975). In some areas the groundwater rise was about 24.4 m with an average rate of rise of 0.46 m/year (Hassan and Bhutta 1996). According to Soomro (1975), waterlogging was first identified in the upper parts of Rechna doab within few years of opening of the Lower Chenab Canal.

A comprehensive study of the geology and hydrology of the Indus Plain was carried out in 1954 by the Government of Pakistan in cooperation with the U.S. International Cooperation Administration to assess the groundwater potential of the Northern Plain in order to formulate reclamation measures that would solve the problems of waterlogging and salinity and restore the productive capacity of the land (Malmberg 1975). The results of these studies provided the basis for the reclamation projects utilizing deep tubewells to lower the groundwater level and supplement the canal water supply. The launch of the first project phase took place in 1960 with the first salinity control and reclamation project. The interfluvial area between the Ravi and Chenab rivers was selected for construction of first salinity control and reclamation project. This project was the first of 18 planned reclamation projects that ultimately included about 21 million acres and more than 28,000 production and drainage wells (Malmberg 1975).

Large scale groundwater extraction for irrigated agriculture in Rechna started by the launching of salinity control and reclamation project. Thousands of large capacity tubewells were installed under this program. In the initial phase more than 10,000 public tubewells (supplying an area of 2.6 Mha) with an average discharge capacity of 80 l/s were installed (Bhutta and Smedema 2007; Kazmi et al. 2012). The project resulted not only in the lowering of the water table but also in supplemented irrigation. This also encouraged farmers to own their individual tubewells and led to a proliferation with a typical tubewell discharge capacity of 28 l/s (i.e. $0.03 \text{ m}^3 \text{ s}^{-1}$) or less. The results of first salinity control and reclamation project indicated that it managed to lower the groundwater level below 1.5 m over an area of 2 Mha and below 3 m over 4 Mha, thereby overcoming the problem of waterlogging significantly. It also reclaimed salt affected area from 4.5 to 7.0 Mha (Qureshi et al. 2010). Moreover, the additional groundwater abstraction by salinity control and reclamation project tubewells increased cropping intensities from 80 to 120% in most of the salinity control and reclamation project areas (IWASRI 1998).

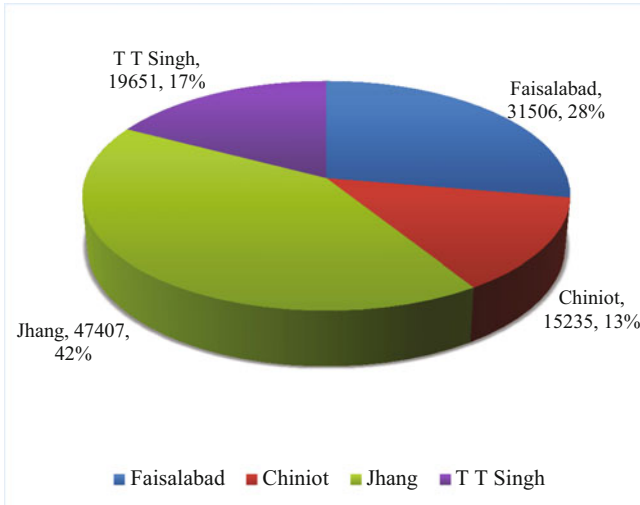


Fig. 9.4 Number of tubewells installed in different districts of Faisalabad division including Faisalabad, Toba Tek Singh, Chiniot and Jhang. The area mainly consist of agricultural lands with mixed cropping system. Major crops grown in the division include rice, cotton, sugarcane, fodder and wheat with higher dependence on groundwater use. (Source: Figure based on own research)

9.1.3.2 Current Status of Tubewells and Groundwater Use

Currently, groundwater is exploited at a huge quantity in the whole country. The total irrigated agricultural area is about 16 Mha and about 9 Mha is located in Punjab, and total share of groundwater pumping in agricultural water use is about 50% (Usman et al. 2015a). According to Punjab Development Statistics Report (2015), there were 1,049,000 tubewells installed in the whole country and alone Punjab is having 867,369 tubewells functional by the end of 2013. As LCC-east is mainly located in the districts of Faisalabad and Toba Tek Singh and 51,157 tubewells were installed in these two districts by the end of 2013. This figure reflects the higher dependence of farmers on groundwater use in the region. The distribution of tubewells in different districts of Faisalabad division can be seen from Fig. 9.4.

The result is drop of groundwater levels in majority parts of the lower Chenab canal irrigation system as can be read from Hassan and Bhuttah (1996) and Usman et al. (2015a), which threatens the sustainability of this resource. To apprehend this phenomenon, there is a dire need to assess the water resources in detail where comprehensive estimation and evaluation of irrigation system components, that contribute to recharge and discharge from the aquifer need to be performed.

The following two case studies were performed in the lower Chenab canal irrigation system. In the first study, a comprehensive assessment of recharge was made, while in the second one, effects of climate change were performed.

9.2 Case Study – I: Estimating Net Groundwater Recharge in Lower Chenab Canal Irrigation System

Sustainability of groundwater is highly dependent on the amount of water that replenishes aquifers, known as recharge. Estimating groundwater recharge is crucial in assessment of water resource availability (Scanlon et al. 2002).

Estimation of recharge may be performed using different methods including direct measurement by lysimeters, tracer techniques, and stream gauging (Lerner et al. 1990). Groundwater modeling approach is another way of estimating recharge if various input components are known with fair accuracy. However, as hydraulic parameters are rarely known and therefore recharge is inaccurately estimated as a lumped parameter. In the current study, groundwater recharge estimation is done by employing water balance approach and different inflow and outflow parameters of water balance equation are worked out separately. The brief description of recharge estimation methodology is presented as follows; however, detailed description of different water balance approaches and its comparison with water table fluctuation method may be seen from Usman et al. (2015a).

9.2.1 Water Balance Approach

Water balance approaches have been widely used for estimating groundwater recharge (Sarwar and Eggers 2006; Maréchal et al. 2006). The water budget for irrigated agricultural regions can be written by the equation (9.1) devised by Singh (2011) and Schicht and Walton (1961).

$$I + R + G_{in} - G_{out} - ET - RO - G_p - G_s = dS \quad (9.1)$$

where I and R are total water from canal supply and rainfall, respectively, G_{in} and G_{out} are lateral groundwater inflow and outflow along a boundary; ET is loss due to evapotranspiration; RO is runoff at surface; G_p is groundwater abstraction by pumping; G_s is groundwater discharge to stream; and dS is the change in groundwater storage. The units of all components are mm per time period.

The simplified version of the above equation may be written if we ignore the surface runoff and groundwater outflow to stream considering the local hydrological conditions in the lower Chenab Canal irrigation system. The above general water budget equation now reads as below:

$$I + R + G_{in} - G_{out} - ET - G_p = dS \quad (9.2)$$

The above equation describes the water budget by incorporating all surface and subsurface parameters for estimation of recharge ignoring detail of each parameter. According to Scanlon et al. (2002), water balance can also be written for saturated

zone (below groundwater). The description of saturated groundwater storage by this principle can be written as below.

$$L_s + G_{in} - G_{out} + IR + RR - G_p = dS \quad (9.3)$$

where L_s is seepage water loss from irrigation canal network, IR is return flow of irrigation from agricultural field and RR is rainfall recharge. The units of all components are mm per time period.

Both equations (9.2) and (9.3) are identical except they offer utilizing of different input data types. For the present study, equation (9.3) was used and remote sensing data and different spatial techniques was applied for input data.

9.2.2 Estimation of Different Recharge Input/Output Parameters

For irrigated agricultural regions, various data types are required including crop, soil, weather, water flow, geology, shape files and piezometric observations. Following is the brief description of recharge estimation from various recharge sources.

9.2.2.1 Canal Geometry and Flow Data

The canal flow and geometry data of different irrigation streams are collected from Irrigation Department, Punjab, Pakistan. Daily data are converted to monthly and then seasonal after integrated for each canal tributary. The irrigation system of lower Chenab canal is designed in a way that separate canals provide irrigation to each irrigation subdivision and hence apartheid of data is easy. Other data include shape geometries of different canals and information about lining/un-lining canal sections.

9.2.2.2 Crop Inventory

Land use land cover mapping at spatial resolution of 250 m for both rabi and kharif cropping seasons were performed using MODIS normalized difference vegetation index spatial data. A number of normalized difference vegetation index composite images were retrieved from both terra and aqua sensors, and after preprocessing of these images, unsupervised classification using *ISODATA* algorithm was performed (Usman et al. 2015b). The temporal profiles of normalized difference vegetation index trends were utilized to identify different major crops in the region. The results of land use land cover classification were validated by constructing error matrixes.

Table 9.1 Summary of MODIS remote sensing data used for soil energy balance algorithm

Data layer	Spatial resolution	Temporal resolution	Purpose
Surface reflectance, band (1–7)	500 m	8 days	Surface albedo, Vegetation index, Land surface water index
Land surface temperature & Emissivity, band (31–32)	1000 m	daily	Land surface temperature, Emissivity

9.2.2.3 Actual Evapotranspiration

Actual evapotranspiration was calculated using soil energy balance algorithm devised by Bastiaanssen et al. (1998) which used different satellite data products for estimation of different variables. The detail of these products can be seen in Table 9.1.

The detailed methodology of soil energy balance algorithm adopted for the current study can be found in Usman et al. (2014, 2015c). The soil energy balance algorithm give daily values of actual evapotranspiration, and from these daily information about actual evapotranspiration, monthly and seasonal maps of consumptive water use were prepared for both rabi and kharif cropping seasons.

9.2.2.4 Net Recharge Components for Water Balance Approach

Different water inflow and outflow components for WBA were worked out at seasonal temporal scales for estimation of net recharge. The detailed description of which is presented as under:

(a) Rainfall

Raster based monthly rainfall data were retrieved from Tropical Rainfall Measurement Mission (TRMM). Spatial data with a resolution of 25 km were downloaded, which were downscaled to 1 km for further use. Local calibration of this data was performed with data from three weather stations located at different places of lower Chenab canal irrigation system. This monthly rainfall data summed up to get seasonal rainfall for all kharif and rabi seasons. Mean, maximum, and minimum rainfalls were calculated in different irrigation subdivision of lower Chenab canal irrigation system along with the standard deviations and coefficients of variation for each season. Lastly, the effective rainfall was estimated by following the United States Department of Agriculture, Soil Conservation Services method. Recharge from rainfall estimated by following guidelines proposed by many different researchers. For instance, Maasland (1968) as reported in Ahmed and Chaudhry (1988) has considered about 20% of total rainfall as recharge. Ahmad and Chaudhry (1988) have reported about 17% to 22% of total annual rainfall as recharge in lower Chenab canal irrigation system. Ashraf and Ahmad (2008) have used 17.9% of total rainfall as groundwater recharge in nearby Chaj Doab, Punjab, Pakistan. All the

proposed guidelines can only yield rough estimates, therefore, in the current study; rainfall recharge is estimated by subtracting monthly effective rainfall plus 5% of total rainfall as unseen losses from total monthly rainfall (Usman et al. 2015a).

(b) Main canal seepage

Estimation of seepage from main irrigation canals was done using two different empirical models developed by the Punjab Private Sector Groundwater Development Project Consultants (1998) and Irrigation Department (2008). These models utilize data of discharge, canal length, wetted perimeter, number of canal operational days in a season and seepage factor. They can be written as:

$$S = 0.052 (Q)^{0.658} \quad (9.4)$$

and

$$RC = 86400.LC.WP.N.SF \quad (9.5)$$

where S is seepage loss or recharge (ft³/s/mile), Q is canal discharge (ft³/s), RC is recharge due to canal seepage (m³), LC is length of canal (m), WP is canal wetted perimeter during its run (m), N is canal running time in a season (d), and SF is seepage factor with recommended values of 0.62–0.75 and 2.5–3.0 m³/s/10⁶ m² of wetted area for lined and unlined canal sections, respectively.

(c) Recharge from distributaries and watercourses

Equation (9.4) can also be used for recharge estimation from distributaries. However, for the current study, a fixed percent of head water diversion was considered as recharge as reported in different studies conducted in the study region (Kennedy 1890; Benton 1904; Blench 1941–1942 and Khangar 1946 (cited in Ahmed and Chaudhry 1988)). Maasland (1968) as cited in Ahmed and Chaudhry (1988) estimated watercourse losses and recommended that about 10–20% of total delivery head is a seepage loss. A value of 10% is considered for the current study.

(d) Recharge from field percolations

Considerable part of irrigation water returns to groundwater through infiltration. A number of researchers has devised different fixed percent values of applied water as recharge. For instance, about 15% of irrigation water is recharge regardless of crop type, according to Maasland (1968). Similarly, Ashraf and Ahmad (2008) assumed 25% of irrigation water as recharge. According to other researchers including Jalota and Arora (2002), Tyagi et al. (2000a, b) and Maréchal et al. (2006) recharge is variable according to crop type and hence they have proposed different coefficients of irrigation return flow for different crops. For the current study, later approach was employed and satellite images were processed to differentiate different

crop areas and assignment of different coefficients of irrigation return flows were done. Following relationship was used for estimation of recharge:

$$IR = TI.F_c \quad (9.6)$$

where IR is recharge from field percolation (mm), TI is the total irrigation water applied at farm gate both from canal and groundwater sources (mm), and F_c is the fraction of water contributing to recharge.

The information about F_c (i.e field application efficiency) for different crops can be taken from Jalota and Arora (2002), and Tyagi et al. (2000a, b). Field percolation loss is about 50% for rice, while it is about 5.6%, 31.2%, 15%, 20% for wheat, kharif fodder, cotton and, rabi fodder and sugarcane crops, respectively.

(e) Estimation of total irrigation water at farm

Total irrigation is equal to estimated actual evapotranspiration under the ideal conditions, where all water supplied at farms is available for the crop utilization; nevertheless, in reality applied water at farm is always greater than actual evapotranspiration due to limited application efficiencies and conveyance efficiencies that are never 100%. Thus, total irrigation may be calculated from the following equation:

$$TI = \left[\frac{(ET - ER) \times 100}{AE} \right] + RO + US \quad (9.7)$$

where AE, ER, RO and UWS are irrigation application efficiency, effective rainfall, runoff and unsaturated water storage, respectively. Effective rainfall is excluded from actual evapotranspiration because total irrigation is total water available at farms from only canal and groundwater sources. Runoff and unsaturated water storage are ignored in equation (6) as very little runoff occur due to bunds on irrigated fields and, for long time periods steady state conditions prevails and the soil water content is constant and, hence, changes can be ignored (Usman et al. 2015a; Yin et al. 2011).

(f) Groundwater pumping

Groundwater pumping was estimated using the following relationship:

$$G_p = TI - CI \quad (9.8)$$

where CI is the net water availability from canal irrigation after incorporating conveyance losses.

(g) Lateral inflow and outflow of groundwater

Inverse modeling using FEFLOW 6.1 groundwater software and PEST was used for estimation of later groundwater inflow and outflow. The modeling results were

verified with Darcy's law (Darcy 1856). For Darcy's law inflow and outflow cross sections were identified by plotting piezometric data and borelog information in Voxler geo-statistical software from Golden software's. The cross sectional flow areas for each irrigation subdivision were estimated as suggested by Baalousha (2005). Groundwater contour maps were prepared using Surfer 8.0. The flow area of each sub section contributing to inflow and outflow was estimated to be the area below the intersection of the regional potentiometric surface.

9.2.3 Results of Case Study – I

9.2.3.1 Land Use Land Cover Mapping

Error matrixes were constructed for different land use land cover types by incorporating 250 control points and polygons. From Table 9.2, it can be observed that overall accuracy for rabi seasons fluctuated between 79.5% and 87.4%. During kharif seasons, the efficiency varied from 76.2% to 80.08%. The overall average accuracies for rabi and kharif were found to be 82.8% and 78.2%, respectively. The results are in concurrence with some other studies of this kind (Thi et al. 2012; Wardlow et al. 2007). Bastiaanssen et al. (1998) reported that overall accuracy generally ranges between 49% and 96% depending upon the spatial data coverage and the field size under study. According to Giri and Clinton (2005), the overall efficiency gives a crude measure of accuracy as its measurement by error matrix is dependent on sampling size. Small sampling size may lead to assign the correct class by chance (Foody 2002), and therefore the kappa coefficient is necessary to measure (Congalton 1996). The value of kappa coefficient results the agreement after removing the errors come by chance by incorporating the off diagonal elements of the error matrices (Yuan et al. 2005). The values of kappa coefficient for each individual season were calculated and shown in Table 9.2. The average kappa coefficient value for rabi seasons was 0.73 with minimum and maximum values of 0.66 and 0.77. For

Table 9.2 Average classification accuracies and kappa coefficient for different land use classes during rabi (i.e. November to April) and kharif (May to October) cropping seasons

No	Year	Rabi		Kharif	
		Overall accuracy	K	Overally accuracy	K
1	2005–2006	87.4	0.77		
2	2006–2007	79.5	0.66	76.2	0.69
3	2007–2008	83.6	0.74	79.3	0.73
4	2008–2009	81.9	0.71	78.1	0.71
5	2009–2010	81.2	0.71	77.0	0.70
6	2010–2011	83.8	0.75	78.6	0.72
7	2011–2012	82.5	0.74	80.1	0.74
Average		82.8	0.73	78.2	0.71

Table 9.3 Coverage of major land use land cover types during rabi (i.e. November to April) and kharif (May to October) cropping seasons

Rabi season			Kharif season		
Year	Class	Area (hectares)	Year	Class	Area (hectares)
2005–2006	Fodder	227,020	2006	Rice	336,947
	Sugarcane	128,257		Fodder	319,260
	Wheat	548,635		Sugarcane	99,519
	Fallow/Barren	22,160		Cotton	136,191
				Fallow/Barren	34,156
2006–2007	Fodder	230,029	2007	Rice	253,017
	Sugarcane	124,575		Fodder	375,766
	Wheat	551,216		Sugarcane	198,080
	Fallow/Barren	20,251		Cotton	76,758
				Fallow/Barren	22,451
2007–2008	Fodder	281,160	2008	Rice	251,654
	Sugarcane	126,627		Fodder	414,699
	Wheat	497,546		Sugarcane	106,228
	Fallow/Barren	20,738		Cotton	131,034
				Fallow/Barren	22,457
2008–2009	Fodder	289,135	2009	Rice	362,218
	Sugarcane	105,722		Fodder	323,286
	Wheat	512,320		Sugarcane	87,172
	Fallow/Barren	18,895		Cotton	116,974
				Fallow/Barren	36,422
2009–2010	Fodder	213,847	2010	Rice	349,121
	Sugarcane	97,907		Fodder	231,065
	Wheat	598,403		Sugarcane	137,540
	Fallow/Barren	15,915		Cotton	179,155
				Fallow/Barren	29,190
2010–2011	Fodder	299,478	2011	Rice	342,038
	Sugarcane	78,435		Fodder	169,562
	Wheat	534,474		Sugarcane	137,791
	Fallow/Barren	13,685		Cotton	259,529
				Fallow/Barren	17,152
2011–2012	Fodder	248,550			
	Sugarcane	113,555			
	Wheat	545,132			
	Fallow/Barren	18,836			

kharif, the average value was 0.71 with a minimum value of 0.69 and a maximum value of 0.74. The findings are in agreement with the results of Altman (1991).

Table 9.3 depicts the distribution of different land use land cover classes from 2005 to 2012 for rabi and kharif seasons. Wheat was found to be major crop during rabi seasons with overall average area of more than 50%. The other dominant crops were rabi fodder and sugarcane with percent areas of 32.3% in 2010–2011, and

13.8% in 2005–2006, respectively. During kharif seasons, rice was found to be highest grown crops with minimum volatility in its command area for different seasons. Sugarcane had a maximum percent area of about 21.4% for 2007 with minimum value of 9.4% for 2009. The minimum and maximum percent values for kharif fodder were 18.3% for 2011 and 44.8% for 2008. In case of cotton, the minimum and maximum values were 8.3% in 2007 and 28% in 2011, respectively.

9.2.3.2 Validation of Soil Energy Balance Algorithm Based Actual Evapotranspiration

ET results using SEBAL are mandatory to validate prior to its use for hydrological studies. The results were validated with ET from advection-aridity approach (Brutsaert and Stricker 1979), as results from lysimeters, Bowen ration energy balance (Bowen 1926), and the eddy covariance (Wilson et al. 2002) were unavailable. The advection-aridity equation used was formulated as:

$$ET = (2\alpha_e - 1) \frac{\Delta}{\Delta + \gamma} Q_{ne} - \frac{\gamma}{\Delta + \gamma} E_a \quad (9.9)$$

where ET is the actual evapotranspiration (mm d^{-1}), Δ is the slope of temperature versus vapour pressure ($\text{kPa } ^\circ\text{C}^{-1}$), Q_{ne} is the ratio between R_n and λ , R_n is net radiation, γ is the psychrometric constant ($\text{kPa } ^\circ\text{C}^{-1}$) and E_a is the drying power of the air (Brutsaert and Stricker 1979; Brutsaert 2005). The effects of advection were scaled by the aerodynamic vapor transfer term E_a :

$$E_a = f\left(\bar{u}_r\right) (e_s - e_a) \quad (9.10)$$

where $f\left(\bar{u}_r\right)$ is the wind function, e_s and e_a are the saturation and actual vapor pressures in mmHg (Brutsaert and Stricker 1979). The wind function was a stelling-type standard equation written as devised by Brutsaert (2005):

$$f\left(\bar{u}_r\right) = 0.26 \left(1 + 0.54f_{U_2}^-\right) \quad (9.11)$$

Where $f_{U_2}^-$ is the mean wind speed at 2 m height (ms^{-1}).

The validity results can be visualized in Fig. 9.5, which indicates satisfactory results for both rabi and kharif cropping seasons. Nevertheless, it is noted that higher Nash Sutcliffe efficiency and relatively low bias values were found during winter seasons (rabi) as compared to summer seasons (kharif). Advection-aridity method performs better under low temperatures as compared to hotter and arid environmental conditions (Hobbins and Ramirez 2001; Liu et al. 2010). Similar types of results were reported for the current study where quite high Nash Sutcliffe efficiency (i.e. 0.92), and relatively low bias (-13.32) were found for rabi seasons. However,

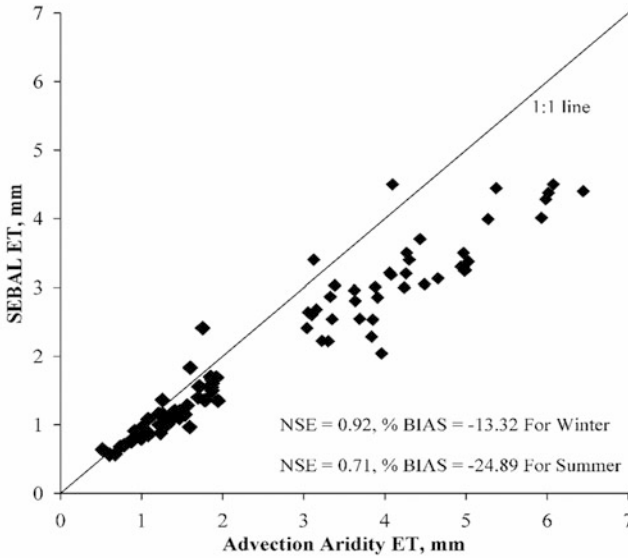


Fig. 9.5 Validation of soil energy balance algorithm based actual evapotranspiration with advection-aridity approach. During rabi seasons (November to April) results are better correlated as compared to kharif seasons (May to October). NSE Nash Sutcliffe efficiency, %BIAS percentage bias error, SEBAL soil energy balance algorithm, ET actual evapotranspiration. (Source: figure based on own research)

for kharif, the values of Nash Sutcliffe efficiency and bias were found to be 0.71 and -24.89 , respectively (Usman et al. 2014).

The actual evapotranspiration during kharif seasons ($546.2 \text{ mm} \pm 47.50 \text{ mm}$) was observed to be about two times higher than in rabi seasons ($274 \text{ mm} \pm 20 \text{ mm}$). The main reason for this was high crop water requirements of rice, cotton, and sugarcane which were triggered by high temperatures during these seasons. Wheat was cultivated at larger areas along with fodder during rabi season, as opposed to this. There was an abrupt change in the trends of actual evapotranspiration for kharif from mid July to September because of higher availability of irrigation water due to monsoon rainfalls, which resulted in better vegetative growth for crops. A relatively steep rise in trend was observed from end of February to end of March, when temperature raised and sufficient soil moisture became available to crops after winter rainfall during the rabi seasons.

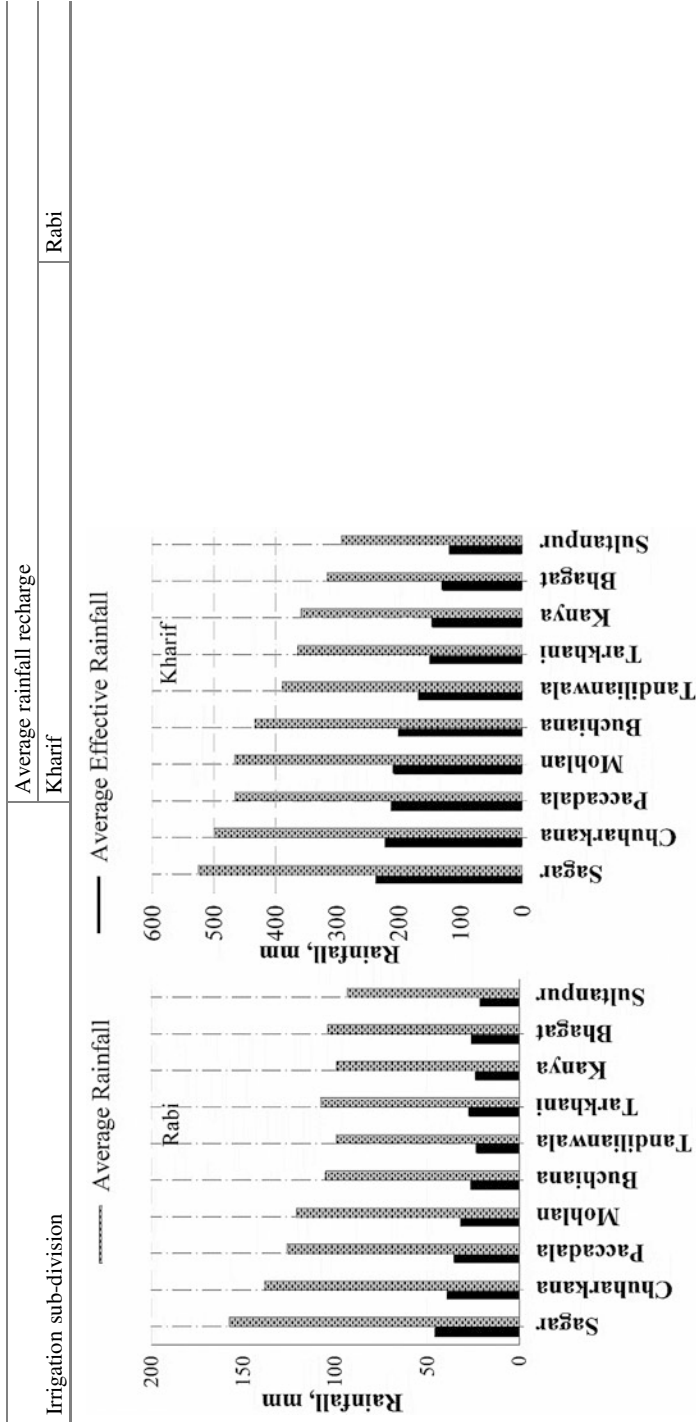
9.2.3.3 Rainfall Recharge

Table 9.4 shows the distribution of average rainfall in different irrigation subdivisions of lower Chenab canal irrigation system for both rabi and kharif seasons. It is visible that rainfall decreases from upper parts of lower Chenab canal irrigation

Table 9.4 Details of average rainfall, average effective rainfall and average annual recharge (mm) in different irrigation subdivisions of lower Chenab canal irrigation system during rabi (November to April) and kharif (May to October) cropping seasons. (Source: figure based on own research)

Irrigation sub-division	Average rainfall recharge	
	Kharif	Rabi
Sagar	127.5 ± 26.9	29.9 ± 10.7
Chuharkana	120.3 ± 26.1	24.3 ± 8.6
Paccadala	106.6 ± 22.9	23.2 ± 8.2
Mohlan	100.8 ± 27.3	20.1 ± 7.7
Buchiana	103.7 ± 23.5	19.0 ± 8.0
Tandilianwala	100.0 ± 24.4	18.7 ± 7.3
Tarkhani	77.5 ± 24.8	17.6 ± 6.5
Kanya	86.8 ± 23.5	16.1 ± 5.5
Bhagat	95.5 ± 28.6	20.7 ± 9.3
Sultanpur	84.8 ± 13.2	17.6 ± 6.9

Table 9.4 (continued)



system to lower parts. The rainfall was higher during the kharif seasons mainly due to monsoon rainfalls from mid-July to mid-September, which accounted for about 65% of total annual average rainfall. Similarly, the average effective rainfall can be seen for each individual irrigation subdivision, however, the individual average effective rainfall values for each cropping year vary due to variability in cropping, rainfall intensity and consumptive water requirements (Patwardhan et al. 1990).

The recharge results for different seasons and irrigation subdivisions indicate that generally higher recharge was found in the upper lower Chenab irrigation system regions as compared to lower ones. The highest recharge was estimated for Sagar with an average value of $127.5 \text{ mm} \pm 26.9 \text{ mm}$ followed by Chuharkana, Paccadala, Buchiana, Mohlan, Tandlianwala, Bhagat, Kanya, Sultanpur and Tarkhani with average values of $120.3 \text{ mm} \pm 26.1 \text{ mm}$, $106.6 \text{ mm} \pm 22.9 \text{ mm}$, $103.7 \text{ mm} \pm 23.5 \text{ mm}$, $100.8 \text{ mm} \pm 27.3 \text{ mm}$, $100 \text{ mm} \pm 24.4 \text{ mm}$, $95.5 \text{ mm} \pm 28.6 \text{ mm}$, $86.8 \text{ mm} \pm 23.5 \text{ mm}$, $84.8 \text{ mm} \pm 13.2 \text{ mm}$, and $77.5 \text{ mm} \pm 24.8 \text{ mm}$, respectively, during the kharif seasons. Bhagat subdivisions showed relatively higher recharge in the lower reaches with more variability, which was mainly associated to higher rice cultivation in the area. For rabi seasons, the variability in recharge for different subdivisions was found low as compared to kharif seasons.

9.2.3.4 Recharge from Other Sources

Table 9.5 shows the detailed results of recharge from different components of irrigation system for each irrigation subdivision during both rabi and kharif seasons. During kharif seasons, after rainfall (i.e. 1003.5 mm), field percolation (809.2 mm) was considered to be major recharge sources in lower Chenab canal irrigation system during the study duration, however, its value was variable for individual irrigation subdivision. The other major sources of recharge were canal seepage (352.7 mm), watercourse losses (258 mm) and distributary losses (226 mm), respectively. The share of field percolation in recharge in comparison to other recharge sources, except rainfall, was almost equal. The lowest contribution was coming from lateral groundwater inflow and outflow (91 mm). For rabi, rainfall (207.1 mm) and field percolation (277.1 mm) were no more major recharge sources, but canal seepage was the dominant source (318.2 mm) followed by watercourse losses (174.2 mm), distributary losses (160.5 mm) and lateral groundwater inflow and outflow (91 mm). It was also to be noted that during the rabi season, rainfall recharge was less due to absent of monsoon rainfalls. The detailed information of different recharge components for each irrigation subdivisions can be found from the following Table 9.5, both for kharif and rabi seasons.

Table 9.5 Detailed groundwater recharge (mm) in different irrigation subdivisions of lower Chenab canal irrigation system by different sources during rabi (November to April) and kharif (May to October) cropping seasons

Irrigation sub-division	Canal seepage		Distributary losses		Watercourse losses		Field percolation		Groundwater inflow and outflow	
	Kharif	Rabi	Kharif	Rabi	Kharif	Rabi	Kharif	Rabi	Kharif	Rabi
Sagar	7.9 ± 2.2	5.1 ± 0.5	15.8 ± 2.1	1.6 ± 0.2	22.8 ± 3.1	2.9 ± 0.4	99.6 ± 13.5	15.2 ± 3.3	15.4 ± 2.2	16.0 ± 1.7
Chuharkana	59.7 ± 3.4	60.2 ± 12.3	14.7 ± 1.6	8.4 ± 1.4	18.2 ± 1.8	10.4 ± 1.9	106.2 ± 14.0	16.7 ± 2.5	3.0 ± 0.8	2.9 ± 0.5
Paccadala	10.9 ± 0.6	8.9 ± 0.8	28.9 ± 1.9	22.8 ± 2.1	27.5 ± 2.6	21.3 ± 3.4	91.0 ± 9.2	31.5 ± 7.6	3.1 ± 0.8	3.4 ± 0.7
Mohlan	44.9 ± 2.5	41.3 ± 4.1	30.4 ± 2.2	20.8 ± 2.1	33.1 ± 2.9	22.0 ± 2.8	118.1 ± 9.4	26.2 ± 4.8	7.0 ± 0.6	6.8 ± 1.0
Buchiana	103.6 ± 1.7	92.9 ± 8.4	23.9 ± 1.3	18.6 ± 1.7	27.1 ± 2.0	18.1 ± 2.1	68.8 ± 8.3	49.0 ± 4.5	-3.0 ± 0.9	-2.9 ± 0.5
Tandilianwala	20.9 ± 1.1	18.4 ± 1.5	21.4 ± 2.7	16.9 ± 2.4	25.8 ± 3.4	20.1 ± 3.9	66.5 ± 5.3	26.3 ± 3.4	0.0 ± 0.4	0.2 ± 0.1
Tarkhani	30.9 ± 1.3	26.6 ± 1.9	27.1 ± 1.8	21.8 ± 2.8	37.7 ± 2.3	29.7 ± 3.5	64.6 ± 10.1	29.0 ± 2.8	9.0 ± 0.7	8.6 ± 0.8
Kanya	41.3 ± 2.1	36.4 ± 3.0	26.0 ± 4.6	20.6 ± 2.3	28.0 ± 4.9	21.3 ± 2.7	60.2 ± 6.1	24.3 ± 3.5	6.5 ± 1.0	6.7 ± 0.7
Bhagat	14.5 ± 0.6	12.3 ± 0.8	18.5 ± 0.9	14.5 ± 1.3	14.9 ± 0.9	11.4 ± 1.4	73.0 ± 10.2	23.5 ± 5.0	22.3 ± 1.0	22.6 ± 1.0
Sultanpur	18.3 ± 0.9	16.1 ± 1.3	19.7 ± 4.1	14.8 ± 4.1	23.1 ± 4.9	17.1 ± 5.0	61.2 ± 3.5	35.3 ± 4.6	27.4 ± 1.8	26.8 ± 2.7

Table 9.6 Groundwater pumping and net recharge (mm) in different irrigation subdivisions of lower Chenab canal irrigation system during rabi (November to April) and kharif (May to October) cropping seasons

Irrigation sub-division	Groundwater Pumping		Net recharge	
	Kharif	Rabi	Kharif	Rabi
Sagar	193.8 ± 31.5	192.4 ± 32.6	95.2 ± 37.7	-121.9 ± 40.8
Chuharkana	225.3 ± 47.6	142.5 ± 24.0	96.9 ± 54.1	-19.6 ± 37.3
Paccadala	145.0 ± 48.6	83.2 ± 33.3	123.0 ± 59.5	27.9 ± 37.5
Mohlan	157.7 ± 41.4	83.5 ± 32.4	176.7 ± 50.1	53.7 ± 40.7
Buchiana	177.9 ± 47.8	116.7 ± 25.0	146.2 ± 50.6	78.0 ± 33.7
Tandilianwala	173.3 ± 29.8	90.5 ± 31.2	61.2 ± 46.1	10.0 ± 39.2
Tarkhani	108.1 ± 25.1	41.9 ± 19.0	138.6 ± 30.5	91.3 ± 31.7
Kanya	169.1 ± 24.0	85.3 ± 29.3	79.7 ± 38.8	40.2 ± 32.3
Bhagat	264.8 ± 33.1	158.7 ± 28.7	-26.1 ± 31.9	-53.8 ± 36.0
Sultanpur	228.7 ± 16.6	134.1 ± 44.1	5.8 ± 30.9	-6.4 ± 51.9

9.2.3.5 Groundwater Pumping and Net Recharge

Groundwater pumping was higher during kharif seasons as compared to rabi seasons at lower Chenab canal irrigation system scale. The detailed analysis of groundwater pumping data showed that highest groundwater pumping was found at two lower and one upper irrigation subdivisions including Bhagat, Sultanpur and Chuharkana with average values of 264.7 mm and 229 mm and 226 mm, respectively (Table 9.6). While, least pumping was found in Tarkhani with an average value of 108 mm, during different kharif seasons. The results of net recharge showed that it was generally positive for all the irrigation subdivisions during kharif seasons excluding two lower irrigation subdivisions including Bhagat and Sultanpur. For rabi seasons, groundwater pumping was observed to be highest in most of the upper irrigation subdivisions of lower Chenab canal irrigation system, which was mainly due to decreased canal flow in spite of less water requirements by the crops, particularly in the Sagar irrigation subdivision, where the net recharge is negative for the whole study period. It was also negative for Bhagat and Sultanpur irrigation subdivisions at the lower locations of lower Chenab canal irrigation system. For rest of the locations, the net recharge was variable from season to season.

The results of net recharge from the current study are comparable to previous studies including Hassan and Bhutta (1996), according to which annual recharge was found to be 60 mm for the Rechna Doab. They also concluded positive recharge for kharif seasons, whereas it was generally negative for rabi seasons. Similarly, Boonstra and Bhutta (1996) conducted a recharge study in the whole Rechna Doab and concluded that positive recharge (i.e. 73 mm) is observed annually. The other studies include Habib (2004) and Bhuttah and Alam (2005), according to which annual groundwater recharge is positive for majority parts of Indus plain.

9.3 Case Study – II: Recharge Under Changing Climate in Lower Chenab Canal Irrigation System

Climate change is important to study as it can induce changes in natural ecosystems (IPCC 2007). Particularly, groundwater has attained least attention in the past under climate change from scientific and other concerned communities (Taylor et al. 2012). According to IPCC (2008), there has been very limited research on the effects of climate change on groundwater although its contribution in world's water use is considerable. The effects of climate change on natural systems are quite complex, for instance, one may question that annual recharge is considerably affected by annual rainfall only (Crosbie et al. 2009), but recharge can also be affected by rainfall seasonality, intensity, humidity, air temperature, and actual evapotranspiration. In arid and semi-arid regions, increased variability in rainfall may increase groundwater recharge due to more frequent rainfalls. But at the same time, actual evapotranspiration can be higher due to elevated temperatures and hence, there is less net recharge (Hetze et al. 2008) and vice versa.

For irrigated regions such as lower Chenab canal irrigation system, the potential parameters of interest may be rainfall and evapotranspiration as both of these can behave differently for recharge due to climate change. Apart from many different water inflow and outflow fluxes, crop consumptive water use and rainfall are very important variables which control recharge rates particularly in the semi-arid and arid regions (Scanlon et al. 2002). Therefore, in the current study groundwater recharge was estimated under the influence of changing patterns of rainfall and actual evapotranspiration.

9.3.1 Downscaling Climatic Data

The outputs of global circulation models cannot be used directly to investigate the impact of climate change in environmental studies on local/regional scale, as their outputs are based on a large grid scale (250–600 km) (Wilby et al. 2000). The most decent strategy is to build a bridge between global circulation model scales (a coarse scale) and local scale (0–50 km) by downscaling (Wetterhall et al. 2006; Xu 1999).

Many downscaling methods, including dynamic and statistical downscaling, have been developed and implemented by utilizing the outputs of global circulation models to downscale climate variables at local/regional scales (Huth 2002; Hay and Clark 2003; Diaz-Nieto and Wilby 2005; Salzmann et al. 2007; Akhtar et al. 2008; Elshamy et al. 2009; Yang et al. 2010; Sunyer et al. 2011; Huang et al. 2011). Statistical downscaling approaches establish statistical links among the local scale and large scale variables and are computationally inexpensive and fast (Wilby et al. 2000). Such approaches are applied for a wide range of climate applications apart from its utility for numerical weather predictions. According to Giorgi et al. (2001), statistical downscaling approach provides local scale information for climate change

impact assessment studies, although its main disadvantage is requirement of long term historical meteorological data.

Many statistical downscaling software tools have been developed to date and statistical downscaling model is one of them. It is widely used throughout the world to downscale important climatic variables like precipitation, temperature and actual evapotranspiration etc. (Chu et al. 2010). This tool is a hybrid of multiple linear regression and stochastic weather generator (Wilby et al. 2000; Wilby and Harris 2006). Multiple linear regression establishes a statistical relationship between gridded predictors (such as mean sea level pressure) and single site predictands (such as rainfall), and produces some calibration parameters. These parameters are then used by the stochastic weather generator to simulate up to one hundred daily time series to create a better correlation with the observed data (Wilby et al. 2000).

9.3.2 Data Requirements of Statistical Downscaling Model

Two types of daily time series, namely daily historic weather station data and large scale variables (National Center for Environmental Prediction (NCEP) daily predictors), were used to develop statistical downscaling model. There are four weather stations located in or near to the study area including Faisalabad, Toba Tek Singh, Lahore and Pindi Bhattian. Daily based long period weather data are required for statistical downscaling model, which were only available for Lahore and Faisalabad stations. From these two stations, daily data regarding maximum temperature, minimum temperature, relative humidity, sunshine hours, wind speed and rainfall were collected from 1960 to 2014. The daily data for Toba Tek Singh were available only from 2009 to 2014, while data were available from 2005 to 2014 for Pindi Bhattian. All such data were collected from Pakistan metrological department.

Statistical downscaling model produces output daily time series by forcing the NCEP or HadCM3 predictors (Mahmood and Babel 2013; Huang et al. 2011), the data of which were obtained cost free from <http://www.cics.uvic.ca/scenarios/index.cgi?Scenarios>, for the period of 1961–2010 and 1996–2050, respectively. H3A2 is the IPCC emission scenarios A2 of HadCM3. HadCM3 was selected for statistical downscaling model because it showed better agreement during evaluation of various global circulation models (Mahmood and Babel 2013; Akhtar et al. 2008; Huang et al. 2011).

9.3.3 Calibration, Validation and Bias Correction

Statistical downscaling models were developed by utilizing NCEP predictors screened for different variables at different locations. Daily data of rainfall and ET were used for calibration of statistical downscaling model from 1961 to 1995. Annual sub-models were developed individually for each predictand. Unconditional

sub-models with fourth root transformation and conditional sub-models without transformation were used for rainfall and actual evapotranspiration, respectively. The calibrated models were used for simulation of the predictands from 1996 to 2010 using NCEP and H3A2 predictors by generating 20 ensembles and the means of these ensembles are used. Different statistical indicators are used for comparison of downscaling results with the observed data including coefficient of determination (R^2), root mean square error (RMSE), mean (M), and relative error in mean (RE_M) for the periods of calibration and validation.

Bias correction was applied to compensate for any tendency to over- or underestimate the mean of conditional processes by statistical downscaling model (Wilby and Dawson 2013). For this purpose, the mean monthly bias factors for different variables were obtained from the calibration period of 1961–1995. Then, these biases are adjusted to downscaled data for the validated period from 1996 to 2010. The statistical comparison is performed between un-biased statistical downscaling model downscaled data of rainfall and actual evapotranspiration, and observed data. Following successful validation, adjusted bias factors are utilized to rectify the current and future downscaled data obtained from HadCM3 predictors to achieve a more realistic picture of future climate (Mahmood and Babel 2013). It is to be noted that the application of these bias corrections for rainfall are only valid to its intensity and also to remove any systematic error occurred by statistical downscaling model downscaling. However, it is assumed that rainfall frequency is accurately simulated by statistical downscaling model (Mahmood and Babel 2013).

9.3.4 *Baselines and Utilization of Scenarios for Groundwater Modeling*

Since specific change is always relative to some baseline time or period, therefore, a baseline is selected for climate change scenarios, which is from 2002 to 2012 for future periods 2016–2025, 2026–2035 and 2036–2045 by using the following relationship:

$$\% \text{change} = \left(\frac{x - y}{y} \right) \cdot 100 \quad (9.12)$$

where x is the mean for the future period e.g., 2016–2025, and y is the mean for the baseline period of 2002–2012.

For the current study, future climate change data was dealt by considering a constant change because the objective is not to track the changes in groundwater recharge yearly; rather the general situation at the end of a particular time period was to be investigated.

Table 9.7 Statistics of observed and downscaled mean monthly actual evapotranspiration and rainfall for calibration period at Lahore and Faisalabad meteorological stations

Predictand	Station	Model	R ²	RMSE (mm)	M (mm)	RE_M (%)
Evapotranspiration	Lahore	Observed			128.5	
		NCEP	0.94	14.2	128.1	-0.3
Rainfall		Observed			38.9	
		NCEP	0.88	24.1	21.5	-44.8
Evapotranspiration	Faisalabad	Observed			132.7	
		NCEP	0.92	15.3	135.2	1.9
Rainfall		Observed			26.9	
		NCEP	0.84	18.1	18.5	-31.3

R² coefficient of determination, RMSE root mean square error, M mean, RE_M relative error in mean

9.3.5 Results of Case Study – II

9.3.5.1 Screening of Predictors

Temperature at 2 m height (temp) was observed to be super-predictor for actual evapotranspiration at Lahore and Faisalabad stations. For both stations, the other predictors included mean sea level pressure (mslp) and super-specific humidity (shum). Super-specific humidity was also a super-predictor for both Lahore and Faisalabad stations in case of rainfall along with zonal velocity at 500 hPa and vorticity at 500 hPa, respectively. The results were consistent with Mahmood and Babel (2013), according to which shum was one of the major super-predictors for the majority of precipitation stations. Similarly, temp was found to be the main predictor for maximum and minimum temperatures. Along with wind velocity, temperature has a high effect on actual evapotranspiration and this behaviour was also witnessed for the current study. The predictors selected for the current study were almost similar to those selected for some other studies with similar predictands (Mahmood and Babel 2013; Hashmi et al. 2011; Huang et al. 2011).

9.3.5.2 Calibration of Statistical Downscaling Model

The calibration period was 35 years from 1961 to 1995. The daily rainfall and actual evapotranspiration data were simulated by statistical downscaling using NCEP variables. The model performed reasonably well in the case of actual evapotranspiration, which can be seen from the results in Table 9.7. The mean simulated values of actual evapotranspiration for both stations were comparable to observed data. However, the results for rainfall are relatively weak. For both stations, the difference between modelled and observed mean rainfall was large. Relative errors of mean were much greater for rainfall than evapotranspiration. Different researchers have evaluated statistical downscaling mode for different variables including rainfall

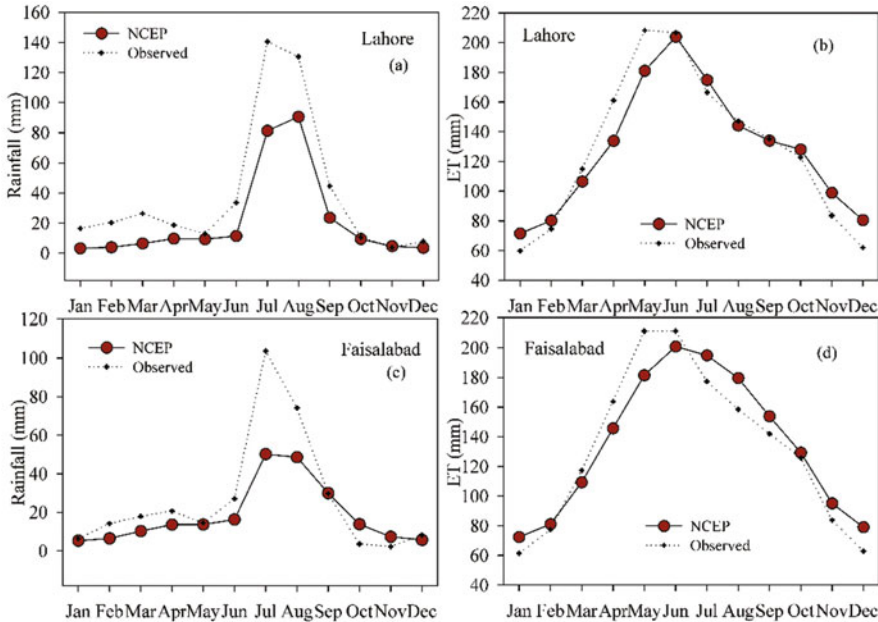


Fig. 9.6 Calibration results of statistical downscaling model. The model respond better for actual evapotranspiration as compared to rainfall due to its more variability in lower Chenab canal irrigation system. NCEP national centre for environmental protection. (Source: figure based on own research)

using different models and reported similar types of results. For example, Huang et al. (2011) developed different models for rainfall downscaling and their results vary from weak to medium values for different performance indicators (e.g. coefficient of determination ranges from 0.11 to 0.97). Whereas, Mahmood and Babel (2013) investigated statistical downscaling model for two models, monthly and annual, and according to them the monthly model performed better (coefficient of determination = 0.99) as compared to the annual model (coefficient of determination = 0.69). Overall, there is a consensus among different studies that temperature and actual evapotranspiration performed better than rainfall (Mahmood and Babel 2013; Dibike and Coulibaly 2005). The possible reason was the heterogeneous nature of the precipitation occurrence/amounts, which is therefore difficult to simulate accurately (Wilby et al. 2000). Moreover, the calibration process of rainfall could be biased by the large number of zero values entered in the multiple regressions (Huang et al. 2011).

Figure 9.6 indicates the graphical comparison between observed data and monthly mean output of statistical downscaling model. In case of actual evapotranspiration, statistical downscaling model underestimated the results from March to May for Lahore and from March to June for Faisalabad. However, it overestimated the results for November, December, January and February for both stations. It also

Table 9.8 Statistics of observed and downscaled mean monthly actual evapotranspiration and rainfall during validation (bias corrected) period for Lahore and Faisalabad meteorological stations

Predictand	Station	Model	R ²	RMSE (mm)	M (mm)	RE_M (%)
Evapotranspiration	Lahore	Observed			127.4	
		NCEP	0.98	7.3	124.2	-2.8
		H3A2	0.99	4.0	127.2	-0.2
Rainfall		Observed			29.2	
		NCEP	0.99	11.2	32.7	10.0
		H3A2	0.99	15.0	34.4	20.1
Evapotranspiration	Faisalabad	Observed			133.4	
		NCEP	0.99	8.4	128.1	-2.9
		H3A2	0.99	6.5	131.4	-1.5
Rainfall		Observed			25.1	
		NCEP	0.99	6.2	28.3	6.7
		H3A2	0.98	9.8	29.7	11.1

R² coefficient of determination, RMSE root mean square error, M mean, RE_M relative error in mean

overestimated results during July to October, which was more prominent for Faisalabad in comparison to Lahore. With regard to rainfall, observed data were underestimated by statistical downscaling model in the majority of months especially in rainy months (July to August). There was only a small overestimation by statistical downscaling model results during October and November in comparison to observed rainfall.

9.3.5.3 Validation of Statistical Downscaling Model with Bias Correction

The calibration of statistical downscaling model results indicated large biases, especially for rainfall, which should be removed for validation results. The current study has adopted the bias correction approach proposed by Mahmood and Babel (2013) and Salzmann et al. (2007). Different statistical downscaling model models for actual evapotranspiration and rainfall were corrected for biases and the detailed results are presented in Table 9.8.

Bias corrected downscaled mean results were also compared graphically with observed data as shown in Fig. 9.7. From all the statistical indicators, it is obvious that both evapotranspiration and rainfall results improved. Especially, the rainfall results improved significantly as coefficient of determination increased from 0.80–0.84% to 0.98–0.99%, root mean square values decreased from 26.52–28.08 mm to 4.04–7.30 mm and relative errors in mean 58.42–64.19% to 10.01–22.47%, for Lahore. Similarly, the results for rainfall at Faisalabad also indicated significant improvement as coefficient of determination increased from 0.76–0.80% to 0.98–0.99%, root mean square error decreased from 17.72–17.91 mm to 6.18–10.72 mm, and relative errors in mean were decreased

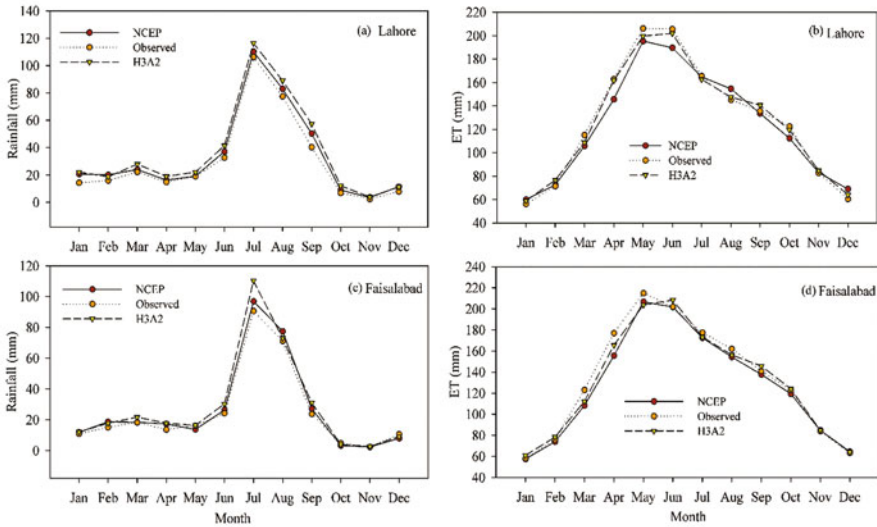


Fig. 9.7 Validation of bias corrected statistical downscaling model results. The results for both actual evapotranspiration and rainfall were improved after removing bias error. NCEP national centre for environmental protection. (Source: figure based on own research)

from 28.34–32.59% to 6.67–13.34%. The results from all variables including NCEP and H3A2 were satisfactory and indicate strong applicability of SDSM to downscale actual evapotranspiration and rainfall under H3A2 emission scenario.

9.3.5.4 Downscaling Results

Table 9.9 presents the projected results for different time durations (i.e. 2016–2025, 2026–2035 and 2036–2045) with reference to the base line period under emission scenario H3A2. According to this, the change in actual evapotranspiration is +2.23% in 2016–2025, +6.18% in 2026–2035 and +5.87% in 2036–2045 at Faisalabad for rabi seasons. The change during kharif seasons is +2.22% at Faisalabad whereas at Lahore the change is +1.36%. The detailed results for other periods can be seen from Table 9.9.

With regard to rainfall, the future positive change during rabi seasons is +1.68% in 2016–2025 at Faisalabad, +4.67% and + 5.79% at Lahore in 2016–2025 and 2036–2045, respectively. Conversely, there is a decrease of –7.31% and –0.18% in 2026–2035 and 2036–2045 at Faisalabad. In case of kharif seasons, the change is positive for all future periods at Lahore.

The selection of Lahore and Faisalabad for downscaling of climatic data was done because long time series were available only for these two stations. The other two stations located inside the study region are Pindi Bhattian (upstream location) and Toba Tek Singh (downstream location). There was a need to investigate whether any

Table 9.9 Future changes (%) in actual evapotranspiration and rainfall at Lahore and Faisalabad meteorological stations till end of 2045 for rabi (November to April) and kharif (May to October) cropping seasons under A2 scenarios

Scenario	Predictor	Season	Faisalabad					Lahore				
			2016–2025	2026–2035	2036–2045	2016–2025	2026–2035	2036–2045	2016–2025	2026–2035	2036–2045	
H3A2	Evapotranspiration	Rabi	2.23	6.19	5.87	2.20	9.46	7.48	2.20	9.46	7.48	
		Kharif	-2.29	2.22	1.58	-10.08	1.36	-0.59	-10.08	1.36	-0.59	
		Annual	-0.67	3.64	3.12	-5.62	4.30	2.34	-5.62	4.30	2.34	
H3A2	Rainfall	Rabi	1.68	-7.31	-0.18	4.67	-6.81	5.79	4.67	-6.81	5.79	
		Kharif	27.86	7.61	11.99	33.52	11.05	13.98	33.52	11.05	13.98	
		Annual	25.56	4.12	9.14	31.81	7.26	14.60	31.81	7.26	14.60	

significant relationship exists between different stations (i.e. between Lahore and Pindi Bhattian, and between Faisalabad and Toba Tek Singh). Owing to time series data, autocorrelations were worked out to see if there was any current time or lag time relationship between different stations. This analysis was based on the daily rainfall data from 2005 to 2012 for Pindi Bhattian and from 2009 to 2012 for Toba Tek Singh. The highest correlation (0.72) was found between Lahore and Pindi Bhattian, followed by 0.50 for Faisalabad and Toba Tek Singh. The correlations between other stations were not very strong, for example, correlations of 0.321, 0.30, 0.421, and 0.305 were found between Faisalabad and Lahore, Toba Tek Singh and Lahore, Faisalabad and Pindi Bhattian, and Pindi Bhattian and Toba Tek Singh, respectively. Generally, the lag time correlation relationship does not depict any strong relationship for any case.

The autocorrelation results show that better correlation is found between Lahore and Pindi Bhattian and between Faisalabad and Toba Tek Singh. Also, Pindi Bhattian and Toba Tek Singh are located at the central locations of upper and lower irrigation subdivisions, respectively. Therefore, it was decided to utilize climate change results of Lahore for upper irrigation subdivisions including Sagar, Chuharkana, Paccadala, Buchiana and Mohlan and results of Faisalabad for lower irrigation subdivisions including Tandlianwala, Tarkhani, Bhagat, Kanya and Sultanpur. Actual evapotranspiration is used directly for estimation of modified recharge while rainfall was first processed for effective rainfall before their utilization for estimation of recharge.

9.3.5.5 Projected Recharge Results

The projected results of recharge, in Fig. 9.8, show an expected increase during 2016–2025 for the kharif seasons. The maximum increase is up to an average value of 139.76 mm for Lahore and upper LCC regions. The increase of 43.51 mm is expected for Faisalabad and for lower LCC regions. Major groundwater recharge in lower Chenab canal irrigation system takes place during kharif seasons due to intensive monsoon rainfalls. The results of current study confirm the findings of Awan and Ismaeel (2015), according to which increase in recharge is expected due to more rainfall from 2012 to 2020 under changing climate conditions. For Lahore and upper regions, the recharge is expected to be stable or increasing for all time durations, whereas for Faisalabad and lower parts of lower Chenab canal irrigation system, the recharge is most likely to decrease during 2026–2045. During rabi seasons, the recharge is expected to be decreasing for all the time periods both for Lahore and Faisalabad regions, however, its quantum is variable and can be seen from the Fig. 9.8. The rate of decrease in recharge is higher during the later decades as compared to 2016–2025 period.

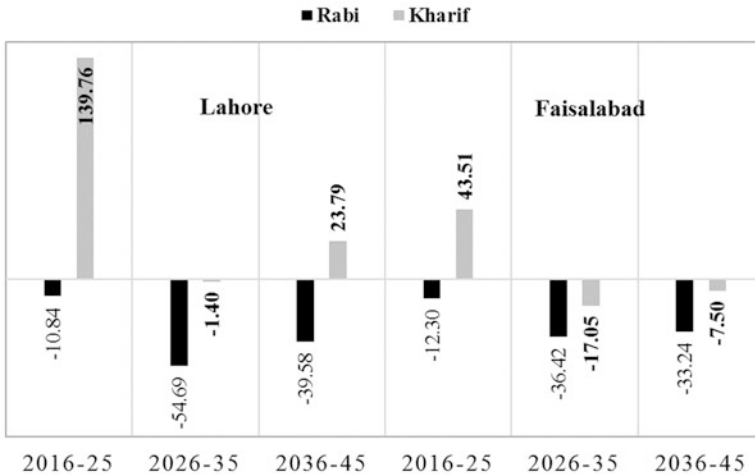


Fig. 9.8 Projected seasonal average recharge (mm) for Lahore and Faisalabad during 2016–2045. During kharif seasons (May to October), the recharge is expected to increase in the upper regions and decreasing in the lower ones contrast to rabi seasons (November to April) where recharge is expected to decrease throughout the lower Chenab canal irrigation system. (Source: figure based on own research)

9.4 Conclusion

Groundwater is an integral part of irrigation for successful agriculture in Pakistan. Present book chapter explores the historical and present trends of groundwater use in the country and particularly for the Punjab province. Moreover, results of two case studies are presented. Estimation of recharge in the lower Chenab canal irrigation system, Punjab, its important sources, and future trends are explored under changing climatic conditions. Following main conclusions are drawn and presented as below:

1. Waterlogging and salinity had been a major issue in Pakistan by late 1930s and early 1940s, due to construction of major canal network in the country and poor drainage network.
2. Launching of different salinity control and reclamation projects after 1960s helped to get rid of water logging and salinity issue in major parts of the country by installing many tubewells.
3. Canal water had been major contributor in irrigated agriculture by the end of 1990s, which was surpassed by groundwater afterwards due to promotion of private diesel operated small tubewells in the country overall, and particularly for Punjab.
4. By the end of 2013, the total number of functional tubewells were 1,049,000 in the country, 867,000 in Punjab and 51,157 in lower Chenab canal irrigation system, which shows the importance of groundwater use for agriculture.
5. Analysis of recharge in lower Chenab irrigation system shows that rainfall was the major source of recharge during kharif (May to October) seasons followed by

field percolation, canal seepage, watercourse losses and distributary losses. For rabi (November to April), canal seepage surpasses rainfall followed by field percolation, watercourse losses, distributary losses and later groundwater inflow and outflow.

6. Groundwater pumping was found higher during kharif seasons as compared to rabi seasons, However, net groundwater recharge found positive for kharif seasons whereas it was found negative during rabi seasons.
7. The daily rainfall and evapotranspiration data were simulated by statistical downscaling model using National Centers for Environmental Prediction (NCEP) variables. The calibration of statistical downscaling model showed reasonable results at both Lahore and Faisalabad weather stations in case of evapotranspiration, however for rainfall, the variation between observed and simulated values were higher which were removed by applying the bias corrections.
8. The projected recharge results showed that overall there will be increase in recharge during kharif seasons for lower Chenab canal irrigation system during 2016–2025 with the major contribution from monsoon rainfalls. For upper parts of lower Chenab canal irrigation system, recharge is expected to be increasing in future, whereas for lower regions of lower Chenab canal irrigation system, it is most likely decreasing during 2026–2045. During rabi seasons, the recharge is expected to be decreasing both for upper and lower regions of lower Chenab canal irrigation system.

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