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ORIGINAL ARTICLE

Estimation of distributed seasonal net recharge by modern satellite data in irrigated agricultural regions of Pakistan

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Abstract Groundwater is inevitable for agricultural production in the Indus Basin of Pakistan. Its management on sustainable basis is only possible by careful appraisal of its recharge potential and dynamics. This study aimed at exploring pixel-based groundwater recharge at 1 km^2 spatial resolution using remote sensing data through water balance method. Moreover, spatially distributed groundwater abstractions are estimated by new approach with the aid of remote sensing data and results are compared with the conventional utilization factor method. Groundwater abstraction estimation from conventional utilization factor method overstates results both for kharif and rabi cropping seasons. Recharge results obtained from water balance method and water table fluctuation approach are comparable both at irrigation subdivision and 1 km^2 spatial scales. During the kharif cropping seasons, rainfall is the main source of recharge followed by field percolation losses while for rabi cropping seasons, canal seepage remains the major source. Net groundwater recharge is mainly positive during all kharif seasons. A gradual increase in groundwater level is observed in major parts of the study area. Improvement in results from water table fluctuation method is possible by better distribution and increased intensity of piezometers while for water balance approach, it is possible by adopting alternative buffer zones for canal seepage. Detailed sensitivity and uncertainty analyses of input/output variables are needed to present the results with confidence interval and hence to support sustainable and economical operation of irrigation system.

Keywords Recharge · Water table fluctuation method · Water balance method · Geospatial techniques · Groundwater abstraction · Irrigated agriculture

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Introduction

Groundwater contributes about 20 % of the fresh water requirement of world's population (Kinzelbach et al. 2003). In many parts of the world, groundwater is often considered as the only perennial water resource, especially in case of arid and semi-arid regions. Nonetheless, groundwater table is declining drastically on a vast geographical area, e.g., in Eastern India, Northern China and Northern and Southern Africa, where the drop rate is 1–3 m/year (Kinzelbach et al. 2003). Pakistan is no exception to this phenomenon where depleting water table poses a great threat to the ever increasing demand for fresh water, both for domestic and agricultural use, in the wake of rapidly growing population. It is reported that about 40–50 % of total consumptive irrigation needs are met through groundwater (Kazmi et al. 2012) except for the domestic consumption. In many parts of the country, it is used either as a single source or in conjunction with canal water (Sarwar and Eggers 2006).

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Generally, groundwater irrigation may not be the most favorable choice for many farmers in the country; however, many irrigators do prefer groundwater mainly due to the flexibility it warrants in their irrigation planning among many other reasons. This does have the counter effect on the groundwater table, which is clearly visible in the form of significant decline in its level in last few years in most parts of the Punjab and Sindh provinces (Qureshi et al. 2010). Another effect of excessive groundwater extraction is the increased electrical conductivity of soil profiles in upper zones, as deeper groundwater is mostly saline leading to increased secondary salinization (Kazmi et al. 2012). As observed by Ahmad et al. (2009), the water quality is relatively poor in downstream parts of Rechna Doab due to higher groundwater pumping as compared to upstream parts of the Doab. This situation is posing severe threats to the sustainability of natural ecosystems in many canal commands of Pakistan (Qureshi et al. 2010).

Pakistan is currently facing a potential challenge of sustainable groundwater management due to insufficient water availability from different sources. However, a careful evaluation of groundwater resources is a prerequisite for its sustainable use. Groundwater recharge and abstraction are the two most important factors in this regard (Cheema et al. 2014). Quantification of these factors also provides a useful benchmark for the evaluation and management of harmful environmental side effects such as declining water levels, reduction of surface water flows, drying up of wells, land subsidence and decreased well yields (USGS 2010). It is worth mentioning that these two factors vary substantially in space and time while being relatively difficult to be determined especially in arid and semi-arid climates (Műnch et al. 2013; Jiménez et al. 2010).

Recharge estimation is often ignored for arid and semi-arid regions mainly because evapotranspiration generally exceeds precipitation, or the difference between annual precipitation and evapotranspiration is not too high (Műnch et al. 2013; Szilagyi et al. 2011). Nevertheless, some occasional heavy rainfall events may exceed evapotranspiration leading to the flow of harmful wastes into aquifers along with recharge water (Gee and Hillel 1988). This situation may result in significant misspecification in case of solute transport groundwater modeling. Ignoring recharge estimation for groundwater flow modeling is also only valid where rainfall is the sole source of irrigation. This is not applicable to cases where artificial irrigation is also applied through a canal network, which mostly prevails in the current study region of Pakistan.

The methods for estimating recharge have been classified according to hydrological zones (surface water and groundwater, e.g., Scanlon et al. 2002), the hydro-geological properties (conductivity, storage etc., e.g., Jiménez

et al. 2010) and; physical and numerical modeling and tracer techniques (Beekman et al. 1999). Scanlon et al. (2002) categorized recharge estimation methods on the basis of three hydrological zones, namely surface water, unsaturated zone and saturated zone. There is no single method available that may be claimed to be comprehensive for every aspect, due to some associated uncertainties with them (Jiménez et al. 2010). The selection of any particular method depends on the availability of data and its applicability for a particular use. For example, water table fluctuation method is only applicable for unconfined aquifer types (Healy and Cook 2002). Moreover, the reliability of recharge estimates using these methods is also dependent on the accuracy and precision with which each component of recharge estimation is performed/accomplished. This is particularly valid as water balance model relies directly or indirectly on the estimation of evapotranspiration. On the other hand, most of the previous studies focusing the under study region (Sarwar and Eggers 2006; Hassan and Bhutta 1996) have utilized potential/crop evapotranspiration instead of actual evapotranspiration that could lead to spurious results compared with those conducted under actual water availability conditions for a particular region (Jiménez et al. 2010).

In recent years, different distributed data inputs are demanded for regional groundwater models (Brunner et al. 2007). These data must include recharge values whereas estimation of spatially distributed recharge on finer spatial scales is still a challenge (Szilagyi et al. 2011). There is one option where remote sensing data with different spatial resolutions can be used directly employing water balance methods for the estimation of recharge. The use of this approach has attained wider acceptance among the scientific community in recent past. Many researchers have successfully utilized various forms of remote sensing data to estimate distributed recharge in different regions of the world (Mahmoud 2014; Műnch et al. 2013; Huang et al. 2012; Szilagyi et al. 2011; Yin et al. 2011; Jiménez et al. 2010; Brunner et al. 2007). Most of these studies have utilized only rainfall and evapotranspiration as major inputs. They did not consider irrigation data in their estimations, which could cause major errors due to underestimation of recharge, especially in arid and semi-arid irrigated regions like in the current study region as heavy irrigation is unavoidably supplied to agricultural fields. Nevertheless, some uncertainties are also associated with the use of remote sensing data. For example, in case of semi-arid environments, the difference between rainfall and evapotranspiration is not too large and henceforth, calculations based on their absolute values may lead to large associated errors (Glenn et al. 2011; Brunner et al. 2004, 2007).

The incorporation of irrigation data or parameters adds further complexity to the recharge estimation (Jiménez et al. 2010). However, according to Brunner et al. (2007), even if the absolute values of different data are uncertain but still it may lead to robust solution of the problem by reducing the degree of freedom of the groundwater models. Considering the limited accuracy of different recharge estimation methods and unreliability of remote sensing data, it is always imperative to use multiple methods for recharge estimation. Although the application of multiple recharge methods may not improve accuracy (Healy 2010), their application may provide some insights into the morphological and hydrological patterns; validity of assumptions and measurement errors (Szilagyi et al. 2011; Brunner et al. 2007). Very few studies have been conducted which use multiple recharge estimation methods concerning the current study area. Most of the available literature utilizes the water balance method and that also at very large spatial scales for the estimation of water recharge (Sarwar and Eggers 2006; Hassan and Bhutta 1996). The current study is an addition towards the estimation of seasonal net recharge using different water balance methods employing both from the conventional recharge data and modern remote sensing data. The comparison of these methods is made at irrigation subdivision level which is significantly smaller than that in the previous studies. The distributed recharge results from remote sensing data are also compared with recharge results from water table fluctuation methods both at irrigation subdivision levels and at 1 km^2 spatial scales. This spatial scale is selected mainly owing to the fact that majority of the remote sensing data used has this spatial resolution and along with the need and challenge to determine spatially explicit recharge rates for model cells on this scale for improving regional models (Szilagyi et al. 2011). The former methods were used due to the two reasons: (1) the inter-comparison among/between these methods would be of greater interest in terms of their accuracy and reliability, and (2) estimation of individual recharge and discharge components are greatly required for policy and regulation point of view. The latter was used to compare recharge results from water balance methods as it is regarded as more accurate and reliable due to its simplicity by ignoring any recharge mechanism and preferential flows (Obuobie et al. 2012; Singh et al. 2010). The applicability of water table fluctuation method in temporal scale is also broader in terms of its flexibility of time span coverage, e.g., from a day to year.

The remainder of the manuscript starts with the description of the study area followed by an overview of its geological and hydro-geological settings. Next, the methodology and recharge governing equations are explained. Finally the discussion on results using different methods and estimation errors are presented.

Materials and methods

Study area

Lower Chenab Canal (LCC), Punjab, Pakistan has been chosen as the study area for this study. The LCC irrigation system was designed in 1892–1898 in the Punjab. Its command area lies in Rechna Doab which comprises of land mass between rivers Ravi and Chenab. The location of the area is between latitude 30°36′ and 32°09′N and longitude 72°14′ and 77°44′E. The entire LCC area can be divided into two parts, LCC east and LCC west. Present study mainly focuses the eastern part of LCC, major part of which lies in the districts of Faisalabad and Toba Tek Singh. Administratively, entire LCC east is distributed split into 10 irrigation subdivisions with overall area of about 1.24 million hectares (Fig. 1a).

The study area under question is mainly categorized as agricultural land with a comprehensive irrigation canal network which is more than one hundred years old. Different crops are grown in the region including rice, wheat, and sugarcane, fodder, cotton, etc. The whole cropping year can be sub-divided into two seasons namely kharif and rabi. The kharif season generally starts from May and ends in October, while rabi season prevails from November to April. Rice and wheat are the two major crops during kharif and rabi seasons, respectively. The other crops cultivated during rabi season are rabi fodders (mainly barseem and oat), while cotton and kharif fodders (mainly sorghum, maize and millet) are grown in kharif season. Sugarcane is the annual crop which is cultivated in the months of September and February (Usman et al. 2012). Separate Land-Use-Land-Cover (LULC) maps were developed for each rabi and kharif seasons for the study period (from rabi 2005–2006 to rabi 2011–2012). For instance, Fig. 1b shows only the crop classified map of major LULC categories for kharif 2011 and rabi 2011–2012 cropping seasons.

The climate of the area fluctuates in terms of temperature and rainfall. Four types of weather seasons are exhibited which include summer, winter, spring and autumn. Summer is hot and lasts longer with temperatures ranging between 21 and 50 °C. During winters, daytime temperature ranges between 10 and 27 °C, whereas night temperature may drop to zero. The average annual precipitation in Rechna Doab varies from 290 mm in the south–west to 1,046 mm in the north-east. Highest rainfalls occur during monsoon period from July to September and accounts for about 60 % of average annual rainfall (Usman et al. 2012). Three weather stations are installed in/near the current study area operated by Pakistan Meteorological Department (PMD), which include Lahore (LHR), Faisalabad (FSD) and Toba Tek Singh (TTS). Historical weather data collected from these stations were used to calculate potential evapotranspiration using
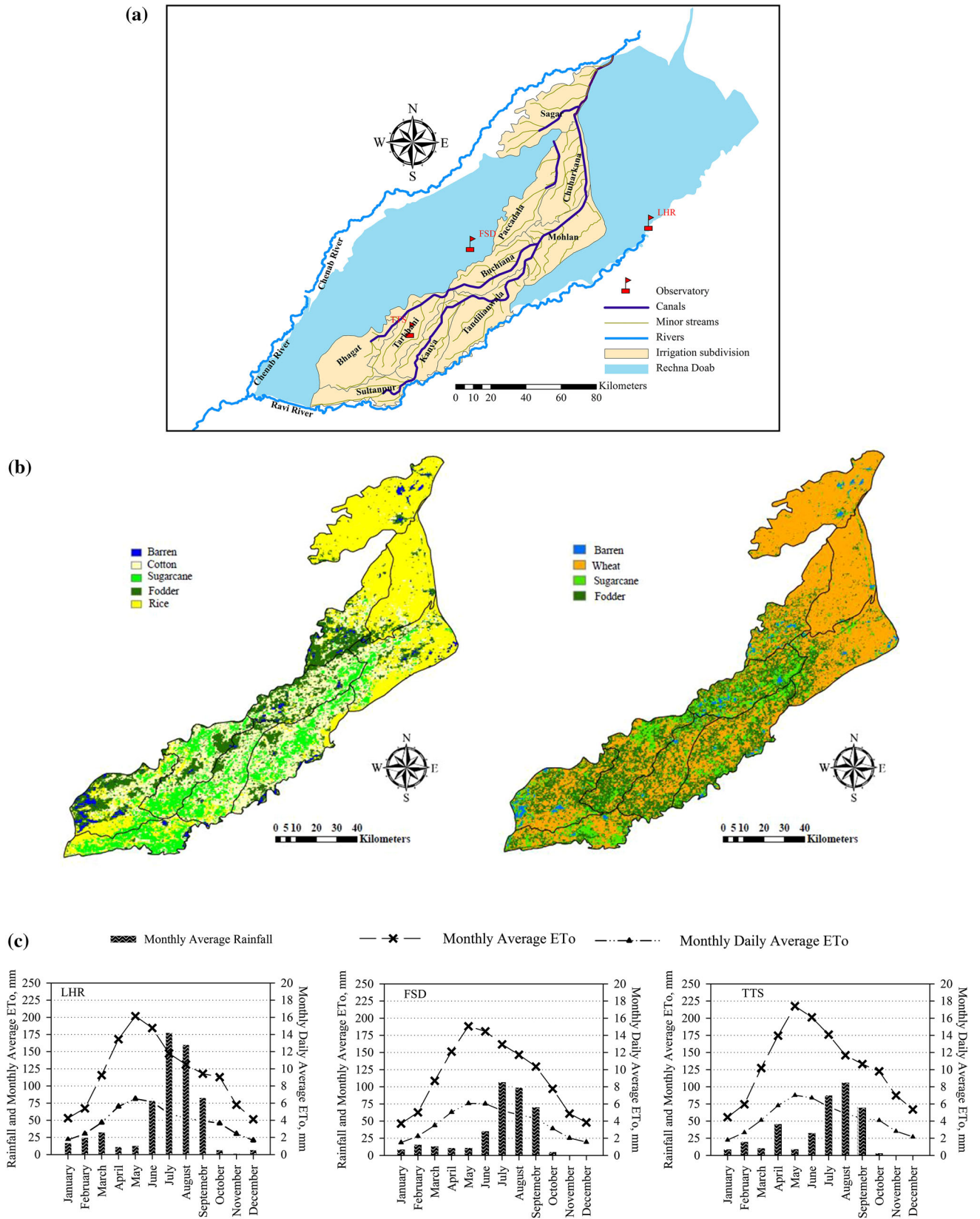
Fig. 1 a Location of study area, b classified maps of major LULC [kharif 2011 (left) and rabi 2011–2012 (right)] prepared using MODIS 250 m NDVI data and c rainfall and potential evapotranspiration at locations in Rechna Doab

Penman–Monteith equation (Allen et al. 1998) and plotted against precipitation on monthly time scale (Fig. 1c). It is evident from the figure that relatively more rainfall occurs at LHR as compared to the other two observatories. The difference between rainfall and potential evapotranspiration increases from LHR to TTS.

Geological and hydro-geological settings

The study area is part of an abandoned flood plain. The deeper part is formed by the underlying metamorphic and igneous rocks of Precambrian age. The area is underlain by highly stratified unconsolidated alluvial material composed of sands of various grades interbedded with discontinuous lenses of silt, clay and nodules of *kanker*—a calcium carbonate structure of secondary origin deposited by present and ancestral tributaries of the Indus River (Sarwar and Eggers 2006). The sediments in the upper parts of the study area consist of medium to fine sand, silt and clay (Fig. 2a). Gravel and coarse sand are uncommon. The origin of clay has not been identified specifically, but they are presumed to be the repeatedly reworked loess deposits of the hills at the north and northwest. Hydro-geological investigations in Rechna Doab were carried out during the 1957–1960 period wherein 327 test holes were drilled throughout the Doab. Maximum thickness of alluvium is not accurately known although the logs of test wells show that thickness is over 200 m or more nearly everywhere. The alluvial complex is of heterogeneous nature and forms a fairly transmissive aquifer system. Soils of some area are fairly homogeneous containing high percentage of silt and fine to very fine sand whereas clay contents are higher in depression areas (Rehman et al. 1997).

Figure 2b illustrates the lithological details of selected test boreholes at three different cross sections in LCC. They indicate that thickness of alluvium complex is relatively higher in lower parts compared with upper parts which contain small lenses of clay and gravel throughout the area. It shows that aquifer is mainly composed of sand with deposits of clay, gravel and silt at different depths. However, there is no typical pattern in the arrangement of these materials the material is highly porous and is capable of storing and transmitting water readily. The horizontal permeability is an order greater than vertical (Bennett et al. 1967). The porosity of the water bearing material ranges from 35 to 45 % with an average specific yield of around 14 %. Khan (1978) has summarized the results of pumping tests and lithological, mechanical analyses of test holes, according to which hydraulic conductivity varies from 24 to 264 m day^{-1} and specific yield values vary from 1 to 33 % in Rechna Doab. Contour map of water table in the study area indicates increasing depths from upper to lower parts (Fig. 2c, e).

Principal of recharge estimation methods and their application

Water balance methods (WBM)

Water balance approaches have been widely used for estimating groundwater recharge (Sarwar and Eggers 2006; Maréchal et al. 2006; Scanlon et al. 2002; Hassan and Bhutta 1996). Groundwater recharge estimation by WBM is an indirect or residual approach (Műnch et al. 2013); in which various components contributing to groundwater flow have to be identified first. Then groundwater recharge is estimated with the help of various measurable physical and chemical parameters (Healy 2010). Various recharge and discharge components concerning the current study area can be visualized from Fig. 3. The water budget for such areas can be written by the Eq. (1) adopted from Schicht and Walton (1961) and Singh et al. (2011).

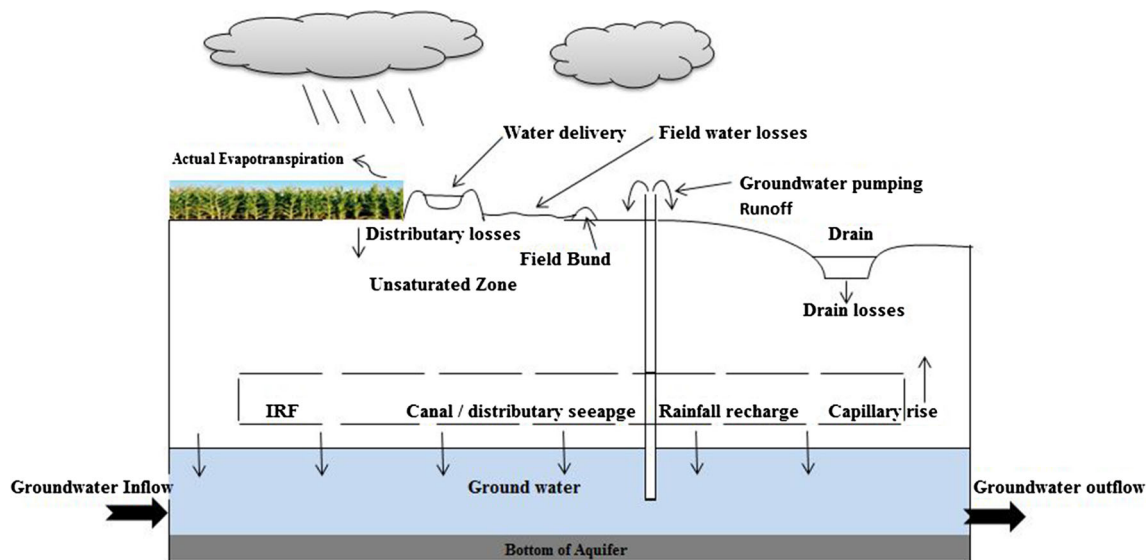$$I + RF + GW_{in} - GW_{out} - ET - RO \\ - GW_p - GW_s = \Delta S \tag{1}$$

where I and RF are total water from canal supply and rainfall, respectively, GW_{in} and GW_{out} are lateral groundwater inflow and outflow in the study area along a boundary; ET represents crop water loss due to evapotranspiration; RO is surface runoff; GW_p is groundwater abstraction by pumping; GW_s is groundwater contribution to stream flow; and ΔS is the change in saturated groundwater storage. The units of all components are in depth (mm) per time period.

Simplifications can be made to above water budget equation by considering the local conditions in the study region. Surface runoff can be ignored as the study area is mainly agricultural with banks on all sides of the fields. Similarly, outflow of groundwater to surface stream does not exist and can be ignored. Thus, the above general water budget equation now reads:

$$I + RF + GW_{in} - GW_{out} - ET - GW_p = \Delta S. \tag{2}$$

Few studies utilizing above water balance equation for estimation of recharge in the current or similar study areas include Singh (2011), Singh et al. (2010), Maréchal et al. (2006) and Hassan and Bhutta (1996). All of them have used lumped values of different recharge inputs and outputs at some larger spatial scales. They did not explore the use of remotely sensed data for recharge estimations. The above equation can be used directly for distributed recharge estimation. But groundwater abstraction and total canal water supply are main hurdles as their spatial distribution is missing. Assuming a uniform distribution of total canal water throughout the area could help ignore its more contribution to groundwater recharge in vicinity of

Fig. 2 **a** Location and geological details of the study area, **b** lithological details of selected bore-logs at three different cross sections (depths in meter from mean sea level) and **c** distribution of aquifer materials, digital elevation model and groundwater contour map in LCC

irrigation network. Similarly, estimation of groundwater abstraction by conventional utilization factor method (reported by Sarwar and Eggers 2006 and Hassan and Bhuttah 1996) falls short to address its spatial distribution in the presence of missing point data about tubewell locations and their discharges. The estimation of groundwater abstraction by utilization factor approach employing relatively wider spatial scale tubewell census data may cause major estimation errors. The detail of utilization factor approach can be found in coming sections. Therefore, it is one of the objectives to estimate net recharge from Eq. (2) using groundwater abstraction from this conventional approach (as usually practiced), and then to make its comparison

with modern approach of groundwater abstraction estimation employing remote sensing data.

Equation (2) describes the water budget by incorporating all surface and subsurface parameters for recharge estimation without going into detail of each parameter. But according to Scanlon et al. (2002), water balance equation can also be written only for saturated zone (below groundwater table). The description of saturated groundwater storage for current study area by this principle can be given by Eq. (3).

$$\Delta S = L_{cs} + (GW_{in} - GW_{out}) + IRF + RFR - GW_p \quad (3)$$

where L_{cs} loss of seepage water from irrigation network to groundwater, IRF is is irrigation return flow from field and

Fig. 3 Schematic diagram for various input and output variables for overall net recharge estimation in the study area

RFR is rainfall recharge. The units of all components are in depth (mm) per time period.

Principally, water balance Eqs. (2) and (3) are similar but they offer exploring of different data inputs for recharge estimation. In this particular study, recharge estimation by Eq. (2) utilizes conventional data (as usual practice) and the data input for Eq. (3) is only from remote sensing by the application of different spatial techniques. Thus, it is more a comparison of different data types for recharge, but for easy understanding, estimation of recharge from Eqs. (2) and (3) will be called as recharge from an usual approach (WBM1) and new approach by utilizing modern remote sensing data (WBM2), hereafter in this manuscript. The estimation of different recharge/discharge components for these two models is explained in later sections.

Water table fluctuation (WTF) method

WTF method has been widely used throughout the world in many studies (Hall and Risser 1993; Hassan and Bhutta 1996; Healy and Cook 2002; Scanlon et al. 2002; Maréchal et al. 2006; Yin et al. 2011; Obuobie et al. 2012). Its advantages include its easy use, low data requirements and applicability in terms of wide temporal scale. This method can be used to estimate distributed recharge with reliable piezometric and specific yield data (Maréchal et al. 2006). According to this method, recharge is calculated as:

$$R = S_y \times \Delta H \tag{4}$$

where R is net recharge between two times, S_y is specific yield (dimensionless), and ΔH is peak water table rise during a recharge period.

Few assumptions are made for the application of WTF method including: (1) rise and fall in water table are only due to recharge and discharge of groundwater, (2) S_y is known and it is constant over the time interval under consideration, and (3) the pre-recharge water level recession can be extrapolated to determine water level rise (Healy and Cook 2002).

Above mentioned method is mostly suitable for shallow water tables with small recharge events but it can also be applied to longer time intervals (Healy and Cook 2002; Obuobie et al. 2012). In the current study area, monitoring shows well-identified large seasonal water table fluctuations due to percolation during monsoon seasons as well as field percolation and daily pumping. A similar situation is reported by Maréchal et al. (2006) in the Indian part of the watershed with almost similar agro-climatic conditions. Moreover, water table position is not an issue because it is mostly within 10 m from the ground surface, which is quite suitable for the application of WTF (Delin et al. 2006). More detail on the suitability of WTF method can be found from Healy and Cook (2002).

Data types and their sources for estimation of recharge

Different types of data were required to accomplish different objectives of this study. These data include information on crop, soil, weather, water flow, geology, shape files and groundwater observations in the study area. Different data types used in the study are given in Table 1 along with their sources.

Rainfall

Monsoon rainfalls are major source of recharge during kharif seasons. Both point and raster based rainfall data is available from Pakistan Meteorological Department (PMD) and

online sources, respectively. The kriging interpolation technique as suggested by Baalousha (2005) could be adopted to obtain spatially distributed rainfall data using point data. However, data from only three stations is not sufficient for reliable interpolated rainfall maps, henceforth, a raster based monthly rainfall data were retrieved from Tropical Rainfall Measurement Mission (TRMM). Spatial data with a resolution of 25 km were downloaded (Refer to Table 1), which were downscaled to 1 km for further use. The downscaling procedure adopted can be found in more detail from Chen et al. (2014). Local calibration and validation of this data is performed with point observatory data. Monthly rainfall data were summed up to obtain seasonal rainfall for all kharif and rabi seasons. The mean, the maximum and the minimum rainfall observations were calculated for each irrigation subdivision for each season along with standard deviations and coefficients of variation. Relative deviations were also worked out for monsoon rainfall as suggested by Singh et al. (2010) to observe the statistical trend among the data. Moreover, the effective rainfall was also estimated following the USDA Soil Conservation Services (SCS) method (Patwardhan et al. 1990).

Canal flow and geometry data

Information about canal flows and channel geometries are very important for estimation of recharge using WBM. This information is collected from irrigation department, Government of Punjab, Pakistan. The daily canal flow data are transformed into volume units by multiplying daily discharge values with time while daily discharge volumes are summed-up to get seasonal discharge volumes for each canal tributary. The irrigation system in the study area is designed in such a way that separate canals distribute water to each irrigation subdivision which renders easy segregation of data. The other data collected from irrigation department include shape geometries of different canals and information on line/un-lined canal sections.

Groundwater data and estimation of water fluctuations (ΔH)

Groundwater piezometric data of good quality are required for the WTF method which is available from Salinity Monitoring Organization (SMO), Pakistan. Piezometric data from about 278 locations are enough to achieve good water table surface. Water table elevations are used to create water table maps with the help of kriging interpolation technique (Maréchal et al. 2006; Baalousha 2005). In order to ensure the quality of interpolation results, a standard operating procedure was followed, namely: (1) distribution of data was examined by both histogram and Q–Q normal plots for normality/abnormality of trends, (2) identification of global trends in data was also performed and any directional trend in data sets was eliminated before interpolation was performed, (3) semi-variogram/covariance cloud was established to observe the spatial autocorrelation in the data, and (4) finally, interpolation was performed. These interpolated maps are carefully evaluated and it is found that in most cases, good distribution of piezometric data gave reliable results. For some seasons, data from few piezometers were not available; therefore, those areas were carefully marked to proceed for further analyses and comparisons with WBM. For the current study, piezometric data for 2005–2011 were used. This information is recorded twice per year at the end of each cropping season, i.e., kharif and rabi. The groundwater contour maps for two seasons including rabi 2006 and kharif 2006 are shown in Fig. 4.

Table 1 Overview of data types and its sources

Data types	Period	No. of stations	Source
Climatic variables	2005–2012	3	Pakistan Meteorological Department (PMD), Islamabad
TRMM rainfall	2005–2012	Raster based	http://pmm.nasa.gov/TRMM
Piezometric water level	2005–2012 (missing for 2008)	About 278 points in LCC east only	Salinity Monitoring Organization (SMO), WAPDA, Pakistan
Bore logs	–	132	WMI, Lahore
Aquifer properties	–	32	IWMI, Lahore
Canal flows	2005–2012 (missing for Rabi 2006–2007)	–	Irrigation Department, Punjab
Shape files	–	–	Irrigation Department, Punjab
Crop data	2005–2012	Raster based	http://glovis.usgs.gov/
Data for actual ET estimation	2005–2012	Raster based	http://glovis.usgs.gov/
Tubewell census	2005–2011	Districts/tehsils	Punjab Development Statistics

Crop data

Different crops have different consumptive water requirements, which may force water table to behave differently both in space and time. Usually, spatially distributed information on LULC is not available at finer spatial resolutions. In LCC, information about different crop's cultivated areas is generally available from local authorities at district levels but spatial distribution of all these crops is missing. Therefore, LULC mapping at spatial resolution of 250 m for all individual rabi and kharif seasons was carried out using MODIS Normalized Difference Vegetation Index (NDVI). A number of NDVI composite images were retrieved from both terra and aqua sensors (Table 1). After pre-processing of these images, unsupervised classification by k-means method which uses ISODATA algorithm (Tou and Gonzalez 1974) was obtained. This technique classifies the entire image into different clusters and each pixel is assigned to a particular cluster based on arbitrary mean vector value. It also permits clusters to change from one iteration to the next by merging, splitting, and deleting. Finally, all pixels are reclassified into the revised set of clusters, and the process continues till there is either no significant change in the cluster statistics or the maximum number of iterations is achieved. For the present study, 0.99 convergence threshold and 100 iterations were selected to perform the classification process (Usman et al. 2014). The temporal profiles of NDVI trends were utilized to identify major crops. The results of this classification were verified by constructing error matrices and their comparison with secondary crop census data.

Actual evapotranspiration (ET)

Estimation of evapotranspiration is mandatory for WBM. Different empirical models are used to estimate its value but spatially distributed ET was estimated for this study. ET was calculated using SEBAL energy balance algorithm (Bastiaanssen et al. 1998) which uses different satellite data products for estimation of different variables. The detail of these products is presented in Table 2.

The detailed methodology adopted in the current study for SEBAL can be visualized from Fig. 5. SEBAL gives daily values of ET. From the daily information on ET, monthly and seasonal maps for crop consumptive water use were finalized for all individual rabi and kharif seasons. Detailed description of SEBAL algorithm is available from Bastiaanssen et al. (1998).

Specific yield (S_y)

Different methods are applicable to obtain values of specific yield (S_y) such as pumping test, laboratory, water budget and empirical methods. However, each method has associated uncertainty leading to few problems in the estimation of S_y. Generally, S_y is set at a certain value but in reality its value varies as a function of depth of water table and time in response to wetting and draining history (Childs 1960). A wide range of values are observed for the same type of material due to complexity of determination and such variation is attributed to natural heterogeneity in the formation material (Healy and Cook 2002). Determination of S_y using laboratory method is preferred over pumping test, which is usually conducted for short times (Lerner et al. 1990). In the current
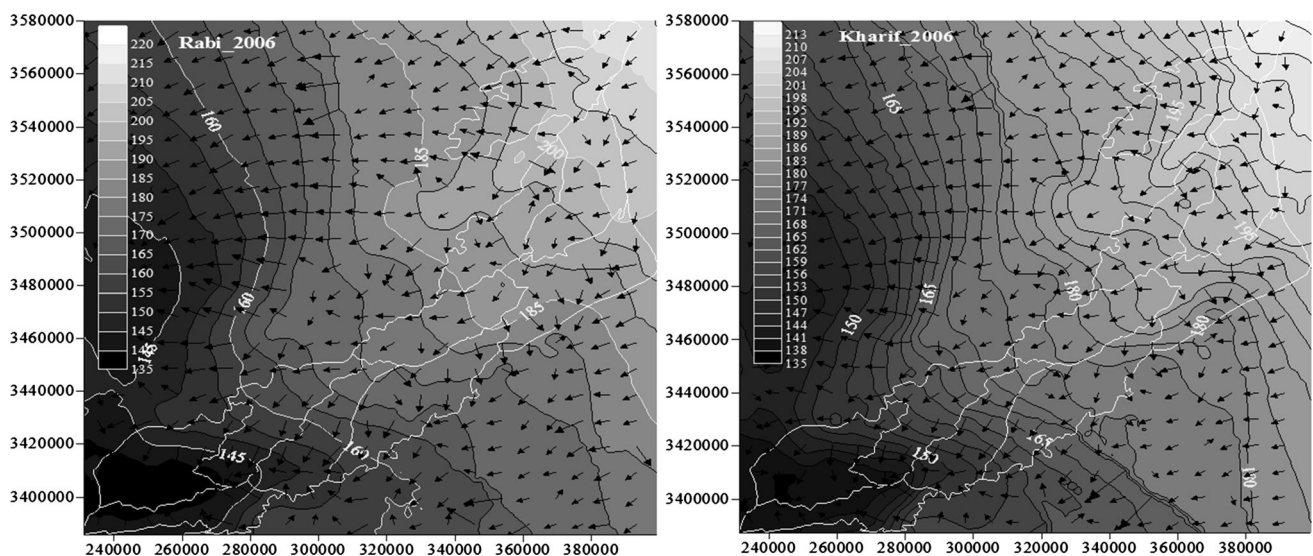

Fig. 4 Groundwater contour maps for rabi 2006 and kharif 2006 seasons

Table 2 Details of data used for SEBAL approach

Data product	Layer	Spatial resolution (m)	Temporal resolution	Purpose
MOD09A1	Surface reflectance, band (1–7)	500	8 days	Surface albedo
				Vegetation index
				Land surface water index
MOD11A1	Land surface temperature and Emissivity, band (31–32)	1,000	Daily	Land surface temperature
				Emissivity

study, S_y values were derived both from the pumping test and from literature (Johnson 1967) against the geological data of the encountered aquifer material from bore logs and water table. Point data values of specific yield for different materials were used to create spatially interpolated maps using geo-statistics in ArcGIS.

Estimation of net recharge components for WBM

For WBM, different recharge and discharge components are measured at seasonal scales to estimate net recharge. The detailed description of each recharge/discharge components and their estimation is explained as follows:

Recharge from main canal seepage

Two different empirical models developed by the Punjab Private Sector Groundwater Development Project Consultants (1998) and Irrigation Department (2008) were employed for the determination of seepage from main canals. The models use discharge, canal length, wetted perimeter, number of running days of canal in a particular season and seepage factor. The methods are:

$$S = 0.052 (Q)^{0.658} \tag{5}$$

and

$$R_c = 86,400 \times L_c \times W_p \times N_d \times \text{SF} \tag{6}$$

where S is seepage loss or recharge (ft^3/s/mile), Q is canal discharge (ft^3/s), R_c is recharge due to canal seepage (m^3), L_c is canal length (m), W_p is wetted perimeter of canal during its run (m), N_d is canal running time in a particular season (d), and SF is seepage factor for the canal with recommended values of 0.62–0.75 and 2.5–3.0 m^3/s/ 10^6 m^2 of wetted area for lined and unlined canals, respectively.

Recharge from distributaries and watercourses

Equation (6) is also applicable for the estimation of recharge from distributaries (Singh 2011). This recharge estimation is compared and verified by other approach

where about 6 % of head water diversion to distributaries is considered as distributary loss in LCC (Ahmed and Chaudhry 1988). Maasland (1968) as cited in Ahmed and Chaudhry (1988) estimated watercourse losses and observed about 10–20 % of total delivery head is seepage loss in the study region.

Recharge from field percolation

Estimation of recharge from irrigated fields is most important as considerable part of water applied to crop returns to groundwater, especially for the rice crop. Its distributed estimation in complex agricultural lands is not possible without remote sensing data. Different guidelines have been put forth for estimation of field percolation which range from ordinary to complex. For example, according to Maasland (1968), a fixed percentage of about 15 % of water delivered to the field is recharge without any consideration to crop type. Similarly, Ashraf and Ahmad (2008) assumed 25 % of water from fields and watercourses as recharge. Other scientists including Jalota and Arora (2002), Tyagi et al. (2000a, b) and Maréchal et al. (2006) did not support using of fixed percentages as recharge but they have considered different coefficients of irrigation return flow for different crop types. This study utilizes the later approach where LULC maps are processed assigning different coefficients of irrigation return flow. The recharge from field percolations is estimated using following relationship:

$$\text{IRF} = I_{\text{FF}} \times D_f \tag{7}$$

where IRF is recharge from field percolation (mm), I_{FF} is the total irrigation water supplied to farms through canal and groundwater sources (mm), and D_f is the fraction of applied water contributing to groundwater recharge.

The information about D_f (i.e., field application efficiency) for different crops can be taken from Jalota and Arora (2002), and Tyagi et al. (2000a, b). For example, percolation losses in case of total applied water are about 50 % for rice, about 5.6, 31.2, 15 and 20 %, respectively, for wheat, kharif fodder, cotton, rabi fodder and sugarcane crops.
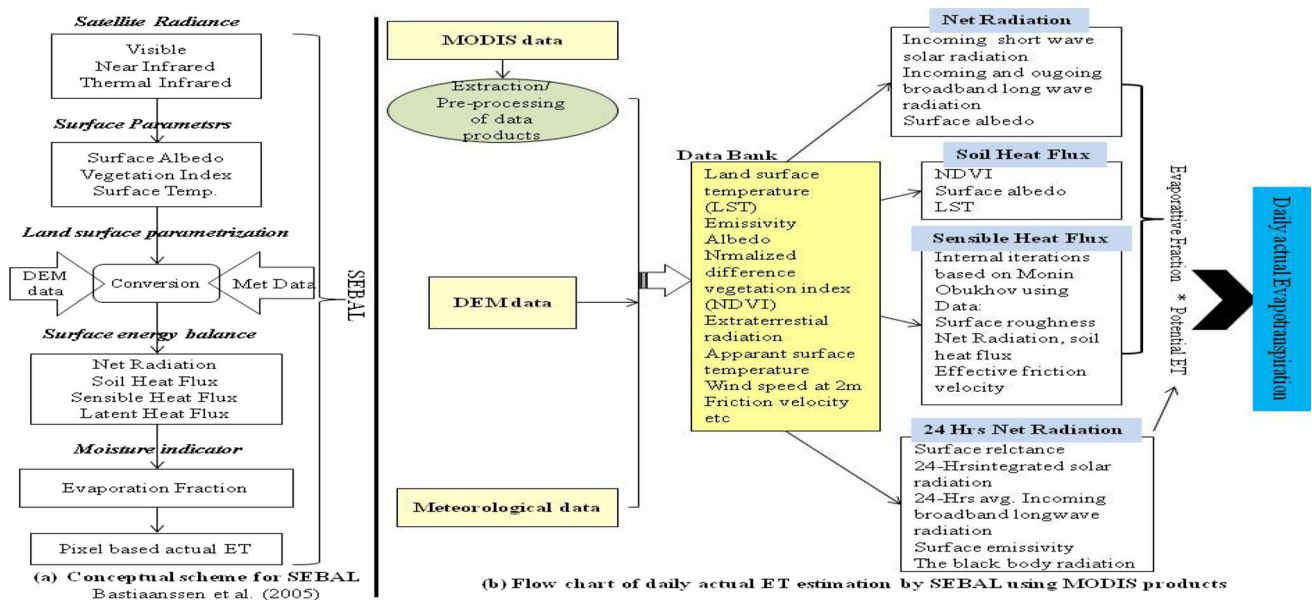
Fig. 5 Methodology for ET estimation by SEBAL approach

Estimation of total canal and groundwater availability at farms

I_{FF} would be equal to estimated ET under ideal conditions, where all water provided at farms is available for crop use; however, in reality this applied water to fields is always greater than ET as the application and conveyance efficiencies are never equal to 100 % for any irrigation system. Therefore, I_{FF} is estimated using Eq. (8).

$$I_{FF} = \left[\frac{(ET - ERF) \times 100}{E_a} \right] + RO + UWS \quad (8)$$

where E_a, ERF, RO and UWS are irrigation application efficiency (%), effective rainfall (mm), surface runoff (mm) and unsaturated water storage (mm), respectively. ERF is excluded from ET because I_{FF} is the only total water available at farms through canal and groundwater sources. The values of application efficiencies are drawn following guidelines from Jalota and Arora (2002), and Tyagi et al. (2000a, b) for different crops types. RO and UWS may be ignored in Eq. (8) as practically very little runoff occurs and, for long term steady state condition, the soil water content is constant letting to ignore changes (Yin et al. 2011).

Groundwater abstraction

Historically, groundwater abstraction in the study area has been estimated by employing utilization factor approach (Sarwar and Eggers 2006, Qureshi et al. 2003 and Hassan and Bhutta 1996). The groundwater abstraction by this method is estimated by Eq. (9).

$$GW_p = 0.000036 \times NPTW \times UTF \times AD \times TOH \quad (9)$$

where GW_p = pumpage of groundwater by tubewells (ha-cm), NPTW = number of tubewells, UTF = the utilization factor for each month, TOH = total operational hours in a year (h), AD = the actual discharge of private tubewell (m^3/s) and 0.000036 = conversion factor.

All stated parameters in Eq. (9) are difficult to obtain accurately for the current study region due to one reason or the other. The tubewell inventory is published by the government of Punjab at district level, which is far bigger in areas than the irrigation subdivisions. The information about tubewell density, average groundwater discharge of tubewells and monthly utilization factor is available from Sarwar and Eggers (2006), Qureshi et al. (2003) and Hassan and Bhutta (1996).

Apart from the limitations of quality data for utilization factor approach, another potential limitation associate with this method is that it gives only average groundwater abstraction value for any region. However, it is nearly impossible to obtain net recharge at pixel scale using this approach keeping in view the focus of current study. Therefore, another technique was applied which can provide distributed groundwater abstraction at finer spatial resolution. The procedure of groundwater abstraction from this method is described as follows:

$$GW_p = I_{FF} - I_{canal} \quad (10)$$

where I_{canal} is the net water availability from canal network after compensating all seepage losses.

The total canal and distributary seepage losses are distributed spatially traversal and along the length of streams

by creating buffers around them. Seepage from watercourses was not possible to be distributed in this fashion due to missing shape files. Similarly, it was also not possible for groundwater inflow and outflow. This is attained by generating vector maps for these parameters as suggested by Cheema et al. (2014).

Recharge from rainfall

Different approaches are used for the estimation of rainfall recharge in the study region. For example, Maasland (1968) has considered about 20 % of total rainfall as recharge. Ahmed and Chaudhry (1988) have reported about 17–22 % of the total annual rainfall as recharge in LCC regions. Ashraf and Ahmad (2008) used 17.9 % of total rainfall as groundwater recharge in nearby Chaj Doab, Punjab, Pakistan. All these reported figures present only the rough estimates, therefore, in the current study; rainfall recharge is estimated by subtracting monthly ERF plus 5 % of total rainfall as hidden losses from total monthly rainfall. Model builder tool in ArcGIS was utilized for this purpose.

Lateral groundwater inflow and outflow

Groundwater inflow and outflow from different irrigation subdivisions were computed using modeling approach. Inverse modeling approach using FEFLOW 6.1 groundwater software and PEST was used. The model area is bounded by main river on southern side, while it is surrounded by two main link canals on the eastern and western sides of the model area. Groundwater recharge estimate from literature was used as an initial guess and also for describing its range for inverse modeling. All the model input variables were known except recharge and groundwater inflow and outflow. Model was calibrated against piezometric data. The uncertainty of groundwater inflow and outflow was also estimated and compared with Darcy's law (Darcy 1856). For Darcy's law, inflow and outflow cross sections were identified from groundwater model and by plotting groundwater level and bore-log data.. The cross sectional flow areas were estimated (as suggested by Baalousha 2005) from each cross section segment of irrigation subdivision boundaries. 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.

Statistical indicators for model evaluation

Different statistical indicators were employed including coefficient of determination, root mean square error, percent bias and Nash Sutcliff Efficiency (NSE) (Singh et al. 2010; Hoffmann et al. 2004; Helweig et al. 2002; Nash and Sutcliffe 1970) for quantifying the difference between recharge from measured data and estimation methods.

Results and discussions

Rainfall data analyses

Figure 6 shows the spatial distribution of rainfall in different irrigation subdivisions for the study period. It is evident that rainfall decreases from Sagar to Sultanpur irrigation subdivisions. CV results show slightly higher values in lower parts as compared to upper parts of LCC (ranging from 0.13 to 0.20). The results about yearly average rainfall for LCC are examined with the help of Mann–Kendall test to observe any trend in rainfall patterns and it shows that there is no significant trend from year to year for the study period ($p = 0.5481$). However, sample size cannot be considered satisfactory for the current analysis ($n = 7$), and the uncertainty of the test would certainly decrease for a large amount of data. Therefore, data were further analyzed for possible variability in another way, i.e., by using the Welch two sample t test, where the average rainfall from different years is compared at the 95 % confidence interval. The results for some selected years point out interesting outcomes. For instance, 2006–2007 showed non-significant differences for all other years except for 2010–2011 and 2011–2012 ($p = 0.0076$ and 0.0296, respectively). Similarly, 2010–2011 is quite wet and it showed a significant difference for other years except 2011–2012 and 2008–2009 ($p = 0.5466$ and 0.2726, respectively). The average effective rainfall for the study duration can also be seen for each individual irrigation subdivision. However, the individual average values for each cropping year vary depending on crop type, intensity of rainfall and crop water requirements, etc. (Patwardhan et al. 1990).

Validation of SEBAL for ET estimation in LCC

Validation of SEBAL results is important before their further use. Generally, SEBAL results are compared with results from lysimeters and other point estimates of evapotranspiration like Bowen ration energy balance (Bowen 1926) and the eddy covariance (Wilson et al. 2002). As the results of evapotranspiration from any of the above mentioned methods are not available for the study area, therefore, SEBAL results are validated with advection aridity method for this study. The advection-aridity equation following Brutsaert and Stricker (1979) was formulated as:
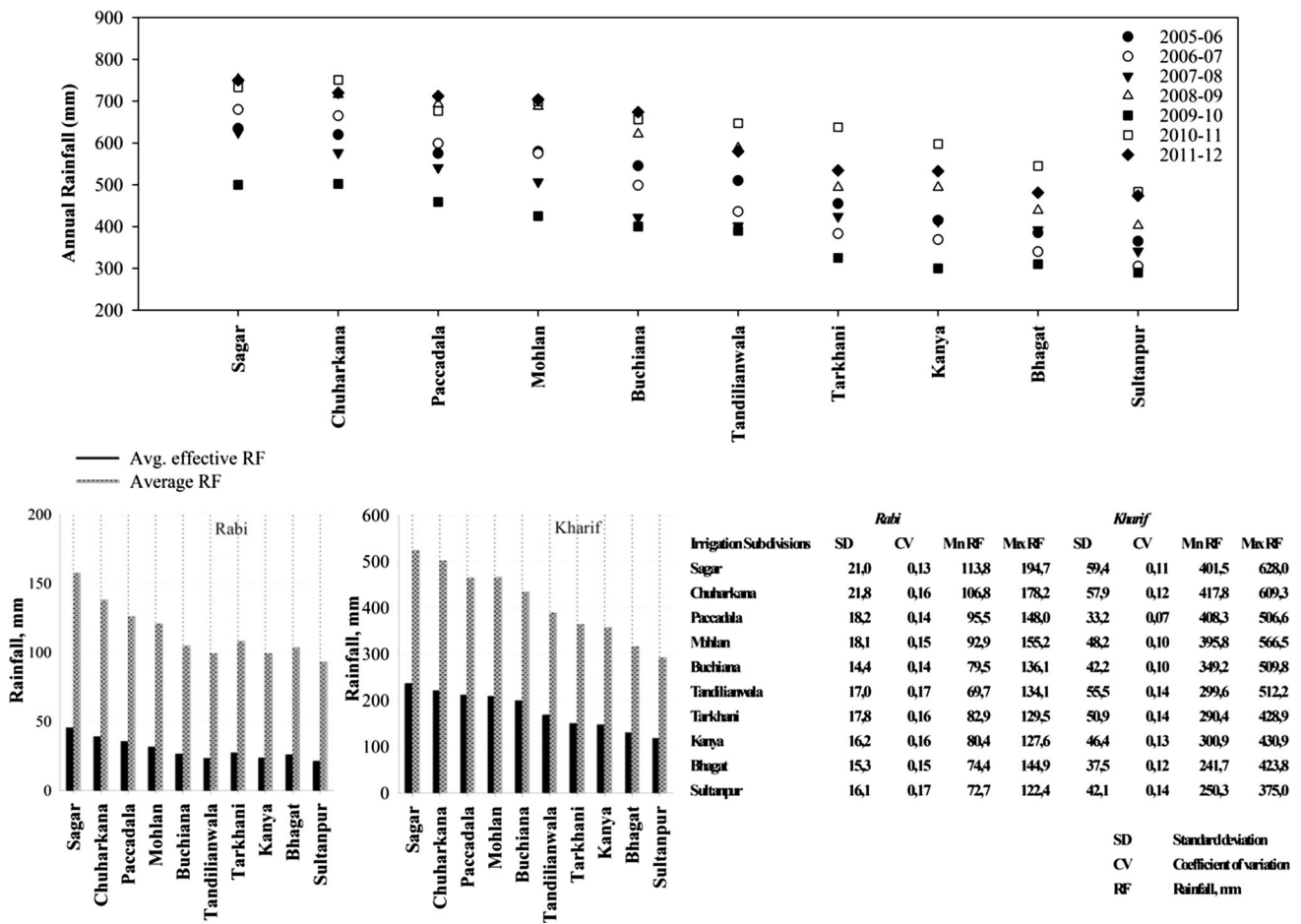
Fig. 6 Distribution of total and effective rainfall during kharif (*right*) and rabi (*left*) seasons for the study period

$$E = (2 \propto_e -1) \frac{\Delta}{\Delta + \gamma} Q_{ne} - \frac{\gamma}{\Delta + \gamma} E_A \quad (11)$$

where E is the actual evapotranspiration (mm day^{-1}), Δ is the slope of vapour pressure versus temperature (kPa °C^{-1}), Q_{ne} is a ratio of R_n and λ, R_n is net radiation, γ is the psychometric constant (kPa °C^{-1}) and E_A is the drying power of air (Brutsaert and Stricker 1979; Brutsaert 2005). The advection effects were scaled by the aerodynamic vapour transfer term E_A expressed as:

$$E_A = f(\bar{U}_r)(e_s - e_a) \quad (12)$$

where $f(\bar{U}_r)$ is the wind function, e_s is the saturation vapour pressure and e_a the actual vapour pressure in mmHg (Brutsaert and Stricker 1979). The wind function used was a stelling-type standard equation expressed as (Brutsaert 2005):

$$f(\bar{U}_r) = 0.26(1 + 0.54 f_{\bar{U}_2}) \quad (13)$$

where $f_{\bar{U}_2}$ is the mean wind speed at 2 m (m s^{-1}).

Advection aridity method has been widely used to perform validation of other methods for actual evapotranspiration estimation. The results shown in Fig. 7 are satisfactory both for rabi and kharif cropping seasons. However, we observe notably higher NSE and relatively low bias values for winter seasons (rabi) compared with those of the summer seasons (kharif). This outcome is supported by Hobbins and Ramirez (2001) and Liu et al. (2010) who argue that advection aridity method performs relatively better under cold environmental condition than the arid ones.

Results of actual ET during kharif and rabi seasons have a significant difference. It is mainly due to variation in climatic conditions, crop types and water availability. The average values of ET from upper and lower irrigation subdivisions of LCC indicate differences for similar crop types. For example, the average range of ET for rice crop is 9.83, 9.67 % for kharif fodder, 10 % for sugarcane while 9.75 % for cotton crop. The difference in ET is less for rabi seasons as for example, it is 1.0 % for wheat, 1.05 % for sugarcane while 0.98 % for rabi fodder. These variations in ET could be even higher if analyses are carried out at finer spatial scales as reported by Usman et al. (2014) about the variation in ET and crop water

productivity in case of wheat and rice crops in the same study region where these two crops constitute the major crops during rabi and kharif seasons, respectively. They report very high spatial variations in ET especially for rice crop at 1 km × 1 km spatial scale concerning the same region. The ET results for current study are obtained at 1 km × 1 km spatial scale thus helping to account for all heterogeneity in ET values with actual water availability at field level. However, this may be impossible to derive crop ET using weather observatory data and generalized crop coefficients. The average total volume of water utilized by various major crops shows that rice and wheat are major consumers of water during all kharif and rabi seasons with an average amount of about 185,349.5 ha m and 150,548.5 ha m, respectively. The shares of sugarcane, cotton, rabi and kharif fodders are 105,399.5 ha m, 82,599.7 ha m, 68,575.8 ha m and 152,856.6 ha m, respectively.

Analysis of recharge from field percolation losses

Figure 8 shows estimated values of recharge from field percolation. It is evident that field percolations are higher for kharif seasons than for rabi seasons. The obvious reason is cultivation of high water demanding crops during kharif. The recharge from field percolation is also variable among different irrigation subdivisions in case of both kahrif and rabi seasons. For example, recharge in the rice-dominant cultivated areas (60–70 % of total area) like Sagar, Chuharkana and Mohlan, etc., is higher than in the other regions courtesy higher water demand by rice while major share returning back as field percolation. Rest of the cultivated area in these subdivisions is occupied by fodder, sugarcane and cotton. The overall average field percolations in Sagar, Chuharkana, Paccadala and Mohlan are

28.35, 30.49, 26.64 and 30 % of the total applied water, respectively. On the other hand, the percolation losses in mix-cropped irrigation subdivisions including Tarkhani, Tandlianwala, Sultanpur, Kanya, Buchiana and Bhagat are 19.7, 20.3, 18, 18.3, 20.4 and 21 %, respectively. These results advocate that the guidelines by Maasland (1968) can be applied to estimate overall average recharge from field percolation for mixed cropping zones whereas they differ for rice-dominant areas.

Similarly, for rabi seasons, wheat is the major crop grown in LCC. Its cultivation is relatively higher in areas dominant in rice cultivation and it occupies about 55–70 % of the total cropped area, especially for Sagar and Chuharkana irrigation subdivisons where it is even higher for some cropping years. The overall average field percolations from Sagar and Chuahrkana irrigation subdivisions are 7.6 and 8.7 %, respectively. Values of field percolations for Paccadala, Mohlan, Tarkhani, Tandlianwala, Sultanpur, Kanya, Buchiana and Bhagat are, respectively, 14.5, 10.5, 12.4, 11.2, 16, 10.2, 20.6 and 10 % of the total water application as percolation losses.

Comparisons of recharge estimates using different methods

Comparisons of recharge estimates were made at irrigation subdivision levels between WBM1 and WBM2, and also for WBM2 and WTF. Figure 9a shows the graph between WB1 and WBM2. From this figure, it is evident that net recharge from WBM1 is significantly lower than the recharge from WBM2 for almost whole data. The difference in among recharge estimates is more pronounced for kharif seasons as compared to rabi seasons (Fig. 9b). For kharif seasons, the values of different statistical indicators

Fig. 7 Validation of SEBAL results with advective aridity method
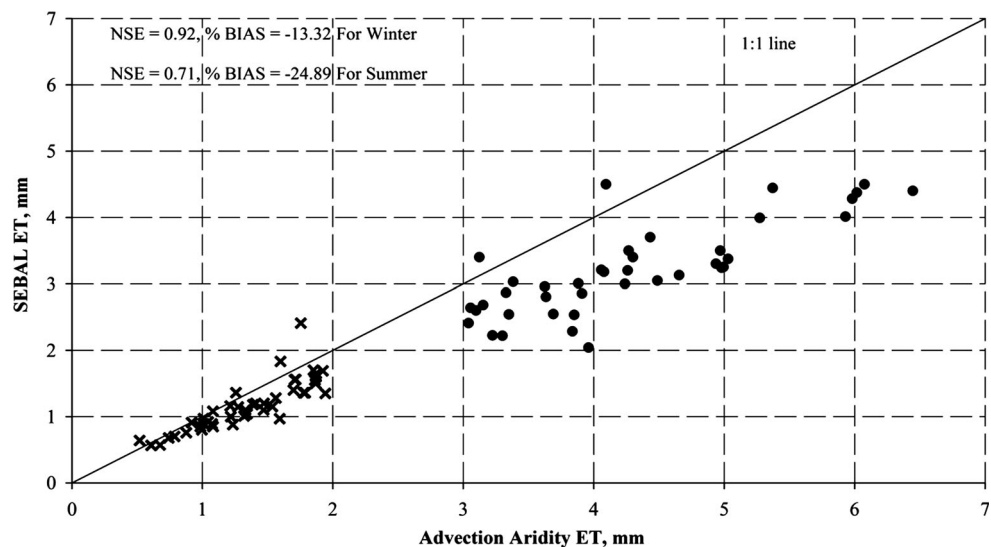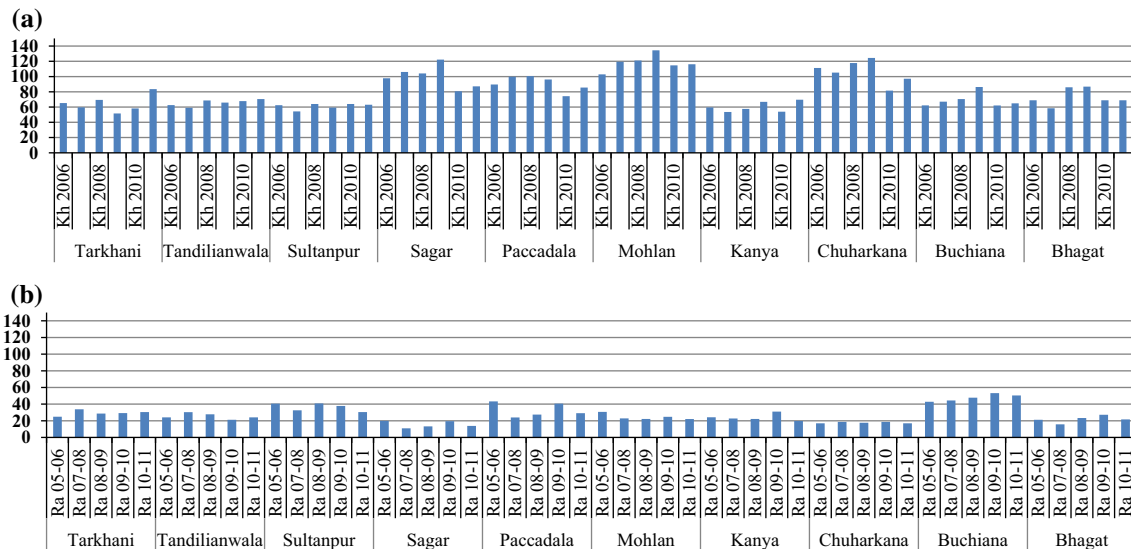
Fig. 8 Field percolation losses (mm) in different irrigation subdivisions **a** for kharif and **b** rabi cropping seasons

including NSE and RMSE are −72.7 % and 104 mm, respectively; however, for rabi seasons, the values are 35 % and 53.1 mm, respectively. Negative value of NSE for kharif season suggests an under-estimation of recharge values by WBM1 in comparison with WBM2. The reason for this large difference in recharge can be gauged by the comparison of groundwater abstractions used for both models. In case of WBM1, the groundwater abstraction is estimated by conventional utilization factor approach. However, for WBM2, the groundwater abstraction is estimated by Eq. (10).

Figure 9b gives the distribution of groundwater abstraction utilizing both methods for various irrigation subdivisions. Very high differences in groundwater abstractions by both techniques are observed. Groundwater abstraction by utilization factor method is very high in almost each irrigation subdivision and for both cropping seasons. This is attributable to very subjective nature of groundwater estimation by utilization factor method. In this case, tubewell intensity for various irrigation subdivisions was extravagated using tubewell census data at district level following the guidelines given by Qureshi et al. (2003). Nevertheless, all these guidelines are very general in nature and may lead to huge differences in calculations particularly at relatively smaller spatial scale, i.e., irrigation subdivision. Moreover, discharges from tubewells in different regions may significantly vary causing erroneous discharge volume calculations. However, in case of utilization factor method, an average discharge value of tubewell is proposed for each study sub-region. This technique also cannot accommodate sudden changes in canal water supply, cropped areas and rainfall thus greatly affecting the estimation of groundwater abstraction for

irrigated areas like LCC. As for example, according to Fig. 10b, there is sudden increase in canal water supply to some irrigation subdivisions which cannot be accounted for by this approach. Moreover, fluctuation in groundwater abstraction by this approach is quite static; however, in reality, it is always variable due to variability in specific cropping area, canal water supply and rainfall in various cropping years.

The other reason of variability between recharge from WBM1 and WBM2 stems from the calculations in evapotranspiration using crop coefficients suggested by Food and Agriculture Organization (FAO) of United Nations. These estimations are generalized and fail to accommodate local variations in water stress to crops stemming from water shortages and other agronomic factors. It can only be overcome by the use of specific energy balance algorithm for actual evapotranspiration estimations. For the current study, however, it is not a case because actual evapotranspiration from SEBAL approach were utilized for calculations of net recharge from both WBM1 and WBM2. Similar could be true for rainfall, where rainfall data from only very few observatories were used to estimate average rainfall for a very large area. These average rainfall observations from only few points do not serve as true representatives for average of a larger area, and hence lead to erroneous estimates of net recharge. However, this study made use of spatially distributed rainfall data from satellite remote sensing in case of both WBM1 and WBM2, which already accommodates the potential bias due to under representativeness in recharge estimation.

The recharge results from WBM2 are also compared with WTF method. Figure 10 shows the relationship of net
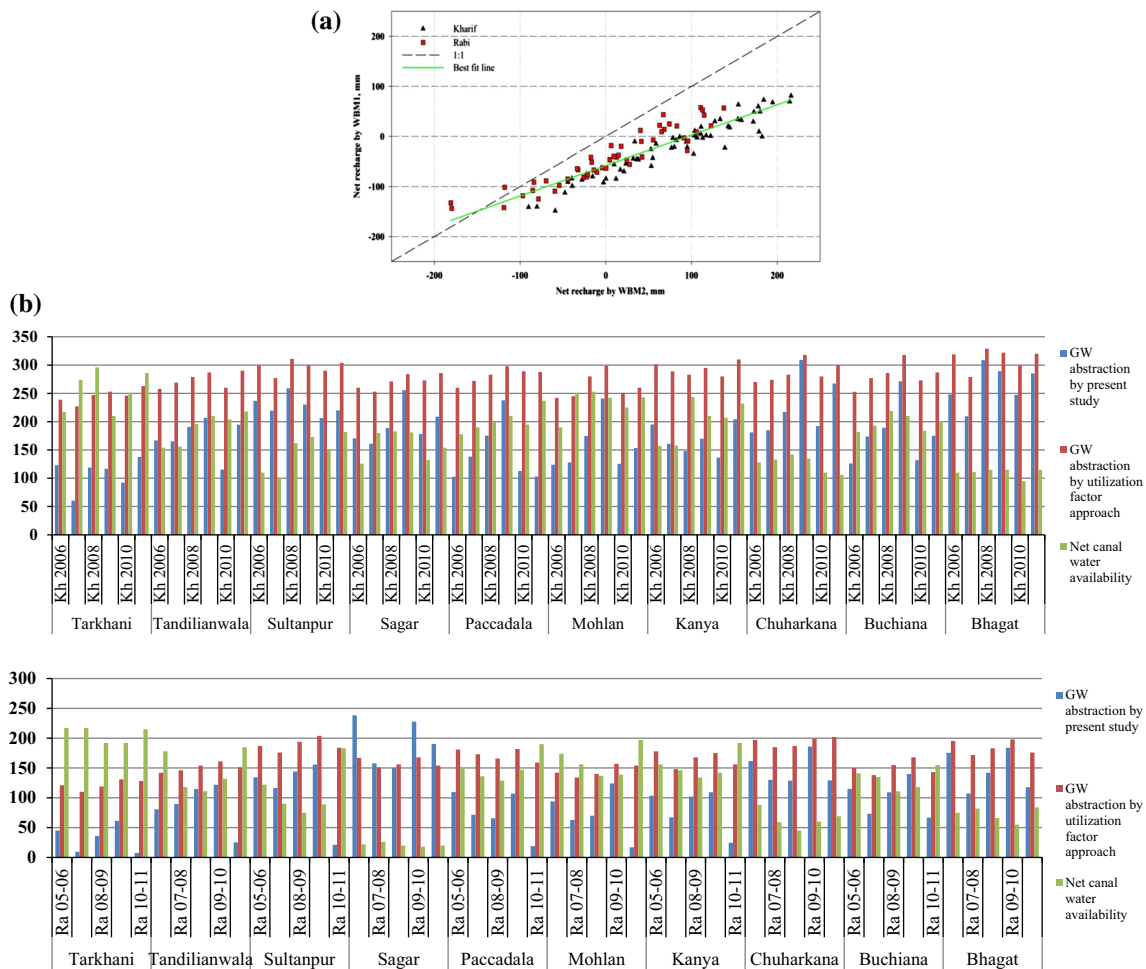
Fig. 9 **a** Comparison between net recharge from WBM1 and WBM2 and **b** difference of groundwater abstraction (mm) from utilization factor and present study approaches (1) for kharif and (2) for rabi cropping seasons

recharge using WBM2 and WTF methods. A significant improvement is observable from the comparison of results both for kharif and rabi cropping seasons, as majority of the points are near the 1:1 line. The NSE and RMSE confirm this coincident of results as their values are 89.4 %, 15.64 mm and, 92.8 %, 14.14 mm for kharif and rabi seasons, respectively.

These analyses were also extended to cater for each irrigation subdivision. It is worth mentioning that comparisons between WBM2 and WTF do not include cropping seasons of rabi 2008–2009 and kharif 2008 as complete piezometric data were missing for the said seasons. It also excludes areas where the spatial coverage of piezometric data was very coarse for some particular times. Table 3 shows the detail of recharge results for each irrigation subdivision. Some variation in results is observed among various irrigation subdivisions, as for example, results are highly comparable for Sagar with NSE of 98 % and RMSE of 14.1 mm; however, it is uneven for Tarkhani irrigation subdivision having NSE and RMSE values of

66 % and 22.1 mm, respectively. The reason may be errors arising either from WBM2 or WTF method.

The comparison of results discussed so far considers only the average values of net recharge at irrigation subdivision level. Since distributed recharge is also estimated at a spatial scale of 1 km × 1 km using WBM2, it is therefore, compared spatially with results from WTF approach as well. For this purpose, specific pixels from specific locations away from the irrigation network were selected at the most homogeneous locations of Chuharkana irrigation subdivision. Before this selection process, both the lithological and piezometric completeness and relatively denser availability of the data were ensured to achieve maximum heterogeneity in net recharge results from WTF method and to yield more realistic comparisons. Such comparisons are generally not well-represented for regions where both piezometers and borelog data are coarser. In such situation, only average net recharge results can possibly be compared with WBM2 thereby ignoring its heterogeneity at finer spatial scales (i.e., 1 km × 1 km).

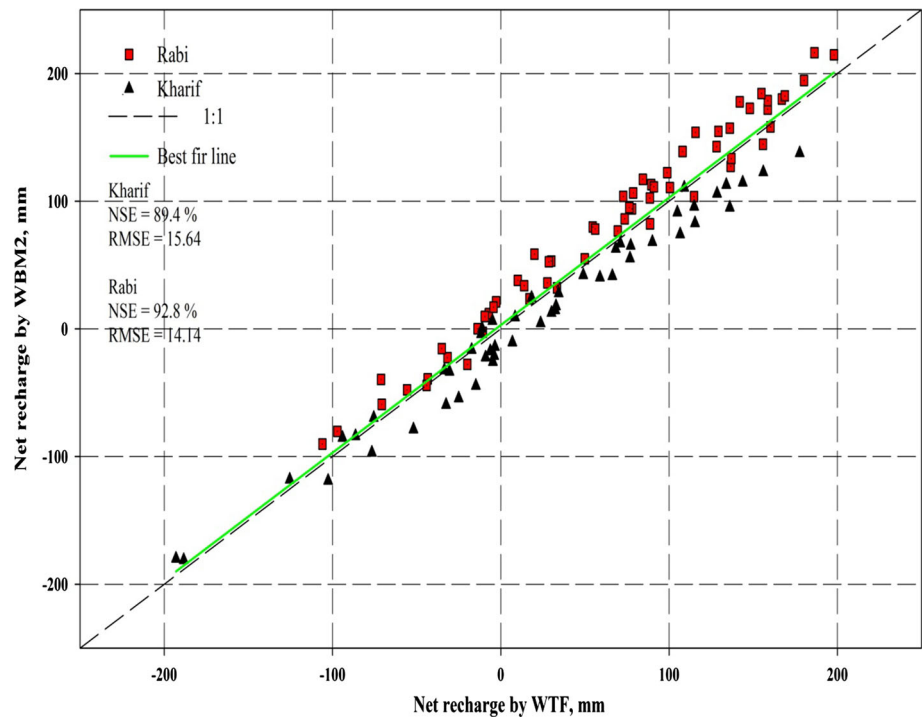**Fig. 10** Comparison between net recharge from WBM2 and WTF

Figure 11a, b show the distributed net recharges from WBM2 and WTF for only kharif 2006 season along with location of selected pixels in the whole selected area. These maps were generated separately for each kharif and rabi season. After retrieving the net recharge values for only the selected pixels for different seasons, the results were drawn separately as shown in Fig. 11c. These results evidently show that both recharge methods behave quite similarly as large values of NSE and lower values of RMSE were found for all three pixels. For pixel (64), values of NSE, RMSE and correlation are 86 %, 21.91 mm and 0.92, respectively, and for pixels (53) and (8), their values are 89 %, 18.6 mm, 0.94 and 84 %, 24.75 mm, 0.92, respectively.

Although the results of net recharge generated by WBM2 and WTF are quite comparable both at irrigation subdivision level and, at pixel scale from homogeneous locations. However, it does not mean that the recharge estimation by WBM2 is also absolutely comparable to local recharge values from any particular area smaller than this spatial scale. This is because the average recharge values at 1 km × 1 km spatial scale reflect only the average recharge conditions for this scale which may not be well-comparable with point measurements from very small fields. For instance, Szilagyi et al. (2011) has compared remote sensing based mean annual recharge from 1 km × 1 km spatial resolution with point based recharge estimation from chloride mass balance. They presented a weak correlation value of 0.57 from their results. Similar is the case for WTF where net recharge at 1 km × 1 km is

estimated from well-separated piezometric points, so it cannot fully reflect local recharge fluctuations at certain locations, e.g., recharge from only rice fields of smaller size. Accommodation of extra heterogeneity is only possible with the use of finer spatial resolution data from remote sensing for WBM2, installation of more piezometers as well as well-distributed data regarding material properties for WTF method.

At the selected spatial scales for this study, further improvement in recharge results by WBM2 is possible through the use of good quality canal gauge data for various locations on irrigation network. This improvement is achieved due to the improved distribution of seepage values on various lengths of canal network as well as testing of alternative recharge buffer zones for irrigation network. The errors from distributed canal irrigation are not as high as each irrigation subdivision is supplied with water from separate distributaries. Moreover, this error is also minimized through the allocation (distribution) of water in varying percentage of total supply for various crops with the help of LULC maps in the current study.

Error in recharge comparison may also emerge for larger spatial scales if WTF method is not carefully implemented (Healy and Cook 2002) irrespective of recharge heterogeneity at very fine spatial scales. A major reason for this error is poor distribution of piezometric data despite its higher intensity. It is extremely advisable to use data from similar piezometric points while calculating recharge for a particular duration. Larger differences of piezometric points could lead to fussy

Table 3 Summary of statistical parameters for different irrigation subdivisions

Irrigation subdivision	RMSE (mm)	NSE	Irrigation subdivision	RMSE (mm)	NSE
Sagar	14.1	0.98	Tandlianwala	18.3	0.87
Chuharkana	25.8	0.85	Tarkhani	22.1	0.66
Paccadala	14.9	0.95	Kanya	15.3	0.88
Mohlan	12.8	0.96	Bhagat	15.2	0.89
Buchiana	20.6	0.88	Sultanpur	20.7	0.86

results. For example, in Fig. 12, piezometric points are shown for two consecutive time scales during the study period. Use of these types of data could create major errors in recharge estimation, especially in encircled regions. Furthermore, proper application of kriging interpolation techniques for piezometric data needs to be carefully executed to create groundwater surface (Baalousha 2005; Maréchal et al. 2006; Yin et al. 2011) and specific yield maps.

Relationship between the number of piezometric points and absolute difference in recharge results between WBM2 and WTF was drawn for regions by splitting each irrigation subdivision into three parts from the piezometric data for different seasons for study duration. From Fig. 13, it is evident that more the number of piezometric points the smaller become the differences given that points are well-distributed in the area.

Details of different recharge components

Annexure 1 and 2 show details of each recharge component and its spatial distribution, respectively, using WBM2 for each irrigation subdivision in LCC for the whole study period (Refer to supplementary material). Figure 14 shows the share of each recharge component both for rabi and kharif seasons. These indicate that during kharif seasons, rainfall is the main source of recharge in all irrigation subdivisions. Its average contribution is about 37 % of the total recharge during the study period. The second highest component is field percolation which is about 30 % of the total recharge. The other components include canal, watercourse and distributary seepage with a share of 13, 9.0 and 8.0 % in total recharge while the minimum share comes from groundwater inflow. Highest groundwater abstractions are observed in two lower and one upper irrigation subdivisions, i.e., Bhagat, Sultanpur and Chuharkana with average values of 264.7 and 229 mm; and 226 mm, respectively. Minimum groundwater abstraction is observed in Tarkhani with an average amount of 108 mm, while it is also in smaller amount in case of Paccadala and Mohlan irrigation subdivisions bearing average values of 144.9 and 157.7 mm, respectively, for all kharif seasons. Therefore, under the described situation of individual average recharge and discharge components, net recharge is positive for almost all the irrigation

subdivisions during kharif seasons except for only two lower irrigation subdivisions (Bhagat and Sultanpur).

For rabi seasons, rainfall (17 %) is no longer the dominant recharge component. The highest recharge contributions during these seasons come from canal seepage and field percolation with an overall share of about 26 and 23 %. The other recharge components include watercourses and distributary losses with values of 14 and 13 %, respectively. However, individual seasonal values interchange between two parameters as given in (Annexure 1). Groundwater abstraction is found to be the highest in most of upper irrigation subdivisions of LCC. Higher groundwater abstractions from aquifer in the upper irrigation subdivisions are due to decrease in canal flow during this season, especially in case of Sagar. Although, the water is required in lesser amounts during these rabi seasons, however, groundwater abstraction increases due to decreased canal flows. From upper parts of LCC, the net recharge is negative for Sagar for the whole study period whereas, it is also negative from Bhagat and Sultanpur in the lower part. However, net recharge for other areas varies from season to season. This situation does not advocate that the total recharge is similar for both rabi and kharif seasons rather it is mainly due to reduced groundwater abstraction as crop water requirements fall in the rabi seasons (Refer to Annexure 1).

The results of net recharge obtained are quite comparable with the results from few previous studies in the region. These studies may differ in coverage of area and applied methodology but are mainly conducted in irrigated areas of Indus Basin, Pakistan. One such study reported a long-term annual recharge of 60 mm in Rechna Doab, Pakistan (Hassan and Bhutta 1996). They also reported a positive recharge in kharif seasons and groundwater depletion during rabi seasons. Boonstra and Bhutta (1996) conducted a regional recharge study for the period of 1965–1990 in Rechna Doab and found a positive annual net recharge of 73 mm. Another long duration study (from 1965 to 2001) conducted by Habib (2004) in Indus Basin observed a positive annual recharge from 1965 to 1994 and then negative afterwards with a decrease from 25 to − 17.9 mm. A recent study covering the whole Indus Basin by Bhutta and Alam (2005) contemplated that annual recharge is either equal to or less than annual discharge
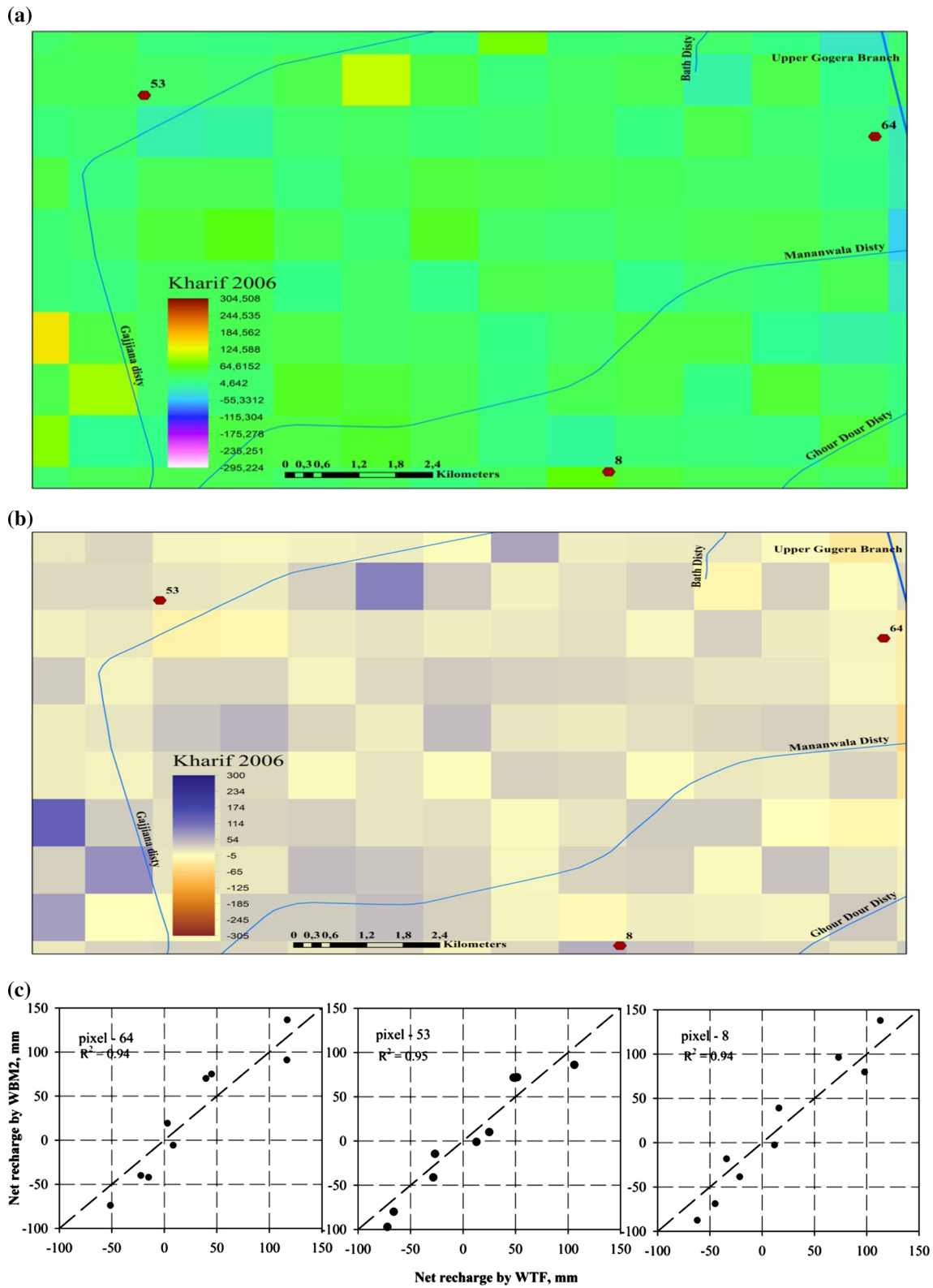
Fig. 11 Distributed net recharge from **a** WBM2 and **b** WTF method for kharif 2006 and **c** comparison of net recharge for selected pixels

Fig. 12 Study area with missing piezometric points in comparison with well-distributed data

whereas, Cheema et al. (2014), suggest a negative recharge of −63.2 mm for the year 2007.

Status of groundwater for the study duration

Average groundwater level changes were drawn for each irrigation subdivision, separately (Fig. 15). Groundwater level seemed to raise in majority of the irrigation subdivisions during the study period. Decrease in water level is observed in Bhagat, Sultanpur and Sagar subdivisions with decrease of −0.661, −0.25 and −0.069 m, respectively. It is important to mention that decreasing water table trend in Sagar is attributable to the increase in rice cultivated area (10–15 %) in recent years, which exerts extra pressure on the water table given nearly the same surface water supply. The continuous rise in water table for most of the upper LCC irrigation subdivisions after year 2010 is mainly due to heavy rainfalls as well as decrease in rice cultivated area in some regions during previous years. For example, in Tandlianwala irrigation subdivision, there is a drop of about 75,000 hectares in rice cultivated area during the last two cropping seasons.

This temporal change of groundwater status is of great help to the policy makers in order to recommend changes in current crop production practices to ensure uninterrupted irrigation water supply to various parts of LCC.

Conclusions and outlook

Estimation of groundwater recharge is integral part of sustainable groundwater management. However, it is largely variable in irrigated areas. In the present study, an effort is made to quantify average recharge at relatively larger scales and its distribution at 1 km × 1 km spatial scales. The main conclusions drawn from the study and outlook for future research and policy intervention are as follows:

1. Estimation of groundwater abstraction by conventional utilization factor approach gives inflated values during both kharif and rabi seasons at irrigation subdivision spatial scales. The reasons are lack of availability of tubewell intensity/density data at desired locations. There are also a number of parameters which are not location-specific and the decision to incorporate these parameters renders this approach to be very subjective and user dependent. Moreover, it is also impossible to estimate distributed groundwater abstraction with this approach.

2. Estimation of distributed groundwater abstraction is possible by an indirect method using remote sensing data which is highly responsive to fluctuations in canal water supply, changes in land use and rainfall.

3. Percolation losses within the fields on the basis of some fixed percentages suggested by previous
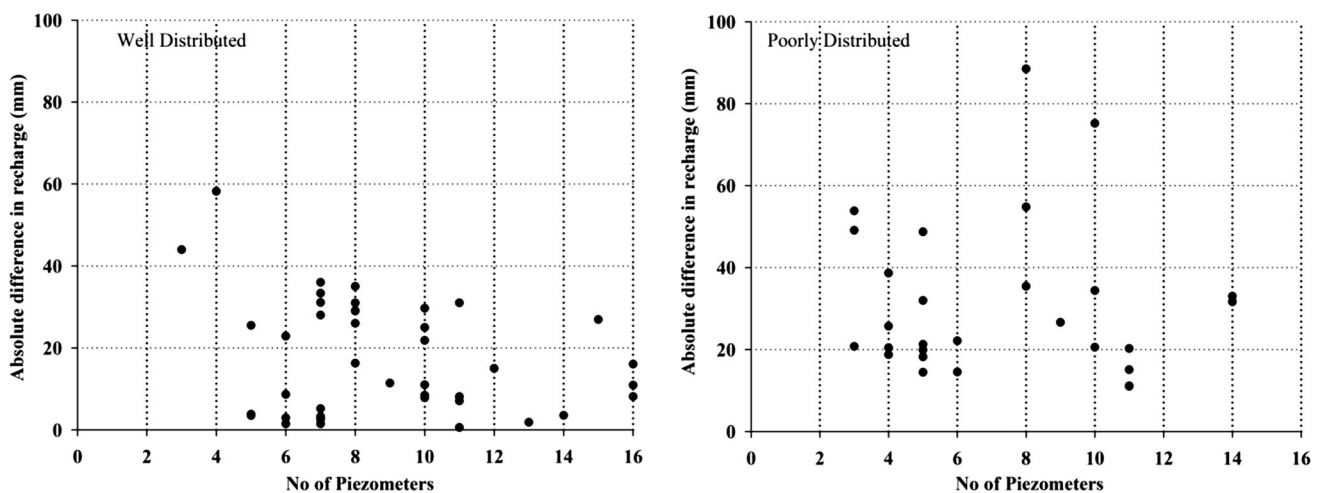
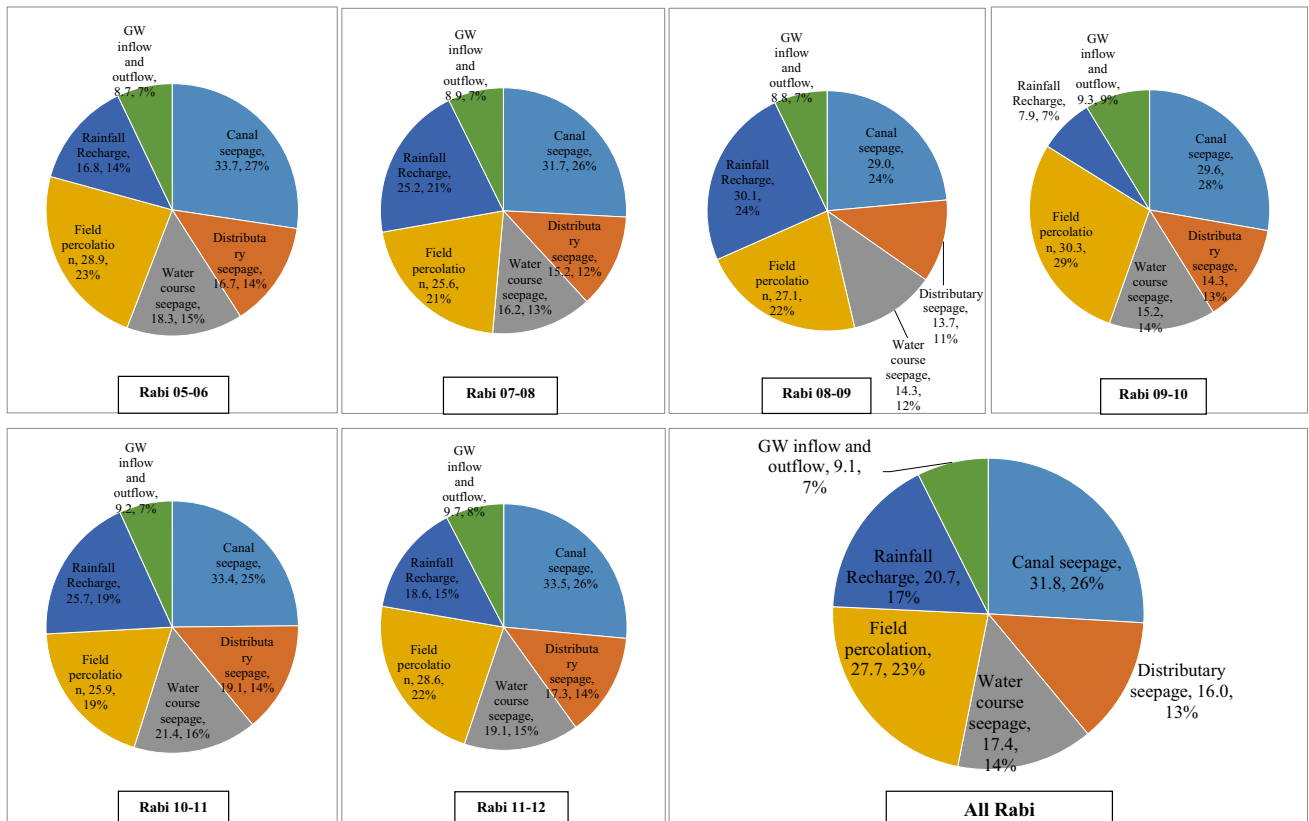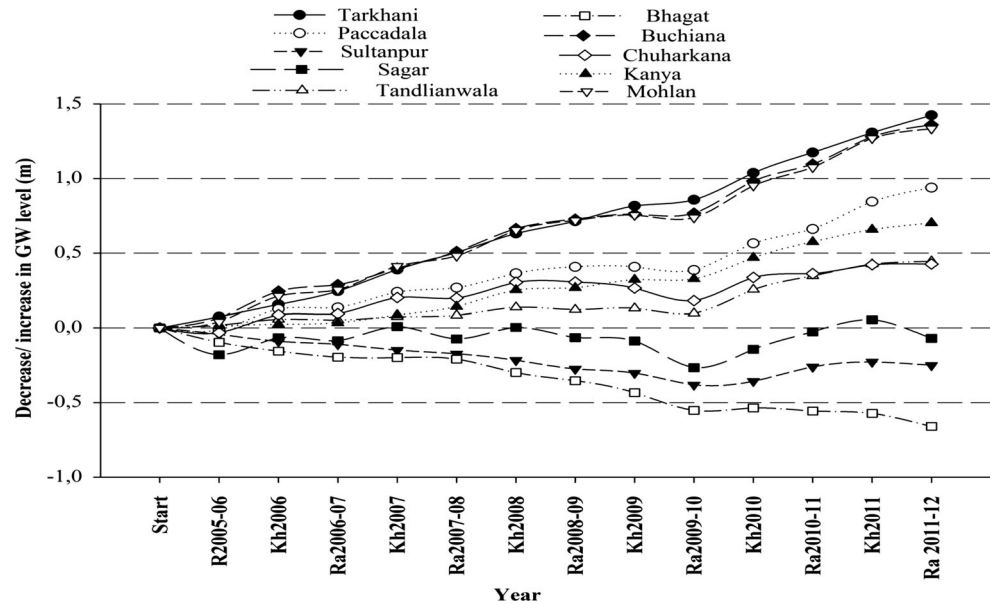**Fig. 13** Relationship between number of piezometers and absolute difference in net recharge
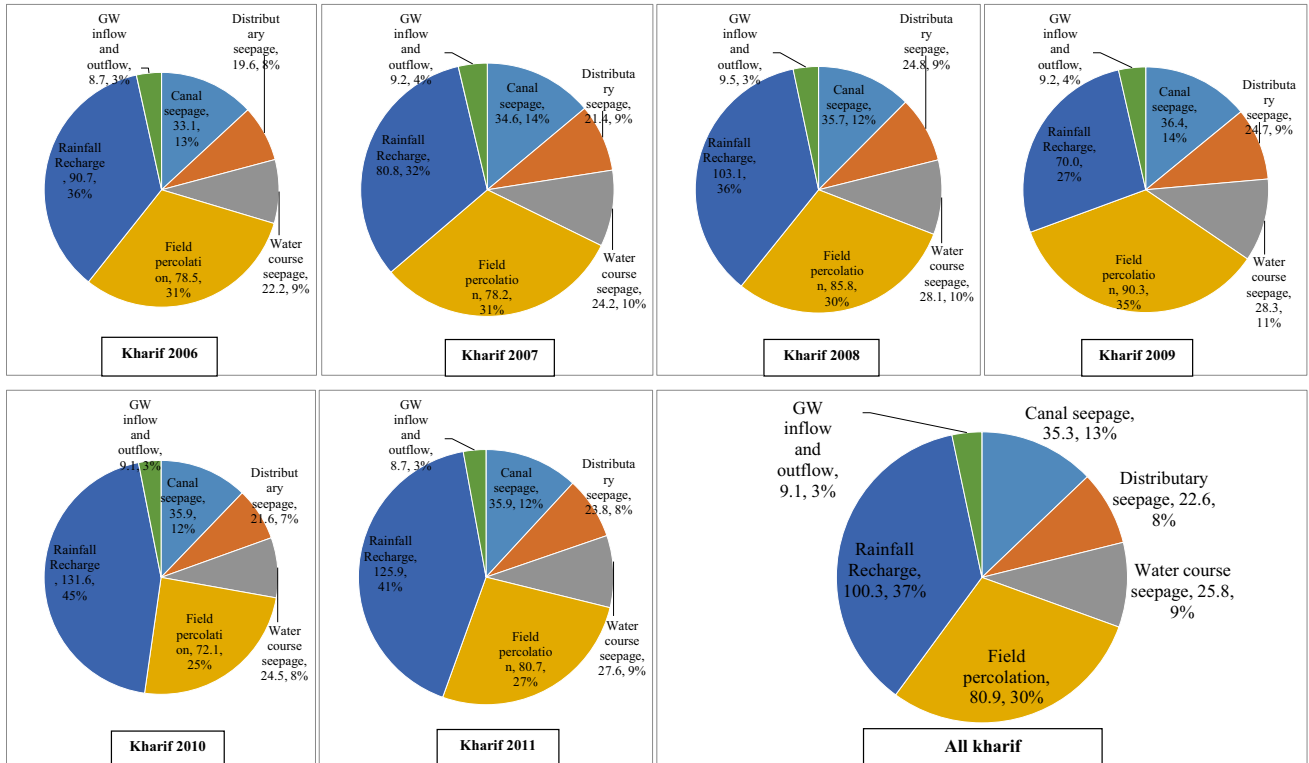
Fig. 14 Distribution of different recharge components in LCC for **a** kharif and **b** rabi cropping seasons

Fig. 15 Decrease/increase in water table during study period for different irrigation subdivision

studies related to the study area are quite different for areas dominated by rice and wheat cultivation as compared to variable percentages considering different crop types. However, this difference is not much pronounced for mixed cropping regions.

4. The net recharge results by water balance approach are comparable with water table fluctuation method both at irrigation subdivision level and at finer spatial scale.

5. Accommodation of more heterogeneity in net recharge is possible through the use of finer spatial resolution data from remote sensing by water balance method and installation of more piezometers along with well-distributed data on specific yield for WTF method.

6. At the studies spatial scales, improvement in recharge results by water balance method is possible through the use of better canal gauge data for different locations of irrigation system which could help its better distribution at different lengths of canal network and also by testing alternative recharge buffer zones for irrigation canal network.

7. The net groundwater recharge is largely variable both spatially and temporally in the study region. In most of the upstream parts of the study area, the recharge is positive during the kharif seasons. This is mainly due to more rainfall during monsoon seasons at these locations. The two remote irrigation subdivisions of Bhagat and Sultanpur have more dependence on groundwater use where abstraction of groundwater is higher than recharge. Rainfall is the main source of recharge during kharif seasons.

8. The recharge results for rabi seasons are quite variable from year to year even for the same locations. Decreased rainfall during these seasons completely alters the trends of recharge whereas canal seepage becomes dominant.

9. Sagar irrigation subdivision in the upper parts of the study area along with lower Bhagat and Sultanpur irrigation subdivisions show declining groundwater trends for the study duration. Rest of the locations show gently increasing groundwater trends. This can be mainly attributed to more rainfalls in the last few seasons and changing cropping patterns in the area.

10. More detailed recharge studies for different crop dominant regions should be conducted to account for variability of different recharge inputs/outputs. Modelling approaches should be utilized to predict the groundwater behavior under different land use and irrigation system scenarios.

11. Modifications in the canal water supply should be proposed based on the location specific groundwater situation and recharge for sustainable water resources in the study area.

12. Studies about sensitivities and uncertainties of different recharge input/output variables should be conducted in more detail to present results with some confidence intervals. This could also lead to economical operation and management of water resources and associated data collections.

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