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ORIGINAL ARTICLE

Soil water budgeting approach to quantify potential groundwater recharge from croplands and groundwater use in a semi-arid region

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Abstract The groundwater resources of semi-arid region in Indo-Gangetic Plain is declining rapidly and necessitates accurate quantification of potential recharge from different agricultural land uses. The potential recharge on a daily basis for three different land uses, such as fallow, rice and non-rice cropped areas for three cropping seasons, was estimated using soil water balance approach. Beside this, the net groundwater use for eight different crops was also calculated. The potential recharge from fallow land was 126 mm year^{-1}, which was 14.9 % of total rainfall. The mean potential recharge from kharif (rainy) and rabi (winter) seasons was 527.3 and 81.7 mm season^{-1}, respectively. Among the rabi crops, least recharge was observed for winter maize and mustard with 29.3 mm season^{-1}, followed by wheat with 108.4 mm season^{-1}. Among the kharif crops, least recharge was observed for green gram with 59.7 mm season^{-1}, followed by soybean with 113.9 mm season^{-1}. Rice had the highest recharge potential of 929.1 mm season^{-1}, followed by maize with 149.1 mm season^{-1} and cotton with 132.7 mm season^{-1}. It was observed that the annual average groundwater use was highest for wheat with 190 mm year^{-1}, followed by winter maize with 188 mm year^{-1}, mustard with 169 mm year^{-1}, paddy with 151 mm year^{-1}, kharif maize with 94 mm year^{-1}, green gram with 15 mm year^{-1}. Cotton and soybean crops exhibited an additional potential recharge of 8 and 114 mm year^{-1} into the groundwater. It was revealed that the maize–wheat cropping system consumed less groundwater than rice–wheat and, therefore, can be considered as a better option for sustainable use of groundwater.

Keywords Soil water balance · Groundwater recharge · Indo-Gangetic Plain · Semiarid region · Groundwater use

Introduction

Groundwater is depleting at an alarming rate in many parts of the world including India. In India, as in other developing countries, agriculture accounts for as much as 85 % of total annual draft (FAO 2012). Projections for the year 2025 indicate that all of northwestern India, the southern plateau and southeastern coastal regions will run into a water-deficit region (IWRS 1997). In semi-arid region of Indo-Gangetic Plain (IGP) in India, especially in the northwest part, the shortage of surface water is a major limiting factor. In these regions, groundwater is the main source of water for irrigation (CGWB 2007). A recent study indicates that IGP constitutes almost 80 % of groundwater irrigation in the country (Patil et al. 2014). Using satellite-based estimates of groundwater depletion, Rodell et al. (2009) found that groundwater is being depleted at a mean rate of 4.0 ± 1.0 cm year^{-1} across the states of Rajasthan, Punjab, Haryana and western Uttar Pradesh of IGP. Therefore, accurate quantification of groundwater recharge is a prerequisite for efficient and sustainable groundwater management in such semi-arid regions (de Vries and Simmers 2002). However, in these

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areas, recharge of groundwater is a complex process due to pronounced spatial and temporal variation of rainfall, soil texture, topography, vegetation, land use, etc. (Lerner et al. 1990; Simmers 1997; Scanlon and Cook 2002; Martos-Rosillo et al. 2015).

Recharge estimation can be obtained from field investigations using (1) water table fluctuation method (2) lysimeter and (3) tracer experiments (Rushton et al. 2006). The water table fluctuation method links the groundwater storage with resulting water table fluctuations through storage parameter (viz. specific yield) and estimates the quantity of water recharged for the given period of time. This method is considered to be promising due to its accuracy, ease of use and low cost of application in semi-arid region (Pirastru and Niedda 2013). However, recharge estimates are liable to become incorrect due to error in specific yield values (Healy and Cook 2002; Beekman and Xu 2003; Rushton et al. 2006) and not considering the lateral inflow of water (Kendy et al. 2003). Lysimeter provides a direct estimation of the recharge (Maloszewski et al. 2006). However, the estimates by this method are location specific and subjected to maintenance related problems. Also, tracer studies have been used in many countries to identify flow dynamics and their pathways in the unsaturated zone and groundwater recharge (Datta et al. 1996; Simmers 1997; Maloszewski et al. 2006; Stumpp et al. 2009; Adhikary et al. 2014), but this technique is laborious, time consuming and expensive (Canton et al. 2010).

Recharge can also be estimated by analyzing interactions between water and air in the unsaturated zone above the water table. But, solving the unsaturated flow equations becomes difficult, as the hydraulic conductivity is a function of the unknown soil water content and hydraulic gradient (Kendy et al. 2003). Consequently, this approach may not be suitable for routine recharge estimates. However, analyses based on unsaturated flow equations do provide information about the redistribution of the infiltration within the soil profile (Scanlon et al. 2006). An understanding of the movement of water in unsaturated zone can also be gained from field investigations pertaining to variation of total soil water potential and moisture content below the ground surface through sensors and data loggers (Delin et al. 2007).

The chloride mass balance (CMB) (Eriksson and Khunakasem 1969) has frequently been used in groundwater recharge studies to estimate the total recharge (Alcalá et al. 2011; Martos-Rosillo et al. 2013; Alcalá and Custodio 2014; Guardiola-Albert et al. 2014). The method is based on the fact that evapotranspiration removes water, but not chloride, leaving chloride concentrated in groundwater, allowing application of simple mass conservation of chloride between rainfall and groundwater. But it fails to accommodate the preferential flow of water through the cracks where point estimate is needed (Somaratne 2015).

Each of the above methods of recharge study provides insights into the flow processes within the soil porous media. However, none of them is suitable for easy estimation of recharge. Rather, a technique based on meteorological and field data available at most locations would be more appropriate. A soil water balance or budgeting technique can be used for routine recharge estimation in many situations, provided that important physical processes are represented adequately (Rushton and Ward 1979; Sarma et al. 1980; Xevi et al. 1996; Chowdary et al. 2003; Rushton et al. 2006).

Earlier studies used various methods to estimate recharge in the IGP. In the northwest part of semi-arid IGP, Jalota and Arora (2002) estimated the percolation from wheat to be 29.4 % of applied water. Dash et al. (2015a) used modeling approach to estimate potential recharge from maize and wheat field as 36.5 and 27.5 % of applied water. In another study, Dash et al. (2015b) estimated potential recharge from paddy as 55.5 % of the applied water. For the region where groundwater is the only source of irrigation, recharge, dependent on the amount of water pumped from the aquifer, will be a poor indicator of future groundwater table decline. Hence, net water use (recharge minus irrigation) can be a better indicator. In other parts of the world, researchers used net water use as an indicator of groundwater decline (Kendy et al. 2003; Yang et al. 2015), but very little information is available regarding this in the semi-arid part of IGP. Keeping these things in mind, this study was undertaken (1) to estimate potential recharge below the root zone of eight different field crops grown in the study area as well as from the fallow lands using soil water balance protocols, and (2) to quantify the net groundwater use by those field crops. Thus, this study will be helpful to select proper crop combinations to reduce the rate of groundwater table decline.

Materials and methods

Study area

The study was conducted at the experimental farm of ICAR-Indian Agricultural Research Institute (IARI), New Delhi, situated between 28°37′22″N–28°39′00″N and 77°8′45″E–77°10′24″E, at an average elevation of 230 m above mean sea level. The Institute is about 473 ha comprising mainly of farm land, residential complexes and office buildings (Fig. 1). Out of 473 ha area, about 280 ha is under intensive agriculture. The climate is semi-arid with an average annual temperature of 24 °C and average annual rainfall of 710 mm. The climatic data of the study

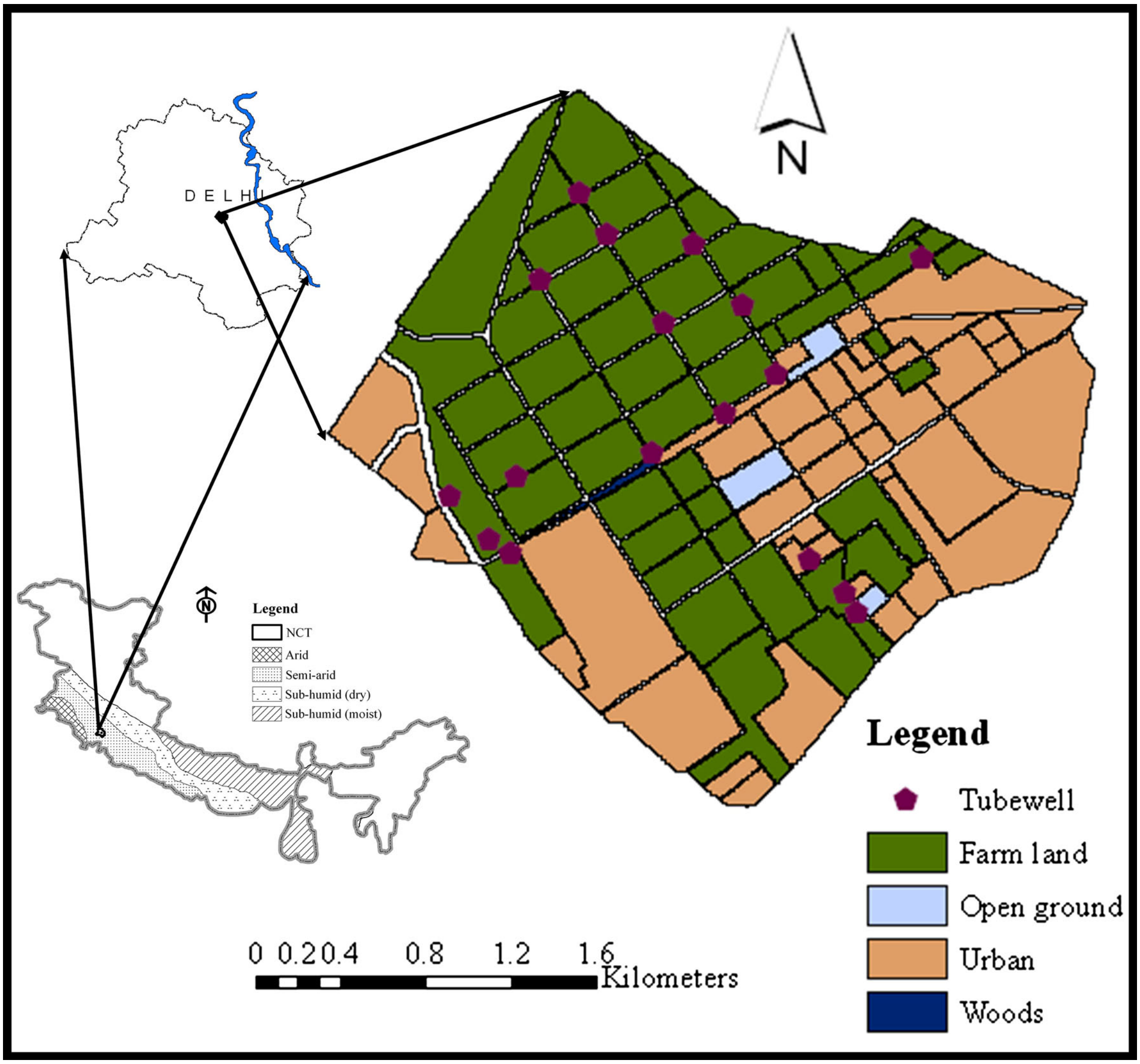

Fig. 1 Map of the study area showing various land uses and the location of the observation wells

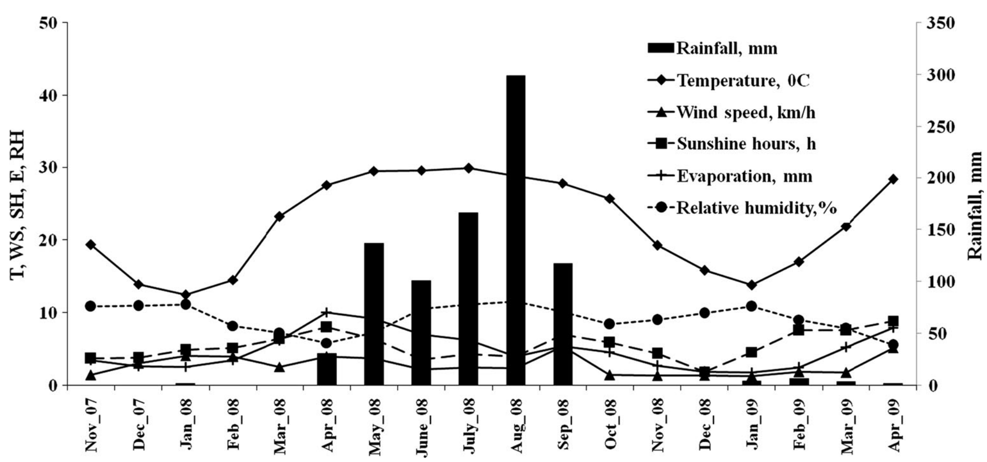

Fig. 2 Meteorological data of the study area during the observation period. *T* temperature, *WS* wind speed, *SH* sunshine hours, *E* evaporation, *RH* relative humidity

area for the observation period are presented in Fig. 2. The soil type varied from sandy loam to clay loam. The hydro-physical properties of the study area are given in Table 1.

Characterization of aquifer involving determination of various aquifer properties viz. specific yield, hydraulic conductivity and transmissibility was reported by Babu Ram and Singh (2003). Electrical resistivity surveys indicated that compact rock occurred at an average depth of 70 m below ground level with an exception near south-west part where a big inverted cone-shaped depression had formed a channel consisting of three layers of clay with sand, sand with kanker and kanker with fractured rock (Biswal 2003). The top of the channel rests in the depth of 40 m below ground level and the apex of the inverted cone at a depth of 90 m. In general, the entire area is suitable for groundwater recharge.

The potential root zone recharge was estimated for two rabi (winter, from November to March) seasons (2007–2008 and 2008–2009) and one kharif (rainy, from June to October) season (2008) (Table 2). The crops cultivated in different blocks of the research farm during the study period were maize, rice, wheat, cotton, green gram, chickpea, mustard and soybean. The irrigation at the IARI farm is being carried out through tube wells. Unconfined, shallow aquifer is found in sand, fine sand with clay, and boulder layers. Depth to groundwater varies from 8 to 16 m below ground level (bgl) throughout the year (Dash et al. 2012).

Soil water balance

In this study, we assumed that after meeting the needs of initial abstraction, infiltration, crop evapotranspiration and saturation of the soil profile, the excess water flows as surface runoff and percolates below the crop root zone. The study was carried out for three different situations: fallow/uncultivated land, rice cropped area and cropped area other than rice.

Soil water balance of fallow land

The equations used for estimating potential recharge from uncultivated or fallow lands (Allen et al. 1998) are given in Eqs. 1 and 2, and their different components are presented in Fig. 3.

$$\mathrm{MC}_i = (\mathrm{MC}_{i-1} \times D) + R_i - Q_i - E_i - P_i \quad (1)$$

$$P_i = R_i - Q_i - (\mathrm{FC} - \mathrm{MC}_{i-1}) \times D, \text{ if } P_i < 0, P_i = 0 \quad (2)$$

where MC_i is soil water content at the end of any day i (mm cm^{-1}), MC_{i-1} is soil water content at the end of the

Table 1 Mean hydro-physical properties of soils in the study area

Soil texture	PWP (mm cm^{-1})	FC (mm cm^{-1})	Bulk density (g cm^{-3})	Saturated hydraulic conductivity (mm day^{-1})
Clay loam	1.73	3.58	1.32	55.0
Loam	1.22	2.82	1.41	336.0
Sandy loam	0.94	2.13	1.54	1044.0

PWP permanent wilting point, *FC* field capacity

Table 2 Cropping pattern followed in the ICAR-IARI research farm during the study period

Field name	Area (ha)	Soil texture	Rabi 2007–2008	Kharif 2008	Rabi 2008–2009
New area	17.74	Sandy loam	Wheat	Rice	Wheat
MB_1	6.21	Sandy loam	Mustard	Green gram	Wheat
MB_2	6.61	Sandy loam	Wheat	Fallow	Mustard
MB_4	6.331	Loam	Mustard	Soybean	Wheat
MB_7	6.601	Loam	Cotton	Cotton	Cotton
MB_9	6.541	Loam	Wheat	Maize	Wheat
MB_{11}	7.05	Loam	Wheat	Maize	Wheat
MB_{12}	6.63	Clay loam	Maize	Maize	Maize
MB_{14}	6.97	Clay loam	Rice	Rice	Wheat
MidB A	7.00	Sandy loam	Wheat	Rice	Wheat
MidB C	6.84	Sandy loam	Wheat	Rice	Wheat
TB_6	5.25	Loam	Chickpea	Fallow	Chickpea
WTC_1	2.40	Loam	Mustard	Fallow	Mustard
WTC_2	5.40	Sandy loam	Wheat	Fallow	Wheat
Toda	8.93	Loam	Fallow	Fallow	Fallow

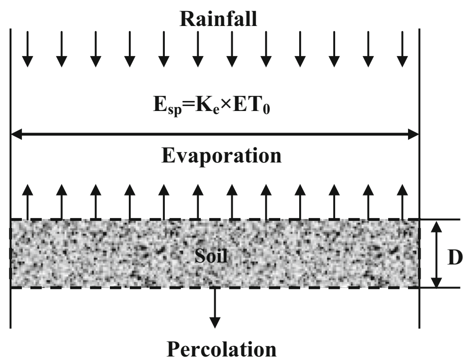

Fig. 3 Different components of soil water balance equation for fallow land

previous day *i−1* (mm cm^{-1}), R_i and E_i are the rainfall and evaporation, respectively, on *i*th day (mm), P_i is percolation out of the soil that is subjected to drying (mm), D is the depth of surface soil layer that is subjected to drying by evaporation (cm) and FC is soil water content at field capacity (mm cm^{-1}).

Estimation of soil water balance components for fallow land

The daily rainfall data for the growing period of each crop were collected from Meteorological Observatory, located at division of Agricultural Physics, ICAR-IARI, New Delhi. Daily runoff values were estimated using the USDA Natural Resource Conservation Services-Curve Number (NRCS-CN) method adapted for Indian conditions (Patil et al. 2008).

In the absence of vegetation, evaporation from fallow land (E_s) occurs in two distinct stages (Fig. 4). The first stage is termed as the "energy limited or constant rate stage", during which, moisture is transported to the soil surface at a rate sufficient to supply the potential rate of evaporation (E_{sp}), which, in turn, is governed by energy availability at the soil surface. E_{sp} is estimated using Eq. 3.

$$E_{sp} = K_e \times \mathrm{ET}_0 \tag{3}$$

where E_{sp} is potential rate of evaporation from soil (mm day^{-1}), ET_0 is reference evapotranspiration (mm day^{-1}) calculated using Penman–Monteith method, and K_e is evaporation constant. The value of K_e is taken as 1.05 for semi-arid climates (Rushton et al. 2006). This constant indicated increased evaporation potential due to the low albedo of wet soil and the possibility of heat stored in the surface layer during previous dry periods.

The second stage is termed as the "soil limited stage or falling rate stage", where hydraulic transport of subsurface water to the soil surface is unable to supply water at the potential evaporation rate. During this stage, the soil surface appears partially dry and a portion of the evaporation occurs from below the soil surface. The evaporation rate during this stage decreases as soil water content decreases as shown in Fig. 4.

The time required to complete the 1st stage is

$$(t_1) = \mathrm{REW}/E_{sp} \tag{4}$$

where readily evaporable water (REW) is the cumulative depth of evaporation at the end of 1st stage (mm). Values of REW were estimated from field studies. Some representative REW values for different soils to a depth of 100 mm, which is subject to drying by evaporation, are given in Table 3 (Allen et al. 1998). In the falling rate stage, the evaporation can be calculated as:

$$E_{sf} = K_r \times K_e \times \mathrm{ET}_0 \tag{5}$$

$$K_r = \frac{\mathrm{MC}_{i-1}}{\mathrm{TEW} - \mathrm{REW}} \tag{6}$$

$$\mathrm{TEW} = (\mathrm{FC} - 0.5\mathrm{PWP}) \times D \tag{7}$$

Fig. 4 Relationship between soil moisture availability and evaporation reduction coefficient. *FC* field capacity, *PWP* permanent wilting point, *REW* readily evaporable water, *TEW* total evaporable water

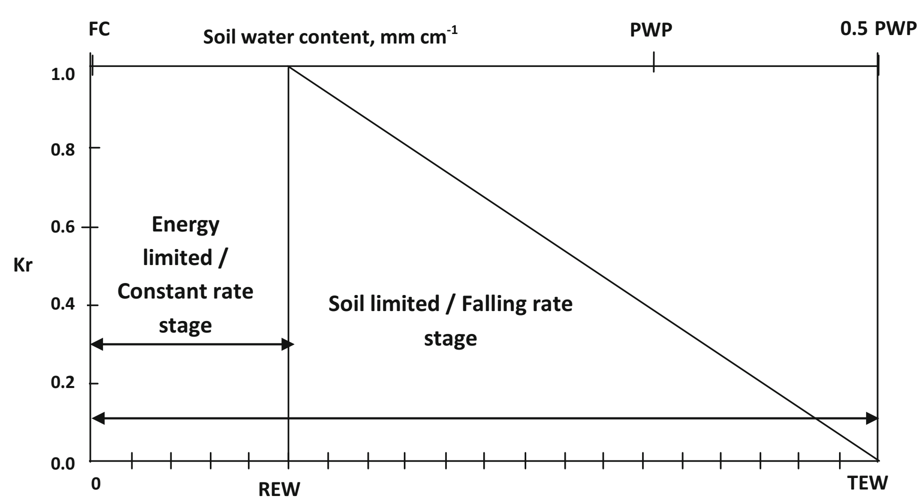

Table 3 Values of Readily Evaporable Water (REW) for a depth of 100 mm for different soil textural class

Soil type	REW (mm)
Sand	2–7
Loamy sand	4–8
Sandy loam	6–10
Loam	8–10
Silt loam	8–11
Silt	8–11
Silt clay loam	8–11
Silty clay	8–12
Clay	8–12

where K_r is soil evaporation reduction coefficient ranging from 0 to 1, Total evaporable water (TEW) is the maximum cumulative depth of evaporation from the soil surface layer (mm) and PWP is soil water content at permanent wilting point (mm cm^{-1}). The soil moisture content at four different depths (0–30, 30–60, 60–90, and 90–120 cm below the ground surface) was measured periodically in a gap of 1 month using gravimetric method (Black 1965).

Soil water balance of rice field

Rice is generally grown under continuously flooded condition with about 5 cm depth of standing water during the crop growing season. For rice, the inflow components in the water balance are irrigation and rainfall, whereas evapotranspiration, percolation and surface runoff are the outflow components. The change in field storage is represented by the change in the moisture content of soil after accounting all the component of water inflows and outflows. The different components of the soil water balance for rice are presented in Fig. 5.

The water balance equation for rice fields can be expressed as follows;

$$\mathrm{WD}_i = R_i + \mathrm{IR}_i - \mathrm{ET}_{c_i} - P_i - Q_i \qquad (8)$$

where WD_i is water depth in the field on ith day, mm; ET_{ci} = Crop evapotranspiration on ith day, mm.

All other components are defined earlier. The time period is considered as 1 day. It is assumed that there is no

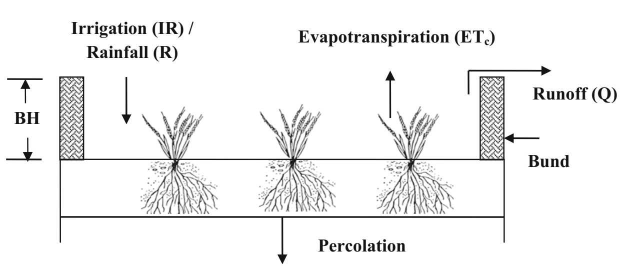

Fig. 5 Different components of soil water balance for rice crop

capillary rise from groundwater as water table is below 8–16 m in the study region.

Estimation of components of soil water balance in rice field

In the present study, rainfall in excess of bund height was considered as surface runoff. In the rice field, a bund height of 15 cm was considered and irrigation was given according to crop water requirement. Again, if a significant amount of rainfall occurred immediately after irrigation, then the total amount of rainfall was treated as runoff due to saturation of the soil. The daily percolation rate out of the root zone (30 cm) layer was computed by Darcy's law adopting the method reported by Singh et al. (2001) and Chowdary et al. (2003). For rice, evapotranspiration is assumed to be equal to potential evapotranspiration if soil moisture content is above or equal to field capacity, and when the moisture falls below field capacity, evapotranspiration is assumed to decrease linearly with soil moisture content between field capacity and permanent wilting point. The evapotranspiration was computed from the product of ET_0 and crop coefficient (K_c) (Allen et al. 1998). The K_c values for rice on weekly basis were obtained from Tyagi et al. (2000).

Soil water balance for non-rice field

In this study, the maximum depth of root growth was considered as the total soil water storage zone. Since root growth varies with time, the soil storage zone was divided into two layers, (1) first layer of depth (RD_a) known as active root zone, in which roots were present at any given time and from which both moisture extraction and drainage would occur and (2) second layer of depth (RD_p) known as passive root zone, from which only drainage would occur (Mandal et al. 2002; Chowdary et al. 2003). Thus, the soil water balance in the active root zone is governed by daily water inflow and outflow rates and in the second layer is governed by drainage into it from the active root zone and drainage out of it as deep percolation (DP_i). It is assumed that the effective rainfall ($R_i - Q_i$) and the applied irrigation (IR_i) on any day were redistributed instantaneously and uniformly over the root zone. The rainfall and applied irrigation in excess of field capacity percolated to the lower passive zone and was instantly redistributed in that zone. The remaining water in the excess of field capacity of the passive zone moved out of it as deep percolation and was considered as potential recharge to groundwater. The different components of the soil water balance for non-rice crops are presented in Fig. 6.

For the active root zone, the average soil moisture content (MC1) at the end of any day (i) can be estimated by the daily soil water balance equation (Chowdary et al. 2003) given by

$$\mathrm{MC1}_i = \frac{[(\mathrm{MC1}_{i-1}) \times (\mathrm{RD}_{i-1}) + R_i - Q_i + \mathrm{IR}_i + (\mathrm{DRD}_i \times \mathrm{MC2}_{i-1}) - P_i - \mathrm{ET}_{ci}]}{\mathrm{RD}_i} \quad (9)$$

for $i = 1, 2, 3 \ldots\ldots\ldots\ldots n$;

where MC$1_{i\text{-}1}$ is the average soil moisture content in the active root zone at the end of previous day (i − 1) (mm cm^{-1}), RD is root depth (cm) attained at any day after sowing, DRD is the incremental root depth over a day (cm), MC2_i is the average soil moisture content in the passive root zone at the end of the previous day (mm cm^{-1}), and n is the number of days in the crop season

The percolation out of the active root zone is given by

$$P_i = [R_i - Q_i + \mathrm{IR}_i] + [\mathrm{FC} - (\mathrm{MC1}_{i-1})] \times \mathrm{RD}_{i-1} - (\mathrm{FC} - \mathrm{MC2}_{i-1}) \times \mathrm{DRD}_i \quad (10)$$

If $P_i < 0$, then $P_i = 0$

For the passive root zone,

$$\mathrm{MC2}_i = \mathrm{MC2}_{i-1}, \text{if } P_i = 0 \quad (11)$$

Otherwise

$$\mathrm{MC2}_i = \mathrm{MC2}_{i-1} + [P_i/(\mathrm{RD}_m - \mathrm{RD}_i)] - \mathrm{DP}_i \quad (12)$$

where RD_m is the maximum root depth.

$$\mathrm{DP}_i = P_i - (\mathrm{FC} - \mathrm{MC2}_{i-1}) \times (\mathrm{RD}_m - \mathrm{RD}_i) \quad (13)$$

If $\mathrm{DP}_i < 0$, then $\mathrm{DP}_i = 0$

DP is the drainage out of the passive root zone as deep percolation.

Estimation of soil water balance components for non-rice field

Daily runoff values were estimated for non-rice field as mentioned in the Sect. 2.3. The percolation and deep percolation were estimated using Eqs. 10 and 13, respectively. To accomplish this, the initial soil water content at the beginning of the season (MC_0, mm cm^{-1}) needs to be known, and was determined gravimetrically (Black 1965). This moisture was assumed to be uniformly distributed within both soil zones. Dry bulk density of the samples was determined by the core method (Blake and Hartge 1986). The crop root zone depth increases with time and attains a maximum value by the end of the flowering period for most crops. The root growth is usually assumed to follow sigmoidal relationship (Chowdary et al. 2003), and was used to determine the root depth. The minimum value of root depth on any day after sowing was equal to 10 cm, as soil evaporation could take place from the top 10 cm of the soil profile. Representative values of RD_m for different crops were obtained from Mohan and Arumugam (1994) and Allen et al. (1998). Evapotranspiration occurs only from the active upper soil layer in the root zone. It depends on the available soil moisture content (MC1) in this layer and potential evapotranspiration. In this study, K_c value was obtained from Mandal et al. (2002); Tyagi et al. (2000, 2003); Kar et al. (2007) and presented in Supplemental Table 1. The crop evapotranspiration was computed from the product of ET_0 and crop coefficient (K_c) (Allen et al. 1998), when product of moisture content and root zone depth is greater or equal to product of critical threshold soil moisture (MCT) and root zone depth. Other wise crop evapotranspiration was estimated using equation given below:

$$\mathrm{ET}_{c_i} = (\mathrm{MC}_i - \mathrm{PWP})/(\mathrm{MCT} - \mathrm{PWP}) \times K_c \times \mathrm{ET}_0 \quad (14)$$

The critical threshold soil moisture is given as:

$$\mathrm{MCT} = (1 - p) \times (\mathrm{FC} - \mathrm{PWP}) \quad (15)$$

where p is the soil water depletion factor which depends on the type of crop and potential evapotranspiration.

A representative set of p values (chickpea = 0.5, cotton = 0.65, green gram = 0.45, maize = 0.55, mustard = 0.55, soybean = 0.55 and wheat = 0.55) for PET 5 mm day^{-1} was used for the present study and the value of p was adjusted for different PET by the method given by Allen et al. (1998). The details of crop characteristics used for soil water balance are presented in Table 4. Irrigation requirement of different crops and dates of application of irrigation were acquired from the field data book of the concerned divisions of ICAR-IARI where the field experiments were carried out during the investigation period.

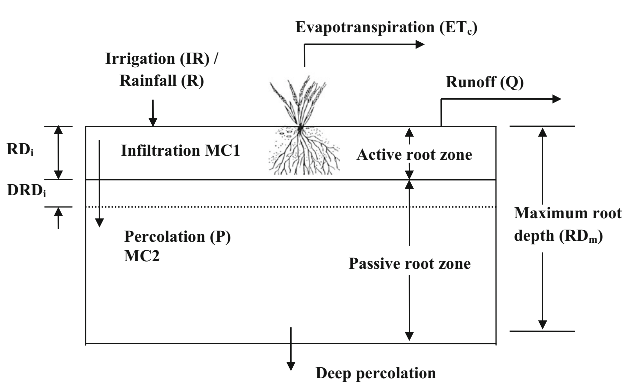

Fig. 6 Different components of soil water balance for non-rice crop

Table 4 Details of crop characteristics used for the soil water balance

Crop	Crop period (days)	Initial Stage (days)	Development Stage (days)	Mid season stage (days)	Late season stage
Chickpea	110–120	35	25	30	20
Cotton	180–200	25	35	85	45
Green gram	80–95	20	25	25	20
Maize	95–125	20	35	40	30
Mustard	100–120	30	20	45	25
Rice	120–150	30	30	50	30
Soybean	130–150	20	25	65	30
Wheat	95–120	15	25	50	30

Measurement of groundwater depth and its prediction through water balance

The groundwater depths at different locations in the study area (Fig. 1) were measured fortnightly from January 2007 to December 2009. Side by side, the groundwater depth was also predicted through water balance using the following equation:

$$\mathrm{FGWD}_t = \sum_{i=1}^{n} f \frac{\mathrm{DP} - I}{\eta} \quad (16)$$

where FGWD_t is the fluctuation of the groundwater depth (m) within the crop growing season; DP and I are the daily deep percolation (potential recharge) and irrigation water applied (m), respectively, during the crop growing season (n days), f is the fraction of the land under irrigation and η is the specific yield or drainable porosity.

Net groundwater use

Net groundwater use (*NGU*), by the crop can be estimated based on *DP* and the amount of groundwater used for irrigation, and which can be calculated as (Yang et al. 2015):

$$\mathrm{NGU}_i = \sum_{i=1}^{n} (\mathrm{DP}_i - I_i) \quad (17)$$

where NGU_i is the net groundwater use for the ith crop, DP_i is the deep percolation obtained from the ith crop, I_i is the amount of irrigation applied for the ith crop and n is the number of days from sowing to harvest (crop growth period). Overall groundwater use for any particular area can be determined by adding up the NGUs for all the crops grown in that area for that season. Negative NGU indicates that the storage in the aquifer has been reduced and positive NGU means that aquifer storage has been increased.

Results and discussion

Potential recharge from fallow lands

The mean potential recharge under fallow land was 126 mm year^{-1}, which accounted for 14.6 % of total rainfall. The variability of potential recharge was primarily dependent on soil texture as the amount of rainfall and its distribution was same over the study area during the observation period. Maximum potential recharge occurred from blocks (MB_1, MB_2, New area, WTC_2) where the soil texture was sandy loam and accounted for 17.9–18.3 % of total rainfall with average value of 18.1 % (Table 5). This was because of comparatively high infiltration capacity and hydraulic conductivity of coarse textured soil. Similarly for the area where the soil texture was loam, the mean potential recharge was 15.0 % of the rainfall. Two blocks viz., MB_{12} and MB_{14} were observed to be having least recharge potential, only about 2.5 and 2.4 % of total rainfall, respectively. This was because of comparatively heavy soil texture (clay loam), with high water holding capacity, less water transmission characteristic and low hydraulic conductivity. The average recharge from this type of soil was only 2.5 % of total rainfall.

Table 5 Mean water balance components, including potential recharge obtained from fallow land for the entire study period (2007–2009)

Parameter	Soil texture		
	Sandy loam	Loam	Clay loam
R (mm)	869.4	869.4	869.4
Q (mm)	302.4	302.4	401.1
IR (mm)	567.0	567.0	468.3
DP (mm)	157.0	130.8	21.4
DP (% R)	18.1	15.0	2.5

R rainfall, *Q* runoff, *IR* irrigation, *DP* deep percolation

Evapotranspiration from different crops

Accurate estimation of ET_c is the pre-requisite for the determination of potential recharge from a crop field. In the present study, in wheat crop, ET_c values ranged from 179.4 to 220.6 mm and 176.4 to 207.2 mm during rabi 2007–2008 and 2008–2009, respectively. Average ET_c of wheat during rabi 2007–2008 was slightly higher (i.e., 1.8 %) than rabi 2008–2009 (Tables 6, 7). The mean seasonal crop ET_c of both the seasons was 194.7 mm, which was found to be less than that reported by Tyagi et al. (2000) ($ET_c = 337$ mm in Indo-Gangetic basin) and Lenka et al. (2009) (160–379 mm at IARI) in the similar semi-arid agro-climatic condition of Northern India. Lower ET_c in the wheat crop observed in this study was due to the lower evaporation rate during the study period. In maize 2007–08, against seasonal rainfall of 1.8 mm, ET_c was found to be 261.2 mm with 240 mm of irrigation. During 2008–2009, ET_c was slightly lower by 2.1 % with seasonal rainfall of 10.7 and 240 mm of irrigation for the same crop. During kharif 2008, in maize, ET_c values ranged from a minimum of 326.2 to 336.2 mm with corresponding irrigation depths of 225 mm. The mean ETc value of maize for kharif 2008 was 329.8 mm, which was observed to be close to the value reported by Tyagi et al. (2003) and Tyagi (2006). The higher ET_c during kharif 2008 in comparison to rabi 2007–2008 and 2008–2009 could be the result of more water application through well-distributed effective rainfall and irrigation, high atmospheric evaporative demand and better crop growth. A comparison between the two crops (maize and wheat) with respect to ET_c showed that ET_c was higher for maize than wheat, indicating higher soil water extraction by maize than wheat, which is again primarily due to the difference in the atmospheric evaporative demand of two crop growing periods. The ET_c values in case of mustard for both rabi 2007–2008 and 2008–2009 were observed to be same and varied from 197.3 to 211.9 mm.

Table 6 Mean water balance components, including potential recharge from root zone of various crops during rabi 2007–2008

Parameters	Sandy loam		Loam			Clay loam
	Wheat	Mustard	Wheat	Mustard	Chickpea	Maize
R (mm)	10.7	1.8	1.8	1.8	1.8	1.8
Q (mm)	0.0	0.0	0.0	0.0	0.0	0.0
ER (mm)	10.6	1.8	1.8	1.8	1.8	1.8
PIR (mm)	75	75	75	75	100	75
IR (mm)	300.0	200.0	295.0	200.0	0.0	240.0
ET_c (mm)	194.8	211.8	189.5	211.8	97.5	261.2
P (mm)	134.6	63.8	119.9	49.9	0.0	55.6
DP (mm)	107.9	39.1	97.2	23.3	0.0	29.6
DP (% input)	28.0	14.1	26.1	8.4	0.0	9.3

R rainfall, *Q* runoff, *ER* effective rainfall, *PIR* pre-irrigation, *IR* irrigation, ET_c crop evapotranspiration, *P* percolation, *DP* deep percolation

Table 7 Mean water balance components, including potential recharge from root zone of various crops during rabi 2008–2009

Parameters	Sandy loam		Loam			Clay loam
	Wheat	Mustard	Wheat	Mustard	Chickpea	Maize
R (mm)	14.6	10.7	14.6	10.7	10.7	10.7
Q (mm)	0.0	0.0	0.0	0.0	0.0	0.0
ER (mm)	14.6	10.7	14.6	10.7	10.7	10.7
PIR (mm)	75	75	75	75	100	75
IR (mm)	290.0	200.0	300.0	200.0	0.0	240.0
ET_c (mm)	191.0	198.5	184.1	197.3	80.6	255.7
P (mm)	134.7	65.6	143.0	43.2	0.0	67.2
DP (mm)	106.4	36.6	114.1	24.1	0.0	29.0
DP (% input)	27.9	12.8	29.3	8.4	0.0	8.9

R rainfall, *Q* runoff, *ER* effective rainfall, *PIR* pre-irrigation, *IR* irrigation, ET_c crop evapotranspiration, *P* percolation, *DP* deep percolation

Potential recharge from cropped area other than rice

Recharge during rabi season

The estimated potential recharge for different crops grown in different blocks in the study area for rabi 2007–08 is presented in Table 6. It was observed that during rabi 2007–08, for wheat, potential recharge was in the range of 25.9–32.8 % of total water input (effective rainfall and irrigation) and the mean potential recharge for wheat was 28 %. Under similar type of soils in north-west part of Semi-arid Indo-Gangetic plain, Jalota and Arora (2002) estimated the percolation from wheat to be 29.4 % of applied water. It was evidenced that, for wheat, mean potential recharge in sandy loam soil was 1.9 % higher than loam soil. There was only one block (MB_{12}) where maize was cultivated during rabi 2007–08. The potential recharge for maize was about 9.3 % of total applied water. This low recharge may be attributed to the presence of clay loam soil, which would cause high abstraction of water through evapotranspiration by creating temporary ponding situation below the soil surface. For mustard, the potential recharge was in the range of 5.8–14.1 % and 5.7 % higher in sandy loam soil compared to loam soil. So it can be understood that recharge depends heavily on soil texture besides the type crop. The potential recharge from mustard was found to be less than that of wheat cultivated in the same soil texture, because the amount of irrigation applied to mustard crop was less than wheat. However, in chickpea, it was found that there was no potential recharge from the crop root zone. This may be due to the fact that the amount of water applied for irrigating chickpea is less and fulfills the evapotranspirative demand of the crop. The mean potential recharge for the rabi 2007–08 was 77.6 mm from all the estimated blocks of IARI under varying soil texture and crops.

Similar results were obtained for crops raised during rabi 2008–2009 (Table 7). The mean potential recharge from the blocks under wheat was found to be 28.6 % of total water used which is similar to the modeling estimate made by Dash et al. (2015a). In case of maize, the potential recharge was about 8.9 %. The potential recharge in mustard was found to be 8.4 and 12.8 % for sandy loam and loam textured soils, respectively. Among the rabi crops, except chickpea, lowest potential recharge was observed for mustard. This was because of its lower water requirement to meet the evapotranspiratve demand for plant growth. Thus, comparatively less amount of water could percolate down below the root zone. The mean seasonal water that could be recharged from the study area during rabi 2008–2009 was found to be 85.9 mm, which was only 10.7 % higher than the previous rabi season.

Recharge during kharif season

During kharif 2008, major crops were maize, cotton, soybean and green gram besides rice. The potential recharges of all these crops (except rice) were estimated and the mean potential recharge from different crops under varying soil texture is presented in Table 8. In case of loamy soil, the average potential recharge for maize was found to be 37.8 % of total applied water, which was supported by the earlier result (35.6 %) of Tyagi (2006). However, for the same crop when the soil texture changes to clay loam, the recharge reduced to almost half (Table 8). Dash et al. (2015a) estimated the potential recharge from maize field as 36.5 % of water applied using a modeling approach. Under similar type of soils in north-west part of Semi-arid Indo-Gangetic plain, Jalota and Arora (2002) estimated the percolation from maize to be 52.9 % of applied water. For cotton, in loamy soil, the potential recharge was found to be 24.3 %, which was in line (33.7 %) with the result obtained by Jalota and Arora (2002), but that was much less than that of maize because of its deeper rooting depths, long cropping duration and high evapotranspiration demand in comparison to maize. For green gram and soybean, the potential recharge was found to be 22.9 and 25.8 %, respectively. During kharif 2008, the potential recharge in maize was found to be the highest among all crops due to its less evapotranspiration capacity and shallow vertical rooting depths with pronounced horizontal growth pattern. Maize cannot arrest water from deeper layer of soil. The mean seasonal potential recharge from the study area during kharif 2008 for crops other than rice was found to be 125.5 mm, which was 27.6 % of total applied water.

Table 8 Mean water balance components, including potential recharge from root zone of various crops in Kharif 2008

Parameters	Sandy loam	Loam			Clay loam
	Green gram	Soybean	Cotton	Maize	Maize
R (mm)	119.2	582.7	683.4	463.1	545.5
Q (mm)	8.3	241.5	262.3	197.8	305.5
ER (mm)	110.9	341.2	421.1	265.3	240.0
PIR (mm)	75	100	0	0	0
IR (mm)	75.0	0.0	125.0	225.0	225.0
ET_c (mm)	186.2	309.5	430.2	325.1	336.2
P (mm)	59.7	123.3	162.1	193.7	153.7
DP (mm)	59.7	113.9	132.7	185.4	76.4
DP (% input)	22.9	25.8	24.3	37.8	16.4

R rainfall, *Q* runoff, *ER* effective rainfall, *PIR* pre-irrigation, *IR* irrigation, ET_c crop evapotranspiration, *P* percolation, *DP* deep percolation

Potential recharge from rice field

Potential recharge for rice was found to be 929.1 mm which was 60.0 % of the applied water (Table 9). This was found to be the highest due to standing water in puddle rice fields and subsequent movement of water below the root zone. Similarly, for Indo-Gangetic basin under kharif rice, Tyagi (2006) estimated the percolation to be about 582.9 mm (59.2 % of total water applied). Using HYDRUS 1D model, Dash et al. (2015b) estimated the potential recharge from rice field to be 55.5 % of total applied water. Under similar type of soils in north-west part of Semi-arid Indo-Gangetic plain, Jalota and Arora (2002) estimated that the percolation from rice field was 65.2 % of applied water.

Annually, the mean potential recharge from the crop root zone was found to be 18.4 % of total water input (irrigation and rainfall). This is comparable with the results (16 % of water input) reported by Ghulam and Bhutta (1996) and Kendy et al. (2003) (range of water input 435–816 mm, the estimated recharge range was 78–209 mm). Rivard et al. (2014) also estimated the recharge amount of 80–175 mm year^{-1} with the rainfall of 865 mm. Further, the results obtained in this study were in line with the studies carried out by Eilers et al. (2007) (potential recharge of 20–76 mm year^{-1} with rainfall of 430 mm in a semi-arid area) and Anuraga et al. (2006) (recharge was 17 % of total rainfall).

Comparison of water budgeting estimates with observed water table depths

During rabi 2007–2008 and 2008–2009, there was a decline in the water table by 1.16 and 1.22 m, respectively, because of withdrawal of groundwater for irrigation purpose. During the same period, the predicted water table declines, using Eq. 22. Besides, the average specific yield of 0.13 was estimated to be 1.37 and 1.32 m, respectively (Table 10). The potential groundwater recharge for the kharif season using the water balance approach for both rice and non-rice fields was 0.53 m. However, as per the observed data of tube wells near the experimental plots, the average water table fluctuation indicated a rise of water table by 0.62 m. The actual amount of water recharged and the potential ground water recharge estimated using the water balance approach was in line with each other. The difference in estimation of 9 cm could be attributable to the average data of water table depth obtained from all the 8 tube wells and existence of only two wells near the rice blocks where maximum potential recharge was estimated using water budgeting approach. There was also an increase in water table depth during April to July 2008. This may be attributed to occurrence of higher rainfall during these months (434.5 mm) of the year 2008 and minimal groundwater use for irrigation due to the existence of minimal cropped area.

Net groundwater use by different crops

There are three ways to reduce the aquifer depletion, viz. by reducing the net water withdrawal (and decreasing the net water use) from the aquifer, by decreasing the irrigated area (Yang et al. 2015) and by growing low water consuming crops. Thus to consider what crop is best for decreasing the reduction of groundwater table, the net water use for each crop from the perspective of groundwater has been calculated using Eq. (23) and shown in Fig. 7. Negative values indicated that groundwater irrigation exceeded recharge, and positive values indicated that the recharge exceeded irrigation. The net groundwater withdrawal of winter wheat was highest among the experimented crops with an average of 190 mm year^{-1} mainly due to the low precipitation in winter and continuous evapotranspiration for regular growth besides application of 296 mm irrigation for winter wheat. This finding was similar to the results obtained by Yang et al. (2015) in North China Plain in which the annual groundwater withdrawal of 198 mm year^{-1} was observed for the winter wheat crop with 225 mm irrigation. For mustard the net groundwater use was 169 mm year^{-1} with 200 mm irrigation, can be considered as high. This was due to ongoing evapotranspiration and low rainfall in the dry winter season. Winter maize, a long duration crop compared to the other winter season crops grown in the area, consumed 188 mm year^{-1} groundwater with 240 mm irrigation. But maize crop when grown during the rainy season used only 94 mm year^{-1} groundwater with 225 mm irrigation. This result was similar to the observation made by Yang et al. (2015) in North China Plain, where they observed an annual groundwater withdrawal of 71 mm year^{-1} for the summer maize with 105 mm irrigation. The availability of rainfall during rainy season in the study area compensated

Table 9 Estimated water balance components, including potential recharge from root zone of rice during Kharif 2008

Field name	R (mm)	Q (mm)	ER (mm)	IR (mm)	ET_c (mm)	DP (mm)	Input (mm)	Output (mm)	DP (%)
MB_{14}	582.7	114.2	468.5	1080	487.4	929.1	1548.5	487.4	60.0

R rainfall, *Q* runoff, *ER* effective rainfall, *PIR* pre-irrigation, *IR* irrigation, ET_c crop evapotranspiration, *DP* deep percolation

Table 10 Observed mean water table fluctuations in the study area for pre-monsoon (July), post-monsoon (November) and pre-summer (April) and its comparison with the data obtained using soil water balance (SWB) approach

Date	Water table depth below ground level (m)	Water table fluctuation (m)	Water table difference estimated by SWB (m)
Nov-07	12.85		
		$\Delta h_{\text{rabi}} = -1.16$	$\Delta h_{\text{rabi}} = -1.37$
Apr-08	14.01		
		$\Delta h_{\text{summer}} = 0.48$	Not calculated
Jul-08	13.53		
		$\Delta h_{\text{kharift}} = 0.62$	$\Delta h_{\text{kharift}} = 0.53$
Nov-08	12.91		
		$\Delta h_{\text{rabi}} = -1.22$	$\Delta h_{\text{rabi}} = -1.32$
Apr-09	14.12		

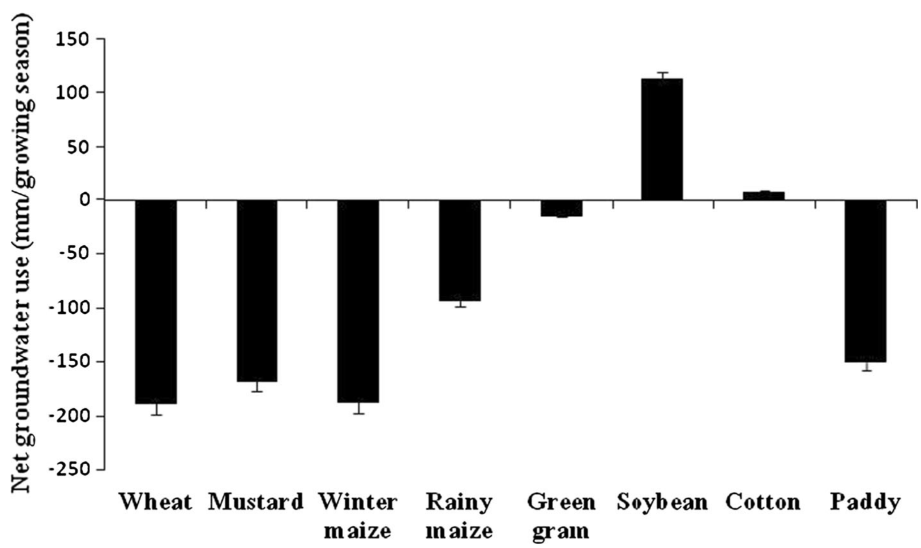

Fig. 7 Distribution of net groundwater use (recharge minus irrigation) of most commonly grown crops in the growing season at IARI research farm in the Indo-Gangetic Plain

the high water demand of maize crop. In contrast to maize, the rice crop used 151 mm year^{-1} groundwater with 1088 mm of irrigation. As rice needs standing water, the rainfall was not sufficient to meet its water demand. Very high deep percolation (929 mm year^{-1}) might compensate the higher irrigation requirement. Therefore, the rice–wheat cropping system is responsible for steady groundwater table depletion. The present study besides the research findings by other researchers corroborated that the rice–wheat cropping system could be substituted with maize–wheat (Jalota and Arora 2002; Lenka et al. 2009; Dash et al. 2015a) to arrest declining groundwater table and assist in attaining sustainability in groundwater irrigation. Under 75 mm irrigation, green gram had annual average net groundwater use of 15 mm year^{-1}, indicating its importance to grow as a rainy season pulse. Cotton provided an extra recharge of 8 mm year^{-1} to the groundwater. Soybean was the most likely crop to reverse the water extraction pattern from the groundwater, replenishing the aquifer by 114 mm year^{-1}. Overall, the annual average groundwater use decreased in the order of wheat > winter maize > mustard > paddy > rainy maize > green gram > cotton > soybean (Fig. 7).

Conclusions

More accurate insights about the seasonal aquifer recharge and net water use are prerequisites for estimating the groundwater balances for effective management of scarce water resources in semi-arid Indo-Gangetic Plain of India. In this study, the potential recharge for three different conditions and net groundwater use for eight crops was estimated using the soil water balance approach. The soil texture played a dominant role in the recharge process and the potential recharge was significantly higher in sandy loam soil than that of the clay loam soil. The mean annual potential recharge from fallow land was found to be 126 mm year^{-1}. The potential recharge from kharif (rainy) and rabi (winter) seasons was 527.3 and 81.7 mm season^{-1}, respectively. The annual average net water use was highest for wheat averaging 190 mm year^{-1}, followed by winter maize with 188 mm year^{-1}, mustard with 169 mm year^{-1}, rice with 151 mm year^{-1}, kharif maize with 94 mm year^{-1}, green gram with 15 mm year^{-1}. Moreover, cotton and soybean provided an extra recharge of 8 and 114 mm year^{-1} into the groundwater. Nonetheless, the groundwater table prediction and the establishment of the relationship between deep percolation and total water applied for different crops using simpler water budgeting protocols assume importance for sustainable groundwater management in semi-arid regions.

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