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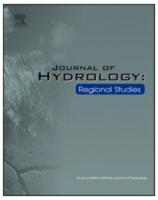

Building resilient agricultural system through groundwater management interventions in degraded landscapes of Bundelkhand region, Central India

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ABSTRACT

Study region: The study was carried out at community scale watershed in one of the fragile ecologies of Central India.
Study focus: This paper quantifies the impact of rainwater management (RWM) interventions on major water balance components, irrigation use, crop intensification and energy consumption and their interrelationships.
New hydrological insights for the region: RWM interventions harvested additional 35 mm of surface runoff in various masonry structures and facilitated groundwater recharge from 720 mm rainfall received. The net groundwater recharge during monsoon season was estimated 75−80 mm; out of this, 25 % (15−20 mm) was used in *kharif* and 75 % (50−60 mm) in *rabi* season. Groundwater recharge largely took place in wet and normal years due to RWM interventions, which supported for meeting freshwater demand in recurring dry years. Increased groundwater recharge helped to enhance cropping intensity from 120 % to 180 % by converting significant fallow lands into productive cultivation. The time required to refill dug wells decreased by 50 % with every one meter increment in hydraulic head. Therefore, well recovery period reduced minimum by 50 % after the project interventions. The study shows a huge untapped potential for sustainable crop intensification by adopting science-based natural resource management approach in fragile eco regions of the semi-arid tropics.

1. Introduction

Water scarcity, land degradation and poor agriculture productivity are the critical challenges of dryland ecologies (Schlaepfer et al., 2017; Singh et al., 2019). These areas experience recurring dry spells and flash floods within monsoon season resulting into poor crop yield and/or crop failure (Middleton and Sternberg, 2013). Globally, drylands are inhabited with marginal and small farmers with about 80 % households earning their livelihoods from agriculture and allied sectors (Robinson et al., 2015). These areas are coincided with chronic poverty and malnutrition as current productivity levels are lower than 1000−1500 kg/ha due to low input application

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and prevalence of traditional farming practices (Rockstrom et al., 2010). The focus of the Green Revolution during 1960s was on irrigated ecology; however, dryland ecologies holds a huge untapped potential to bridge the current yield gap (Llewellyn, 2018; Armanda et al., 2019). There are number of evidences which clearly demonstrate that the current productivity levels can be enhanced by 2–5 folds by adopting integrated genetic natural resource management approach (García-Palacios et al., 2019). This approach holds promise to lift millions of poor households out of poverty trap (Fritz et al., 2019; Mastrángelo et al., 2019).

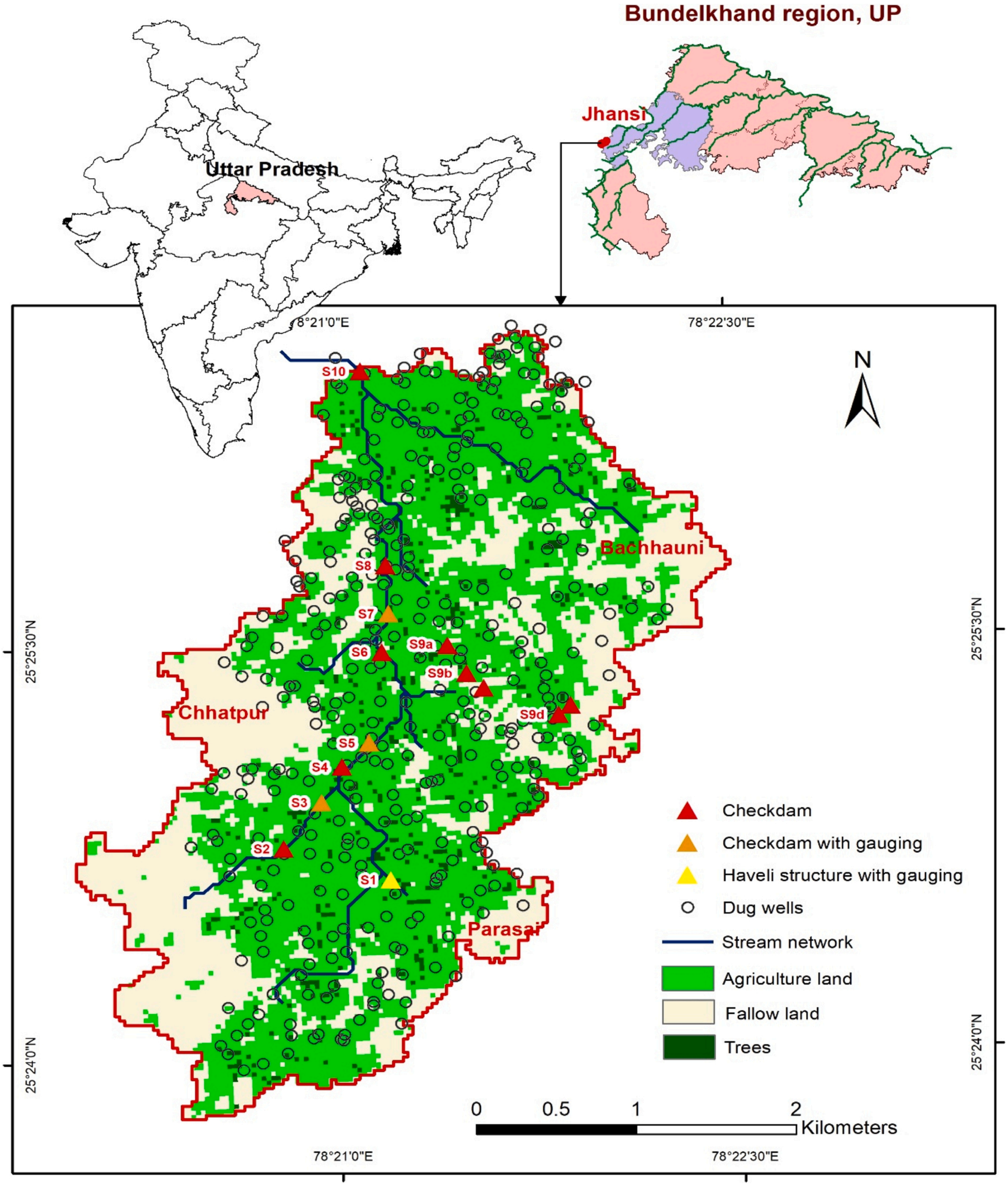


Fig. 1. Location of *Parasai-Sindh* watershed in Jhansi, Bundelkhand region of Central India; Figure also shows stream networks, dug wells along with major land use classes.

Natural resource management framework offers pragmatic approaches for addressing water scarcity and land degradation through decentralized soil and water conservation practices at micro and meso scale landscape (Rockstrom and Falkenmark, 2015). Various *in-situ* and *ex-situ* interventions, also called as rainwater management (RWM) interventions are the package of biological and engineering measures which facilitate harvest of surface runoff within the field and primary stream networks by following ridge-to-valley approach (Dixit et al., 2007; Reddy et al., 2018; Abbasi et al., 2019; Abera et al., 2020; Ricciardi et al., 2020). Water harvested through these measures can be utilized within the landscape unlike large irrigation projects in which catchment and commands are entirely different which raises conflicts among stakeholders (Zhang et al., 2017). In recent decades, there is increasing investment on different RWM interventions especially in Asian and African countries by multiple national, international and private agencies to support United Nations agenda of sustainable development goals (Douxchamps et al., 2014; Garg et al., 2020a, 2020b; Mezegebu et al., 2020; Abera et al., 2020).

Realizing the importance of RWM interventions, India has invested about US$14 billion on natural resource management measures through various public welfare programs since 1990 (Wani et al., 2011; Meter et al., 2016; Mandal et al., 2020). These programs have focused on most fragile ecosystems in the country and Bundelkhand region of central India as one of the focal regions (Gupta et al., 2014; TERI (The Energy and Resources Institute), 2018). Bundelkhand region which is shared between Uttar Pradesh and Madhya Pradesh states is one of the hotspots of poverty and malnutrition covering 6 million ha inhabited by about 15 million people (Shakeel et al., 2012). The long term rainfall data collected for 23 stations in Uttar Pradesh part of Bundelkhand region (7 districts) shows that there was decline in annual rainfall of 200 mm in six decades pushing the region into vulnerable state (Rao et al., 2013; Thomas et al., 2015; Garg et al., 2020a). The region experiences frequent droughts and intermittent long dry spells during monsoon and therefore, farmers are reluctant to cultivate *kharif* crops (*i.e.*, cultivate during monsoon) due to uncertainty in rainfall pattern. They largely tend to cultivate single crop during *rabi* season (*i.e.*, cultivate during post monsoon) using residual moisture or supplemental irrigation (Thomas et al., 2014; Singh, 2020). The traditional practices of decentralized rainwater harvesting locally called as *haveli* system has off late become dysfunctional due to social apathy and neglect (Sahu et al., 2015; Garg et al., 2020b). About 70–80 % of the region is dependent on shallow groundwater system for agricultural and domestic use which is largely under stress as these wells are functional for only a few months (Shah, 2009; Thomas et al., 2014). Farmers in the region generally follow the calendar based irrigation scheduling and still follow traditional technique of flood irrigation method which holds poor distribution efficiency and consume more energy (Garg et al., 2016). Due to poor groundwater yield and prolonged well recovery period in the region, drudgery on women and children is increasing multifold and at the same time the cost of cultivation on irrigation application also increases as more number of labors to be engaged on day-to-day basis (Padmaja et al., 2020).

There are no insights about the irrigation use pattern, crop specific irrigation requirements, energy consumption and its relationship with groundwater availability in dug wells. Much efforts have not gone towards quantifying the benefits of various RWM interventions on major water balance components such as surface runoff and groundwater recharge, cropping system, productivity and land use change. In the absence of hydrological monitoring, most of the structural designs are based on empirical equations and those are not validated with variable topography, soil types, land degradation levels, and land use. Moreover, there are no insights available on how the RWM interventions are helpful in terms of well recovery period and associated energy consumption especially in shallow dug well system. Inadequate database on these aspects is also one of the reasons for demonstrating the efficacy of decentralized rainwater management initiatives and influence necessary policy interventions to guide prioritized investment in this area.

In this backdrop, International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) along with Indian Council of Agricultural Research - Central Agroforestry Research Institute (ICAR-CAFRI), Jhansi established a site of learning in one of the degraded landscapes of Bundelkhand region of Uttar Pradesh, India between 2012 and 2016 for an in depth scientific inquiry with an objective to analyse the impact of RWM interventions on : i) partitioning of water balance components such as groundwater recharge and outflow from the watershed; ii) irrigation availability and crop intensification; and iii) well recovery rates and energy consumption at farm and landscape scale.

Table 1
Landscape topography, land use and demographic details of Parasai-Sindh watershed.

Parameters	Parasai-Sindh watershed
Villages	Parasai, Chhatpur Bachhauni
Area (ha)	1246
Altitude (m above mean sea level)	270−315
Land use (ha)	
Agriculture	1105
Degraded forest	6
Wasteland (scrubland)	66
Others	73
Demographic details (based on 2011 census)	
No of households	417
Average holdings (ha/HH)	3.12
No of dug wells	388
Depth of wells	9.2 (Std ±1.5)

2. Material and methods

2.1. Parasai-Sindh watershed: an overview

Parasai-Sindh watershed is located in Babina block of Jhansi district, Uttar Pradesh state of Central India covering 1246 ha (12.46 sq km) of geographical area. It comprises three villages, namely *Parasai*, *Chhatpur* and *Bachhauni* located between 25°23′56″ to 25°27′9″ N and 78°19′45″ to 78°22′42″E (Fig. 1). Soils of this watershed are categorized as Alfisols, which holds poor retention capacity (available water 100−120 mm/m). Farmers in Parasai-Sindh watershed are mostly dependent on agriculture and livestock based activities. About 75 % of total area was under cultivation; 20 % left fallow and 5% under other uses before 2011 (pre watershed intervention period). This landscape has low to moderate slope of 1–3 % and all farmers follow the flood irrigation method. Blackgram and greengram are cultivated under rainfed condition and groundnut with minimum supplemental irrigation during *kharif* season. Whereas, wheat, chickpea and barley are dominating crops during the *rabi* season, which was cultivated with the support of supplemental irrigation. Total 388 dug wells were the source of the irrigation. Table 1 shows the topography, soil type and land use details of the study watershed.

2.2. Rainwater Management interventions

Parasai-Sindh watershed was largely suffering from severe water scarcity (Garg et al., 2020a). Available groundwater was not sufficient to meet domestic and agricultural demand before 2011. To address water scarcity, a range of *in-situ* and *ex-situ* soil and rainwater conservation measures were implemented between 2012 and 2016 (Garg et al., 2020a). Bundelkhand region has traditional rainwater harvesting system called *haveli,* which in many villages is mostly degraded or dilapidated due to social apathy and technical reasons. One such *haveli* structure in Parasai village was rejuvenated with a modified engineering design with a storage capacity of 73, 000 m^3 by submerging 8.5 ha fields at upstream. In place of earthen embankment, a masonry core wall was constructed such that it could withstand heavy inflow during high rainfall incidents. Excess runoff was disposed-off safely through a masonry outlet. This structure acted as a reservoir during monsoon period while it was cultivated during *rabi* season by draining the remnant rainwater stored in the structure during October. In addition, nine masonry check dams of a total harvesting capacity of 25,000 m^3 were also constructed on the main and sub-drains at suitable sites by following ridge-to-valley approach (refer Fig. 1).

2.3. Data monitoring and analysis

To understand the impact of RWM interventions on water balance components, the state-of-the-art monitoring system was established. Surface runoff, groundwater table and irrigation use was monitored as described below.

Rainfall which is the only source of water for agriculture, human and livestock consumption was partitioned in different water balance components as defined in Eq. 1:

$$\text{Rainfall (mm)} = \text{Surface runoff (mm)} + \text{Groundwater recharge (mm)} + \text{Evapotranspiration (mm)} + \text{Change in soil moisture content(mm)} \quad (1)$$

2.3.1. Surface runoff

Out of the ten rainwater harvesting structures constructed in the study watershed, runoff gauging equipment was installed at four locations (S1, S3, S5 and S7). A stilling well was constructed on the upstream of the check dam and an automatic pressure transducer, i.e., DIVER (Model DI801 TD, having capacity of recording 10 m pressure head) was placed at the bottom of the stilling well (Garg et al., 2020a) to measure outflow volume. Outflow is the spilled over runoff from check dam, *i.e.*, runoff generating at the respective location after harvesting water in upstream structures.

The DIVER was programed to record pressure head at 15-minute intervals. The measured pressure head was used to estimate outflow at respective gauging stations (i.e., S1, S3, S5 and S7 in Fig. 1). Outflow was estimated at a given site by following steps detailed below (Eqs. 2 and 3):

$$\text{Spillover discharge } Q_t\ (\text{m}^3/\text{sec}) = 1.705 \text{ x } L \text{ x } (h_t)^{1.5} \quad (2)$$

Where, L is length of the rectangular weir and h_t is depth of runoff layer passing from gauging station at a given time;

$$\text{Spillover volume } (\text{m}^3) = \text{spillover rate } (\text{m}^3/\text{sec}) \text{ x time interval (sec)} \quad (3)$$

2.3.2. Groundwater recharge and utilization

The water table of 388 dug wells in Parasai-Sindh watershed was measured using water level recorder on monthly scale between 2011 and 2017.

Water table fluctuation (WTF) method is a well-accepted technique for estimating groundwater recharge in hard-rock regions (Sharda et al., 2006; Dewandel et al., 2010; Glendenning and Vervoort, 2010; Garg et al., 2020c). Water balance captured by WTF method is defined by mass balance equation (Eq. 4):

Net groundwater recharge (mm) = change in hydraulic head before and after monsoon (m) × specific yield (-) X 1000 + water withdrawal during monsoon period (mm) (4)

Specific yield was considered 0.02 from earlier estimates by Singh et al., 2014 and Garg et al., 2020a. Water table data was converted to estimate groundwater (GW) recharge and freshwater utilization during monsoon and post-monsoon seasons. Further, GW utilization/uptake is estimated using difference in water table between November and May during the respective years.

2.3.3. *Cropping system, irrigation use and energy consumption*

Area cultivated under different crops for *kharif* and *rabi* seasons was recorded for the entire watershed between 2012 and 2016. For understanding the irrigation application, DIVERs were placed in five selected dug wells and programmed to record water level fluctuations at every 30 min interval between 2014 and 2016. Hydraulic head drops rapidly during the pumping, which was captured with continuous monitoring. If the hydraulic head drops more than 0.1 m (in 30 min), pumping is considered and pumping time was calculated. Volume of water pumped was further estimated using energy balance equation (Eq. 5).

$$Q = \frac{P\ x\ Pump\ Efficiency}{H\ x\ g\ x\ \rho} \tag{5}$$

Whereas, Q = pump discharge (m^3/sec); P = pump power (Watt); g = 9.8 m/s^2; ρ = density of water = 1000 kg/m^3; H = total head (m).

In this calculation, pump efficiency was considered 65 % (Belaud et al., 2019; Sarbu, 2016). Due to various joints and pipe connections in irrigation system, a three-meter head loss was also considered. Total volume of water pumping was calculated using Eq. 6:

Irrigation volume (m^3) = Q (m^3/sec) x t (hours of pumping) x 3600 (sec/hour) (6)

In this paper, pre intervention is when the data is compared with before the inteventions began in the study watershed (2011, 2012).

3. Results

3.1. *Impact of RWM interventions*

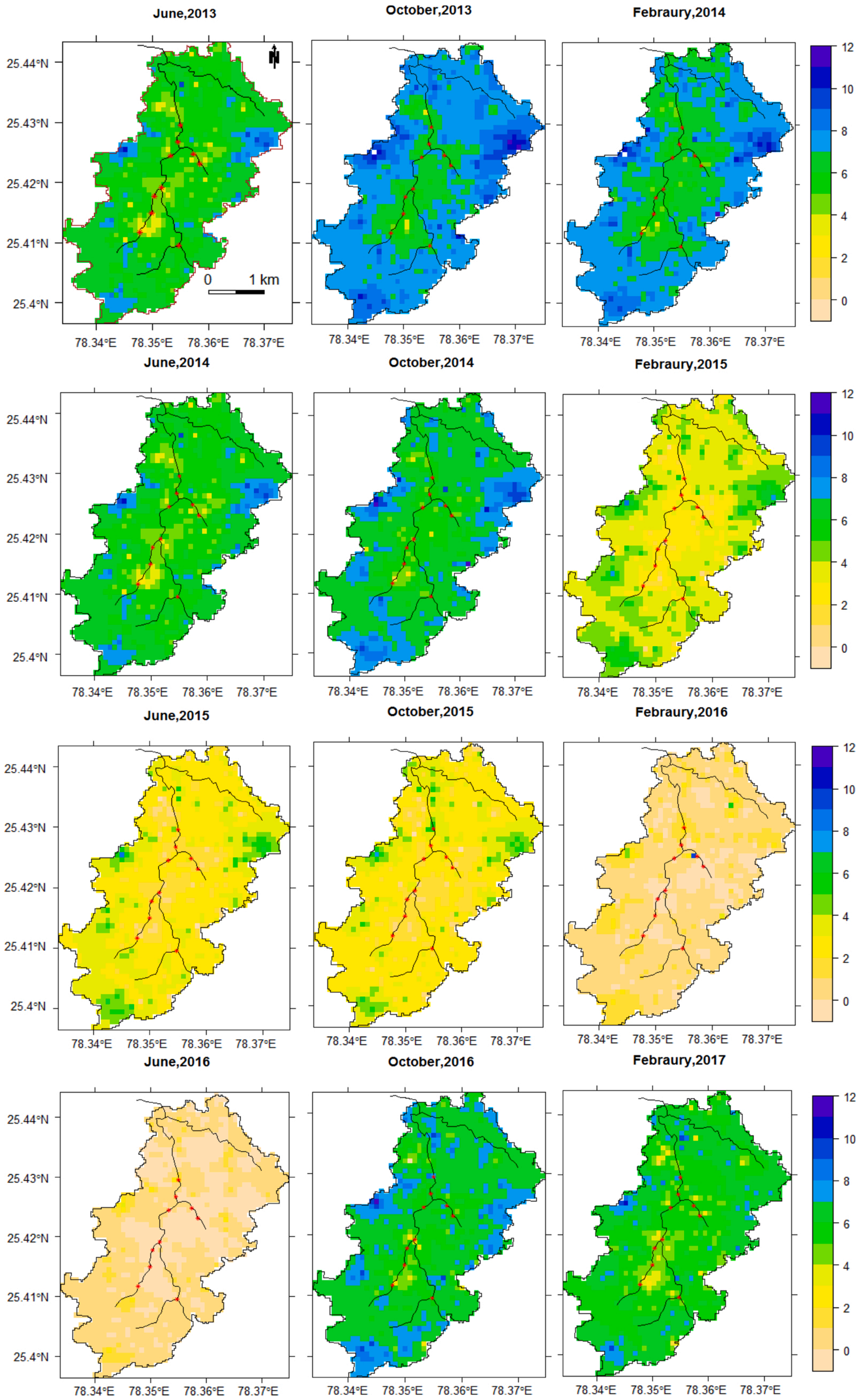
3.1.1. *Water balance components of Parasai-Sindh watershed*

Table 2 summarizes water balance components of *Parasai-Sindh* watershed during monsoon (June-October) and post monsoon (November-May) seasons for the period of study. June is the beginning of the water year and ends by May during the following year.

Table 2

Major water balance components during monsoon (Jun-Oct) and post-monsoon (Nov-May) seasons during study period.

Particulars	2011–12	2012–13	2013–14	2014–15	2015–16	2016–17	2017–18	Average (2013–17)	Average (2014–17)
RW storage capacity created (m^3)	0	7500	79,700	82,200	82,200	98,000	98,000		
Year	Wet	Normal	Wet	Dry	Dry	Normal	Dry		
Monsoon period (June-October)									
Rainfall (mm)	1189	825	1276	520	404	768	631	720	580
Runoff at S1 of catchment 80 ha (mm)	NA	NA	356 (29 %)	12 (2.3 %)	0 (0%)	210 (27 %)	102 (16 %)	136 (19 %)	81 (14 %)
Runoff at S5 of catchment 567 ha (mm)	NA	NA	351 (28 %)	5 (01 %)	0 (0%)	124 (16 %)	15 (2%)	99 (14 %)	36 (6%)
Measured hydraulic Head in June (m)	3	1.2	2.1	5.9	2.7	0.6	1.11	2.5	2.6
Measured hydraulic Head in Oct (m)	4.5	4.6	7.4	6.6	2.7	6.6	4.4	5.5	5.1
Hydraulic head increment in dug wells due to recharge (m)	2.9	4.4	5.4	1.5	0.7	7	5.7	4	3.7
Head decline due to irrigation in *kharif* (m)	1	1.5	0.2	1.1	0.9	0.9	1.7	1	1.2
Total GW recharge during monsoon (mm)	58	89	108	30	14	140	114	80	75
Total groundwater utilized in *kharif* (mm)	21	30	4	22	19	18	33	20	23
Post monsoon period (November-May)									
Rainfall (mm)	57	126	147	32	35	46	45	61	40
Av hydraulic Head in May (m)	1.2	2	5.9	2.8	0.6	1.1	1.6	2.4	1.5
Head declined due to irrigation in *rabi* (m)	3.7	2.6	1.5	3.8	2.1	5.5	2.8	3.2	3.6
Total groundwater utilized in *rabi* (mm)	75	51	31	77	41	109	57	63	71



(caption on next page)

Fig. 2. Spatial and temporal variability of hydraulic head from June 2013 to Feb 2017 (June: beginning of monsoon; Oct: end of monsoon; Feb: by end of rabi season).

Water balance components were divided over two major seasons: i) monsoon period between June and October, which receives 85 % of total annual rainfall; and ii) post monsoon period between November and May during the following year.

A total of 79,700 m^3 storage capacity was created during the summer (April-May) of 2013 which was 80 % of total target in Parasai-Sindh watershed. The impact of this effort began to show since the monsoon season of 2013 (June 2013 onwards). Water balance studies over a period of five years showed that the watershed received an average rainfall of 720 mm between 2013 and 2016. Runoff measured at S1 (i.e., upstream location of watershed) was 19 % (136 mm) and 14 % (99 mm) at S5 (i.e., downstream location of watershed). Groundwater recharge on an average was estimated to be 80 mm during the monsoon period. Out of this, 19 mm groundwater was utilized in *kharif* and 63 mm in *rabi* seasons.

A large variability was observed in these components between the years depending on the total rainfall, its intensity and distribution. Rainfall received during 2013 (wet year) between June and October was 1276 mm. This resulted in a significant gain in terms of enhanced groundwater table, as average hydraulic head in dug wells increased from 2.0 m to 7.4 m which is equivalent to 108 mm of GW recharge. It was also noted that dug wells in year 2013 achieved their maximum saturation level, as water table in most of the wells reached close to land surface. Outflow measured at S5, which spilled over downstream, was 351 mm constituted 28 % of total rainfall of that year.

In addition, year 2013−14 recorded a rainfall of 147 mm during post-monsoon season (November-May) as well. In the year 2013−14, the amount of net GW utilization during *kharif* and *rabi* seasons was 4.0 and 31 mm, respectively. Residual soil moisture (by monsoon end) and post-monsoonal rains largely met the crop-water requirement with the support of supplemental irrigation during *rabi* season. Average hydraulic head recorded was 5.9 m in dug wells by end of May 2014 (compared to 7.4 m as maximum storage)

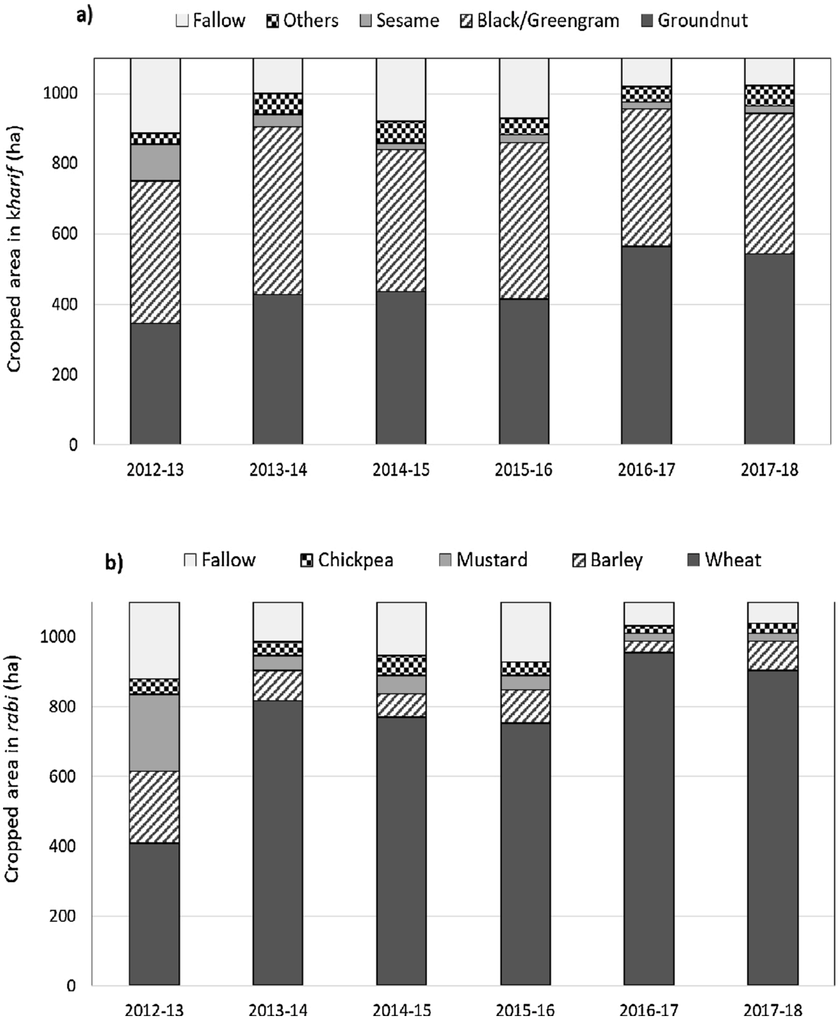


Fig. 3. Change in cropped area a) during *Kharif* and b) *rabi* between 2012 and 2017.

which indicates that 20 % of the available groundwater was utilized (Table 2).

Rainfall recorded between June and October during 2014–15 was 520 mm. As this was one of the dry years, generated outflow from watershed (at S5) and groundwater recharge were a mere 5.0 mm (1 % of total rainfall) and 30 mm (5.7 % of total rainfall) respectively. Groundwater utilization during *kharif* and *rabi* was recorded at 22 and 77 mm, respectively. Despite poor groundwater recharge during 2014–15, the Parasai-Sindh watershed did not experience water scarcity, as significant carryover storage was available in the shallow aquifers from the previous year.

The year 2015–16 was the driest with only 404 mm rainfall between June and October. Average hydraulic head in dug wells was 2.7 m in beginning of the monsoon (June 2015). GW recharge was found 14 mm and absolutely no runoff was recorded. A total 19 mm of groundwater was utilized in *kharif* and 41 mm in *rabi*, which brought average hydraulic head in dug wells below 1.0 m (0.6 m).

Year 2016–17 was a normal year with a rainfall of 768 mm between June and October, resulted in 124 mm outflow (16 %) and a significant amount of groundwater recharge (140 mm). Average hydraulic head in dug wells increased from 0.6 to 6.6 m during the monsoon season. Decent rainfall during monsoon recharged the aquifer to its 90 % potential (6.6 m vs. 7.4 m). Farmers utilized 18 mm and 109 mm of groundwater for supplemental irrigation during *kharif* and *rabi* seasons respectively and the average groundwater level declined from 6.6 m to 1.1 m. Table 2 also shows groundwater balance during the year 2011 represent in the pre-watershed development scenario. Hydraulic head increased from 3.0 m in June to 4.5 m in October showing a net increment of 1.5 m. In addition, 1.05 m (21 mm) equivalent water was utilized within *kharif* season for supplemental irrigation. Thus, total groundwater recharge in 2011 was 58 mm, despite 1189 mm of rainfall (wet year).

3.1.2. Groundwater dynamics

Spatial and temporal variability of hydraulic head measured between 2013 and 2016 is presented in Fig. 2. Temporal layers of hydraulic head were derived from measured data of dug wells using inverse distance interpolation technique. We present hydraulic heads three times, i.e., before monsoon (June), after monsoon (Oct) and end of *rabi* season (Feb) for respective years and results for wet (2013), dry (2014), very dry (2015) and normal (2015) years. Variation in hydraulic head ranged from 1.0–12.0 m on spatial and temporal scale. Due to a good rainfall during the year 2013, hydraulic head in more than 85 % of the landscape was in range of 8–12 m and in the rest, it ranged between 5–8 m. Dug wells reached their full potential as a maximum head of 12 m was recorded in more than 85 % wells. Due to recurring dry years (2014 and 2015), hydraulic head declined subsequently, especially during post monsoon seasons. Hydraulic head by end of Feb 2014, Feb 2015 and Feb 2016 was recorded as 6–10 m, 2–5.9 m and 0–1.9 m, respectively. Whereas no difference in hydraulic head was found between June and Oct months in 2014 and 2015 indicating that the recharge that occurred during monsoon period was equal to water consumed during *kharif*. However, normal and wet years contributed in terms of enhanced groundwater. Rainfall during 2016 resulted in all the dry wells turning functional and the hydraulic head ranged between 6–10 m by end of October 2016.

3.1.3. Crop intensification and change in cropping pattern

Fig. 3a and b show the change in cropping pattern both in *kharif* and *rabi* since 2012. The year 2012 was the first year of project implementation represents the non-intervention status. Groundnut and black/greengram were the dominant crops during *kharif* season. With increased water availability, the area under groundnut increased from 350 ha in 2012 to 550 ha in 2016. The fallow land during *kharif* also declined from around 200 ha to 80 ha during the same period. A significant change was observrved cropping pattern especially in *rabi* season. Area under wheat which was 400 ha in 2012 increased to 800 ha in 2013 and 2015 and it further increased to 950 ha in 2016. Area under mustard which was nearly 200 ha came down to less than 10 ha and area under barley also declined from 200 ha to less than 50 ha during the same period. Wheat crop which is a staple food and the main source of dry fodder (straw) for livestock became the preferred crop among farmers with increased availability of water resources. It is interesting to observe even in

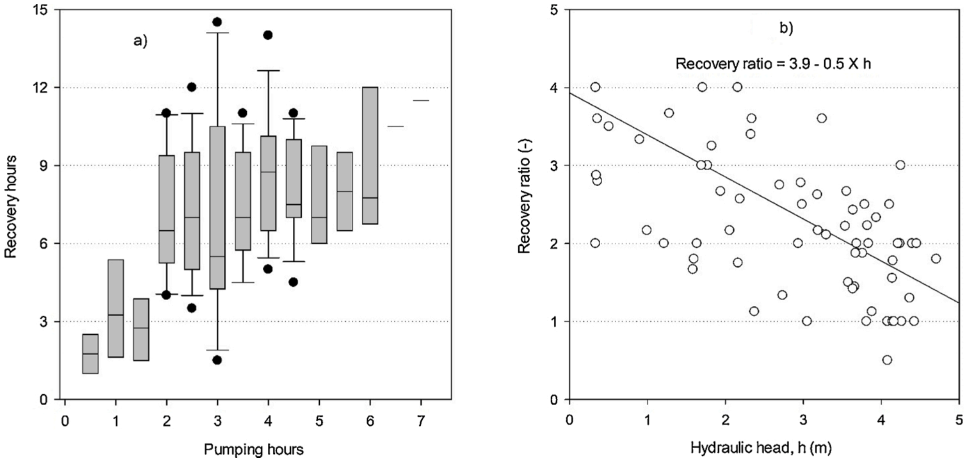


Fig. 4. Relationship of water hydraulic head vs recovery ratio in selected wells.

2014 and 2015 which were dry years, farmers could cultivate wheat crop in more than 70 % of total watershed area. Fallow area came down to less than 50 ha and about 150 ha was brought into productive cultivation especially in the upstream.

3.2. *Water-energy nexus*

3.2.1. *Groundwater pumping and recovery dynamics in dug wells*

To understand the relationship between groundwater pumping and recovery rate of water refilling in shallow dug wells, DIVERs data were analyzed. Fig. 4a describes the relationship between pumping hours vs. total recovery hours of selected dug wells. Recovery period is the time required to refill the dug well after switching off the pump. Recovery ratio (ratio of recovery period and pumping period) strongly correlated with the average hydraulic head of the watershed at a given time (Fig. 4b). When the average hydraulic head in the watershed was 4.0 m (refer Fig. 2), the recovery ratio was between 1 and 2. On the other hand, the recovery ratio was between 3 and 4 at 1.0 m hydraulic head. Higher hydraulic head helped to develop steep hydraulic gradient which facilitated faster refilling of dug wells (less than half the time compared to before interventions) than with a lower head. Regression line further indicates that with every meter increment in water table, the time required for refilling decreases by 50 %.

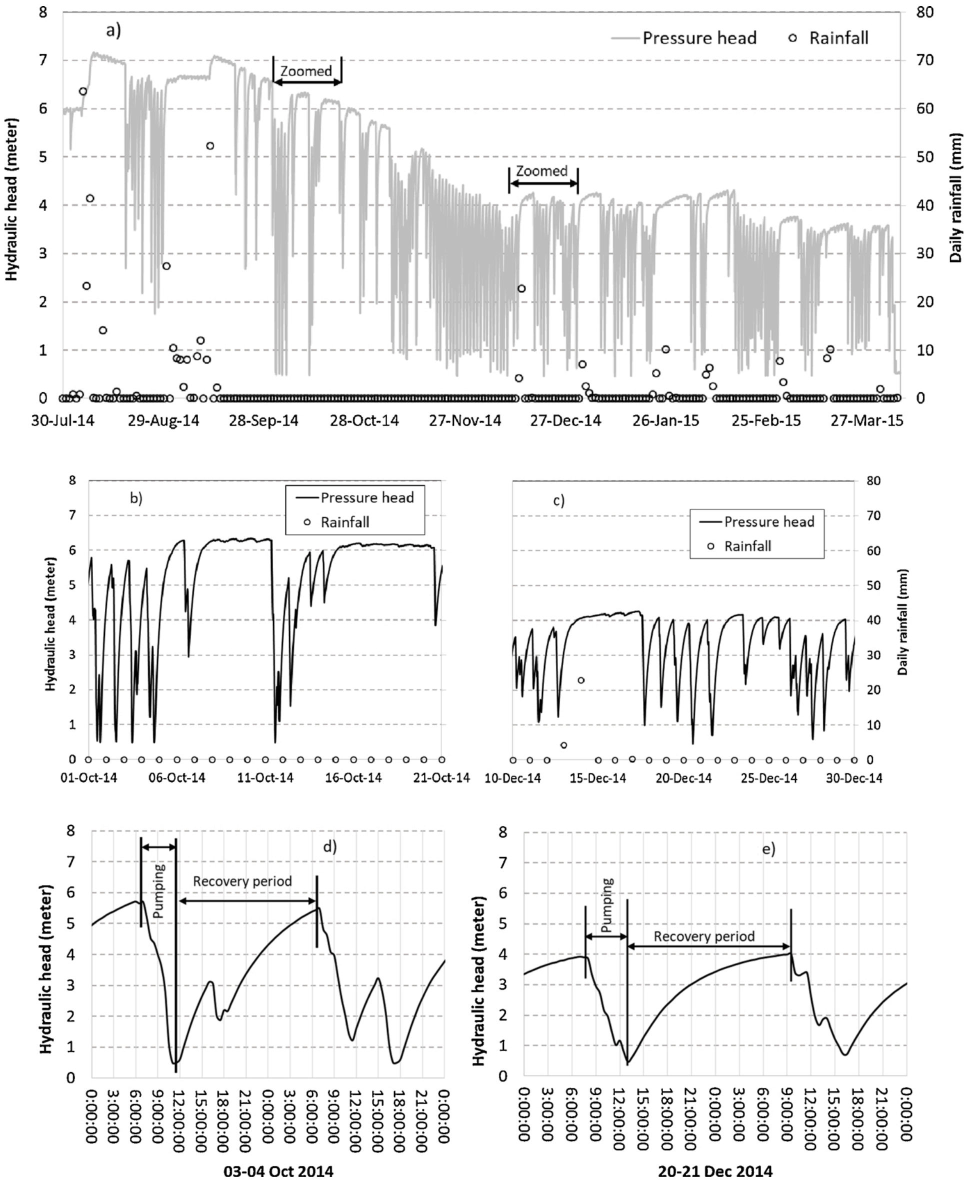


Fig. 5. Pumping and recovery pattern of selected dug well during 2014-15; Fig a) shows GW fluctuation and pumping-recovery fluctuation along with rainfall between July 2014 and March 2015; Fig b) zoomed for 20 days during October; Fig c) for December months; Fig d) and Fig e) showed pumping period and full recovery cycle for selected one day in October and December months.

3.2.2. Irrigation water and energy demand

DIVER data generated for one of the wells that supported a cultivable area of 1.8 ha is presented in Fig. 5 for year 2014−15 to illustrate irrigation application pattern. Of the 1.8 ha, the farmer cutivated vegetables in 0.2 ha and groundnuts in 1.6 ha with the support of supplemental irrigation drawn from the dug well during *kharif* season. Whereas in *rabi* season, the farmer cultivated wheat in 1.6 ha and continued vegetable cultivation in 0.2 ha. Both the crops were irrigated from the same well. DIVER data obtained from the well shows that water was pumped for 105 h in *kharif* and 355 h in *rabi* season using 1.5 horse power (1 HP = 746 W) capacity. The amount of irrigation provided in *kharif* and rabi season was estimated as 225 mm and 570 mm, respectively and the total energy consumed was 515 kW h.

The hydraulic head in the dug well was 7.0 m during July 2014 and it declined to 6.0 m during Oct 2014. Further, the hydraulic head in the dug well reached to 3.5–4.0 m during February and March 2015. Intermittent rainfall in *kharif* and *rabi* seasons helped reduce the irrigation requirment and also recharged groundwater levels (Fig. 5). During dryspells, the farmer pumped water almost every day as farmer irrigated a portion of field (0.2−0.25 ha/day) by following flood irrigation method and covered the entire field on rotation basis (Fig. 5b and c). Fig. 5d & e present a closer view of pumping and recovery characteristics of the monitored well during 03−04 October 2014 and 20–21 December 2014, respectively. With a continous pumping of 5 h on 3 October 2014 (6:30−11:30 h), the water level in the well dropped from 5.7 to 0.5 m. It took almost 18 h to refill the well to its initial level. It shows that recovery ratio was 2.5. Subsequently on 20–21 December 2014, a 5 h continuous pumping between 8:00−13:00 h brought water level from 4.0 m to 0.5 m and it took nearly 20 h to refill the well to its original level indicating recovery ratio 4.

Quantity of irrigation applied to different crops (groundnut and vegetables in *kharif*; wheat and fodder in *rabi*) as measured during the study is summarized in Fig. 6a. The total irrigation applied in groundnut in different years was 210−250 mm; whereas irrigation applied to cultivate vegetables ranged in between 210 and 380 mm in *kharif*. This range is largely due to rainfall variation from year to year. Similarly, the quantity of irrigation in wheat ranged between 200 and 390 mm while the range was between 220 and 550 mm for fodder crops during *rabi* season. The energy consumption ranged between 50 kW h/crop/ha and 380 kW h/crop/ha depending on the quantity of irrigation applied (Fig. 6b).

Fig. 7a shows gross irrigated area in Parasai-Sindh watershed between 2012 and 2016. Groundnut was the main crop during *kharif* which requires supplemental irrigation especially during dry spells; whereas barley and wheat were cultivated during *rabi* season with groundwater support. Gross area irrigated in 2012 was 1000 ha compared to 1600 ha in 2016. Irrigated area under groundnut increrased from 390 ha to 600 ha and wheat area increased from 400 ha to 980 ha. However, irrigated area under barley declined during this period. Total energy consumption for irrgation during different seasons and years is presented in Fig. 7b. Over 70 % of the total energy consumption for irrigation was recorded in *rabi* season as the *kharif* season crops were supported by monsoonal rainfall. The total irrigated area and the distributon of rainfall during a season are the determining factors for total energy consumption. During the year 2013 which was one of the wet years, irrigation application was minimal both in *kharif* and *rabi* seasons. Therefore, energy consumption was 75 kW h/ha including *kharif* and *rabi* season. Energy consumption increased in 2014 and 2015 as more number of irrigations were required to compensate the deficit rains during those years and the energy requirement recorded was 130–180 kW h/ha. The year 2016 was a normal rainfall year which covered highest area under irrigation due to enhanced water availability. Farmers tended to apply higher number of irrigations as the water levels in their wells was higher which in turn resulted in higher energy consumption (up to 225 kW h/ha) on average.

4. Discussion

4.1. Building climate resilience in fragile landscapes

Bundelkhand region of central India is experiencing recurring droughts. Long-term climate data shows that the average rainfall in the region has declined by 200 mm over past 6 decades (Rao et al., 2013; Garg et al., 2020a). As runoff is the most sensitive parameter,

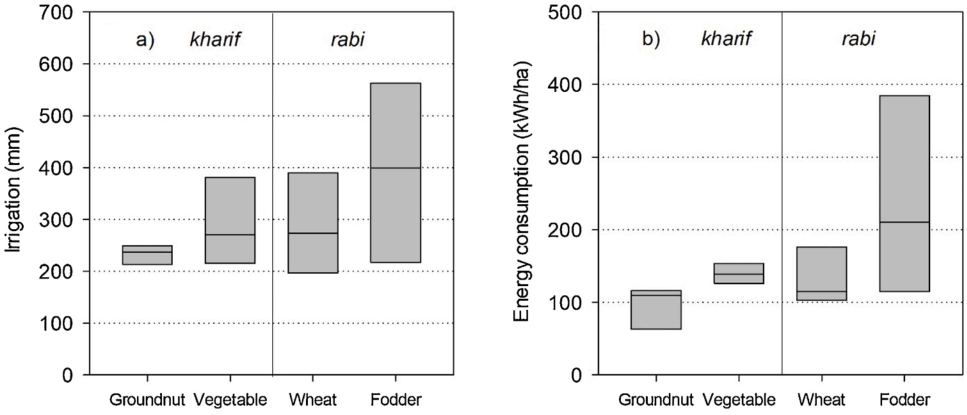


Fig. 6. Crop-wise irrigation application and energy consumption in Parasai-Sindh watershed.

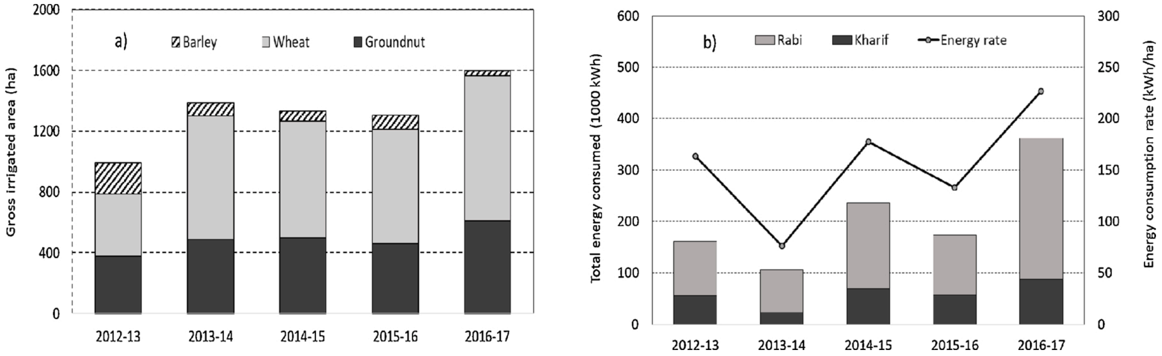


Fig. 7. a) Gross irrigated area and b) energy consumption in Parasai-Sindh watershed.

with declining rainfall pattern the RWM interventions can play an important role in mitigating the effects of climate change. This region is also characterized by hard rock geology and perched water table is formed during monsoon which is characterized by poor specific yield. As the rainfall distribution in this region is highly skewed and the entire rainfall is received in about 20–40 days during a year (80 % rainfall mostly between June and October), the RWM interventions provide opportunity to hold a fraction of water and facilitate for groundwater recharge. In the absence of RWM interventions, it is realized that the runoff generated is not available for the upstream users and besides leading to flooding in downstream areas. Results from this study clearly show that once the perched water table is recharged, it can serve to meet water demand in the consecutive years. The perched water table also has its saturation limit (i.e., 120−130 mm) as water table in 2013 and 2016 reached almost the ground level in more than 90 % of the wells and it was not possible for further harvest of recharge.

Water balance analysis shows that the RWM interventions enhanced groundwater availability from 45 mm to 80 mm. Enhanced availability of water triggered farmers to intensify their cropping system. The soil moisture in fallow lands was lost as non-productive evaporation before the project intervention. With improved groundwater availability these lands and the residual moisture held in them were converted into productive evapotranspiration thereby enhancing the overall land and water use efficiency. This study also provides insights into the recovery ratio of groundwater pumping in shallow dug well systems. The recovery ratio is strongly correlated with the average hydraulic head of the watershed. The recovery hours in treated watersheds ranged from 10−20 hours during different months. Whereas during non-intervention stage, the recovery hours were almost double as available hydraulic head was 2−3 m lower than it was in the treated condition. This has a number of implications in terms of labour engagement, cost of cultivation, drudgery and energy consumption. The cost of cultivation also went down drastically due to the project intervention as farmers were able to irrigate their fields at sizable scale (0.5–1.0 acre) each day compared to 0.1−0.3 acres before the intervention. This was keeping the entire family, including women and children, busy in irrigating the fields for the entire season, as the water in their wells was limited and the recovery period was long. With increased availability of groundwater, irrigated area and number of irrigations per ha increased by 30–50 % and enhanced crop productivity by 20–70 %. This benefit further translated in terms of enhanced fodder availability, milk production and net income which was increased by more than twice compared to pre-intervention stage (Garg et al., 2020a,b).

The field scale (2−5 ha) water balance indicated that the quantity of irrigation applied during monsoon and post-monsoon periods range between 200 and 550 mm depending on soil moisture status and rainfall distribution. Whereas the water balance of the entire watershed (1200 ha scale) indicated that the net consumption of groundwater ranged between 30 and 140 mm during post-monsoon season. This indicates that a significant amount of return flow (>60 %) from irrigated water into the shallow aquifer system. All the farmers in the watershed largely practice flood irrigation method, which has poor distribution efficiency and more than 50 % of water might be returning back to the shallow aquifer system. An introduction of efficient irrigation method (e.g., solar photovoltaic pumping based sprinkler system) along with irrigation scheduling protocol may enhance the irrigation use efficiency and reduce energy consumption (Santra et al., 2016; Santra, 2021). However, there is a need for validation of sprinkler system in this region. In addition, as the landscape in the watershed holds up to 3% of land slope and is also characterized by poor retention capacity, landform management interventions such as laser land leveling in suitable fields can further enhance the irrigation distribution efficiency thereby reducing energy consumption and cost of cultivation (Ali et al., 2018;).

The *haveli* system of Bundelkhand region, the traditional practice has become defunct and dilapidated in last 3–4 decades holds enormous potential for revival of the region for ensuring water security and erosion and flood control. The *haveli* system holds an opportunity to harvest surface runoff in a decentralized manner so that the catchment and the command area are within the premises of the hydrological boundary. In general, *havelis* are designed with 20−200 ha of catchment which submerge 1−10 ha (< 5% of the catchment) landscape on the upstream during monsoon. However, farmers whose lands get submerged as part of the *haveli* system during *kharif* season, do not lose much, as they cultivate *rabi* crop using residual soil moisture and with the support of supplemental irrigation which ensures an assured harvest unlike the *kharif* crop which is often subjected to droughts and dry spells. Besides, the fertility levels of the *haveli* fields are 30−40% higher than the normal fields due to the presence of high organic carbon and humus which compensates their loss during the *kharif* season and at the same time, water harvested in the *haveli* system rejuvenate all nearby dug wells (Sahu et al., 2015). Thus, the *haveli* system offers a win-win for the farmers while also serving the ecosystem. Garg et al., 2020a showed that the unit water harvesting cost of *haveli* system was US$ 0.05−0.1/m^3 compared to US$ 0.5–2.0/m^3 for other rainwater harvesting structures such as check dams.

4.2. Comparison with other studies

There is increasing interest among various stakeholders to understand and prioritize their investment in creating irrigation facilities for avoiding recurrent crop failures in fragile ecosystems such as the one under study. However, there is not much scope for investing in riverine irrigation projects in many parts of the country like India which are too expensive in terms of ecological and human resettlement costs. This leaves with an option of finding decentralized rainwater harvesting solutions to provide the quintessential moisture for crop production. Most parts of India that receive an annual rainfall of over 500 mm are found suitable for such initiatives. Thus, this area offers huge untapped potential to pursue sustainable intensification through scientific design and monitoring of decentralized rainwater harvesting systems. There are, however, not many studies on the typical issues of fragile ecosystems like Bundelkhand. Singh et al. (2014) described that agricultural water management interventions in one of the degraded highlands in Tikamgarh district of Madhya Pradesh has transformed livelihood of the farmers with improved availability of groundwater for domestic and agriculture sector. This study also showed that RWM interventions have reduced land degradation and soil loss by 4–5 times. Similarly, a few of other studies in southern India (Garg et al., 2012; Garg and Wani, 2013; Karlberg et al., 2015; Anantha and Wani, 2016; Anantha et al., 2021a) show various ecosystem services which were strengthened by introduction of rainwater harvesting interventions in hard rock agriculture watersheds. With increasing water stress under changing climatic conditions, evidence based solutions are needed (Singh et al., 2018; Garg et al., 2021; Anantha et al., 2021b). Intensive hydrological and impact monitoring needs to be strengthened in different parts of the region which are characterized by a variety of soil types, topography, land use, and land degradation levels. This will help in making prudent investments for restoring degraded ecologies to benefit the poor and smallholder farmers inhabiting them in large numbers.

5. Conclusion

The Parasai-Sindh watershed of 1246 ha was developed with various RWM interventions between 2012–2016 in Jhansi district of Uttar Pradesh in Bundelkhand region of Central India, which typically represents semi-arid tropics. Below are the key findings of the study:

- The water balance analysis showed that the Parasai-Sindh watershed received 720 mm of rainfall between 2013 and 2017, out of this 19 % runoff (136 mm) was recorded at upstream site of 80 ha catchment; whereas runoff downstream across 567 ha was recorded 14 % of total rainfall (99 mm). Thus, it indicated that 37 mm of net harvested runoff was retained within the watershed due to various rainwater harvesting interventions.
- The water balance components varied largely in over the study period (2012–2016). Out of the five years, one was normal, one wet and three were dry years. Runoff generated in wet years was in the range of 28–29 % of total rainfall (1276 mm) which made a significant contribution to groundwater recharge without affecting downstream water availability as the total runoff generated during this year was much higher than the harvested capacity. The runoff during the dry year was in the range between 0–10 % of the total rainfall (400−630 mm). In the normal year, of the 768 mm rainfall, runoff recorded at different sites ranged between 16 and 27 %. RWM interventions reduced the downstream water availability significantly (∼40 %) mainly in the normal years.
- Groundwater level monitoring indicated that the net increase in water table in treated watershed was 4.0 m, which was equivalent to 80 mm of groundwater recharge. Out of this, 25 % (20 mm) is utilized during *kharif* and 75 % (60 mm) during *rabi* seasons. Further, year-to-year variability showed that the net recharge in monsoon period was only 14 mm in 2015 under 50 % deficit rainfall condition compared to 140 mm in 2016 with 768 mm rainfall. On the other hand, groundwater recharge in control watershed was found at 45 mm on an average which was utilized almost in equal segment (20−25 mm) in *kharif* and *rabi* seasons
- The groundwater recharge in wet or normal years helped to meet agriculture demand in recurring dry years as shallow aquifer system filled quickly during wet years and held it up to two years. Improved groundwater availability enhanced irrigated acreage both in *kharif* and *rabi* seasons by 50 % compared to no-intervention stage. Farmers in *rabi* season shifted their crops from chickpea, mustard and barley area to wheat. Over 100 ha land, which was under permanent fallow was brought into productive cultivation.
- The recovery ratio of shallow dug well system strongly correlated with hydraulic head of the watershed. With every 1.0 m decline in hydraulic head, the recovery period increased by 50 %. Improved groundwater table helped to reduce recovery period to 10−20 h from 30 to 40 h. Results show that energy consumption for irrigating 1.0 ha land was between 75 and 225 kW h/season depending on amount of annual rainfall and its distribution over seasons in respective years.

The preceding discussion suggests that there is huge opportunity for sustainable crop intensification in the degraded landscapes which suffer from water scarcity, land degradation and mono cropping systems. *Haveli* renovation system is one of the promising solutions to address some of the critical issues associated in alleviating poverty and ensuring food security in line with the United Nations sustainable development goals.

Author statement

Below are contribution by different authors in this study:

Ramesh Singh: Project implementation and data collection; Kaushal K Garg: Conceptualization, data analysis and manuscript writing; KH Anantha: Conceptualization, and manuscript writing; Venkataradha Akuraju: data analysis; Inder Dev: reviewing and editing; Sreenath Dixit: reviewing and editing; SK Dhyani: reviewing and editing.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2021.100929.

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