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Building climate resilience in degraded agricultural landscapes through water management: A case study of Bundelkhand region, Central India

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ABSTRACT

Rainfall variability and water scarcity continue to hamper the food and income security of smallholder farming systems in poverty-affected regions. Innovations in soil and water management, especially in the drylands, are critical for meeting food security and water productivity targets of Agenda 2030. This study analyzes how rainfed agriculture can be intensified with marginal impact on the landscape water balance. The impact of rainwater harvesting structures on landscape hydrology and associated agricultural services was analyzed in the semi-arid Jhansi district of Bundelkhand region in central India. The Parasai-Sindh pilot watershed was subjected to a 5-year (2012–2016) monitoring of rainfed system improvements in water availability and crop intensification due to surface water storage (*haveli* system), check dams, and field infiltration structures. Hydrological processes were monitored intensively to analyze the landscape's water balance components. Rainwater harvesting (RWH) structures altered the landscape's hydrology, limiting average surface runoff from 250 mm/year to 150 mm/year over the study period. Groundwater levels increased by 2–5 m (m), alleviating water scarcity issues of the communities in recurring dry years. Nearly 20% of fallow lands were brought under cultivation. Crop yields increased by 10–70% and average household income increased from US$ 960/year to US $ 2700/year compared to that in the non-intervention landscape. The combined soil–water–vegetation efforts strengthened water resilience and environmental systems in agricultural landscape.

1. Introduction

Increasing population pressure, change in food habits, and expanding urbanization are driving the increase in demand for freshwater globally (De Fraiture and Wichelns, 2010; Gerten and Heinke, 2011; Wiltshire et al., 2013; Davis et al., 2017). There is increasing competition among different anthropogenic sectors such as domestic, agriculture, industries and also for the biosphere (Garg et al., 2012; Molle and Berkoff, 2006; Niu et al., 2019). This led to increasing stress among different sectors/stakeholders for their share on the available water resources (Al-Saidi, 2017; Punjabi and Johnson, 2019). Mekonnen and Hoekstra (2016) reported that globally about 4 billion people live under severe water scarce conditions for at least one month of the year; 3.3 billion for at least three months; and 1.8 billion for at least half a year. Climate change has also created more uncertainty in water availability, increased risk, and production and economic losses (Wiltshire et al., 2013; Mekonnen and Hoekstra, 2016; Singh et al., 2017; Sishodia et al., 2018; Malek et al., 2018; Lu et al., 2019; Aggarwal et al., 2019). As agriculture is the largest consumer of freshwater, its declining availability has a direct impact on food security, sustainability, and livelihoods for millions of rural households, especially in developing countries like India (Berchoux et al., 2019; Garg et al., 2020; Zarei et al., 2020).

There is limited potential left for crop intensification and also to enhance agricultural productivity in irrigated systems; while a relatively large untapped potential exists in rainfed systems, if existing challenges are addressed (De Fraiture and Wichelns, 2010; Tilman et al., 2011; McLaughlin and Kinzelbach, 2015). The large yield gap in rainfed systems could be bridged by implementing natural resource management (NRM) interventions (Rockström et al., 2009a, 2009b;

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Suresh et al., 2014; van Ittersum et al., 2016; Davis et al., 2017; Rao et al., 2017). While rainfed systems in the semi-arid tropics are resourceful, their full potential has not been realized due to poor management of natural resources (Mandal et al., 2020). Land and water use efficiencies range between 30 and 40% since a significant amount of freshwater is channeled through non-productive evaporation (Bell et al., 2018). Various NRM practices have been implemented to conserve and enhance resource use efficiency that can lead to crop intensification and productivity gains (Reddy et al., 2017; Vema et al., 2017; Kroeger et al., 2019).

The rainfed semi-arid tropics are characterized by variable rainfall, high incidences of drought and flood, land degradation, and poor agricultural productivity (Suresh et al., 2014). These regions mostly coincide with high poverty hotspots (Harris and Orr, 2014). Integrated landscape management (also called watershed management) has recently gained enormous traction and interest as an approach to conjunctively address water-soil-crop production and livelihood boundaries (Mondal et al., 2020). Watershed interventions help enhance resource availability by conserving/protecting land and water resources that catalyze crop intensification, production gains, and build resilience (Singh et al., 2014; Dile et al., 2016; Reddy et al., 2017; Kroeger et al., 2019).

India is one of the leading countries that have implemented large-scale watershed management programs (Hope, 2007). The Government of India along with several international donor agencies have invested more than US$ 14 billion since 1990 (Mandal et al., 2020), helping the country address land degradation, water scarcity, food insecurity, and improve rural livelihoods (Kerr, 2002; Hope, 2007; Garg et al., 2011; Mondal et al., 2017; Reena and Singh, 2019). However, limited efforts have gone into monitoring and understanding the impact of rainwater harvesting interventions on hydrological processes, water balance components, upstream water utilization versus downstream water availability, land use change, agricultural productivity, and income (Glendenning et al., 2012), with the exception of a few agro-hydrological studies (Garg et al., 2011, 2012; Singh et al., 2014; Karlberg et al., 2015) at meso-scale watersheds (5–50 km^2). Most of the watershed planning has been based on assumptions and a lack of understanding of upstream–downstream trade-offs that would facilitate resource optimization. Together, these lacuna have impeded planning and resource prioritization as well as led to unclear assessments of the resilience building necessary for environment and livelihood improvements.

To address these gaps, a meso-scale watershed monitoring scheme was designed and developed to inform adaptive management and resilience building. This case study evaluates the hydrological, agricultural, and economic impacts monitored in paired meso-scale watersheds in Bundelkhand region of central India for five years. It analyzes the impact of low-cost rainwater harvesting structures on (i) landscape hydrology, specifically on surface runoff and shallow groundwater recharge; (ii) upstream–downstream water availability; and (iii) crop intensification, agricultural productivity, and household income.

2. Material and methods

2.1. Bundelkhand region, Central India

Bundelkhand region of Central India lies between the Indo-Gangetic Plains to the north and the Vindhya range to the south. It is a gently sloping upland (mean slope = 3%, which ranges between 1% and 5%) distinguished by an unproductive hilly terrain with sparse vegetation, although it was historically forested (Tyagi, 1997). The region comprises parts of Uttar Pradesh and Madhya Pradesh states in India. Most inhabitants in the region are dependent on agriculture/livestock-based activities and approximately 33% of the area is covered by degraded forest, grazing land, and degraded wasteland (Gupta et al., 2014). Bundelkhand has a high incidence of poverty (30–55% in different districts); low literacy rate (57% overall, 43% in women); and highly vulnerable women and landless people (Varua et al., 2018; Mitra and Rao, 2019; Padmaja et al., 2020).

Mean annual rainfall in the region is 750 mm and unevenly distributed throughout the year. The wet season (called *kharif*) between July and September has 85% of the annual rainfall and the remaining 15% is distributed throughout the remaining nine months. This has had an adverse impact on regional water balance, especially on groundwater recharge (Singh et al., 2014). The wet season has a higher mean temperature (35 °C) while the dry season (*rabi)* has a lower mean temperature (10 °C). Based on long-term data analysis (1971–90 and 1991–2004), Rao et al. (2013) observed that about 581,000 ha under semi-arid moist climate in Bundelkhand region of Uttar Pradesh have shifted to semi-arid dry and arid climates.

Bundelkhand is largely dependent on shallow groundwater resources for domestic and agricultural uses. Due to the hard-rock geology, groundwater recharge mainly occurs in shallow and unconfined aquifers characterized by poor specific yield (1–3%). The water level in open/dug wells (4–8 m deep) is depleted rapidly after the monsoon, with communities having to endure water scarcity, especially during the summer (Singh et al., 2014). The region's undulating topography, high temperature, poor and erratic rainfall, and low soil fertility have led to poor agricultural productivity (0.2–2.0 t/ha) and food insecurity (Shakeel et al., 2012). Farmers in the region grow low water-consuming crops like groundnut, black gram, sesame, and millets during the Kharif (wet season), and wheat, chickpea, barley, mustard, and lentils during the rabi (dry) season (Table 1). Crops grown during the wet season (e.g., groundnut) may require supplemental irrigation during dry spells, whereas most of the crops grown in the dry season (chickpea, barley, and wheat) require irrigation support.

Almost every village in Bundelkhand region has a traditional rainwater harvesting tank system called *haveli*. The *haveli* system evolved over 300–500 years ago and consists of a 50–150 m length of earthen embankment 4–10 m wide and 1–3 m high across the slope depending on the extent of catchment (Prakash et al., 1998; Shah, 2003; Sahu et al., 2015; Meter et al., 2014, 2016). Traditionally, communities would maintain tank bunds, desilt, repair water outlets, and schedule water release (Meter et al., 2016). Normally, the catchment of the *haveli* system ranges from 0.2 to 2.0 km^2. Runoff generated from the catchment is harvested during the monsoon and used for multiple purposes (Prakash et al., 1998). The groundwater recharge during the monsoon and harvested rainwater provide supplemental irrigation to nearby fields during dry periods. Once the monsoon recedes, the impounded rainwater is drained out and the tank bed is prepared to cultivate *rabi* crops using residual soil moisture (Prakash et al., 1998; Sahu et al., 2015). Drained water from the *haveli* is used in pre-sowing irrigation by downstream farmers and surplus water is released through drainage networks (Prakash et al., 1998). The productivity of crops fed by the *haveli* in the rabi season is 15–25% higher than that from fields nearby due to the deposited silt and organic matter (Sahu et al., 2015). The *haveli* system that once used to meet the freshwater demand in the region, gradually became defunct mainly due to the disintegration of water user groups and rural institutions (Shah, 2003; Niti Ayog, 2012; Reddy et al., 2018).

Realizing the importance of the *haveli* structures, public welfare programs have made significant efforts towards their repair and maintenance since 2000. In addition, other rainwater harvesting structures such as check dams (masonry structures across drainage networks to harvest surface runoff), gully plugs (low-cost structures across drainage networks to lessen the speed of surface runoff), and farm ponds (small water storage structures within fields used for supplemental irrigation) have been constructed as drought mitigation measures (Gupta et al., 2014; TERI, 2018). However, the average life of these structures is relatively short (2–5 years) due to their poor design and construction quality. Therefore, the region has not realized the full

Table 1
The crop calendar of major crops in Bundelkhand region, Uttar Pradesh, Central India.

Season	Crops	Crop duration (days)	Irrigation status	Jun	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
Kharif (wet and hot)	Black gram	70-75	Rainfed		■	■	■								
	Sesame	70-75	Rainfed		■	■	■								
	Millet	90-100	Rainfed		■	■	■	■							
	Groundnut	110-120	1-2 irrigations		■	■	■	■							
Rabi (dry and cold)	Mustard	110-130	Rainfed					■	■	■	■	■			
	Lentil	110-130	Rainfed					■	■	■	■	■			
	Chickpea	120-130	1-2 irrigations						■	■	■	■	■		
	Barley	120-130	2-3 irrigations						■	■	■	■	■	■	
	Wheat	120-140	3-5 irrigations						■	■	■	■	■	■	

Note: The kharif season coincides with the monsoon period whereas the rabi season coincides with the winter period.

potential of groundwater recharge (TERI, 2018). It is reported that about 30% of earthen structures have collapsed due to seepage and failure in piping and sloughing (Foster, 1999; Foster et al., 2000; Foster and Fell, 2000a, 2000b; Fell et al., 2003; Mansuri and Salmasi, 2013).

2.2. *Parasai-Sindh watershed: an overview*

The Parasai-Sindh watershed located in Babina block of Jhansi district in Uttar Pradesh covering 12.46 km^2, was chosen to develop a study site between 2012 and 2016. It comprises three villages, namely Parasai, Chhatpur, and Bachauni located between 25°23′56″ to 25°27′9″ N and 78°19′45″ to 78°22′42″E (Fig. 1). Simultaneously, a neighboring watershed of 11.0 km^2 (in Hatlab village) was identified as a control, with no soil–water-crop interventions. A baseline survey was conducted in the identified villages to gain an understanding of their biophysical, social and economic conditions (Table 2). The majority of farmers in both the watersheds were generating about 80% of agricultural income from crop production and 20% from milk production. Daily wage labour was also a source of income for small and marginal farmers. These paired watersheds (Parasai-Sindh and Hatlab) have a relatively flat topography with an average slope of 2%. Agricultural land cover ranged between 86% and 88% of the total geographical area while 12–14% comprised degraded forest and scrubland used mainly for grazing by livestock. Groundnut, black gram, and sesame were the major *kharif* (wet season) crops grown while wheat, mustard, and chickpea were mainly grown in *rabi* (dry season) (Table 1).

More than 80% of the open wells in the villages were dry soon after the monsoon due to limited groundwater recharge. The villages have a good distribution of dug wells (Fig. 1), upstream to downstream. In the event of drinking water scarcity and lack of alternative livelihood opportunities, a large number of people from the rural community migrated to nearby cities. In dry years, the villagers were largely dependent on external sources and private tanker suppliers for water for domestic use, especially during March-May. Cattle were usually abandoned due to water and fodder shortages.

Soils in both the watersheds are shallow Alfisols and Entisols (10–50 cm soil depth), coarse gravelly, light textured with poor water-holding capacity (80–120 mm/m), and with low organic carbon (< 1%) (Kumari et al., 2015). There were 388 open wells in the treated watershed and 296 in the control watershed which were the primary source of water for domestic and agricultural uses. There were no deep aquifer tube wells in these watersheds due to hard rock aquifer (granite) and poor specific yield (1–3%). The topography, land use, and demographic details of both the watersheds are shown in Table 2.

The study involved analyzing the impact of RWH interventions on water resource availability and crop intensification, for which the interventions implemented are described in Section 2.3., followed by the methods and instruments used to monitor hydrological data in Section 2.4. Results on upstream vs. downstream water availability from generated surface runoff (Figs. 4 and 5) and reservoir water balance (Fig. 6) under the *haveli* system in the treated watershed are discussed in Sections 3.1 and 3.2 respectively. The impact of the interventions on groundwater availability calculated by comparing pressure head in the treated and control (paired) watersheds is discussed in Section 3.3 (Fig. 7), and their impact on cropping intensity, crop yield, and average annual household income before and after the project is dealt with in Section 3.4 (Figs. 8 and 9 and Table 3).

2.3. *In-situ and ex-situ rainwater harvesting measures*

2.3.1. *Rejuvenating a rainwater harvesting tank (haveli)*

One of the defunct *havelis* was located at the most upstream location of the landscape with a catchment area of 0.8 km^2 (S1 in Fig. 1). Its traditional design was improved. The diameter of the existing outlet was expanded to dispose-off the excess runoff during very heavy rainfall events. The mud embankment wall that would breach during heavy inflows was replaced with a cement concrete core wall. This rejuvenation undertaken in 2012 created nearly 73,000 m^3 of water storage capacity. Fig. 2 shows the masonry outlet of the *haveli* structure and the concrete core wall (> 100 m) built as well as the wheat crop grown using residual soil moisture and supplemental irrigation during rabi season.

2.3.2. *Construction of check dams*

Constructing check dams is very common in watershed projects (Abbasi et al., 2019). To enhance groundwater recharge, a series of check dams were constructed along the drainage line following the 'ridge-to-valley' approach (Fig. 1). Structures S1, S2, S3, S4, S5, and S10 were constructed in 2012; structures S9 a,b,c,d (grouped as S9) in 2013; and structure S6, S7, S8 in 2015. These are reinforced stone masonry structures with nearly 1.5–2.0 m crest height having rectangular weirs to dispose of excess surface runoff during flood events. Their storage capacity varies between 1500 m^3 and 8000 m^3 depending on drainage density, topographical features, and stream width. A total storage capacity of 23,200 m^3 was created through check dams.

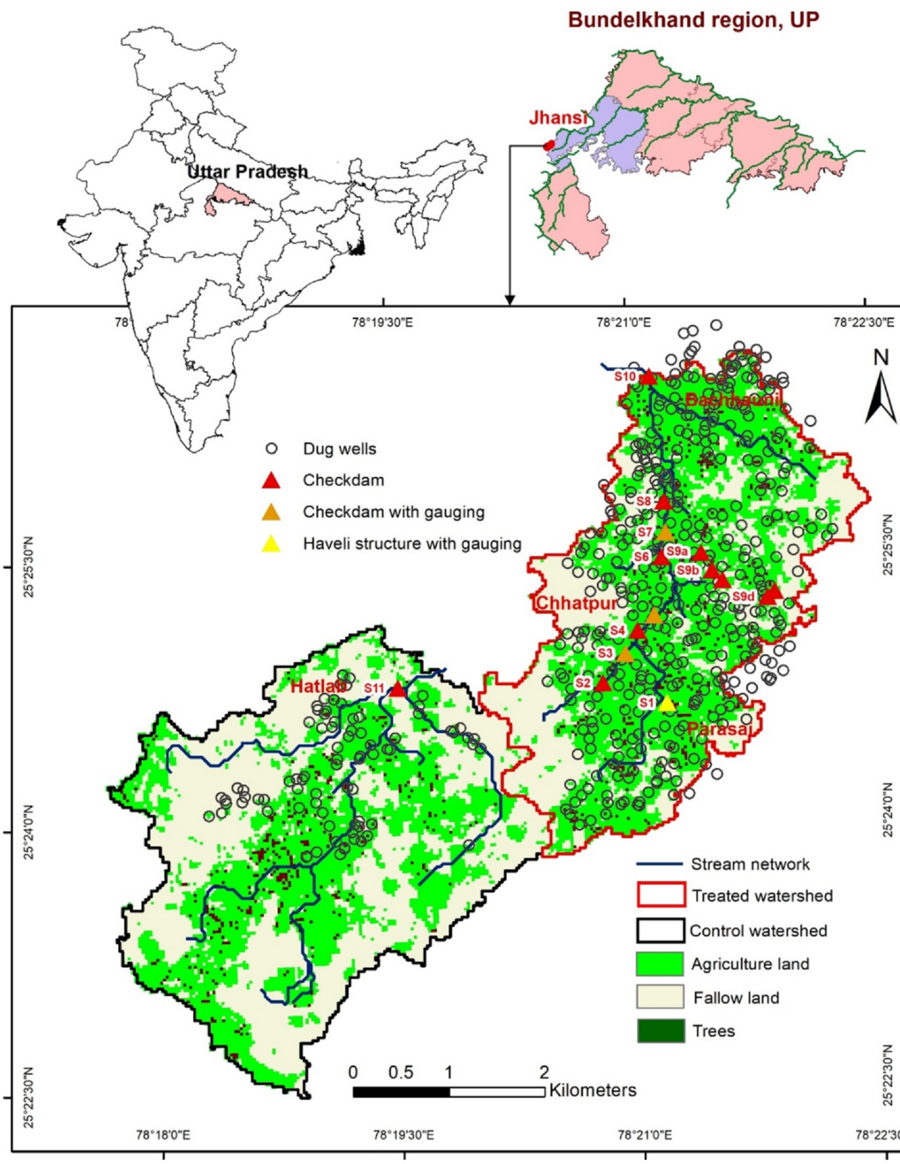

Fig. 1. The Parasai-Sindh watershed in Jhansi showing stream networks, the distribution of dug wells, major land-use classes and control watershed (*Hatlab*). S1 is the *haveli* structure, S2–S11 are check dams; and S1, S3, S5, and S7 are gauging stations.

2.3.3. In-situ rainwater harvesting measures and crop management interventions

In-situ rainwater harvesting (e.g., contour/graded bunds) enhances soil moisture availability and crop productivity, and controls land degradation and soil erosion (Sharda et al., 2007; Naik et al., 2015). Large fields (20,000–30,000 m^2) were divided into relatively smaller areas (3000–5000 m^2) to reduce runoff velocity while harvesting a fraction of runoff from across the field bunds. Nearly 25,000 m long field bunds with the cross section of 1–1.5 m^2 were constructed. Field outlets were stone pitched for guided disposal of excess runoff. Teak (*Tectona grandis*) saplings were planted at the base of the field bunds at 3-m intervals to strengthen the bunds and to serve as an additional source of income to farmers in the long run. Farmer participatory field demonstrations were conducted on soil test-based fertilizer application, improved crop cultivars and integrated weed and disease management between 2012 and 2015 along with capacity building initiatives.

2.4. Data monitoring and impact analysis

2.4.1. Runoff gauging

Of the nine rainwater harvesting structures constructed in the study watershed, runoff gauging stations (Fig. 1) were installed at four locations (S1, S3, S5, and S7) in two phases; S1, S3, and S5 were constructed in 2012 and S7 in 2015. Hydrological data (inflow, outflow and volume) was monitored during the project period. Runoff data from the control watershed could not be retrieved as loggers were lost from gauging stations.

A stilling well was constructed upstream of the check dam. An automatic pressure transducer, i.e., DIVER (with pressure head capacity of 10 m) was placed at the bottom of the stilling well (Fig. 3) programed to record pressure head at 15-minute intervals, to estimate inflow and spillover. The relationship between depth vs. storage capacity and depth vs surface area was established for each of the check dam sites by undertaking a topographic survey.

Runoff data generated at different check dam sites were analyzed (Sections 3.1 and 3.2). The quantity of inflow and spillover were calculated on a daily, monthly and seasonal basis and the data compared

Fig. 2. (Top) A view of the water harvested during the wet season (kharif) taken from the outlet of the *haveli* structure) and (bottom) the crop cultivated in the *haveli* bed using residual soil moisture during post-monsoon/rabi season taken from upper side of the *haveli* field.

with that in dry, normal, and wet years. The relationship between rainfall and runoff was also compared.

2.4.2. Groundwater monitoring

The depth of the water table in all the 388 dug wells was monitored manually at monthly intervals during 2011–2017 using a water level indicator, an electronic device (Solinst: 101B Water Level Meter). The groundwater levels were converted into pressure head (hydraulic head at a given time) by deducting the measured depth from the well depth. Similarly, 150 dug wells in the control watershed were monitored during 2014–2017. A 't' test was performed to study the different impacts on groundwater availability (pressure head difference and functioning status) in both the watersheds.

Table 2
The topography, land use and demographic details of Parasai-Sindh watershed.

Parameters	Treated watershed	Control watershed
Villages	Parasai, Chhatpur Bachhauni	Hatlab
Area (km^2)	12.46	11.0
Altitude (m above mean sea level)	270–315	270–310
Land use (%)		
Agriculture	88.4	86.4
Degraded forest	0.5	2.4
Wasteland (scrubland)	5.3	4.1
Others	5.8	7.2
Demographic details (based on 2011 census)		
Number of households	417	395
Average holdings (ha/household)	3.12	3.1
Number of dug wells	388	296
Depth of wells	9.2 (Std ± 1.5)	9.5 (Std ± 1.6)

2.4.3. Crop intensification and agricultural productivity

Data on the cultivated area in individual fields in both *kharif* (wet season) and *rabi* (dry season) seasons were recorded to capture changes in cropping pattern and crop intensification due to watershed interventions. Crop cutting estimates were captured from 50 farmers' fields to measure crop yields and the cost of cultivation. Groundnut and black gram in *kharif (wet season)* season and wheat, chickpea, mustard, and barley in *rabi* (dry) season were selected for crop cutting studies between 2011 and 2016. An area of 9 m^2 from two representative locations in designated fields was marked and crop produce was collected. The harvested produce was sun-dried for 2–3 days; grain and straw weight were recorded separately and crop yields were estimated per hectare. The data was then used to estimate the total agricultural production in the entire watershed in the respective years. Total net income for kharif (wet season) and rabi (dry season) was estimated taking

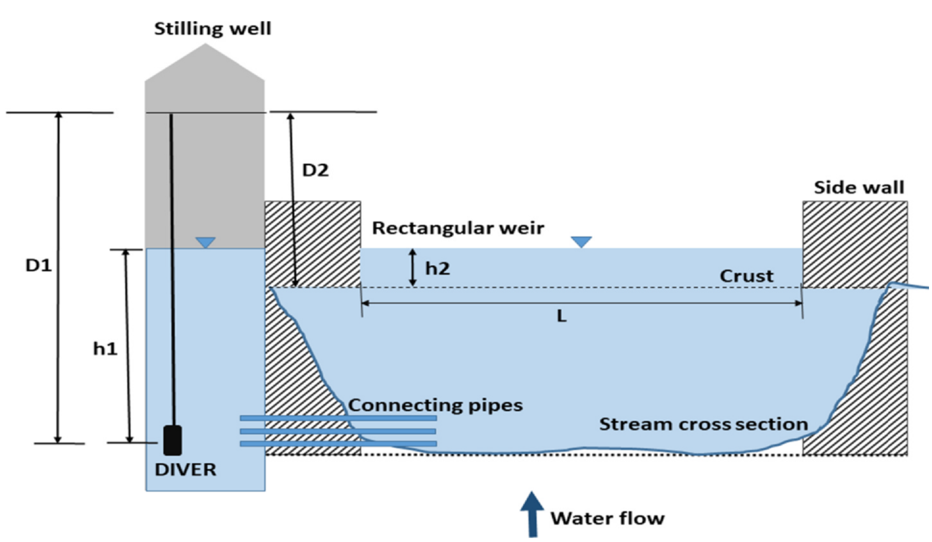

Fig. 3. A schematic diagram of a runoff gauging station.

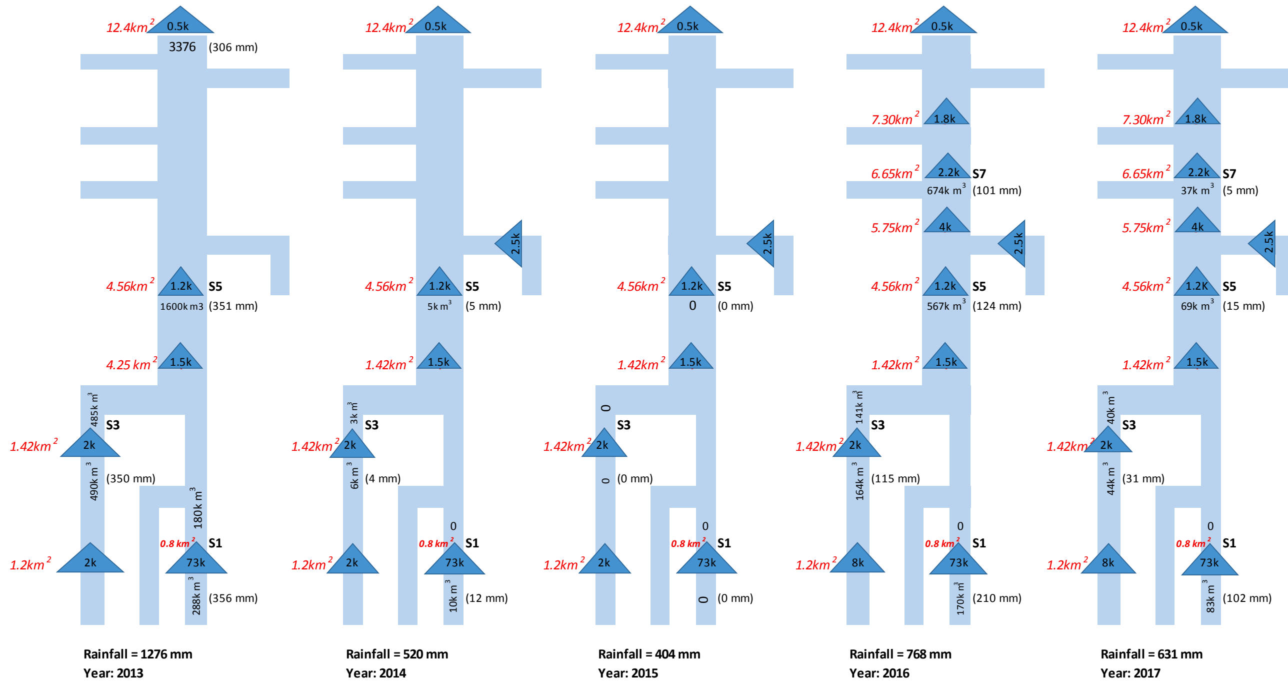

Fig. 4. Rainwater harvesting structures constructed (year-wise), their catchment area (in km^2), reservoir storage capacity (figure inside triangle in m^3), measured inflows and ouflows (inside stream networks in m^3; parentheses shows in mm) at Parasai-Sindh watershed from 2013 to 2017. The triangles represent structures constructed over a period of time and the lines show the stream network.

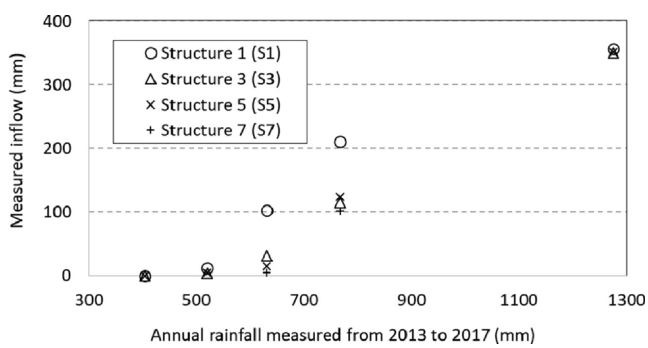

Fig. 5. A comparison of surface runoff (inflow) at upstream (S1) and downstream (S3, S5, and S7) locations between 2013 and 2017 monsoonal periods (Jul–Oct).

into account total yield, market price, and cost of cultivation. Net income from milk production was similarly estimated from individual households.

3. Results

3.1. Surface runoff

Surface runoff varied significantly with annual rainfall. Only intermediate rainfall years (2 of 5, i.e., 2016 and 2017) affected water availability downstream following the RWH interventions. Fig. 4 summarizes the inflow (runoff) at all the four gauging locations and annual rainfall during the project period. Runoff coefficient changed with rainfall quantity and intervention density both on spatial and temporal scales. The runoff coefficient at gauging stations S1, S3, and S5 during the high rainfall year of 2013 ranged between 14% and 28%. S1 (*haveli* tank), which is located upstream (0.80 km^2 catchment) received 28% of total rainfall as runoff while S5 (5.67 km^2 catchment) received 27%. No significant reduction was observed in runoff up to S5, as surface runoff generated was much higher than the storage capacity of the watershed in the wet year. Data further showed that inflows and outflows at S1 were 288,000 m^3 (356 mm) and 180,000 m^3 (222 mm), respectively. A total 108,000 m^3 of runoff was harvested at S1 in 2013, which is 1.47 times its storage capacity. The inflows into structures downstream (S2, S3, S4, and S5) were much higher than their storage capacities.

During the dry year of 2014, the runoff received at different monitoring stations was less than 2% of the total rainfall. Inflow received at S1 was 12 mm (i.e., 10,000 m^3) and all the runoff was harvested within the structure. Similarly, a small quantity of surface runoff was locally harvested and negligible runoff was observed downstream. No surface runoff could be recorded due to deficit rainfall in 2015 (50% deficit compared to the long-term average seasonal rainfall).

During 2016, the inflow measured at different monitoring stations was between 124 mm and 210 mm, indicating that the runoff coefficient varied from 16% to 27%. The highest runoff coefficient of 27% was recorded at S1, which gradually fell to 16% in the downstream location (S5). Data showed that 170,000 m^3 of inflow was received at S1, which was fully harvested into the *haveli* tank with no spillover water from S1 during monsoon 2016. This shows that the *haveli* tank harvested 2.32 times more runoff than its storage capacity between June and October 2016. The year 2017 was a partial deficit year with 631 mm of total rainfall received during the monsoon (22% less than the long-term average). Inflows recorded at S1, S3, S5, and S7 were 102 mm, 44 mm, 15 mm, and 5 mm, respectively, clearly showing that runoff was harvested by the upstream structures. Runoff coefficients at various locations ranged from 2 to 16% (Fig. 5).

The inflow received at S1 represents the non-intervention stage as there was no structure built above it, whereas other sites were subject to intensive rainwater harvesting measures. More than 90% of the runoff generated when rainfall was up to 600 mm was captured by various rainwater harvesting structures, and very little was left for the downsteam ecosystem. On the contrary, about 40% of the generated runoff was harvested during normal rainfall years (about 800 mm rainfall). Significant difference in runoff reduction was observed at S1 and S5 ($p = 0.02 < 0.05$).

However, there was no significant reduction in inflows during wet years (rainfall > 1200 mm) at dowstream sites as the runoff generated

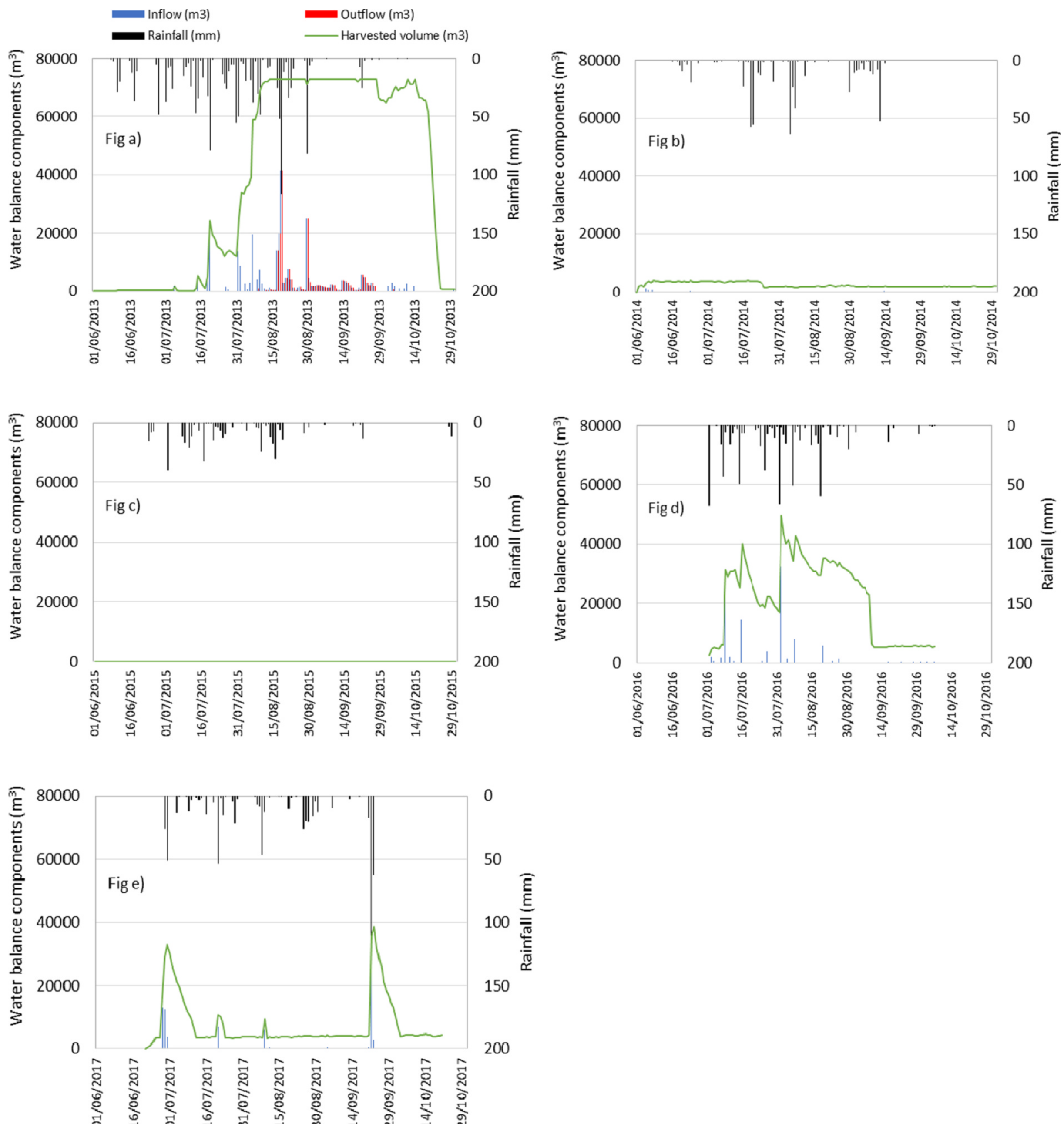

Fig. 6. Measured inflows, harvested volume and outflow (spillover) in response to daily rainfall in S1 for (a) 2013 (wet year); (b) 2014 (dry year); (c) 2015 (very dry year); (d) 2016 (normal year); and (e) 2017 (dry year).

was much higher than the storage capacity created upstream.

3.2. Reservoir water balance

Fig. 6a–e show the components of the *haveli's* (S1) reservoir water balance (inflow, outflow and storage) and rainfall at daily intervals between 2013 and 2017. In order to maintain uniformity in measuring units, inflow, outflow and reservoir storage are represented in volumetric terms (cubic meter). In 2013, the inflow received up to 15 August 2013 was harvested within the structure and no outflow was measured. After filling the structure, both inflow and outflow volumes were found to be almost the same after 15 August as the *haveli* was at its full capacity and all the generated runoff was disposed of downstream (Fig. 6a). On the other hand, in 2014, 2016, and 2017, the inflows generated by different rainfall events was not sufficient to fill the *haveli* to its full capacity and no outflow was recorded. Inflow in 2014 was negligible (Fig. 6b) and no inflow was recorded in 2015 (Fig. 6c). Hydrographs of 2016 (Fig. 6d) and 2017 (Fig. 6e) show that inflows received with 50 mm or higher intensity rainfall events were harvested entirely. As farmers do not directly pump the water from the structure, harvested runoff infiltrated into the underlying shallow aquifer. Cumulative inflow received at S1 between 2013 and 2017 was 0.551 MCM (million m^3), of which 0.371 million m^3 was harvested.

3.3. Groundwater dynamics

Pressure head measurements in dug wells in the two watersheds showed that RWH interventions led to significant infiltration and greater retention of water for a longer period in the improved watershed, thereby enhancing water security both for domestic and agricultural purposes. Fig. 7 shows the pressure head in dug wells in the treated (2011–2017) and control (2014 and 2017) watersheds against

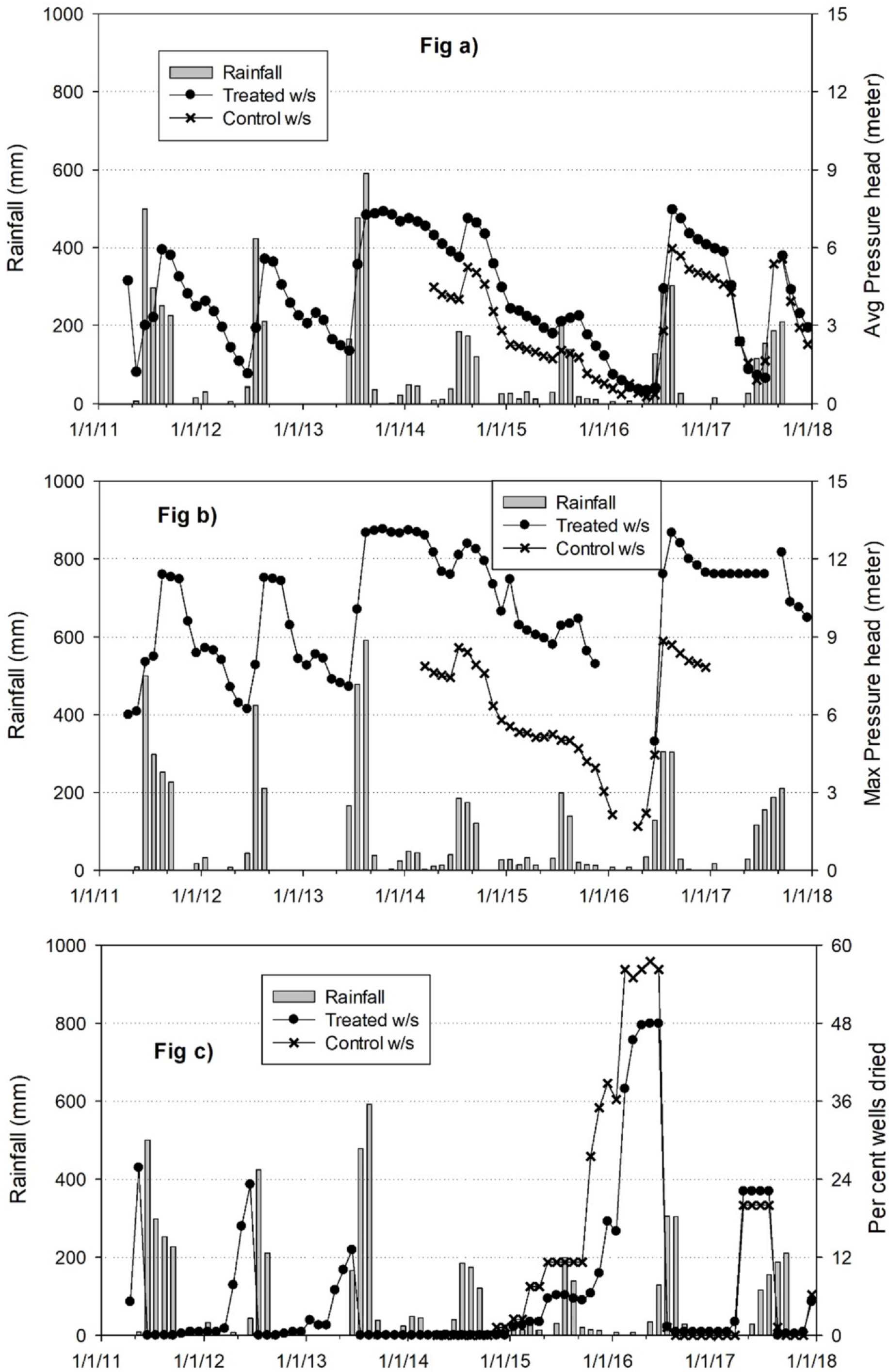

Fig. 7. A comparison of (a) average pressure head; (b) maximum pressure head in dug wells; and (c) percentage of dried wells in treated and control watersheds (2011–2017).

monthly rainfall. As 80% of the annual rainfall falls between July and October, the pressure head increased during the monsoon season, with its magnitude depending on the amount of rainfall received. The pressure head in the post-monsoon season (between Nov and May) declined as groundwater was withdrawn for irrigation use. The average depth of dug wells in treated and control watersheds were 9.2 m and 9.5 m and the maximum well depth recorded were 14 m and 14.5 m, respectively. Fig. 7a compares the average pressure head in treated and control watersheds and also the pressure head before project implementation (2011–12) and after (2013–17).

Pressure head in dug wells was sensitive to rainfall received during the monsoon and water use during the post-monsoon season. Pressure head in the treated watershed was always higher than that in the control watershed ($p = 0.02 < 0.05$). The average pressure head in treated and control watersheds varied from 0.5 to 7.5 m and 0.3–6.0 m, respectively. On an average, an additional 2.0 m pressure head was recorded in the treated watershed compared to that in the control watershed. This difference was found significant, especially during dry years. Fig. 7b shows the maximum pressure head recorded in different months in the studied watersheds, which varied from 5 m to 16 m in the treated watershed and from 2 m to 9 m in the control watershed.

A remarkable difference in pressure head was noted in the Parasai-

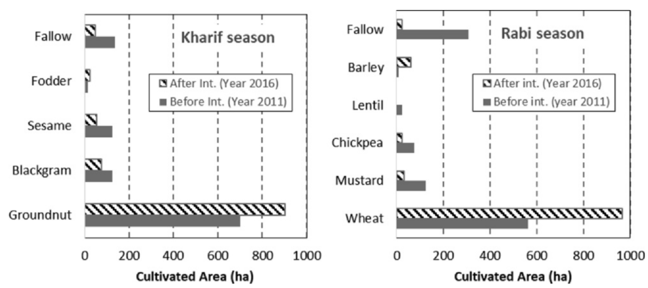

Fig. 8. Change in cropped area during *kharif* (wet) and *rabi* (dry) seasons before (2011) and after (2016) the watershed interventions.

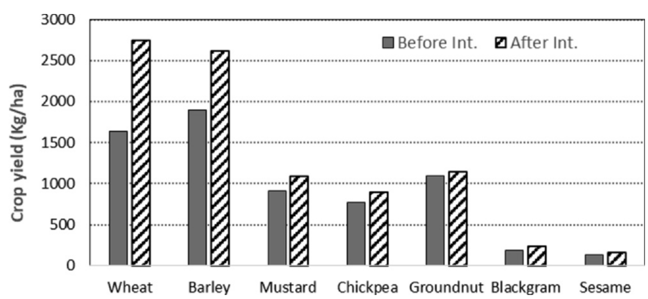

Fig. 9. A comparison of yields of different crops before (2011) and after the watershed interventions (2014).

Table 3
Changes in household income from agriculture and livestock before and after the watershed interventions.

Details	Before	After
Kharif (wet season) area under cultivation (ha)	968	1057
Net income generated in *kharif* (wet season) (Million US$)	0.26	0.38
Rabi (dry season) area under cultivation (ha)	797	1083
Net income generated in *rabi* (dry season) (Million US$)	−0.05	0.35
Total Net income from agriculture (Million US$)*	**0.21**	**0.73**
Buffalo population	950	1300
Milk yield (L/day/animal)	6	8.5
Annual Income from Livestock (Million US$)	**0.19**	**0.40**
Total net income (Million US$ /year)	0.40	1.13
Number of households (HHs)	417	417
Average increase in income (US$/HH/Year)	**960**	**2700**

* 1 US$ = 52.83 INR (2012 as base year).

Sindh watershed before project implementation (2011–12) and after (2013–17). The years 2011 and 2013 experienced rainfall of more than 1100 mm. Average pressure head during Oct 2011 and Oct 2013 were 6.0 m and 8.0 m, respectively, showing an additional 2.0 m gain. Average pressure head during May 2012 and May 2014 were 1.0 m and 5.0 m, respectively (a 4.0 m difference) indicating the positive impact of rainwater harvesting interventions on building groundwater resilience. P value (p = 0.011) also indicated that the average pressure head from both the watersheds are significantly different.

Fig. 7c compares the percentage of wells that dried up in treated and control watersheds (data for the control watershed was only available after April 2014). As indicated earlier, 2015 was one of the driest years with a total rainfall of 404 mm and 2016 was close to a normal year (768 mm). Results showed that about 5% of the dug wells in the treated watershed and 10% of them in the control watershed were dry even during the monsoon season in 2015 (June–October) due to deficit rainfall. After the end of the monsoon, 30% of the wells dried up in the control watershed compared to 6% from the treated watershed by November 2015. By the end of February 2016, 17% of the dug wells were dry in the treated watershed compared to 37% in the control watershed. A major change was recorded by the end of March 2019, as about 40% and 57% of wells were dry in treated and control watersheds, respectively. Shallow perched groundwater is mainly pumped between November and March for farmers towards supplemental irrigation for *rabi* (dry season) crops. No noticeable change was observed in the status of dug wells between April and May 2016, as there were not many agricultural activities except fodder cultivation in less than 5% of the fields. Subsequent to high rainfall in July 2016, all the dug wells in the treated and control watersheds were rejuvenated.

3.4. Impacts of RWH on crop intensification, crop yield and household income

Increased groundwater availability led to a shift in cropping pattern in Parasai-Sindh watershed during *kharif* (wet) and *rabi* (dry) seasons. Unproductive fallow land was rehabilitated and brought under cultivation; assured supplemental irrigation in dry seasons increased crop yields between 10% and 70%; and farmers grew higher value crops than before. Fig. 8 shows changes in cropping patterns during *kharif* (wet season) and *rabi* (dry) seasons. Nearly 80–100 ha that used to be sown with sesame and black gram were converted to groundnut; and about 110 ha of fallow land came under cultivation after the watershed interventions. Fig. 8 shows average crop yields before and after project implementation. No significant change was observed in the yields of groundnut, sesame and black gram cultivated in the *kharif* season under rainfed conditions, as supplemental irrigation was provided for *rabi (dry season)* crops. The average pod yield of groundnut was 1100 kg/ha, and those of black gram and sesame ranged between 300 and 400 kg/ha and 250–300 kg/ha, respectively.

The impact of various rainwater harvesting interventions was more tangible during the *rabi (dry)* season both in terms of change in cropping pattern and increased crop yields. About 300 ha had been left fallow before the watershed intervention; this came down to less than 30 ha following the interventions. The area under mustard (cultivated as a rainfed crop on residual soil moisture) decreased from 120 ha to about 30 ha and that of chickpea from 80 ha to about 20 ha, while a substantial increase in area was observed in barley (5 ha to about 50 ha) and wheat (550 ha to 950 ha) after the interventions (Fig. 9). With increased groundwater availability, most of the rainfed and fallow lands were converted into barley and wheat-based cropping systems. There was a 50–70% increase in yields of wheat (1700 kg/ha to 2700 kg/ha) and barley (1900 kg/ha to 2600 kg/ha) and chickpea while that of mustard increased by 10–15% (100 kg/ha to 150 kg/ha). This increase in cropped area and yields had a positive impact on total agricultural production. Increased groundwater availability also had a positive impact on green fodder availability and vegetable cultivation, as the area under cultivation during the summer increased from 5 ha to 70 ha. With increased fodder availability (both dry and green), farmers made investments in livestock (specifically buffaloes). This promoted diversification besides aiding farm families with stable incomes from household dairies.

Table 3 compares the household income generated from agriculture and livestock before and after the watershed interventions. Before the implementation, the total net income generated from agriculture and livestock together stood at US$ 0.21 Million and US$ 0.19 Million, which increased to US$ 0.73 Million (threefold) and US$ 0.40 Million (twofold), respectively. On an average, household income which was US$ 960/year, increased to US$ 2700/year, a gain of US$ 1740 /year.

4. Discussion

4.1. Landscape approach for sustainable water resource availability

Decentralized rainwater harvesting helped enhance water security and human well-being in a degraded watershed. Rainwater harvesting to improve water retention and storage capacity helped quick recharge of the aquifer and provided useable water for agriculture. Unlike surface storage leads to evaporative losses during summer when the maximum temperature in the region reaches 40–47 °C with pan evaporative demand of 12–20 mm/day, diverting runoff in a shallow perched aquifer through water harvesting allowed freshwater availability for a long period. This eliminated drought in Parasai-Sindh watershed despite recurring dry years (Figs. 7 and 8). Filling the shallow aquifer once in a rainfall surplus year came in handy for two consecutive dry years. Given climate variability and the increasing frequency of drought, this landscape approach promises to achieve sustainable water resources use in degraded landscapes.

The renovation of traditional rainwater harvesting structures in the region has huge untapped potential. Thousands of such defunct structures exist that require modification in design to function under new rainfall regimes. The *haveli* in Parasai village used 0.08 km^2 under submergence out of 4.0 km^2 (i.e. 2%) over which the village is spread. The unit cost of rainwater harvesting in the *haveli* system is far cheaper compared to other measures such as building check dams or farm ponds. The cost of renovating the *haveli* in the current study came to US $ 15,000, providing a storage capacity of 73,000 m^3. This is in comparison to the average investment of US$ 6600 made on a check dam with a storage capacity of 3000 m^3. The unit cost of renovating the *haveli* was US$ 0.21 /m^3 compared to US$ 2.2 /m^3 for a check dam.

4.2. Upstream benefits vs downstream water availability

Runoff and groundwater recharge are highly influenced by rainfall variability in the semi-arid agricultural landscapes of India (Garg et al., 2011; Singh et al., 2014). About 450–500 mm rainfall was found to be the minimum threshold to initiate runoff and enable groundwater recharge. The current study showed that in the absence of RWH structures, the quantity of runoff in dry years would have had negligible impact at downstream sites while no significant reduction in water availability was observed during the wet year. In a normal year (700–900 mm), these structures harvested nearly 40% of runoff, significantly reducing water availability at downstream locations. Since water in downstream locations was used for domestic, agriculture and industrial purposes, scaling-up such interventions may require incentive mechanisms to compensate downstream water users.

While watershed interventions negatively affect downstream water availability only during normal years, they assure supplemental irrigation in the uplands, which are most vulnerable to mid-season droughts and hence also to climate change (Rockström et al., 2009a, 2009b; Rockström and Karlberg, 2009; Shah, 2009). Due to poor infrastructure and degraded landscapes, upland areas are largely cultivated by poor and deprived communities (including tribes) who often struggle for food and basic amenities (Ahmed et al., 2007). It is possible to build groundwater resilience under a declining rainfall situation in Bundelkhand region by diverting a fraction of surface runoff into shallow aquifers through various soil and water conservation measures. During the wet year, RWH structures facilitated groundwater recharge to its full potential, helping build resilience to face the consequences of two consecutive dry years. Increased groundwater availability enhanced cropping intensity and crop production. Availability of supplemental irrigation helped plan for *rabi* (dry season) cultivation and about 20% of the total area in the watershed, including a significant portion of permanent fallow, was brought under cultivation. This enhanced land and water use efficiency, food security, and incomes of the resource-poor communities. Such efforts towards the equitable distribution of resources like rainwater across terrains that consist of fertile lowlands and unproductive uplands, can bridge income gaps within a community (Rao et al., 2017).

4.3. Future scope

Extensive data monitoring and impact analysis are essential to design a rainwater management strategy and plan on a regional scale, as well as to follow up on impacts of implementation. The dearth of systematic monitoring in rapidly transforming agricultural landscapes in developing economies hampers water management and its long-term sustainability. Similar efforts are needed in other districts of Bundelkhand region which has large variability in terms of rainfall, topography, soil types, and cropping systems. Data from the current study could provide the basis for regional scale simulation modeling, as not much data is available for model calibration and parametrization. A thorough analysis of climate variability and remote sensing techniques could be used for water resources planning and management at river basin and regional scales.

5. Conclusion

A meso-scale watershed of 12.46 km^2 was developed between 2012 and 2016 in Bundelkhand region of Central India to improve water availability and transform agriculture. The major interventions included the renovation of traditional rainwater harvesting structures called *haveli*, building check dams, field bunding, and farmer participatory crop demonstrations. The interventions led to the creation of about 100,000 m^3 capacity of rainwater storage which significantly enhanced groundwater recharge. Water balance analysis showed that agricultural water management interventions reduced surface runoff by 40% during normal years but without significant reduction during wet years. The recharge of shallow groundwater aquifers once in a wet year helped sustain groundwater availability in subsequent years. Groundwater levels in dug wells increased by 2–5 m, bringing into cultivation about 20% of the total cultivable area which had been left fallow before the project. In addition, the availability of an assured source of supplemental irrigation prompted farmers to replace low income generating crops like mustard and chickpea with barley and wheat, thereby enhancing their income and food security. With increased water availability, the risk of crop failure diminished. Yields of wheat and barley increased by 50–70% and those of chickpea and mustard by 10–15%. Crop intensification along with productivity enhancement initiatives increased total crop production multifold. Increased water availability also triggered diversification of livelihood sources into dairying. Average household income saw a jump from US$ 960/year to US$ 2700/year within four years of the project period. This study underlines the scope of scaling-up the renovation of traditional *havelis* to address water scarcity and build resilience to climate change.

CRediT authorship contribution statement

Kaushal K. Garg: Conceptualization, Writing - original draft, Formal analysis, Methodology, Validation. **Ramesh Singh:** Project administration, Supervision, Investigation, Data curation, Validation. **K.H. Anantha:** Writing - original draft, Methodology, Formal analysis. **Anand K. Singh:** Data curation, Validation, Formal analysis. **Venkata Radha Akuraju:** Software, Methodology. **Jennie Barron:** Writing - review & editing. **Inder Dev:** Writing - review & editing. **R.K. Tewari:** Validation. **Suhas P. Wani:** Funding acquisition, Resources. **S.K. Dhyani:** Project administration. **Sreenath Dixit:** Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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