Hydrological assessment of Haveli-based traditional water harvesting system for the Bundelkhand Region, Uttar Pradesh, India

Liansangpuii[1,*], Ramesh Singh[2], R. M. Singh[1], K. N. Singh[3] and S. K. Kar[1,4]

[1]Department of Farm Engineering, Institute of Agricultural Sciences, Banaras Hindu University, Varanasi 221 005, India
[2]ICRISAT Development Centre, International Crops Research Institute for the Semi-Arid Tropics, Patancheru 502 324, India
[3]Department of Soil and Water Engineering, IGKV, Raipur 492 012, India
[4]Indian Council of Agricultural Research-Indian Institute of Soil and Water Conservation, Dehradun 248 001, India

Water harvesting is a critical component of any approach to alleviating India's water crisis. Traditional rainwater harvesting systems are found in every region of the country. Haveli is one such system found in almost every village in the Bundelkhand region, Uttar Pradesh, India. A defunct Haveli in the Parasai–Sindh watershed of Jhansi district, Uttar Pradesh, was rejuvenated by providing a cement concrete core wall to the earthen embankment to address the problem of breaching, and the existing outlet was also expanded. This study was conducted from 2013 to 2019 to analyse the hydrology of the rejuvenated Haveli and to understand its impact on surface-water availability and recharging groundwater. The study period was divided based on long-term southwest monsoon (SWM) as wet (SWM > 20%), normal (SWM ± 20%) and dry (SWM < 20%) years. It was found that the Haveli could harvest about 1.91–2.0 times, 1.13–1.72 times and 0.2 times its capacity during a wet, normal and dry year, respectively. There was a 1.41 m difference in hydraulic head between pre- and post-Haveli rejuvenation in a wet year, whereas, a normal year, the difference was 2.71 m.

Keywords: Groundwater resources, hydrological assessment, southwest monsoon, traditional rainwater harvesting structure, water scarcity.

RAINFALL is India's major source of water, supporting surface and groundwater resources. The southwest monsoon (SWM) contributes about 75–90% of annual rainfall in the country[1,2]. India's vulnerable agricultural system is still heavily dependent on rainfall, and a disastrous monsoon season can devastate the economy[3]. India's economy, particularly its agricultural industries, may have to confront severe water shortages in the next decades[4,5]. Decreasing annual rainfall trends are observed in different parts of the country[6–8]. Drought-prone regions have expanded even in areas which have never experienced drought before[9–11]. In the upcoming decades, the frequency of droughts is also likely to increase[12]. By 2050, almost all of India's basins will be water-scarce and per capita water availability will also decrease[13–15].

In the Bundelkhand region, Uttar Pradesh (UP) of India, the onset of most of the drought events occurs during the *kharif* season and terminates by August or September, thereby severely affecting the agricultural crops[16]. The Bundelkhand region is under moderate to severe drought vulnerability conditions, hence requiring appropriate drought-proofing measures in terms of water harvesting structures, check dams, etc.[17].

Rainwater harvesting is one of the methods to tackle the upcoming water challenge in India and provide climate resilience to its population[18,19]. Through rainwater harvesting, the run-off from rainfall is collected and stored for domestic use, irrigation and recharging groundwater[20,21]. Rainwater harvesting has a long history in India[22,23]. Traditional water harvesting can reduce the problem of water scarcity in the country[24,25]. To boost utilizable water resources, India's National Water Policy of 2002 proposes the resurrection of traditional water harvesting technologies[26]. Such policies are gaining traction as a result of the awareness that huge and medium irrigation projects in the past have sparked economic and environmental criticism[27–29].

The traditional rainwater harvesting tank system known as Haveli is found in almost all villages in the Bundelkhand region. The Haveli system has evolved over the course of 300–500 years. In this system, rainwater is impounded against an earthen embankment across the prevailing land slope during monsoon (*kharif* season). Generally, the Haveli system has a catchment area of 20–200 ha. The length, width and height of the earthen embankment are in the range 50–150 m, 4–10 m and 1–3 m respectively. The harvested water is used to recharge groundwater and provide supplemental irrigation to nearby fields. On the withdrawal of monsoon, the harvested rainwater is drained out, and the moist Haveli bed is tilled for sowing *rabi* crops. Water drained from the Haveli system is utilized for pre-sowing irrigation by downstream farmers, while excess water is discharged through the drainage system. Due to the accumulated silt and organic materials, Haveli fields are 15–25% more productive than

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*For correspondence. (e-mail: fanaisangpuii@gmail.com)

the surrounding fields[30–32]. The soil in the Bundelkhand region has a coarse texture and low organic matter, which leads to poor soil bonding capability. Therefore, the Haveli is prone to embankment failure when exposed to heavy rainfall. Also, due to poor design and construction quality, the typical life expectancy of the Haveli is short; it ranges between 2 and 5 years[33]. There is a large untapped potential for water harvesting and conservation in the Bundelkhand region through the Haveli[34,35]. This is because thousands of Havelis are not functioning to their full capacity[36].

In the present study, the impact of a rejuvenated Haveli on the water balance components at a micro watershed-scale was evaluated for seven years, i.e. 2013 to 2019. This work is part of a project that implemented rainwater harvesting interventions on degraded landscapes of the Bundelkhand region, by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Hyderabad, along with ICAR – Central Agroforestry Research Institute (ICAR-CAFRI), Jhansi.

Materials and methodology

General description of the study area

The study was carried out at the Parasai–Sindh watershed in Babina block, Jhansi district (Figure 1). The watershed comprises three villages, namely Parasai, Chhatpur and Bachauni, covering an area of 1246 ha (12.46 sq. km). It is located between 25°23′56.0″–25°27′9″N lat. and 78°19′45″–78°22′42″E long. The elevation of the watershed varies from 270 to 315 m amsl. The topography of the watershed is rather flat, with an average slope of 2%. In the watershed, the soils are shallow Alfisols and Entisols having soil depth of 10–50 cm, coarse gravelly, light-grained, with a low water-holding capacity of 80–120 mm/m and less than 1% organic carbon[37]. According to the 2011 census, the total number of households in the three villages is 417. The average landholding is about 3.12 ha/household. Agricultural land covers between 86% and 88% of the overall geographic area, while degraded forest and scrubland, utilized primarily for livestock grazing, cover 12–14%. The principal *kharif* (rainy season) crops are groundnut, blackgram and sesame, while *rabi* (winter season) crops include wheat, mustard and chickpea. Crop production accounted for about 80% of agricultural income in the watershed, while milk production accounted for 20% of the total income. Small and marginal farmers relied on daily-wage labour to supplement their revenue.

Methodology

Selection of the Haveli structure

A defunct Haveli in the Parasai–Sindh watershed, Jhansi, having an eroded embankment with inadequate outlet, was selected for rejuvenation. The earthen embankment was improved by providing a cement concrete core wall to address the problem of breaching. The existing outlet was also expanded. Figure 2 shows the rejuvenated Haveli structure during the monsoon and post-monsoon seasons. The rejuvenation work was carried out in 2012 under a project implemented by ICRISAT and ICAR-CAFRI. The drainage area contributing to the Haveli was demarcated using Arc GIS 10.3 module ‘hydrology’ from the Spatial Analyst tool with DEM data obtained from NASA, USA (https://power.larc.nasa.gov/) having a resolution of 30 m. A topographic survey was carried out to determine the volume and surface area of the structure. Later, the relationship between the water level, volume and surface spread of the structure was developed using Surfer software. Hydrological data such as inflow, outflow and volume during 2013–19 were monitored to study the impact of low-cost, traditional rainwater harvesting structures on surface run-off and shallow groundwater recharge.

Rainfall

Daily rainfall data collected using a recording-type rain gauge for the period 1983–2018 at the ICAR-CAFRI were used for analysis. As Haveli are used for harvesting SWM rainfall, the rainfall during this season for the study period was classified according to that of the India Meteorological Department. The study period was divided based on long-term SWM as wet (SWM > 20%), normal (SWM ± 20%) and dry (SWM < 20%) years[38].

Water balancing of the Haveli

As shown in eq. (1), the surface water balancing approach was used to quantify the different water balance components[39].

$$V_i = V_{i-1} + R + Q_{\text{in}} - E - P - Q_{\text{out}} - O, \tag{1}$$

where V_i is the volume of water stored in the Haveli in the morning of day$_i$[L^3], V_{i-1} volume of water stored in the morning of the previous day$_{i-1}$ [L^3], Q_{in} the volume of inflow to the Haveli [L^3], R the daily precipitation over the Haveli [L], E the daily evaporation from the Haveli [L], P the daily percolation from the Haveli [L], Q_{out} the daily spillover amount from the structure [L^3] and O is the volume of water withdrawn or utilized from the Haveli [L^3].

Assessment of different water balance components

An automatic pressure transducer, viz. DIVER (model DI801 TD), capable of recording 10 m pressure head, was used for monitoring the daily water level in the Haveli. It was placed at the bottom of a stilling well that was constructed at upstream of the Haveli. The transducer was

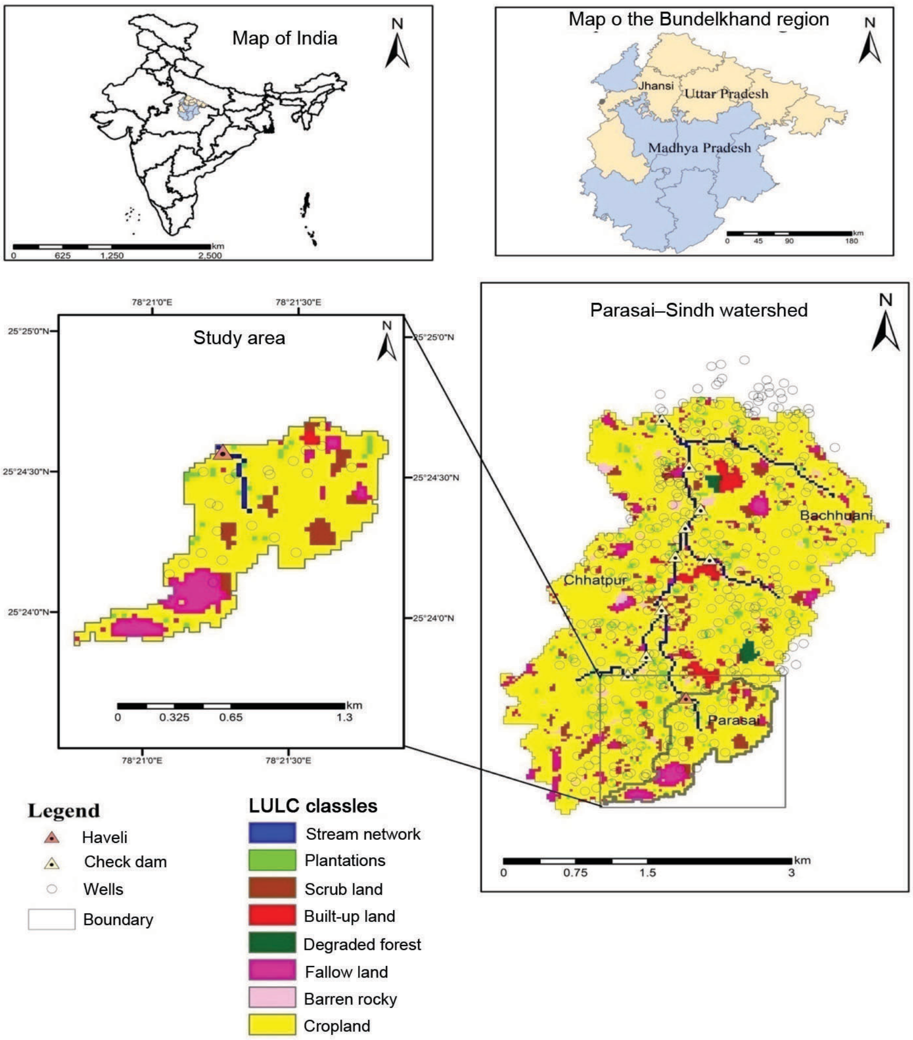

Figure 1. Location map of the study area.

Figure 2. ***a***, Harvested water in the Haveli during monsoon season. ***b***, Cultivated Haveli bed during post-monsoon season.

programmed to record the pressure head every 15 min interval from 2013–2019. Data from DIVER were collected every year prior to its reinstallation before the onset of SWM. The difference in water level recorded between a given time interval was used to calculate storage volume. The inflow and spillover amount was estimated for the Haveli using eqs (2)–(5) as follows[40]

$$\text{Spillover rate } [L^3T^{-1}] = 1.705 * L * H^{1.5}, \tag{2}$$

where L is the length of the rectangular weir, i.e. 5.3 m for Haveli structure and H is the depth of water layer passing down the rectangular weir $[L]$.

$$\text{Spillover volume } [L^3] = \text{Spillover rate } [\mathrm{L}^3\mathrm{T}^{-1}] * \text{time interval } [T]. \tag{3}$$

$$\text{Inflow volume } [L^3] = \text{Change in reservoir volume at a given time interval } [L^3] + \text{spillover volume } [L^3]. \tag{4}$$

$$\text{Change in reservoir volume } [L^3] = \text{Reservoir volume at time } t_i\,[L^3] - \text{Reservoir volume at } t_{i-1}\,[L^3]. \tag{5}$$

Daily precipitation data were obtained from the mass curve of an automatic rain gauge installed in the Parasai–Sindh watershed. The daily evaporation data were obtained from a Class A Pan Evaporimeter at the ICAR– Indian Institute of Soil and Water Conservation (ICAR–IISWC), Datia, about 35 km from the watershed. Percolation was calculated as the closing term of daily water balancing. As the water was not directly pumped for any purpose from the Haveli, the change in storage volume was due to evaporation and percolation.

Monitoring of groundwater

The groundwater level of 22 wells in the micro watershed was monitored manually. The average depth of dug wells was 10.7 m, with a maximum and minimum depth of 17.8 and 5.1 m respectively. The average diameter of the dug wells was 4.42 m, with 7 and 3 m as the largest and smallest diameter respectively. The readings were taken monthly using an electronic water-level meter (Solinist: 101 B, Canada) from 2011 to 2019. The difference in groundwater level between pre-rejuvenation and post-rejuvenation was compared. Groundwater level before 2013 was taken as pre-rejuvenation and after 2013 as the post-rejuvenation period. The hydraulic head at different wells was obtained by deducting the measured groundwater level from the well depth.

Results and discussion

Rainfall characteristics

The annual mean rainfall over Jhansi was 825 mm from 1983 to 2018. Figure 3 represents the SWM rainfall variations over the study period. The rainfall collected from the watershed was classified into wet, normal and dry years using the long-term average rainfall of Jhansi station, as there was no rain gauge installed in the watershed before its development. Table 1 shows the amount of rainfall received and the number of rainy days during each year in the study area. The years 2013, 2018 and 2019 fall under the wet category, whereas 2016 and 2017 are normal years, and 2014 and 2015 fall under dry years. The wet years have above 900 mm rainfall. Rainfall between 580 and 900 mm is received during normal and below 580 mm during dry years.

Stage volume and spread area relationship

To know the volume of harvested water and the respective water spread area, the stage volume and stage surface area

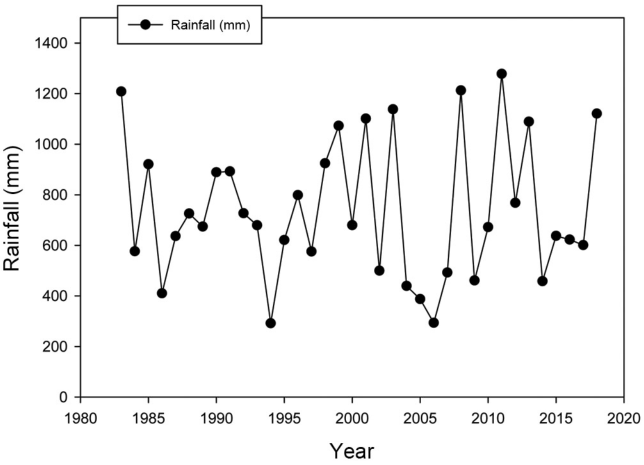

Figure 3. Southwest monsoon (SUM: June–September) variations of rainfall over Jhansi, Uttar Pradesh, India from 1983 to 2018.

Table 1. Rainfall and number of rainy days between 2013 and 2019 southwest monsoon (SWM)

Year	Rainfall (mm)	No. of rainy days	Remarks*
2013	1276	59	Wet
2014	520	32	Dry
2015	404	34	Dry
2016	768	58	Normal
2017	630	36	Normal
2018	953	48	Wet
2019	1002	54	Wet

*Wet year: Annual SWM is >900 mm. Normal year: Annual SWM is 580–900 mm. Dry year: Annual SWM is <580 mm.

relationship was developed for the Haveli (Figure 4). The stage volume and stage surface area are shown with reference to the crest level of the structure (showing water level depth zero at crest level). The Haveli structure, at its full capacity, can harvest about 73,000 m^3 of generated run-off from the contributing watershed. The water spread area of the Haveli is about 8.82 ha (i.e. 88,200 sq. m). Stage volume–area data were retrieved for analysing the water balance of the Haveli at various stages.

Daily water balancing of the Haveli

Figure 5 shows the different water balance components for the Haveli from 2013 to 2019. In 2013, an inflow of 3000 m^3 was received in the Haveli on 1 July from 42 mm rainfall. About 85,700 m^3 run-off volume was harvested from 13 July to 8 August from 14 rainfall events. Outflow from the Haveli started on 9 August, as it was filled to its full capacity. In 2014, an inflow volume of 5500 m^3 was harvested on 18 and 19 of July. Three rainfall events in August produced an inflow volume of 5100 m^3. An inflow volume of 2000 m^3 was harvested during September. Rainfall events that can produce run-off inflow to the Haveli did not occur in 2015. In 2016, water started accumulating in the structure on 1 July with a volume of 30,000 m^3. With the inflow of 35,000 m^3 run-off volume on 1 August, the Haveli received an inflow in excess of its full capacity, so there was outflow from the structure. On 7 and 19 August, outflow volume of 21,000 and 18,200 m^3 respectively, was observed. In 2017, inflows received with rainfall events of 50 mm or higher were harvested entirely, and no spillover was observed. During 2018, a combined inflow volume of about 5000 m^3 was recorded on 28 and 29 June. Rainfall occurred everyday between 19 and 27 July, with cumulative rainfall of 255.3 mm generating a cumulative inflow volume of 49,700 m^3. An inflow volume of 32,000 m^3 on 1 September produced excess run-off volume, which the Haveli cannot store. In 2019, theinflow was first observed on 4 July. A cumulative inflow volume of 168,000 m^3 was generated from three rainfall events on 7, 8 and 9 July. Thus, a spillover volume of 104,200 m^3 was measured. An inflow volume of 40,000 m^3 was observed on 3 August, producing an outflow volume of 11,300 m^3.

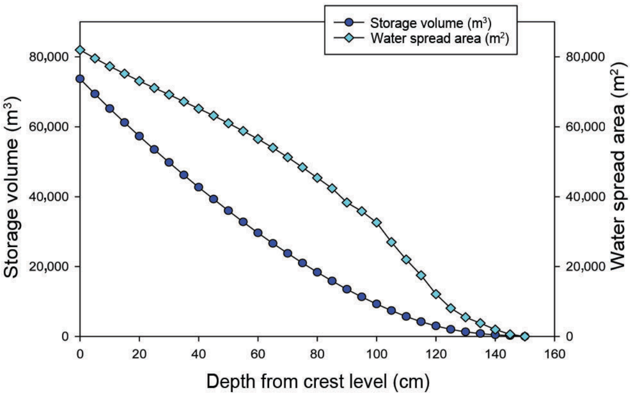

Figure 4. Stage volume and stage area relationship of the Haveli.

Assessment of water balance components

Data monitoring at micro- and meso-scales has to be increased to better understand the upstream and downstream water trade-offs due to the construction of rainwater harvesting structures in a catchment, as there is potential for negative consequences at different watershed scales[41–43]. Table 2 shows the estimates of different water balance components from 2013 to 2019. The highest inflow and outflow volumes were received in 2013, as this year also received the highest annual rainfall for the study period. The volume of inflow was 288,000 m^3, and the outflow volume was 147,900 m^3. The total harvested volume was 140,100 m^3. From this, a volume of 101,890 m^3 was percolated, and 21,920 m^3 was evaporated. The remaining volume of 16,290 m^3 was drained at the end of October. In 2014, with rainfall of 520 mm, an inflow volume of 11,600 m^3 was observed. There was no outflow from the structure during this year. So, all the inflow volume was completely harvested within the structure. A total volume of 11,260 m^3 was percolated, and a volume of 340 m^3 was lost in evaporation. The low volume of evaporation was due to water standing in the Haveli for only a few days. 2015 saw no inflow into the Haveli as there were no run-off producing rainfall events, while 2016 received a total inflow volume of 170,200 m^3. The outflow volume was 44,415 m^3. A volume of 101,030 m^3 was percolated, and 23,560 m^3 was evaporated. By the time of water removal, a volume of 1195 m^3 was present in the Haveli. There was no outflow from the Haveli during 2017. The total harvested volume was 83,000 m^3. The percolated and evaporated volumes were 55,300 and 12,230 m^3 respectively. The volume of water balance at the end of October was 15,470 m^3. Outflow was observed during 2018 and 2019. The harvested volume in 2018 and 2019 was 138,990 and 149,530 m^3 respectively. In 2018, the percolated and evaporated volume was 99,030 and 21,450 m^3 respectively. In 2019, volume of 98,630 and 21,245 m^3 had percolated and evaporated respectively. During a wet year, the Haveli structure can harvest about twice its storage capacity. During normal years, it can harvest about 1.4–1.7 times its storage capacity. During a dry year, the Haveli structure can harvest about 0.2 times its storage capacity. The result of water balancing shows that during a wet year, about 56% of the total inflow volume is released after the Haveli is filled to its full potential and through drainage of the Haveli after the monsoon. The negative effect on downstream water availability during a dry year is reduced in a wet year, especially when the watershed receives rainfall above 1000 mm.

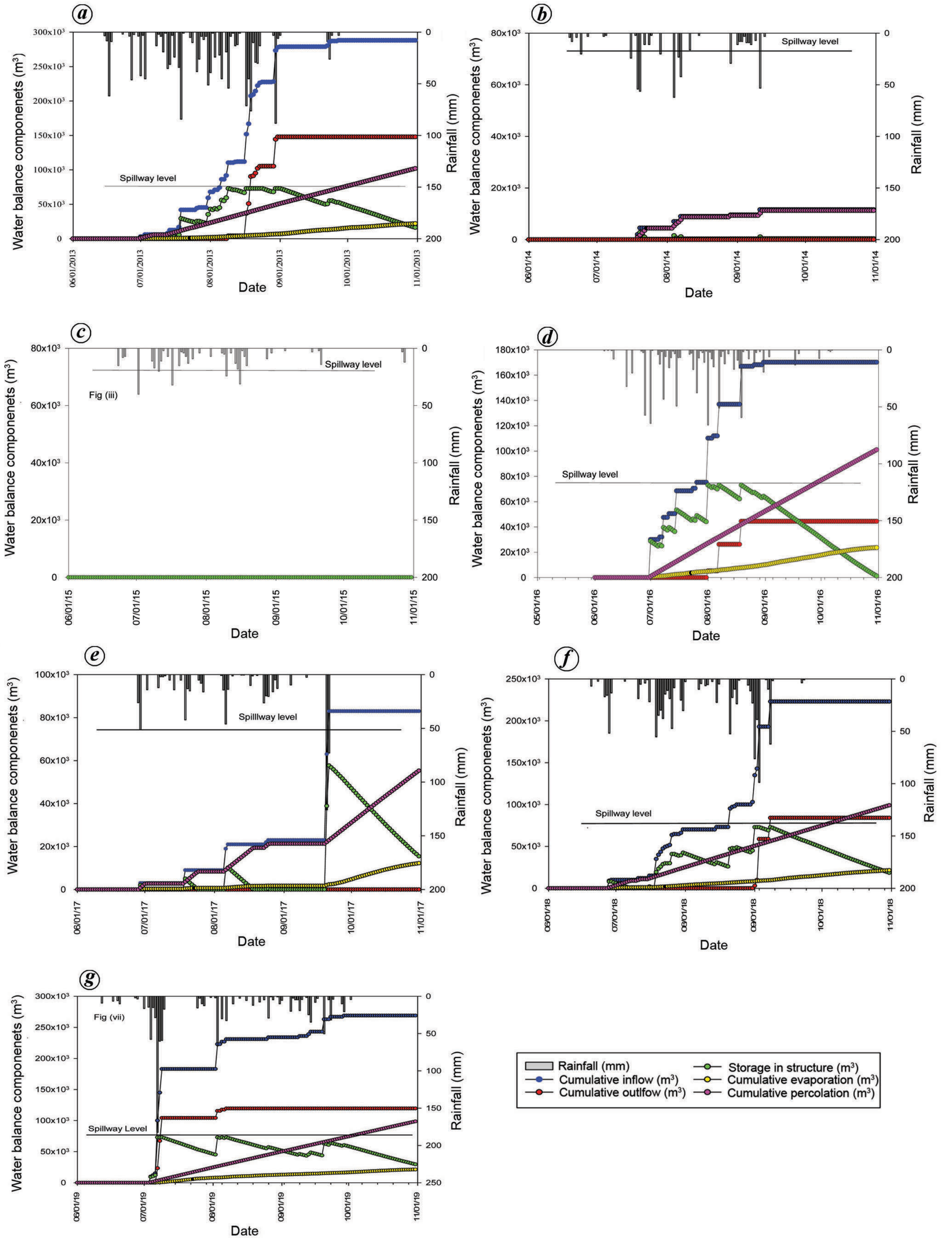

Figure 5 *a*–*g*. Plots of water balance components in response to daily rainfall in the Haveli for the years 2013 to 2019.

Table 2. Assessment of water balance components of the Haveli for the years 2013–2019

Year	Rainfall (mm)	Inflow (m^3)	Outflow (m^3)	Harvested amount (m^3)	Percolation (m^3)	Evaporation (m^3)	Balance (m^3)	Harvested volume/ capacity
2013	1276	288,000	147,900	140,100	101,890	21,920	16,290	1.92
2014	520	11,600	0	11,600	11,260	340	0	0.16
2015	404	0	0	0	0	0	0	0.00
2016	768	170,200	44,415	125,785	101,030	23,560	1195	1.72
2017	630	83,000	0	83,000	55,300	12,230	15,470	1.14
2018	953	223,000	84,010	138,990	99,030	21,450	18,510	1.90
2019	1002	269,000	119,470	149,530	98,630	21,245	29,655	2.05

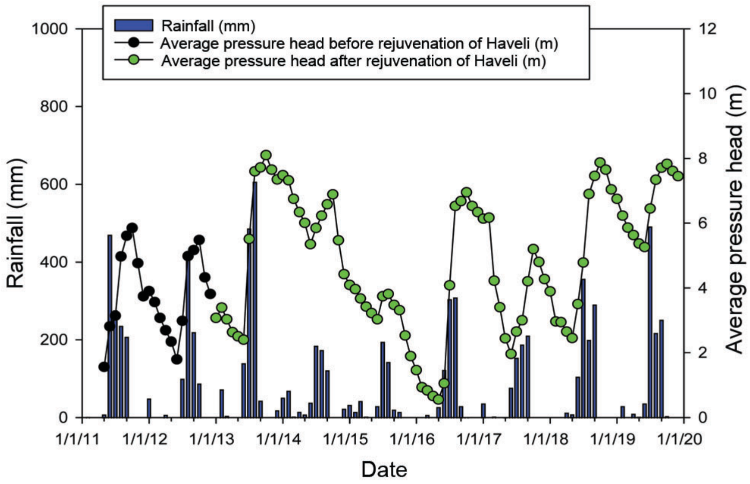

Figure 6. Monthly average pressure head variation for the periods of 2011 to 2019.

Dynamics of groundwater

Figure 6 shows the monthly variation of hydraulic head in the well over the study period, i.e. from 2011 to 2019. The groundwater had recharged during the SWM season. In 2013, before the commencement of the monsoon (May), the hydraulic head was 2.5 m, which increased to 8.1 m at the end of the monsoon season (October), showing an increment of 5.6 m. By May 2014, the hydraulic head decreased to 6.01 m due to extraction from the wells during the post-monsoon season. With the arrival of monsoon, the water level increased and by the end of October, the hydraulic head was 6.89 m, showing an increase of 0.88 m. The increase in the hydraulic head during 2015 was the lowest at 0.27 m, as the watershed witnessed a dry year. In 2016, the hydraulic head increased to 6.95 m during October from 0.55 m in May. So, it increased by 6.4 m during this year. In 2017, the monthly average hydraulic head during October was 5.2 m and the lowest during June with a value of 1.96 m. An increment of 3.24 m in the hydraulic head was observed in 2017. In 2018, before the commencement of monsoon, the hydraulic head was 2.45 m, and at the end of monsoon period, it was 7.87 m. Thus the increment in hydraulic head was 5.42 m. At the end of the study period, the hydraulic head had increased to 7.83 m during October from 5.37 m in May.

To know the impact of the Haveli on recharging of the groundwater, the increase in hydraulic head before and after its rejuvenation was compared between the wet and normal years. The years selected for post-rejuvenation were 2013 and 2016, receiving SWM of 1276 mm and 768 mm respectively. The years 2011 and 2012 were the wet and normal ones selected for pre-rejuvenation. During 2011, the SWM was 1300 and 824 mm during 2012. For a wet year, there was a difference of 1.41 m in the hydraulic head between pre- and post-rejuvenation of the Haveli. A difference of 2.71 m in the hydraulic head was observed for pre- and post-rejuvenation of the Haveli structure for a normal year. It was found that good recharge during the wet year helped sustain groundwater availability in the succeeding years. It is well understood that in a catchment, upstream lands are susceptible to drought and climate change[44]. However, through the construction of water-harvesting structures, the availability of water can be improved in the watershed, ensuring supplemental irrigation during the dry seasons.

Conclusion

A defunct Haveli was renovated in a micro watershed in 2012 in the Bundelkhand region, UP. About 73,000 m^3 of rainwater storage capacity was generated through the interventions. The hydrological data of the Haveli were constantly monitored, and hydraulic evaluation was performed by a water balance approach from 2013 to 2019. The analysis was found that the Haveli can harvest about 28% to 34% of the annual rainfall during a wet year, about 16% to 27% of the annual rainfall during a normal year, and about 2.8% of the annual rainfall during a dry year. Enhancement in groundwater recharge was observed from the monitored dug wells in the watershed. The groundwater level rose by 2–6 m in the different wells. With the increase in water availability, farmers could increase area of crop cultivation, while the area under fallow land in the watershed was reduced. Farmers switched from low income-producing crops like mustard and chickpea to barley and wheat, with a reliable supply of supplemental irrigation becoming available. The risk of crop failure was reduced, and the production of crops was enhanced. In addition to agriculture, there was diversification of sources of income. Since freshwater is now readily available for domestic use, even in summer, women and children no longer have to endure the hardship of fetching water from long distances.

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