Assessment of Traditional Rainwater Harvesting System in Barren Lands of a Semi-Arid Region

Basant Yadav[a], Nitesh Patidar[b], Anupma Sharma[b], Niranjan Panigrahi[c], Rakesh K. Sharma[d], V. Loganathan[e], Gopal Krishan[b], Jaswant Singh[f], Suraj Kumar[b], Alison Parker[c]

[a]Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, 247667, India

[b]National Institute of Hydrology, Jal Vigyan Bhavan, Roorkee - 247 667

[c]School of Water, Energy and Environment, Cranfield University, Cranfield Mk43 0AL, UK

[d]Department of Chemistry, Indian Institute of Technology Jodhpur, Jodhpur-342037

[e]Department of Civil Engineering, Indian Institute of Technology Roper, 140001, India.

[f]Department of Hydrology, Indian Institute of Technology Roorkee, 247667, India

Abstract

In semi-arid and arid regions, groundwater is the primary source for domestic, agricultural, and industrial supply. Scattered and erratic rainfall in these regions makes groundwater recharge more complex. Small-scale rainwater harvesting using both traditional and modern rainwater harvesting structures has been seen as a solution to the deepening groundwater crisis in India. In this study, shallow infiltration ponds locally known as *Chaukas* were studied to understand their groundwater recharge role and pastureland development. Potential groundwater recharge from these shallow infiltration ponds was estimated using the HYDRUS-1D model, simulating the sub-surface processes in the root zone. Field data collected in the year 2019 is used to calibrate the model for field conditions, while monsoon period data (July-August) of 2020 is used to validate the developed model. The developed model was then used to predict the potential groundwater recharge for the monsoon periods of the year 2019 and 2020.The shallow infiltration ponds allow approximately 5% additional rainfall to be available as potential

recharge. The near soil surface moisture also helps develop natural grass cover used for pasture in the early dry periods. Analysis of the vegetation in the past 10 years suggests that these shallow infiltration ponds have converted barren lands into eco-hydrologically productive pasturelands. These *Chauka* systems have helped in sustainable water resources management in these water stressed regions along with the additional livelihood support through developed pasturelands for animal husbandry. They have potential wide application across India and beyond, as they simply require slightly sloping, barren land above an unconfined aquifer.

Keywords: Rainwater Harvesting, Groundwater Recharge, Semi-arid Regions, HYDRUS

1. Introduction

The development of life on earth and human progress depends strongly on the availability, and use of water, and groundwater is an important resource for humans contributing 50% of drinking water and 20% of irrigation water globally (Villholth, 2006). Over 55% of India's population, which is the home to 15% of the global population, relies on groundwater for an array of different activities, such as irrigation, water for cattle, domestic consumption as well as industrial uses (Moriarty et al., 2004). Groundwater use in India increased exponentially since the 1950s, soaring from 20 $km^3 year^{-1}$ to 251 $km^3 year^{-1}$in 2010 (Shah, 2007; FAO,2016;), making it the world's greatest groundwater abstracter, surpassing the USA and China combined (FAO, 2016). It is estimated that India generates 9% of its GDP from groundwater abstraction (Mudrakartha, 2007). As it is more flexible and reliable than the public water service, 85% of the rural population and 60% of the irrigated agriculture have become dependent on groundwater. This trend has been bolstered by decreasing capital costs and generous public energy subsidies (World Bank, 2010). Because of this ever-increasing use of groundwater, the Central Ground Water Board (CGWB) classified 16% of India's aquifers as overexploited and an additional 3% as in a critical state (CGWB, 2017). Sheetal (2012) reported local water table level drop by up to 16 m between 1980 and 2010, while Sarah et al. (2014) mentioned, in several states, decline rates of 1 to 2 $myear^{-1}$ since 2000. Such declines impact small-scale farmers relying on groundwater for irrigation (Singh et al., 2002; Zaveri et al., 2016). Furthermore, the declining water table has led to deterioration of groundwater quality in many locations (Coyte et al., 2018). Panda et al (2020) cite India as an example of surface greening and subsurface drying. As signs of aquifer over-exploitation started to accumulate in the 1960s, Managed Aquifer Recharge (MAR), or Artificial Recharge, emerged to alleviate some of the pressure on the groundwater resources (Sakthivadivel, 2007).

In India, where rainfall patterns are highly variable, rainwater harvesting has been used for centuries. Applied to MAR, the principle is to store a fraction of the vast run-off volume generated during the monsoon, increasing its residence time and allowing it to percolate into depleted aquifers. It has received growing attention from governmental and civil institutions and was included in the central government policies on groundwater management in the 1990s (Sakthivadivel, 2007). In the latest version of its Master Plan for Artificial Recharge to Ground Water, the CGWB (2013) highlighted the ambitions to build a total of 11 million recharge structures with a recharge capacity of 85.5 billion cubic meters per year. This would account for 34% of India's total groundwater abstraction in 2010 (FAO, 2016). Many different structures can be built for rainwater harvesting in arid to semi-arid environments. Check dams (small dams typically built, in MAR application, across ephemeral rivers) are one of the most common, with the CGWB (2013) aiming to build almost 300,000 of them. Very localised solutions also exist, such as the shallow infiltration ponds *(Chaukas*) in Rajasthan, a system developed by a local community organisation, Gram Vikas Navuyak Mandal Lapodiya (GVNML).

Practitioners consider that the main hydrological impact of *Chauka* is to increase and maintain soil moisture rather than recharging the aquifer themselves (GVNML, 2007). This increase, combined with seeding, provides the community with grazing areas for several months a year, which increase pastureland and supports livelihoods. Additional benefits include erosion control, an increase in biodiversity, and an improved living environment (GVNML, 2007). However, the localized rainwater harvesting structures tend to have small storage capacity, and the impact of an individual structure is considered relatively small (Sharda et al., 2006). They may not be reliable in drought years and may not provide any additional benefits in catchments with other larger MAR structures (Kumar et al., 2008). Rainwater harvesting using these small structures can redistribute the available water resources across the catchment by increasing the annual amount of rainfall that becomes recharge, which changes other water balance components, including evaporation and streamflow (Glendenning and Vervoort, 2010). Various rainwater harvesting methods have been studied to understand their hydrological impacts on the surrounding aquifers (Badiger et al., 2002; Gontia and Sikarwar, 2005; Neumann et al., 2004; Sharda et al., 2006; Stiefel et al., 2009; Scanlon et al., 2009). However, there has not been any study on the recharge potential of these traditional shallow infiltration ponds. The overall study reported here therefore sets out to achieve two aims. The first was to quantify the recharge potential of these shallow infiltration ponds in barren lands. The second was to determine their impact on vegetation cover.

2. Study area

Rajasthan is a northern state in India also known as desert state of India has a coverage of 342,239 km^2, which is 10.4 % of India's total geographical area. It is the largest state in Indian by area and ranked 7th in the population of the country. The majority of Rajasthan terrain is barren and lacks vegetation coverage, which is an indication of little water present. The soil types in Rajasthan are mostly sandy, loamy, saline, alkaline, and chalky (calcareous). The majority (91%) of their drinking water is groundwater, and 66 % of the aquifers in Rajasthan are overexploited (CGWB, 2012).

Due to water shortage, the various rainwater harvesting structures were installed to harness rainwater in the Lapodiya catchment. Figure 1 shows a map of Lapodiya catchment depicting the various water harvesting structures such as Farm ponds, *Talab*(ponds), *Chauka* system, *Nadis* (small ponds), and *Anicut* (check dams). In this region, rural villages with pastoral characteristics have a small population that practices mainly agricultural activities such as crop cultivation and animal husbandry as their means of survival. A Non-Governmental Organization (NGO) Gram Vikas Navuyak Mandal Lapodiya (GVNML) implemented a *Chauka* and *Nadis* system to take on the problem of water quantity and quality. *Chauka*s are infiltration ponds developed locally to support pastoral lands in the early dry season. The ponds store catchment runoff, while the check dams act as a barrier to reduce the amount of river water from flowing out of the catchment. During the monsoon season, the excess rainwater from *Chauka* and ponds flows into the river. This seasonal river meets a larger dam downstream that provides water to many districts in Rajasthan. This network of ponds, check dams, and *Chauka* systems harness the rainwater during the monsoon season for future use. At the same time, they maintain the soil moisture at a satisfactory level for pasture growth. GVNML proactively network with the residents to mobilise, supervise, and coordinate their effort better to manage the water resources with the pond system so that their agricultural activities can be sustainable. The rainwater harvesting using these traditional and modern structures has been considered useful by local people in developing the pasturelands and enhancing groundwater recharge. However, such claims have not been proven scientifically in this region.

[**Fig. 1.**]

The Central Ground Water Board of India (CGWB, 2015) divided the yearly climate in Rajasthan into three major conventional seasons; the hot weather season (March to end of June); monsoon season (End of June to September), and the cold weather season (October to February). The climate in Lapodiya catchment is typical of a semi-arid region with hot summers commencing in March and continuing until June. The mean maximum temperatures in this region reach as high as 48^0 C in June, while the temperatures drop in January between 7.7^0 C and 21^0 C (CGWB, 2015). Rainfall is the major source of groundwater recharge in the state. The state receives 90 % rainfall from the southwest monsoon between June and September. The average yearly rainfall in the Jaipur district is 575.7 mm (1971-2014) and the total annual potential evapotranspiration is 1744.7 mm (CGWB, 2017).

2.1. Geology, hydrogeology, and soils

Aquifers in this region comprise hard rocks of the Bhilwara Super Group, comprising granulitic gneisses, quartz mica schist, phyllite, and granite pegmatite intrusive (CGWB, 2013). In these aquifers, groundwater movement is controlled by the pore size, continuity, and interconnectivity of weathered and fractured parts and other secondary porosities. The geological profile with depth of the Lapodiya catchment is given in table 1. Groundwater in the Lapodiya region occurs both in the weathered zone and bedrock in unconfined conditions.

[Table 1.]

2.2. Rainwater harvesting (RWH) structures

In the study area, rainwater harvesting is practiced, and many water conservation structures have been constructed in the watershed by GVNML and government organizations. Government schemes such as Integrated Watershed Management (IWM) and Mahatma Gandhi National Rural Employment Guarantee Act (MNREGA) programs have played a significant role in rainwater harvesting practices. Various types of traditional and modern RWH structures are found in the Lapodiya catchment. *ANICUTS* are check dams like structures built on common land and dam the main reach of the river. They are generally made of cement and stone or concrete. These structures have a very large impact on local groundwater tables (Glendenning and Vervoort, 2010). *NADI* is the smaller pond-like structure built in a relatively impermeable area to store runoff water. The harvested water in these structures is generally used for livestock drinking. *TALABs* are pond-like structures with high raised bunds on three sides and made of locally excavated earth material. These structures are similar to *NADIS* but with larger water holding capacity and constructed near to villages. The harvested rainwater is collected in the *TALAB* for various uses such as bathing, laundry, livestock drinking, and occasional irrigation. *FARM PONDS* are small tank or reservoir like constructions that are constructed on the private lands to store the surface runoff generated from the catchment area. *CHAUKA* is a shallow infiltration pond-like structure built in series to store water in the near soil surface for grassland development (Fig. 2).

The *Chaukas* in Lapodiya catchment are a unique RWH system developed indigenously by a local community organisation GVNML. The *Chauka* forms an enclosure usually, about 2000 m^2, built across a gently sloping area by placing earthen dykes on the sides. One *Chauka* trench can contain up to 25 to 30 cm of water when it is filled. Figure 2 shows the *Chauka* system's conditions during the monsoon season (Fig. 2a) and post-monsoon season (Fig.2b) of 2019. They are designed to hold limited runoff water that slowly infiltrates in the soil and are built-in series so that when one *Chauka* gets filled it would overflow to the adjoining *Chaukas*. The excess water from the *Chaukas* flows to the nearby *Nadi* or *Talab*. Practitioners consider that the main hydrological impact of *Chauka* is to increase and maintain soil moisture rather than recharging the aquifer themselves.

[Fig. 2.]

[Fig. 3.]

3. Methodology

3.1. Monitoring network development and data collection

The Lapodiya catchment was identified for conducting detailed studies of the *Chauka* system over 2019 to 2020, because *Chauka* system in Lapodiya is the oldest in the region, which allowed gathering some historical knowledge of the system's hydrological significance. The *Chauka* system presented in Fig. 3 is located around 1.5 km in the north-east of the Lapodiya village. A local observatory was established in the catchment to collect the daily data for rainfall, temperature, and evaporation. An automatic raingauge, Class A evaporation pan, and thermometers were installed in Lapodiya village which is around 1.5 km away from the C*hauka* system. To understand the hydrogeology, one 12.7 cm or 5-inch diameter borehole (BH1), as shown in Fig. 3, was drilled in the study area using a down-the-hole drill (DTH rig), and sediment samples were collected at every one-meter interval. Further, the BH1 was also monitored at weekly interval for depth to water level (D_w) below ground level (bgl). D_w was also observed on a weekly interval in BH1 between June 2019 to September 2020. To measure the soil moisture tension in the *Chauka* field during the monsoon period of 2019 and 2020, a gypsum block sensor in conjunction with a watermark soil moisture meter was used. The sensors were installed at 30 cm and 60 cm depth in the centre of a *Chauka*, which measures the soil water potential between 0 and -200 kPa (0 and 200 centibars). Further, trial pits of 150 cm were dug to collect the soil samples at a depth of 30 and 60 cm, which were used for soil texture classification.

3.2 Potential groundwater recharge estimation using HYDRUS 1D

The water flow and root water uptake in the *Chauka* system were simulated using HYDRUS-1D (Šimůneket al., 2005) assuming that the soil is homogeneous and isotropic. It is also assumed that the liquid flow process does not get affected by the air phase and the contribution of the thermal gradient is negligible in the water flow. The governing equation for water flow is the 1D Richards equation:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left[K\left(\frac{\partial h}{\partial x}+1\right)\right]-S \tag{1}$$

Where h is the soil water pressure head (cm); θ is the volumetric water content (cm^3cm^{-3}); t is the time (d); x is the spatial coordinate (cm); K is the unsaturated hydraulic conductivity function ($cm\ d^{-1}$) and S is the sink term ($cm^3\ d^{-1}$), representing the water removed from a unit volume of soil per unit time due to plant water uptake, which is the daily evapotranspiration. The sink term is specified in terms of a potential uptake rate and a stress factor (Feddes et al., 1978):

$$S(h) = \alpha(h)\, S_p \tag{2}$$

where S_p is the potential root water uptake rate [cm^3 cm^{-3} d^{-1}] and $\alpha(h)$ is the dimensionless water stress response function $(0 \leq \alpha \leq 1)$ which simulates the impact of soil moisture stress on the root water uptake. For $\alpha(h)$, we used the functional form introduced by Feddes et al. (1978):

$$\alpha(h) = \begin{cases} \dfrac{h - h_4}{h_3 - h_4}, & h_4 < h \leq h_3 \\ 1, & h_3 < h \leq h_2 \\ \dfrac{h - h_1}{h_2 - h_1}, & h_2 < h \leq h_1 \\ 0, & h \leq h_4 \ or \quad h > h_1 \end{cases} \tag{3}$$

Where h_1 and h_4 are the anaerobiosis and the wilting point above and below which root water uptake is null, respectively; h_2 and h_3 are the pressure heads between which root water uptake keeps the maximum rate. *Chauka* system is covered with natural grass during the rainfall season, and hence values for these parameters were taken from the database contained in HYDRUS-1D (Šimůnek et al., 2005).

According to the van Genuchten–Mualem constitutive relationships (Mualem, 1976; van Genuchten, 1980), the soil water retention and soil hydraulic conductivity functions are given by

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{\left[1 + |\alpha h|^n\right]^{1-1/n}}, & h < 0 \\ \theta_s, & h \quad 0 \end{cases} \tag{4}$$

$$K(h) = K_s S_e^l \left\{1 - \left[1 - S_e^{n/(n-1)}\right]^{1-1/n}\right\}^2 \quad (5)$$

where S_e is effective saturation:

$$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r}$$

and where θ_r and θ_s are the residual and saturated water content ($cm^3\ cm^{-3}$), respectively; K_s is the saturated hydraulic conductivity ($cm\ d^{-1}$). The parameters α (cm^{-1}), n, and l are empirical coefficients affecting the shape of the hydraulic functions.

The numerical grid was discretized in 200 nodes of 0.005 m each to form a regular 1m long grid and a surface area of 1 m^2. The model was divided into two layers representing the upper (0-60 cm) and the lower soil horizons (60-100 cm), based on the soil sample analysis of the trial pit in the study site (Fig. 4). At the soil surface, and atmospheric boundary condition with a surface layer was selected. The surface layer condition permits water to build upon the surface, which represents the *Chauka* conditions. The *Chauka's* are like small infiltration trenches, which are around 25 to 30 cm deep. The height of the surface water layer increases due to precipitation and reduces because of infiltration and evaporation. In the considered *Chauka* system, trenches of 25 cm depth (P_d) were excavated in around 10% area (A_t) of the total *Chauka* area (A_c). Since the soil moisture changes were monitored in the non-trenched area, the 25 cm depth was converted to an equivalent ponding depth (P_{ed}) of 0.65±0.005 cm over the remaining monitored area using Eq. 6.

$$P_{ed} = \frac{P_d}{A_c - A_t} \tag{6}$$

[Fig. 4.]

Free drainage was considered as the lower boundary condition. To compute the evapotranspiration over a reference surface the Hargreaves equation (Hargreaves et al., 1985) was applied, which uses the daily maximum-minimum temperature and the extra-terrestrial solar radiation information. The value of global solar radiation's extinction coefficient was taken as 0.463, as suggested in the HYDRUS-1D manual (Šimůnek et al., 2008). Leaf area index values at various growth stages for the grass was obtained from the National Oceanic and Atmospheric Administration (NOAA) Climate Data Record (CDR) for 2018 and 2019 (Vermote and NOAA CDR Program, 2019). Based on the observation taken in the field using a trial pit, value for the maximum root depth of grass in *Chauka* was taken as 50 cm (Fig. 4).

3.3 Soil hydraulic parameters estimation

Hydrus-1D requires the soil hydraulic parameters such as θ_r, θ_s, K_s, α, n, and l, which can be determined using physical properties of the soil. Soil texture is determined by the relative proportion of sand, silt, and clay, as presented in Table 2. Soil samples (both disturbed and undisturbed) were collected from the *Chauka* site to obtain the sand, silt, and clay fractions (Gee et al., 2002). A sieve and particle size analyser was used to determine soil texture, and the results were recorded as the percentage of sand, silt, and clay. USDA classification system was used to convert quantitative data to the textural classification (Burman et al., 2019). The undisturbed soil samples were used to estimate the soil bulk and dry density using the oven-dry method**.** A

Guelph permeameter (model 2800k1, Soil Moisture Equipment Crop, Santa Barbara, California) was used to determine the saturated hydraulic conductivity of the soil. A pressure plate experiment was done to obtain the field capacity and wilting point of the soil, which refers to moisture content corresponding to matrix suction value of 33 Kpa and 1500 Kpa, respectively. The obtained soil retention curve was fitted with the RETC model (van Genuchten, 1980) to obtain soil retention parameters, as shown in Table 3. The saturated hydraulic conductivity was estimated using Rosetta (Schaap et al., 2001), a pedotransfer function model that predicts hydraulic parameters from soil texture and related data.

3.4 Model Calibration and validation

Soil parameter estimation based on field observations or laboratory analysis involves high uncertainty for most practical applications (Luo and Sophocleous, 2010). Inverse modeling has been used to estimate the soil hydraulic parameters using the time series of measured soil water content and pressure head as objective functions for parameter optimization (Jacques et al., 2002). The inverse solution in HYDRUS-1D is accomplished using the Levenberg-Marquardt nonlinear minimization method (Marquardt, 1963), a standard approach for soil hydraulic parameters estimation. The water flow and root water uptake process were selected during the optimization of soil hydraulic parameters using an inverse solution approach. The van Genuchten model (1980) was selected for the soil hydraulic properties, which requires calibration of some parameters such as θ_r, θ_s, K_s, α and n. The observed soil moisture data from the C*hauka* system between July and September 2019 was used for the calibration of model parameters. The error between observed and simulated pressure heads in the upper and lower soil layer was minimized during the optimization of parameters. Though the model using automatic optimization for the parameters, a trial and error approach was also used simultaneously to make s automatic optimization for the parameters. A trial and error approach was also used simultaneously to ensure that the program converges to the same global minimum in the objective function. All the parameters' initial values were changed under the trial and error procedure to achieve global optimization. The soil moisture data of the year 2020 for monsoon period (July-August) was used to validate the calibrated soil hydraulic parameters. During the validation process, observed and simulated pressure heads were compared. Statistical indicators such as RMSE and R^2 were used to assess the agreement between observed and simulated values.

3.5 Vegetation changes

In the semi-arid regions, soil moisture plays an integrative role in surface processes and the productivity and sustainability of such ecosystems (Porporato et al., 2002; Mishra and Singh, 2010; Legates et al., 2011; Jin et al., 2011). Soil moisture is an effective water source for plant growth in the semi-arid regions (Yang et al., 2012), and its response to the changes in land cover indicates the sustainability of vegetation restoration in the region. To identify the potential transformations from bare to vegetation in the study area resulting from soil moisture conservation in the *Chauka* system, Normalized Difference Vegetation Index (NDVI) was derived at seasonal and decadal scales for the years 1993–2019. NDVI is a difference between reflectance in Near-infrared (NIR) and Red spectral bands normalized by their sum. It varies between -1 and 1 wherein the higher values reflect vegetation and lower values indicate other classes such as bare ground and water. The NDVI has been the most widely used vegetation index to monitor vegetation coverage, health and phenology using remote sensing images at local and global scales (Cao et al., 2018; Patidar and Keshari 2020). In this study, a time-series of Landsat images, including 418 images, was used to derive NDVI time-series. The time-series data includes images from three different Landsat sensors, including Thematic mapper (TM), Enhanced TM plus (ETM+) and Operational Land Imager (OLI) (Table 2). The time-series analysis was performed in Google Earth Engine (Gorelick et al., 2017).

[Table 2.]

4. Results

The assessment of *Chauka* system of Lapodiya catchment is presented in this section for monsoon periods of 2019 (June-September) and 2020 (June-September). The calibration and validation results are presented for July-September (2019) and July-August (2020), respectively, as the data of soil moisture variations was available for this period only.

4.1 Soil properties

Table 3 shows the soil textural fractions and the bulk density of the soil profile depths of 0-60 cm and 60-100 cm in *Chauka* system Lapodiya. The physical analysis indicates that the soil profile varies in texture with depth, changing from silt loam in the upper layer to sandy loam in the bottom layer. The bulk density of the soil profiles is 1.78 g cm^{-3} and 1.89 g cm^{-3} for 0-60 cm and 60-100 cm depth, respectively. The critical value of bulk density for restricting root growth varies with soil type (Hunt and Gilkes, 1992) but in general bulk densities greater than 1.6 g cm^{-3} tend to restrict root growth (McKenzie et al., 2004) and indicates that soil porosity is low and soil is highly compacted. It may also cause poor movement of air and water through the soil. Initial and optimized soil hydraulic parameters of the soil profiles are provided in Table 4. The optimized K_s value for 0-60 cm soil profile is higher (2.801 cm day^{-1}) than the 60-100 cm profile

(0.933 cm day^{-1}) in line with the bulk densities of both the soil profiles. The computed *Ks* values confirm the findings of Kelishadi et al. (2014) and Kabir et al. (2020) which suggest that the soil hydraulic conductivity in semi-arid regions is lower in the pasture soils as compared to the other cultivated soils. This is related to the lower organic matter content and a higher degree of compactness of pasture soils.

[Table 3.]

[Table 4.]

[Fig. 5.]

4.2 Rainfall variability and depth to water level (D_w)

Rainfall in this area is characterised by high variability and highly localised events. Rainfall intensity and its distribution plays a significant role in potential recharge estimation. Figure 5 shows the rainy days of different rainfall depth interval for the monsoon periods of the year 2019 and 2020. According to the India Meteorological Department (IMD), a rainy day has been defined as a day with rainfall of 2.5 mm or more. The recorded rainfall for the monsoon period of 2019 was 700 mm, which was distributed within 32 rainy days between July and September with four rainfall events of over 70 mm. In contrast, total rainfall of 760 mm in the monsoon season of 2020 was distributed within 36 rainy days with three large events of 50-60 mm. In 2020 there were a more days with rainfall between 10 to 50 mm (Fig. 5) than in 2019. Even though the total amount was lower in 2020, if there are more days when the soil is saturated it allows more infiltration to take place and reduces runoff (Table 6. In contrast, 2020 had more rainfall events with low rainfall depth resulting in less runoff and more groundwater recharge. The rainfall variability and distribution will influence the recharge abilities of *Chauka* system, as these small storage structures require frequent ponding to maintain the free draining conditions below root zone depth.

Figures 6 and 7 show the daily rainfall, potential evapotranspiration, and corresponding change in depth to the ground water level (D_w) in the *Chauka* system during the monsoon seasons of 2019 and 2020. The potential evapotranspiration varies within 2 to 4.5 mm day^{-1} for both the monsoon season of 2019 and 2020. The measured D_w throughout the monsoon season varies within 1 to 5 m. In the 2019 monsoon season, the D_w decreased after the frequent rainfall events in July-August and increased in late September due to pumping in the surrounding agricultural fields (Fig.6). The trend of D_w in the 2020 monsoon season is presented in Fig.7, which shows that the early rainfall events in June have no impact on the groundwater level due to low-intensity rainfall, high evapotranspiration, and high soil moisture deficit in this period. Regular rainfall events with minimum dry spells in July and August provided substantial recharge and D_w was reduced by 2.27 m (bgl) at the end of compared to the pre-monsoon season (Fig. 7).

[Fig. 6.]

[Fig. 7.]

4.3 Model calibration and validation

Simulation of field conditions using HYDRUS-1D using the hydraulic parameters obtained from the RETC and Rosetta model were in poor agreement and mismatch with the field data.

Therefore, the model parameters' calibration was done using the field-based pressure head data in the objective function. Table 5 provides the goodness of fit measures for both calibration and validation stage. The coefficient of determination (R^2) of pressure head variation in the calibration stage for both soil profiles were 0.87 and 0.81. Further, the root mean squared error (RMSE) for pressure head data at the calibration stage was 35.66 and 26.74 cm for upper and lower soil profiles. Similarly, the R^2 values during the calibration stage of soil water content were 0.89 and 0.87, while RMSE was 0.005 and 0.004 for the upper and lower layers. At the validation stage, the $R^2$for pressure head data were 0.84 and 0.69 and RMSE were 40.65 and 36.63 cm for upper and lower soil profiles, respectively. Validation of soil water content in both the soil profiles was found acceptable, as the R^2 were 0.85 and 0.76 and RMSE was 0.006 and 0.005. Though the variability in the pressure head was higher, in our case, the calibration and validation performance were acceptable for most cases.

[Table 5.]

With the fitted parameterization, Hydrus-1D was then used to forecast the root zone soil moisture dynamics for pastureland during the monsoon season of 2019 and 2020. Figures 8 and 9 show the variation in pressure head and soil water content for two depths (0-60 and 60-100) in the soil profile with the fitted parameters (Hydrus 1D) at the calibration and validation stage, respectively. The above-mentioned figures give a visual comparison of overall model performance during the calibration and validation stages. The high R^2values for both soil profile depths for pressure head shows the agreement between the field-measured and Hydrus simulated results. A similar trend was observed with RMSE values for both the depths. HYDRUS 1D performance for soil water content simulation was good for both calibration and validation stages, however, the modeling performance of the pressure head for the validation dataset shows moderate performance compared to the calibration dataset.

[Fig. 8.]

[Fig. 9.]

4.4 Water balance and groundwater recharge

This *Chauka* system is used as pastureland in the monsoon season and provides a significant opportunity for groundwater recharge. The calibrated model of the *Chauka* system was used to estimate the potential groundwater recharge during the monsoon period of the year 2019 and 2020. Since the area is barren land, rainfall (P) was the only input component. Evaporation *(E)*, runoff (Q_r), water uptake by the natural grassroots (T), drainage below the soil zone (R_e), and soil water storage change (dv) in the root zone were considered as the output components. Excess water drained below the soil zone was considered as the potential groundwater recharge. An approximate ponding depth of 6.5 mm was considered to estimate the potential recharge for the monsoon period of 2019 and 2020.

The water balance obtained from the calibrated and validated HYDRUS-1D model of the *Chauka* system (6.5 mm ponding) for the monsoon period in 2019 and 2020 is presented in Table 6. Evapotranspiration (evaporation and root water uptake) for both the year was 238.55 mm and 266.72 mm. Evapotranspiration *(ET)* increases with increasing seasonal water input, which in this case, includes rainfall only. The average evapotranspiration rate for the 2019 and 2020 monsoon periods was 1.95 mm/day and 2.18 mm/day, respectively. The availability of water for *ET* was more in the monsoon period of 2020, resulting in higher *ET*. The *ET* rate also increases with the decrease in D_w, and therefore reduced depth to water level in 2020 could have enhanced the average *ET* rate (Fig. 11). The bareness of the land and moderate slopes, in combination with high rainfall intensity and low evapotranspiration, cause significant surface runoff in these areas. As presented in Table 6, in the monsoon period of 2019, approximately 37% of total rainfall is lost through runoff, while it was 23% for the 2020 monsoon period. The higher runoff in the year 2019 was the result of high-intensity rainfall events distributed in a small time period. It is evident from Fig. 6 and Fig. 7 that the high-intensity rainfall is concentrated in few days with many dry spells in the 2019 monsoon season, however, it is well distributed between July and August months of 2020.

[Table 6.]

In the monsoon season of 2019, the total potential groundwater recharge was 222.25 mm which is about 31.75% of the total rainfall of 700 mm (Table 6). Potential groundwater recharge was also estimated for the monsoon season of 2020, which was 258.44 mm, approximately 34% of the total rainfall of 760 mm in this period. Change in the soil water storage in this region can be attributed to recharge and evapotranspiration from groundwater. In the monsoon period of 2019, the change in storage was negative (Table 6) due to a lack of rainfall and a high evapotranspiration rate in September. However, the change in soil water storage during the monsoon period of the year 2020 was positive, as recharge is the dominating factor at this stage. Table 6 also presents the absolute error in the water balance for both the 2019 and 2020 monsoon periods, which is less than 3% for both the years.

Table 6 also presents the scenarios with zero ponding depth or surface water layer, to highlight the importance of *Chauka* system in barren lands. The depth of ponding on *Chauka* surface increases due to precipitation and reduces because of infiltration and evaporation. In the year 2019, 6.5 mm of ponding (Eq. 6) increased the potential amount of recharge from 186.60 mm (no ponding) to 222.25 mm. The impact of such an increase could also be seen in the reduction of runoff amount from 313.77 mm to 259.19 mm. Similarly, in the year 2020 monsoon period, the estimated potential recharge increased from 177.05 mm in with no ponding case to 258.44 mm for 6.5 mm ponding. Reduction in the runoff from 239.96 mm to 179.99 mm was also observed when 6.5 mm ponding was allowed on the *Chauka* system surface. The comparative analysis of zero ponding and 6.5 mm of ponding on the *Chauka* system indicates that the small storage rainwater harvesting structures like *Chauka* have the potential to provide substantial groundwater recharge.

4.5 Water table response

To monitor the water table response due to recharge from *Chauka* system, a borehole (BH1) was installed and monitored on weekly basis since June 2019. The region surrounding the *Chauka* system is used for both rainfed and irrigated agriculture. Groundwater is extracted from large diameter wells using diesel pumps operating extensively for irrigation during the winter season, resulting in the groundwater table's decline. As shown in Fig. 10 that the depth to water level was 4.85 m in mid-June 2019 (16th June) and decreased up to 2.14 m by the end of September (29th September). The total rise in the depth to water level in this period was 2.71 m with an average rate of 25.57 mm/day. The obtained cumulative bottom flux (potential groundwater recharge) from the developed model was also mapped with the depth to water level rise in BH1 (Fig. 10), which suggests that the estimated potential recharge is acceptable.

[Fig. 10.]

Figure 11 shows the D_w declines in BH1 during the monsoon season of the year 2020 along with the increase in cumulative bottom flux (potential groundwater recharge), which follow a similar rising trend supporting the suitability of the approach adopted. In this period, depth to water level was reduced from 3.41 m in early July (5th July) to 0.91 m at the end of September (20th September) 2020. In this period, the depth to water level reduced up to 2.5 m with an average decline rate of 28.73 mm/day. The rate of decline in the depth to groundwater level in different years could be due to the variability in the amount and intensity of rainfall in the local area.

[Fig. 11.]

Groundwater occurrence in these low porosity hard-rock areas is found in the weathered and fractured zones that primarily govern groundwater storage and transmission in these rocks. A constant specific yield of 0.1 was used based on the studies conducted in similar lithological formations of Rajasthan state (COMMAN, 2005; Glendenning and Vervoort, 2010). By taking the potential recharge value of 222.25 mm and a constant S_y of 0.1, the D_w in the 2019 monsoon period was reduced up to 2.22 m (Re/S_y). Similarly, in the monsoon period of 2020, the reduction in D_w from the potential recharge of 258.44 mm was 2.58 m. The specific yield based decline in D_w of 2.22 m is 18% less than the actual D_w decline of 2.71 m in 2019. However, in the monsoon period of 2020, it is 3.2% higher comparing to the 2.5 m actual decline. It is important to note here that the spatial variation in the specific yield can be very significant due to heterogeneity and anisotropy in aquifer properties that are characteristic of hard rock aquifers. The specific yield of hard rock aquifer also varies with the depth due to change in fracture density and porosity with depth (Maréchal et al., 2004; Dewandel et al., 2006). Therefore, a sensitivity analysis was performed to identify the optimum value of Sy for the Lapodiya sub-catchment.

The Sy values ranging from 0.01 to 0.15 were used to convert the estimated potential recharge into the water level rise in the aquifer. The analysis suggest that a Sy value of 0.1 produces minimum error between the estimated water level rise and observed water level rise in BH1 for both 2019 and 2020 monsoon periods.

4.6 Impact on vegetation

Uncontrolled grazing in the study area has left the pastures completely denuded of perennial grass cover, frequently replaced by annual unpalatable grasses, and ultimately reduced to almost bare soil. Under such circumstances, Aristida sp (locally known as *lapla*) is the only vegetation that predominates (GVNML, 2007). Community lands were the source of the basic livelihood of the people, especially the poor; therefore, pasture improvement and plantation strategies were followed to rejuvenate the lost pasturelands. Soil moisture conservation through rainwater harvesting in the *Chauka* system provides essential water for plant growth in the semi-arid region of Lapodiya. The development of *Chauka* system in the barren land of Lapodiya was done to convert this wasteland into a pastoral land. The practice to conserve rainwater in the area resulted in altering the land-surface characteristics such as vegetation cover affecting the partitioning of rainfall into evapotranspiration, runoff, and subsurface drainage.

[Fig. 12.]

The change in the vegetation cover of this area could be seen in Fig. 12, which presents the average NDVI maps of the *Chauka* system for the periods 1993–2002, 2003–2012 and 2013–2019. The NDVI maps (Fig 12 a, b and c) depict an increase in NDVI values throughout the

Chauka system which indicates increased vegetation coverage since 1993. The average of NDVI for the years 1993 to 2002 varies between 0.15 and 0.25 which increased with the increased vegetation as shown by increased number of pixels with higher NDVI (0.20 to 0.25) in the years 2003 to 2012. A considerable change can be seen in the NDVI map of 2013-2019 wherein the NDVI increased significantly for entire *chauka* system and varies between 0.25 and 0.35. The *chauka* system has also led to improved vegetation coverage during dry seasons as can be seen in temporal profile of NDVI from 1993 to 2019 (Fig. 12 (d)). The NDVI values since 2009 are consistently high which indicates positive impacts of *chauka* system on vegetation health and density.

In the year 1981, the area was completely barren. The renovation and augmentation of water resources started in this area in the early 1980s. The people of nearby villages decided to conserve rainwater and soil moisture, which led to the innovation of the *Chauka* system. Such intervention's early impact could be seen in successive decades where the vegetation cover increased as indicated by annual average NDVI (Fig 12 d). The average NDVI increased from 0.15 in 1993 to 0.23 in 2019. In the present conditions, *Chauka* system serves the needs of Lapodiya village by providing assured pastureland in the early dry periods. Further, investigations are suggested to understand the role of *Chauka* system in ecological sustainability and land cover improvements.

5. Discussion

The water balance in the *Chauka* system for the monsoon season of both 2019 and 2020 suggests that the *Chauka* system's additional storage provides more water for potential groundwater recharge (Table 6). This is further confirmed by the comparative analysis of zero ponding and 6.5 mm ponding scenario over the *Chauka* surface, which suggested that the additional ponded water on the *Chauka* surface reduces runoff significantly in both the 2019 and 2020 monsoon seasons. The average daily groundwater level rise of BH1 in 2020 was higher (28.73 mm/day) than in 2019, as the larger number of rainy days permitted more recharge, even though the total rainfall was less in 2020 (Fig. 5). The recovery of well water level in the *Chauka* system also reflected a similar pattern as found in the cumulative potential recharge in both 2019 and 2020 monsoon seasons (Fig. 10 and Fig. 11).

The groundwater level rise in BH1 due to the recharge was estimated using a constant specific yield. Data on aquifer parameters such hydraulic conductivity and specific yield is scarce in India (Chinnasamy et al., 2015). In this case a specific yield of 0.1 was used based on the studies conducted in similar lithological formations of Rajasthan state (COMMAN, 2005; Glendenning and Vervoort, 2010). The difference between the observed groundwater level rise and estimated groundwater level rise based on the specific yield was 18% in 2019 and 3.2% in 2020 monsoon periods. Specific yield affects the accuracy and confidence level of recharge rate (Kim et al., 2010). Other potential sources of uncertainty include soil hydraulic parameters, the daily reference evapotranspiration rate, rainfall, and root water uptake parameters (Jiménez-Martínez et al., 2009).

The average annual rainfall in the study area for the last 34 years (1971-2014) is 575.7 mm (CGWB, 2017), while the average annual pan evaporation can reach as high as 1744.7mm (CGWB, 2017). This combination of low precipitation and high evaporation in semi-arid regions results in lower soil moisture content (Yang et al., 2012), making the soil moisture insufficient to meet the introduced vegetation's growth needs. Landscape management, such as micro-topography reconstruction, can effectively increase rainwater infiltration (Previati et al., 2010; Rejani and Yadukumar, 2010). The NDVI time-series analysis in the Lapodiya region from 1993 to 2019 indicates that the soil moisture conservation through *Chauka* system has contributed significantly to the sustainable growth of native vegetation (Fig.12). However, a detailed investigation of soil moisture dynamics and its relations to vegetation growth and sustainability in different seasons, and effects of landscape management on soil moisture dynamics is recommended for future research. This study was performed on small field site with soil moisture and water level recorded at a single location and hence it is limited to one dimensional analysis. However, the local impact of these small scale rainwater harvesting structures on the amount of recharge is clearly demonstrated in this study. Future studies could consider the spatial variability in the recharge potential of these systems using more detailed data at both spatial and temporal scale. The catchment level impact of these structures will require consistent data on the number, physical specifications and types of structures that exist in the catchment, as well as rainfall characteristics, streamflow, and aquifer properties.

There have been various studies to estimate groundwater recharge in the north west of India. Rangarajan and Athavale (2000) used the tritium injection method in a rainfed grassland setting in 1972-1973 and 1994-1995 and reported the median recharge rates of 35, 43, and 67 mm/year, representing 8, 9, and 14% of precipitation (460, 470, and 491 mm), respectively. Scanlon et al. (2010) studied the recharge potential of a rain-fed/irrigated cropland using the Cl mass balance approach and nutrient availability method and found a similar recharge rate of 61–94 mm/year (10–16% of precipitation, 600 mm/year) for rain-fed agriculture in a study area in Jaipur. Both of these studies were in areas where no MAR structures were present. Conversely, Glendenning and Vervoort (2010) made field observations in the Arvari River catchment of Rajasthan, where check dams and ponds had been constructed to recharge groundwater. They calculated the potential recharge in the range of 200 to 300 mm, which is close to the results reported in this study.

The *Chauka* system caused an additional 5.09 % and 4.86% of the total rainfall to become groundwater recharge during the monsoon season of 2019 and 2020 respectively (Table 7). This is again similar to Glendenning and Vervoort (2010) who found that check dams and ponds contributed an additional 6 to 7 % of recharge, and also Sharda et al. (2006) and Badiger et al. (2002) who studied various MAR structures and found that that up to 10% of rainfall becomes potential recharge. The significant contribution of these *Chauka* systems in intercepting the runoff and allowing it to infiltrate into the ground surface provides a promising small scale solution for water scarcity in the semi-arid regions. The evidence presented here suggests they are effective at increasing both recharge and vegetation and should be considered for implementation more widely. This study suggests there are few geographical constraints to their application, if there is slightly sloping, barren land above an unconfined aquifer this approach could be tried. This study also highlights the potential value in traditional rainwater harvesting systems to restore the depleted shallow groundwater aquifers and should be added to those documented elsewhere (for example Sharma and Everard, 2017). Traditional approaches are well adapted to local demand, culture and hydro-geography.

[Table 7.]

6. Conclusion

Small-scale rainwater harvesting using both traditional and modern rainwater harvesting structures is being implemented in India to alleviate declining groundwater stores, but there is a need for a better understanding of the impacts of many small rainwater harvesting structures and their wider role in water resources management. The data collected during this study in the monsoon periods of 2019 and 2020 highlighted the importance of these traditional structures in semi-arid regions. The *Chauka* system transforms approximately 5% rainfall to recharge in both 2019 and 2020 monsoon seasons. Further, the vegetation index derived from satellite data also highlights the contribution of *Chauka* system in altering the near soil surface moisture, which helps develop pasturelands used in early dry periods.

CRediT authorship contribution statement

Basant Yadav: Conceptualization, Data collection, Data Curation, Methodology, Formal analysis, Writing – original draft. **Nitesh Patidar:** Formal analysis, Writing-review, and editing. **Anupma Sharma**: Conceptualization, Funding acquisition, Supervision, Writing-review, and editing. **Niranjan Panigrahi**: Formal analysis, Writing-review, and editing. **Rakesh Sharma**: Writing-review, and editing. **V Loganathan**: Writing-review, and editing. **Gopal Krishan**: Writing-review, and editing. **Suraj Kumar**: Data collection and analysis. **Jaswant Singh**: Data collection and analysis. **Alison Parker**: Conceptualization, Funding acquisition, Methodology, Supervision, Writing-review, and editing**.**

Declaration of competing interest

The authors declare no competing interests

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Data availability statement

Data underlying this paper can be accessed at: https://10.17862/cranfield.rd.13348424

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