PLOS WATER

RESEARCH ARTICLE

Estimation of groundwater recharge in semiarid regions under variable land use and rainfall conditions: A case study of Rajasthan, India

Basant Yadav[1], Alison Parker[2]*, Anupma Sharma[3], Rakesh Sharma[4], Gopal Krishan[3], Suraj Kumar[3], Kristell Le Corre[2], Pablo Campo Moreno[2], Jaswant Singh[5]

1 Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Uttarakhand, India, **2** School of Water, Energy and Environment, Cranfield University, Cranfield, United Kingdom, **3** National Institute of Hydrology, Jal Vigyan Bhavan, Roorkee, India, **4** Department of Chemistry Indian Institute of Technology Jodhpur, Jodhpur, India, **5** Department of Hydrology, Indian Institute of Technology Roorkee, Uttarakhand, India

* a.parker@cranfield.ac.uk

OPEN ACCESS

Citation: Yadav B, Parker A, Sharma A, Sharma R, Krishan G, Kumar S, et al. (2023) Estimation of groundwater recharge in semiarid regions under variable land use and rainfall conditions: A case study of Rajasthan, India. PLOS Water 2(3): e0000061. https://doi.org/10.1371/journal.pwat.0000061

Editor: Andrea Zanini, University of Parma: Universita degli Studi di Parma, ITALY

Received: March 17, 2022

Accepted: December 9, 2022

Published: March 22, 2023

Peer Review History: PLOS recognizes the benefits of transparency in the peer review process; therefore, we enable the publication of all of the content of peer review and author responses alongside final, published articles. The editorial history of this article is available here: https://doi.org/10.1371/journal.pwat.0000061

Data Availability Statement: Data underlying this paper can be accessed at: 10.17862/cranfield.rd.12967961.

Abstract

In the semiarid regions of India, the annual rainfall is very low (~650 mm) and erratic; hence groundwater recharge is vital to support crops, especially in the winter season. For groundwater budgeting it is essential to consider how groundwater recharge is affected by both land-use and rainfall distribution. This study used a soil water balance approach, considering hydrological, meteorological, hydrogeological and crop information to understand the recharge process in semiarid regions. The approach was used at a sub-watershed scale where farmers grow rainfed and irrigated crops. Delayed recharge response on the water table was considered to estimate actual recharge, which closely matches the observed water levels in the field. The recharge estimated in rainfed agricultural lands, rainfed-irrigated agricultural lands, and barren lands was 29%, 17%, and 31% of the total inflow.

1. Introduction

In arid and semiarid areas where irrigated agriculture prevails, accurate groundwater recharge estimation is crucial for assessing scarce water resources and their sustainable management [1, 2]. In India, as in many other developing nations with agriculture-based economies, water resources are critical for economic development, and agriculture accounts for approximately 85% of the total annual abstraction [3, 4]. Therefore, accurate estimation of the current groundwater recharge rate is essential for efficient and sustainable groundwater management in these regions. However, groundwater recharge estimation in semiarid regions has been a challenging task due to temporal variability of precipitation in semiarid climates, spatial variability in soil characteristics, topography, vegetation, and land use, and uncertainty in hydrogeological variables [4, 5].

Variable rainfall should undoubtedly be considered during recharge estimation, as the recharge in semiarid areas is erratic and may only occur on a few occasions per year [6].

Funding: Natural Environment Research Council (NE/R003351/1 to AP). The funder had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing interests: The authors have declared that no competing interests exist.

Therefore, considering recharge as a proportion of mean annual rainfall is not practical, as the recharge rate is determined by the distribution of extreme events over threshold levels [7, 8]. In India and other East Asian countries, more than 75% of the annual rainfall occurs during a 4-month monsoon season. The rainfall variability is perceived as the greatest threat to agricultural production in arid and semiarid regions, especially where rainfed agriculture is prevailing [9].

Similarly, land-use changes directly impact the groundwater recharge rate, mechanism, and spatio-temporal variability [10–13]. Potential recharge in a specific land use condition depends on the physical state of the soil surface as it controls soil hydraulic properties (water retention and hydraulic conductivity) and hence the infiltration process [14]. Crops can collect sub-surface moisture and transpire water to the atmosphere [15]. Where there is no or partial vegetation, bare soil evaporation is significant [16], which decreases as the water table falls [17]. A non-varying crop coefficient (Ke = 1.05) can be used to estimate bare soil potential evaporation from potential evapotranspiration [3].

There is no single method universally applicable for the accurate estimation of the groundwater recharge rates [18, 19]. It is important to distinguish 'actual recharge' reflected on the water table and 'potential recharge', which is merely water that infiltrates below the soil layer [18]. Actual recharge has been estimated under various field conditions using methods that include empirical formulas, hydrograph analysis, water budget, water table fluctuation, tracer methods, calculations using Darcy's law in the unsaturated zone, and numerical methods [18]. A soil water balance or budgeting technique can be used for routine potential recharge estimation in many situations, provided that physical processes are represented adequately [15]. For example, conceptual understanding and impact of geological formation on the recharge mechanism and recharge rates were highlighted in Fitzsimons and Misstear [20] and Chung et al. [21]. A soil water balance approach, along with detailed information from the FAO report including crop evapotranspiration [3], can be used to estimate recharge. Eilers et al. [22] used this approach to estimate recharge in semiarid regions of Nigeria. Further, de Silva and Rushton [16] applied this approach when studying rice fields in the tropical climate of Sri Lanka. Rushton et al. [23] recently used this method to estimate recharge in a multi-aquifer system of north-west Bangladesh. However, the applicability of soil moisture balance techniques in semi-arid regions has been questioned as often the magnitude of recharge is often comparatively less than the other variables such as evapotranspiration [5, 24, 25]. This can be overcome if the recharge is estimated using daily time steps coupled with an understanding of near-surface processes in the soil zone and subsequent water movement through underlying strata [18, 23].

Several studies have considered the impact of land-use change during recharge estimation using various direct or indirect approaches [18, 26–28]. Similarly, the impact of rainfall seasonality, intensity, and distribution has also been studied independently under various climatic conditions [29–31]. However to the best of our knowledge, the combined impact of land-use changes and rainfall variability on the groundwater recharge in semiarid conditions has not been studied before. Therefore, this study aims to examine the effect of land-use change and rainfall variability on groundwater recharge and evaluate the impact on crop conditions. This was achieved by quantifying the soil water balance components on various land use patterns using observed data in the study site. Further, the soil water balance approach's estimated recharge in the soil zone was converted into actual recharge reflected on the water table using a delayed recharge process. Obtained actual recharge was validated using water level data obtained from large diameter open wells. This approach provides flexibility to consider natural processes, rainfall variability, and land-use change while estimating actual groundwater recharge and understanding its role in the sustainability of rainfed and irrigation-based crops by providing routine recharge estimation at the local scale.

2. Materials and methods

2.1 Study area

Lapodiya watershed of Jaipur district was selected as a study area. This watershed has a semi-arid climate, a variety of different land-use patterns, and rainfall conditions where rainfed and irrigation-based agriculture are practiced. Because of the scarcity of surface water resources, inhabitants depend mostly on groundwater for both domestic and agricultural water supply [32]. Fig 1 shows the Lapodiya watershed (23.3 km^2) located around 90 km west of the city of Jaipur in Rajasthan, the driest state of India where 90% of rural and 50% of urban water supply is met by groundwater [33]. The average annual rainfall in the study area for the last 34 years (1971–2014) is 575.7 mm, out of which over 90% is distributed in the monsoon season (June–October) and is subject to a lot of inter-annual variations, with a standard deviation of 205 mm [34, 35]. The area has been classified as semiarid as, over a year, rainfall represents less than 50% of potential evapotranspiration [36]. The mean maximum temperatures in this region can be bas high as 48˚C in June, while in January the temperatures drop to between 7.7˚C and 21˚C [37].

The Lapodiya watershed has a small population of 1764 inhabitants, and agriculture is a primary source of livelihood for 87% of the workforce [38]. The farming system is complex in the study area as some farmers grow two to three crops in a year. The cropping seasons are divided into three periods, Kharif (monsoon season), Rabi (winter), and Zaid (summer). In the Kharif season (July-October), generally, maize, millet, sorghum, groundnut, black gram, mung-bean, and vegetables are grown, which are entirely dependent on rainfall. In the rabi season (November-February), crops like wheat, barley, mustard, and gram are grown, while in Zaid (March-June), fodder crops are grown in the areas where irrigation is available. Groundwater-based

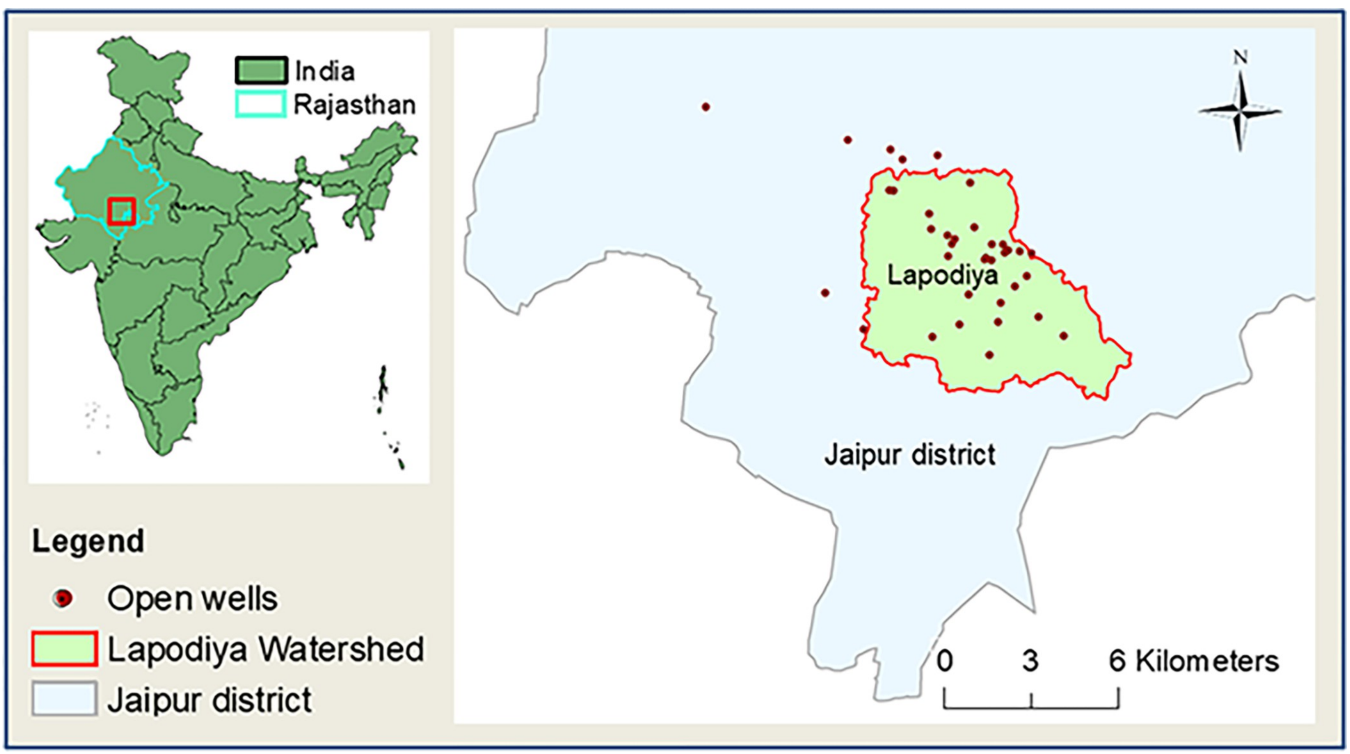

Fig 1. Lapodiya watershed with the locations of 36 large diameter open wells which are used to observe water levels from March 2019 to May 2020.

https://doi.org/10.1371/journal.pwat.0000061.g001

Table 1. Geological profile with a depth of Lapodiya catchment.

Depth (m)	Geology		Source
0 to 1	Sandy loam and loam soils		[41]
1 to 20	Weathered gneiss	Highest Water Level = 1.64 m (bgl)	[35]
		Lowest water level = 4.72 m (bgl)	
20 to 40	Schist mixed with mica, quartz, and feldspar pieces		[35]
From 40 to 80	Bhilwara Super Group, comprising of granulitic gneisses, quartz mica schist, phyllite along with granite and pegmatite intrusives		[35]

https://doi.org/10.1371/journal.pwat.0000061.t001

irrigation using large-diameter open wells abstracts water from shallow aquifers. Deep tube wells are not used due to the deep aquifer's high salinity. The shallow aquifers has moderate salinity and high fluoride concentration, but it is deemed fit for irrigation.

Aquifers in this region comprise hard rocks of the Bhilwara Super Group, comprising granulitic gneisses, quartz mica schist, phyllite, and granite and pegmatite intrusive [39]. In these aquifers, the movement of groundwater is controlled by the size, continuity, and interconnectivity of weathered and fractured parts and other secondary porosities. A report from Rajasthan Ground Water Department [40] suggests that the topsoil (<1 m) is dominated by sandy loam and loam soils. Further, weathered gneiss is from 1 to 20 m, and the deeper region (>20 m) is dominated by schist mixed with mica, quartz, and feldspar pieces (see Table 1). Bedrock depth is about 40 to 80 m deep, and most of the aquifers are unconfined in this region [35]. Groundwater in this area occurs both in unconsolidated Quaternary formations and consolidated formations at shallow depth under water table conditions and semi-confined conditions at depth.

2.2 Field data collection

The watershed selected in this study has never been studied scientifically, so the historic information was very minimal. A local observatory was established in the watershed to collect daily rainfall, temperature, and evaporation data. Historic daily rainfall data for the period of 2010–2019 was also gathered from the department of irrigation, government of Rajasthan (http://water.rajasthan.gov.in/content/water/en/)

Further, a monitoring network of 36 large diameter open wells was established to record the water table depth at weekly intervals from March 2019 to June 2020. Before selecting these open wells, a survey was conducted of all the wells (open wells and tube wells) in the study area, and water samples were collected. These 36 open wells were selected as they represent the varying quantity and quality of groundwater conditions in this watershed. Out of 36 open wells, 4 have a depth less than 10 m; 23 are between 10 to 20 m deep and, 9 are more than 20 m deep. Most of these wells are being used for irrigation and domestic purposes; however, nine wells are inactive or abandoned. The local non-governmental organization (NGO) staff were trained to collect meteorological and groundwater table depth data. During the field visits, farmers were interviewed to obtain historical information about the water conservation structures, large diameter open wells, drilling methods, irrigation systems, and crop patterns. Further, these farmers also provided crop and irrigation information (i.e. photos and videos) for the study.

To understand the hydrogeology, two 12.7 cm or 5-inch diameter boreholes, as shown in Fig 2, were drilled in the study area using a down-the-hole drill (DTH rig), and sediment samples were collected at every one-metre interval. Analysis of collected samples and pumping tests in the study area suggests that the average hydraulic conductivity of unconfined aquifers in the study area consistently varied from 1 to 6 m/day, and the average specific yield varied

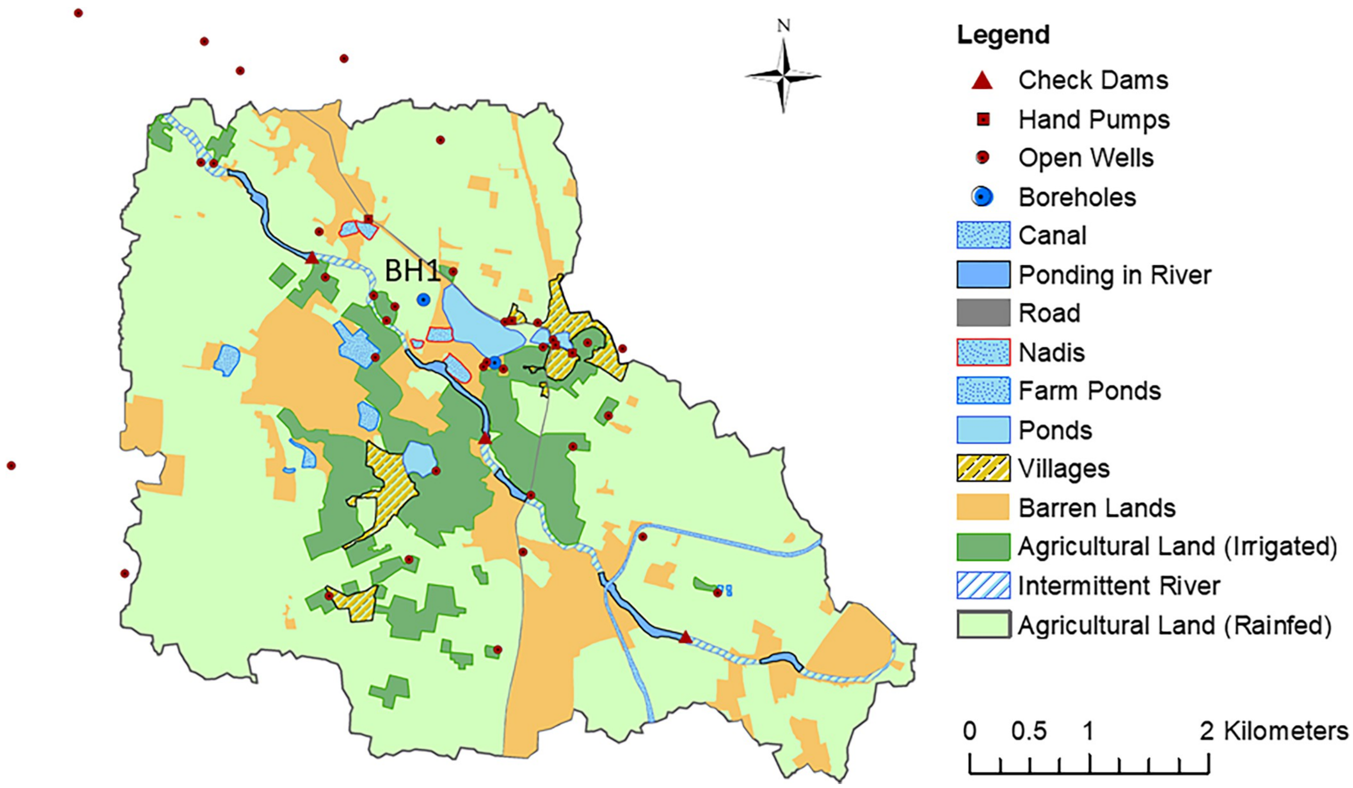

Fig 2. Land use map of Lapodiya watershed, showing the agricultural and barren land-use area used for the recharge estimation using the soil water balance approach.

https://doi.org/10.1371/journal.pwat.0000061.g002

between 1 and 7%. The data for crop patterns and land use were collected through a village-level survey in 2019–20. The land use data is divided into three categories, i.e., rainfed agriculture, irrigated agriculture, and barren land. Fig 2 shows that in this watershed, out of 23. 3 km^2 area, 65% is rainfed, 11% is irrigated, 19% is barren land, and the rest is covered by ponds, farm ponds, and rural settlements.

2.3. Soil moisture balance method for recharge estimation

The potential recharge from agricultural (rainfed and irrigated) and barren land was calculated using a soil water balance approach (SWB) suggested by Rushton et al. [15]. The SWB method is based on the concept that soil becomes free-draining when the soil moisture content reaches a limiting value called field capacity; then excess water drains through the soil to become recharge. The SWB method requires knowledge of precipitation, evaporation, crop parameters, soil parameters, crop scheduling, irrigation frequency, irrigation scheduling, and irrigation depth. The soil water balance method components and their mathematical formulation are presented below.

Potential evaporation from a soil surface (ES) and potential transpiration (ET_C) of a crop can be calculated using reference evapotranspiration for grass ET_0,

$$ES = K_E \times ET_0 \tag{1}$$

$$ET_C = K_C \times ET_0 \tag{2}$$

where K_E is the coefficient of evaporation and K_C is the crop coefficient [3].

The total available water (TAW) in mm is calculated as:

$$TAW = 1000(\theta_{FC} - \theta_{WP})Z_r \quad (3)$$

θ_{FC} is the moisture content at field capacity, θ_{WP} is the moisture content at wilting point, Z_r is rooting depth (m). Readily available water, $RAW = p \times TAW$, p is a factor between 0.2 and 0.7 [3].

The total evaporable water (TEW) in mm is calculated as:

$$TEW = 1000(\theta_{FC} - 0.5\theta_{WP})Z_E \quad (4)$$

Where, Z_E is bare soil depth (m). A coefficient of 0.5 was introduced before θ_{WP} since evaporation can dry the soil to mid-way between the wilting point and oven dry. The value for Readily evaporable water *(REW)* ranges typically from 5 to 12 mm and is generally highest for medium and fine-textured soils. Typical values for REW are given in Table 19 of Allen et al. [3].

Stress factors for transpiration K_S and evaporation K_S' can be estimated as:

$$K_S = \frac{TAW - SMD}{TAW - RAW} \text{ when } RAW < SMD < TAW$$

$$K_S{}' = \frac{TEW - SMD}{TEW - REW} \text{ when } REW < SMD < TEW$$

when K_S and K_S' = 0, this suggests that the soil moisture deficit (SMD) is higher than TAW and TEW, therefore transpiration and evaporation are zero. However, K_S and K_S' = 1 suggests that the actual transpiration and evaporation equal their potential rate.

When $SMD \geq TAW$, actual evapotranspiration (AE) is equivalent to water available for evaporation (AWE). However, if $RAW < SMD < TAW$, actual evapotranspiration (AE) is calculated as:

$$AE = AWE + K_S(PE - AWE) \quad (5)$$

The reduced soil moisture deficit for the day following a significant input (rainfall or irrigation) can be represented as:

$$SMD_{t+1} = SMD_t - (AWE_t - AE_t - NSS_t), \text{ where } t \text{ is time in days} \quad (6)$$

When $SMD_t = 0$ and $P > 0$ or irrigation $I_r > 0$, the amount ($AWE_t - AE_t - NSS_t$) becomes the potential recharge (R). Therefore, the potential recharge (R) is calculated as:

$$R = (AWE_t - AE_t - NSS_t) \text{ if } SMD_t = 0 \text{ and } P > 0 \text{ and/or } I_r > 0 \quad (7)$$

Table 2. Runoff coefficients used for the runoff estimation from a rainfall event based on the soil moisture deficit (*SMD*) and rainfall depth.

Rain (mm/d) SMD (mm)	0	20	40	70	100
	Runoff coefficients				
0	0.06	0.1	0.14	0.24	0.34
15	0.04	0.06	0.1	0.18	0.24
30	0.02	0.04	0.06	0.12	0.18
60	0.01	0.02	0.04	0.08	0.12
90	0	0.01	0.02	0.04	0.08
120	0	0	0.01	0.02	0.04

https://doi.org/10.1371/journal.pwat.0000061.t002

Estimation of runoff in this study was done using an approach recommended by Rushton (2003) [41] in which the coefficient of runoff (*ROC*) is dependent on rainfall depth (*P*) and soil moisture deficit (*SMD*). The runoff coefficients were multiplied with rainfall depth to estimate runoff depth. The runoff coefficients were modified based on study area soil type and rainfall depth. Table 2 presents the runoff coefficients for a sandy loam soil watershed in semiarid conditions. These coefficients are linearly interpolated for various rainfall depth and soil moisture deficit conditions to estimate the runoff at a daily interval.

After runoff, remaining water is infiltrated in the soil surface and subjected to evapotranspiration, which depends on the crop and surface soil layer properties. Evapotranspiration can be estimated using the FAO-56 Penman–Monteith (PM) equation as this is considered to be the most accurate estimate of reference evapotranspiration (ETo). However, it requires a broad range of data that may not be available or of reasonable quality. Therefore in this study where very limited data was available, to compute the evapotranspiration over a reference surface ET_0, the Hargreaves equation [41] was applied, using the daily maximum-minimum temperature and the extra-terrestrial solar radiation information. A combined crop coefficient K_{CM} (for bare soil and crop) is calculated using the percentage of bare soil area and the cropped area to estimate the evapotranspiration in various land use conditions. Evaporation from bare soil depends on the thickness of the surface soil layer (Z_E), which is subjected to drying by evaporation. Table 3 presents coefficients for bare soil (K_E) and crop (K_C) values adopted from Allen et al. [3] and adjusted for local climatic conditions.

The distribution of soil moisture significantly determines the evapotranspiration, especially under the condition when *SMD* is greater than *RAW* or *REW* and there is significant rainfall. Rushton [42] introduced a near-surface storage (*NSS*) concept and suggested that under a significant soil moisture deficit and substantial rainfall condition, moisture is retained near the soil surface and continues to provide water for evapotranspiration for a limited number of days after the rainfall. *NSS* is a fraction of distributed moisture in soil zone, which is available to reduce the SMD [42]. The *NSS* value depends on the vertical hydraulic conductivity of the soil. The *NSS* is specifically valid in these semiarid regions to support crop growth. Retained water near the soil surface is available for shallow plants roots during the different growth stages and dry periods between rainfall events.

Therefore, available water for evapotranspiration (*AWE*) depends on *SMD* and *NSS* retained near to the soil surface from the previous day's input (rainfall or irrigation). Water available through infiltration ($In = P–RO$) along with the previous day *NSS* provides water for evapotranspiration. The amount of water that is still available after actual evapotranspiration (*AE*) and *NSS*, contributes to the reduction of soil moisture deficit. The excess rainfall or irrigation after SMD approaches zero ($AWE_t–AE_t–NSS_t$) becomes potential recharge (*R*). Table 4 presents the list of parameters used in the soil water balance model to estimate the recharge in

Table 3. Crop coefficients for the estimation of evapotranspiration from crops and bare soil at different growth stages, suitably modified for local climatic conditions.

Crops	$K_{C(in)}$	$K_{C(mid)}$	$K_{C(late)}$
Millet	0.3	1.06	0.3
Wheat	0.7	1.21	0.3
Grass	0.3	0.81	0.75
	K_E		
Bare soil	1.05	1.05	1.05

in = initial stage; mid = middle stage; late = late stage

https://doi.org/10.1371/journal.pwat.0000061.t003

Table 4. List of SWB model parameters along with the source of information for three types of vegetation in the sandy loam soil of the Lapodiya watershed.

SWB Parameters	Symbol	Millet	Wheat	Grass	Source
Depth of roots (m)	Z_r	0.6	1	0.5	Field evidence
Depth of surface soil layer for drying (m)	Z_e	0.25	0.25	0.25	[3]
Initial soil moisture deficit (mm)	SMD_b	70	70	70	Field evidence
Fraction for near-surface storage	$FrNSS$	0.25	0.25	0.25	Field evidence
Depletion factor	p	0.5	0.5	0.5	[3]
Moisture content at field capacity (m^3/m^3)	θ_{FC}	0.18	0.18	0.18	[3]
Moisture content at wilting point (m^3/m^3)	θ_{WP}	0.06	0.06	0.06	[3]
Water stress coefficients	K_S	0–1	0–1	0–1	[3]
Runoff coefficients	ROC	Table 1	Table 1	Table 1	[41]

https://doi.org/10.1371/journal.pwat.0000061.t004

the Lapodiya watershed. The present study was conducted in a data-scarce region where no historical absolute values of used parameters were available for calibration and validation. Therefore, in this study, the concept of plausibility was used to assess the adequacy of the soil water balance model [43]. The concept of plausibility assumes that if the model captures and represents the complex hydrological system reasonably, it will be able to compute a credible water balance. A model is judged based on the structure and test results in this approach. This approach was successfully used by Rushton et al. [15] and Eilers et al. [22] while using the soil water balance approach to estimate the potential recharge in semiarid northeast Nigeria. Further, cumulative potential recharge estimated using soil water balance was validated using observed water level rise in the field, which proves the adequacy of the applied soil water balance approach for groundwater recharge estimation.

2.4 Soil water balance in rainfed, irrigated and barren lands

In the study area, monsoon season crops are entirely dependent on rainfall; therefore, the conceptual model for this period includes inflows due to rains and outflows due to bare soil evaporation, crop evapotranspiration, and excess runoff. At the onset of monsoon, when the millet crop is planted, the soil moisture deficit in the beginning (SMD_b) is higher than TAW. As the excess rainfall infiltrates the soil zone, SMD_b is reduced where $RAW<SMD_1<TAW$, however, the millet crop remains stressed. Further rainfall is infiltratedand this brings SMD_1 to $SMD_2<RAW$, and at this stage, $PE = AE$ and the millet crop has sufficient water for its growth and development (Fig 3A). Further percolations bring SMD_2 to SMD_3, which means the soil zone has reached its field capacity, and excess water is being percolated to below the soil zone as potential groundwater recharge (*Re*).

Irrigation is primarily used in the rabi season, starting in early November and ending in February. This season's crops include chickpea, wheat, barley, and green peas, which generally require irrigation during the early, growing, and mature stages. Crops in this season are grown using groundwater-based irrigation, and hence, in this case, the inflows also include irrigation. The first irrigation brings SMD_b to $SMD_1<RAW$, which allows wheat planting. After 21 days of sowing (DAS), second irrigation (45 DAS) is provided, which reduces SMD_1 to $SMD_2<RAW$, as shown in Fig 3B. At this stage, the wheat crop has enough water available for evapotranspiration and crop growth. Further irrigations at 65, 90,105, and 125 (DAS) keep SMD less than RAW without providing any excess water for potential groundwater recharge. Therefore, in this case, irrigation-based winter wheat does not contribute to the potential groundwater recharge.

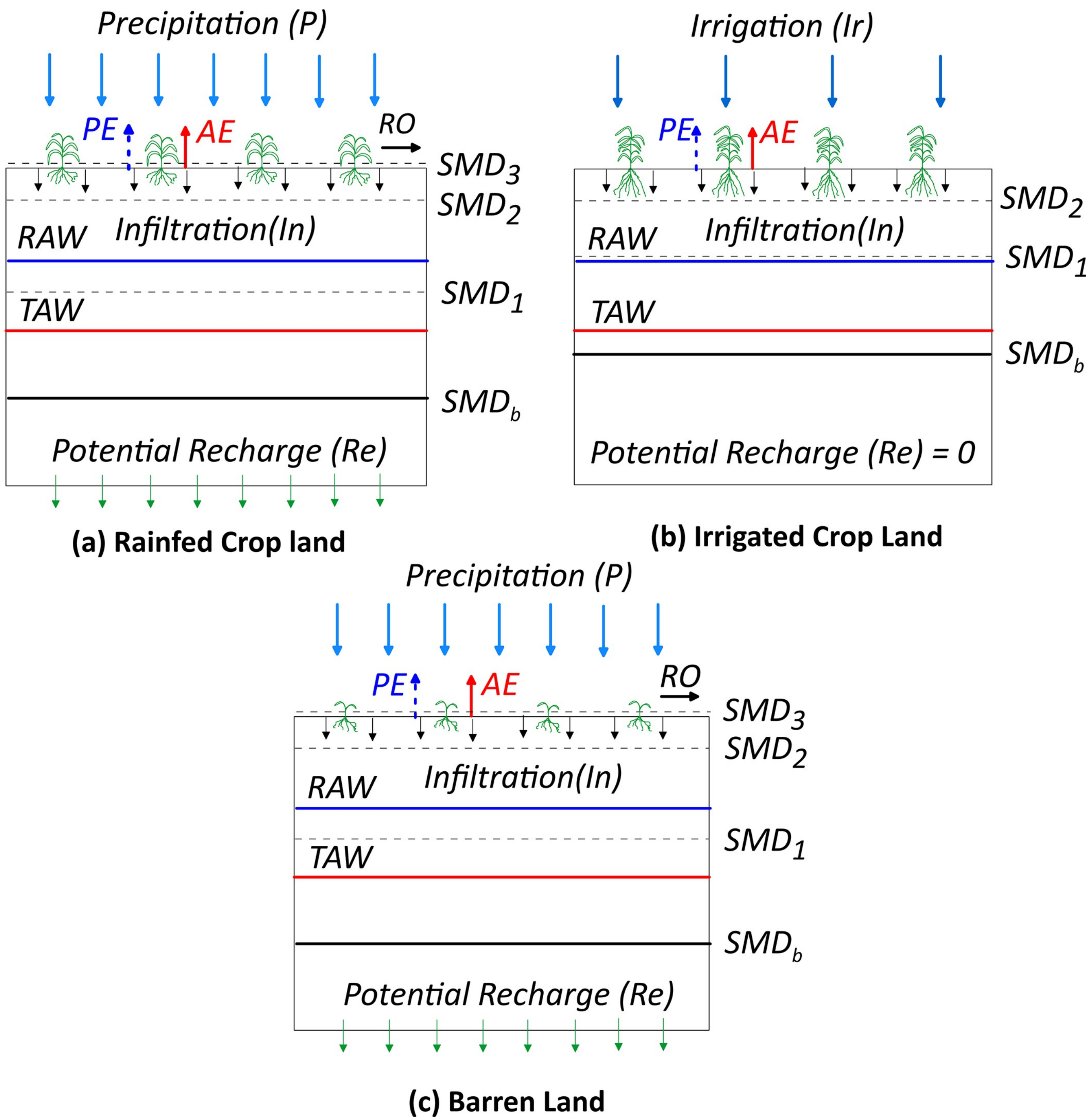

Fig 3. Conceptual model of soil water balance for a) rainfed cropland, b) irrigated cropland and c) barren land.

https://doi.org/10.1371/journal.pwat.0000061.g003

In this study area, barren lands cover a significant proportion of the area. They include both managed grazing grounds locally known as chaukas (small infiltration pits, [44, 45]) and unmanaged grazing areas covered in shrubs. The barren lands are used as grazing grounds for cows and goats. Fig 3C depicts a conceptual model for barren lands which is similar to the one presented in Fig 3A for rainfed crops. However, in this case, the millet crop is replaced by natural grass. Evaporation from bare soil depends on the atmospheric conditions and moisture content in the soil profile. The bare soil evaporation happens in three stages, namely: weather-controlled stage, soil profile control stage, and residual slow rate stage. In the weather-controlled stage, evaporation occurs at a constant rate as the soil is moist and able to supply water for evaporation. In the soil profile stage, evaporation rate is equal to the rate at which the gradually drying soil profile can provide water for evaporation. Lastly, at the residual slow rate stage, evaporation has virtually ceased as the surface soil is dry, and water is held only in the disconnected pores that are immobile. The limited bare soil evaporation and smaller root growth of grass in barren lands result in less evapotranspiration thus making more water available for potential groundwater recharge.

2.5 Delay between potential and actual recharge

The estimated potential recharge leaving the soil zone will eventually join the water table. However, it has been observed in many studies that there can be some delay between the potential recharge leaving the soil zone and the response at the water table [42]. Time is required for recharged water in the top layer of the unsaturated zone to move downward. This delay in the downward movement of recharged flux can be related to recharge rate, soil-water content, and water table depth. This delay is required for the pressure front from increased deep drainage to move downward through the unsaturated zone [46, 47]. Such delays can also be attributed to the matrix storage in the deep vadose zone [48, 49]. This delay can further increase with increased aquifer depth [50]. Lee et al. [51] suggested that if the depth of the unsaturated zone is more than 18 m, the time lag between potential recharge and water table response increases rapidly. Moreover, complex geology including vertical fissures, or high permeability zones make this delay estimation even more challenging. Therefore, such a delay can be simulated using coefficients based on field observations [42]. In this study, the selected site's unsaturated zone thickness varies between 5 and 10 m. The water levels of a piezometer (BH1) were collected daily and studied using hydrographs to identify the delay between rainfall and response on the water levels. The estimated daily potential recharge from SWB was matched with a daily incremental water level increase in BH1 to identify the delay factors, which later were used to transform the potential recharge into actual recharge.

Daily water level rise and estimated incremental potential recharge depth of current day (t) and previous days (-t) were used to identify the delay factors as presented in Eq (8). The two coefficients (0.1 and 0.05) are used to explore the methodology, but when it is applied in practice, a smoother distribution is used. The approximated coefficients are site-specific and may change for other field conditions.

$$R_t = \sum_{t=-5}^{t=1} (0.1 \times R_t) + \sum_{t=-14}^{t=-6} (0.05 \times R_t) \tag{8}$$

Where R_t represents the recharge in day t.

2.6 Sensitivity analysis

The SWB model is based on various hydrogeological, meteorological, and crop parameters, which are either measured in the field or taken from literature. A sensitivity analysis is needed to address uncertainty in the model output due to the model input parameters which include crop coefficient (K_{cm}), maximum root depth (Z_{max}), total available water (TAW), near-surface soil storage (NSS), and runoff coefficient (ROC). These parameters represent the characterization of the catchment, vadose zone, and crop conditions. The selected parameters were varied between the maximum, and minimum values within the range suggested in Allen et al. [3] and Rushton [42]. The crop coefficient and maximum root depth were further modified for the local conditions. Since the area has semiarid climates and moderate wind speeds, around 6% higher value of crop coefficient was used. From the given range of rooting depth in Allen et al. [3], the smaller values for rooting depth were used for irrigated areas and the larger values for modelling rainfed conditions. A series of simulations were performed on individual parameters by a given amount of perturbation and estimating the potential recharge to evaluate the impact of change in these parameters. The sensitivity of a parameter was assessed by calculating the relative change in the potential recharge with respect to the original potential recharge value.

3. Results

The SWB in this area is used for three major land uses, i.e., rainfed agricultural land, irrigated agricultural land, and barren land from 1st June 2019 to 31st May 2020. Further, the impact of rainfall variability on groundwater recharge and sensitivity of the soil water balance approach was analyzed between 1st June 2010 and 31st May 2020. The results are presented on a water year basis, starting in June and ending in May the following year. Information oncropping patterns, irrigation depth, and cropping schedule was collected from a farm in the southeast part of the study area.

3.1 Recharge in rainfed agricultural lands

Millet was a primary rainfed crop in the study area, planted on 4th July 2019, just after the first few rainfall events, and harvested on 17th October 2019. Fig 4 shows a detailed analysis of the estimated potential recharge in rainfed agricultural land for monsoon season with millet planted in sandy loam soil. Fig 4(A) presents rainfall from June 2019 to November 2019 and corresponding runoff in Fig 4(B). Most of the rainfall was received between July and August, which is also the growing and maturing period for monsoon crops. Fig 4(C) presents the crop coefficients for millet and the stress factors. In the early growth stage, the area covered by crop was smaller; hence bare soil evaporation dominated. However, during the maturity stage, the crop covered over 90% of the area, and thus contribution from bare soil evaporation was minimal. The crop coefficient decreased significantly when the crop reached its harvesting stage from mid-September to mid-October. Once the crop had been harvested, the surface was exposed to bare soil evaporation. Various essential stages during the potential recharge estimation in Fig 4 are indicated by numbers (1 to 4).

1. This is the pre-monsoon stage and, at this stage, the $SMD > TAW$. The AE will be zero except for days where any rainfall events have occurred and when NSS provides water. Further, the initial rainfall events do not impact the SMD as the rainfall depth is less than PE.
2. At this stage, SMD is less than zero; therefore, the first recharge occurs. Rainfall depth at this stage is very high, which reduces SMD to zero and provides water through NSS for evapotranspiration for the next few days. As enough moisture is available through direct rainfall and NSS, PE equals AE for the next few days. The millet crop was planted at this stage.
3. This is a dry spell during the monsoon, typical in the study area. At this stage $RAW > SMD > TAW$, and therefore crop is stressed as shown in Fig 4C, where K_s is less than one and hence $AE < PE$ at this stage.
4. This is the harvesting stage of the millet crop. Fig 4D shows that the PE and AE are decreasing as matured millet crop reduces soil evaporation due to full canopy cover. Also, the crop

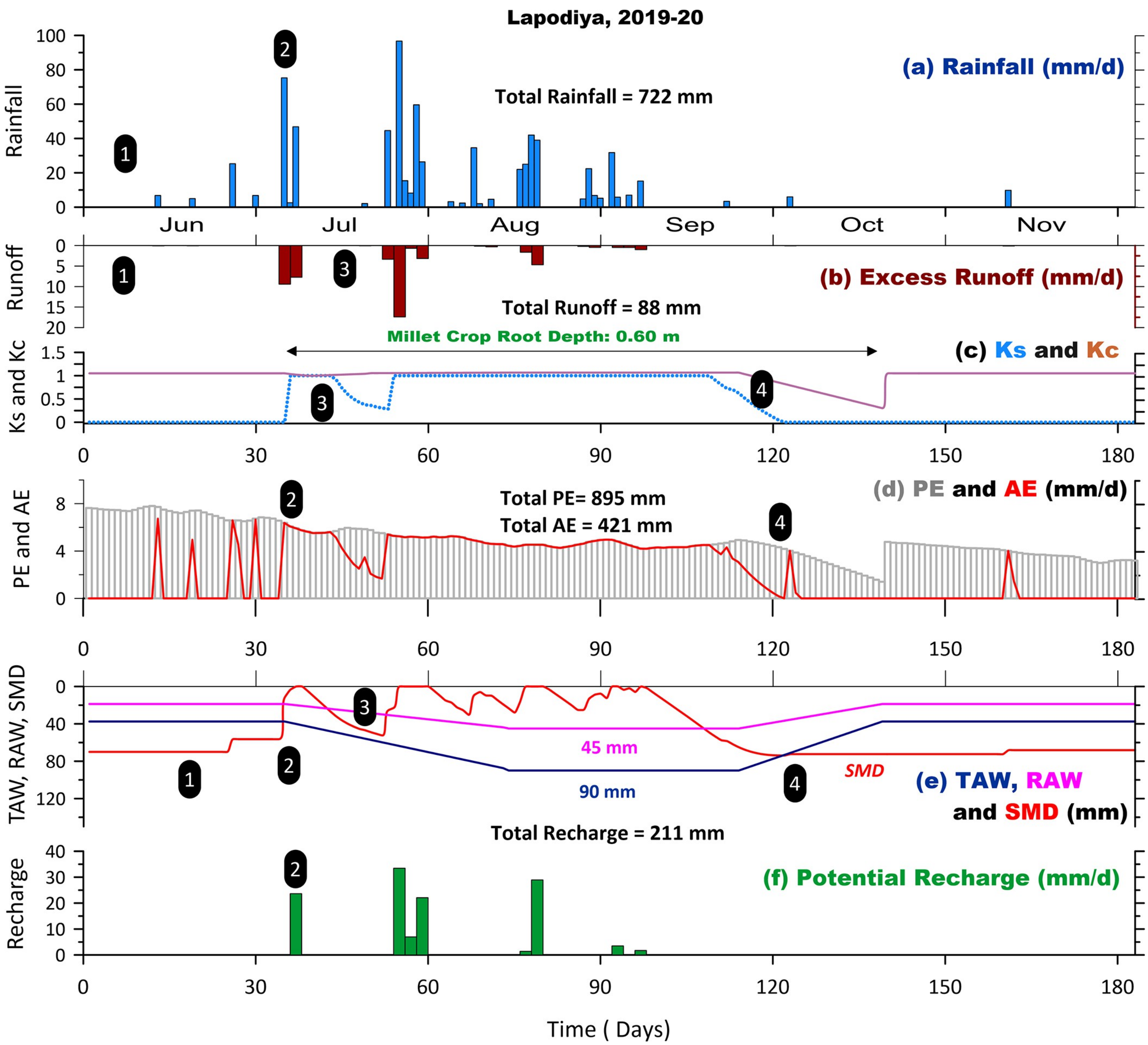

Fig 4. Soil water balance components and parameters for a semiarid rainfed agricultural area with a millet crop in Lapodiya watershed in 2019–20. Specific comments for time points one to four are provided in section 4.1.

https://doi.org/10.1371/journal.pwat.0000061.g004

is mature and drying for harvesting; therefore, roots have very limited transpiration ability. Further, the lack of rainfall has also increased the SMD, which is between *RAW* and *TAW*, as presented in Fig 4E.

Fig 4 presents the total water balance (mm) for June 2019 to Nov 2019. Total inflow in the form of rainfall was 722 mm. The outflows include 88 mm as runoff, 421 mm as actual evapotranspiration, 211 mm as potential recharge below the soil zone, and 2 mm to reduce the SMD at the end of November 2019. Fig 4F shows the total recharge for this period, which was 29.22% of the total inflows (i.e., rainfall = 722 mm).

3.2 Recharge in rainfed and irrigated agricultural lands

The second crop in the region is entirely dependent on irrigation and hence restricted to a small area with sufficient water for irrigation. The crop was planted on 4th November 2019 and was harvested on 2nd April 2020. Irrigation was provided at different growth stages [3]. Groundwater is the primary source of irrigation; however, surface water stored in the check dams is also used for the first few irrigations in the fields near the intermittent river. Fig 5 presents the estimated potential recharge in an agricultural area where rainfed millet and an irrigated winter crop are grown. Total irrigation provided in the field was approximately 480 mm, distributed in six irrigation schedules as shown in Fig 5A. The conditions for recharge during

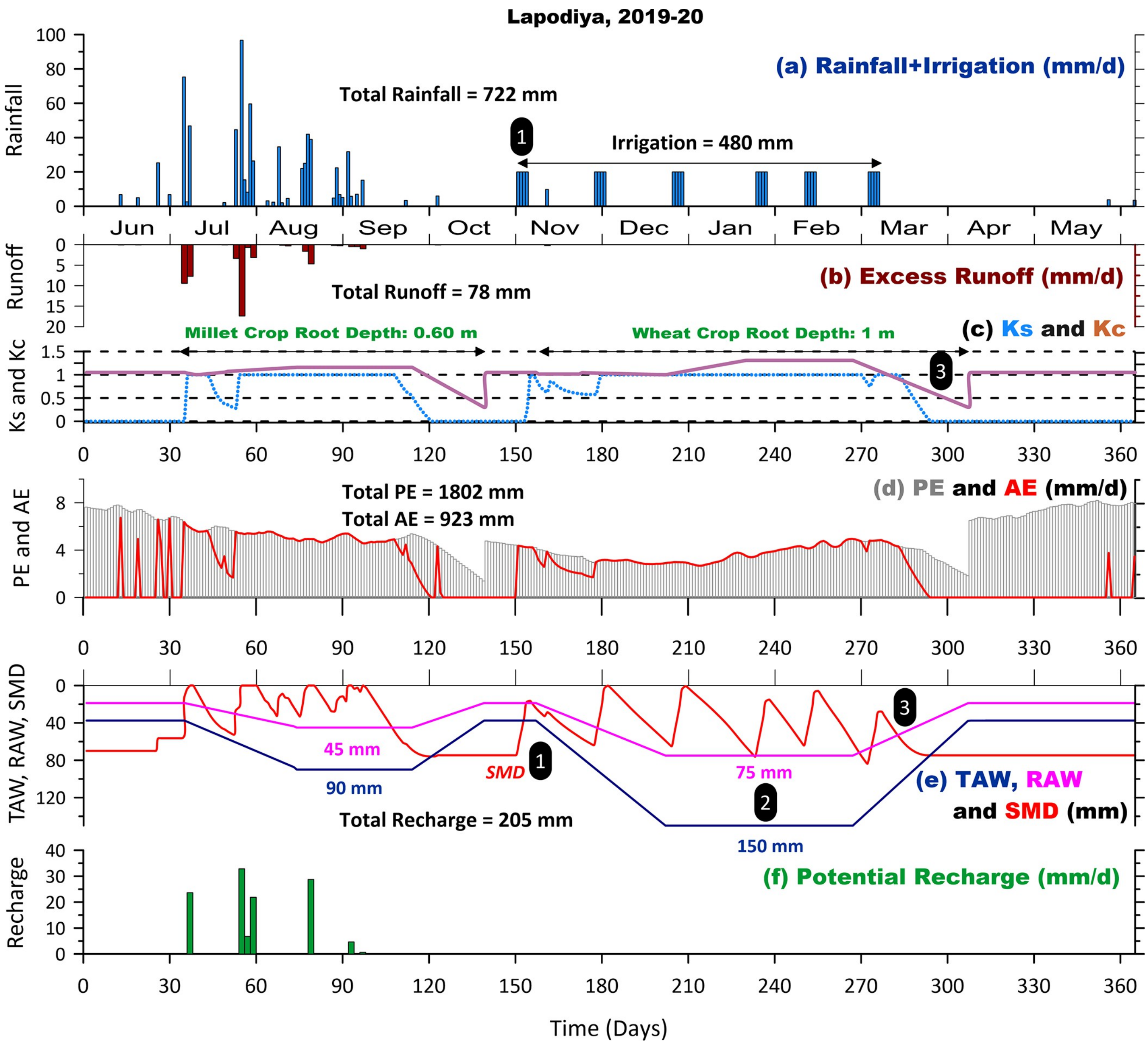

Fig 5. Soil water balance components and parameters for a semiarid agricultural area with millet and wheat crop in Lapodiya watershed in 2019–20. Specific comments for time points one to three are provided in section 3.2.

https://doi.org/10.1371/journal.pwat.0000061.g005

rainfed millet crops are the same as shown in Fig 4. The critical conditions during the winter wheat crop under irrigation are presented through numbers in Fig 5.

1. This is a stage where the winter wheat is planted after 18 days of the harvesting of millet. The SMD>TAW and hence irrigation were applied before seven days of planting. Due to irrigation, the *SMD* was reduced, and therefore wheat could grow successfully. However, it is also apparent from Fig 5C that the K_s value is less than one, and consequently, the crop is still under stress.
2. At this stage, the wheat crop has achieved maturity, and roots are fully developed. Frequent spells of irrigation have kept $SMD<RAW$ and $AE = PE$. However, precise irrigation depth and frequency do not allow any water as runoff or recharge, as shown in Fig 5B and Fig5F respectively.
3. This is the harvesting stage of the wheat crop; both *PE* and *AE* have reduced due to full canopy cover and dry roots. The last irrigation just managed to protect the crop from stress. However, the *SMD* has still increased due to actual evapotranspiration.

Fig 5 presents the total water balance (mm) for June 2019 to May 2020. Total inflow in the form of rainfall and irrigation was 1202 mm. The outflows include 78 mm as runoff, 923 mm as actual evapotranspiration, 205 mm as potential recharge below soil zone, and -4 mm to increase the *SMD* at the end of May 2019. Fig 5F shows the total recharge for this period, which was 17% of the total inflows. It is evident from Fig 5 and various conditions discussed above that the irrigated winter wheat in the study area does not provide any potential recharge. The supplied irrigation water depth and its frequency were sufficient to grow a healthy crop without allowing any water as runoff or recharge.

3.3 Potential recharge estimation in barren lands

The study area has significant barren lands as managed and un-managed pastures and provides a substantial opportunity for groundwater recharge. Following a similar approach discussed in Fig 4 for millet, the estimated potential recharge for barren lands with natural grass is presented in Fig 6. The natural grass grows after the first rainfall events and matures in mid-September. Intense grazing after monsoon reduces canopy cover and exposes the surface soil layer to bare soil evaporation.

Fig 6 presents the total water balance (mm) for June 2019 to May 2020. Total inflow in the form of rainfall was 722 mm. The outflows comprise 102 mm as runoff, 401 mm as actual evapotranspiration, 223 mm as potential recharge below soil zone, and -4 mm to increase the *SMD* at the end of May 2019. Fig 6F shows the total recharge for this period, which was 30.8% of the total inflows. Limited canopy cover and short root depth reduce *AE* by 4.75% compared to the *AE* in agricultural lands. Therefore, the barren lands contributed 5.7% more recharge than the agricultural lands when a millet crop was grown under similar climatic conditions.

3.4 Delayed groundwater recharge

Fig 7 presents a rainfall-recharge analysis for the monsoon period (July-September) in 2019. The estimated potential recharge plotted in the upper part of Fig 7B is for barren land with natural grass cover. It is evident at point 1 in Fig 7 that the first significant potential recharge occurred due to the second rainfall event as the first few rainfall events decreased *SMD* to bring the soil moisture content to field capacity. The estimated potential recharge at point 1 was then matched with the incremental rise of the water level in BH1, which is plotted in the bottom part of Fig 7B.

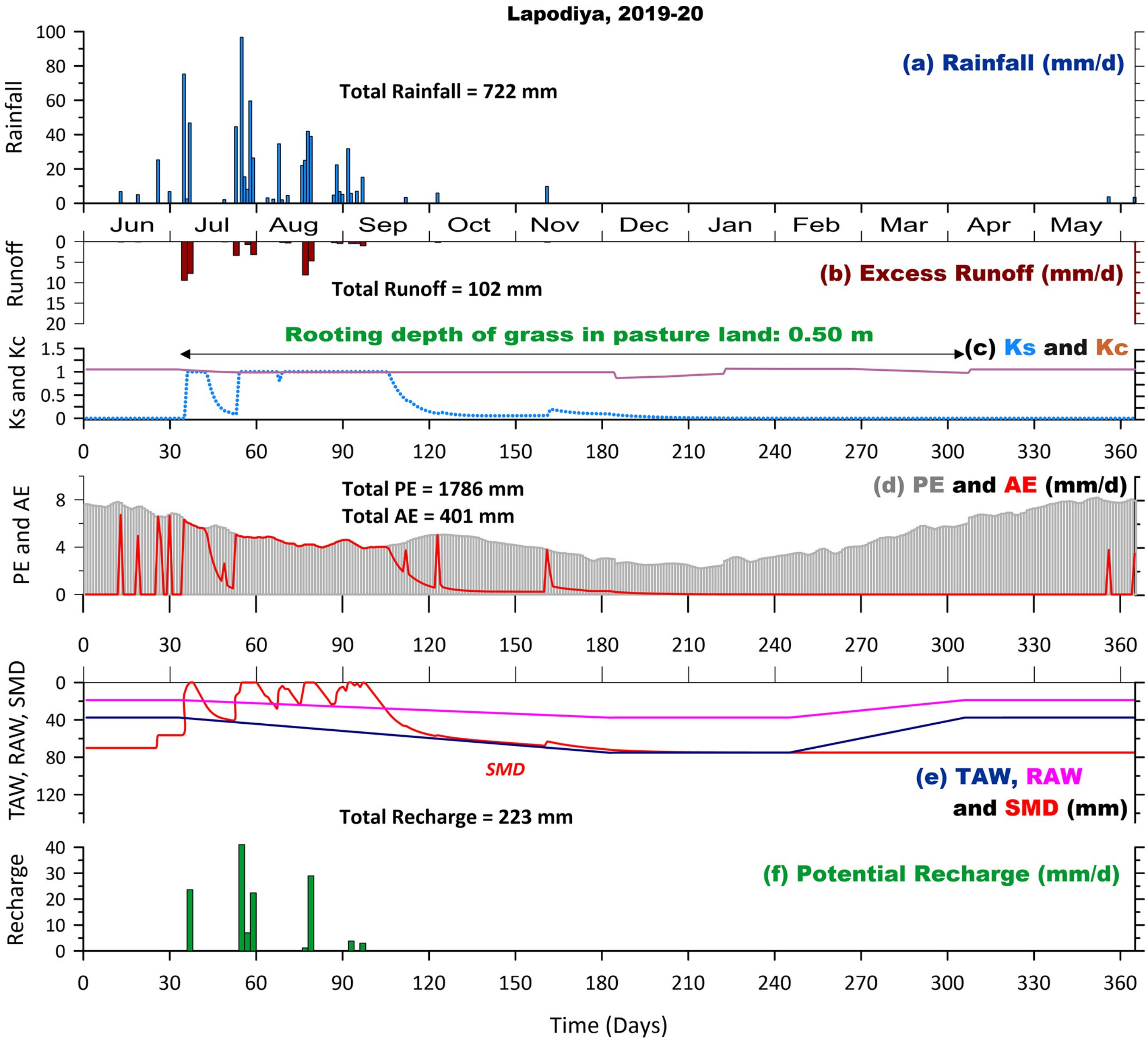

Fig 6. Soil water balance components and parameters for a semiarid barren land with natural grass cover in Lapodiya watershed in 2019–20.

https://doi.org/10.1371/journal.pwat.0000061.g006

At point 1 in Fig 7A, the rainfall depth of an event was 46.8 mm, which provided 26 mm as potential recharge. The incremental water level rise of BH1 in the past 15 days was equivalent to 24.57 mm, which is obtained using the specific yield of 0.07. The total recovery of potential recharge at the water table is 94% below the soil zone, which suggests that the delay factors closely represent the physical delay process. The distribution indicates that the first 50% of potential recharge is reflected at the water table in the next five days while the rest takes another ten days to join the water table. Further, it is evident at point 2 in Fig 7 that the delay factors are acceptable. Therefore, the water level rise follows the cumulative potential recharge pattern and can be explained as a result of a piston-displacement mechanism through the soil

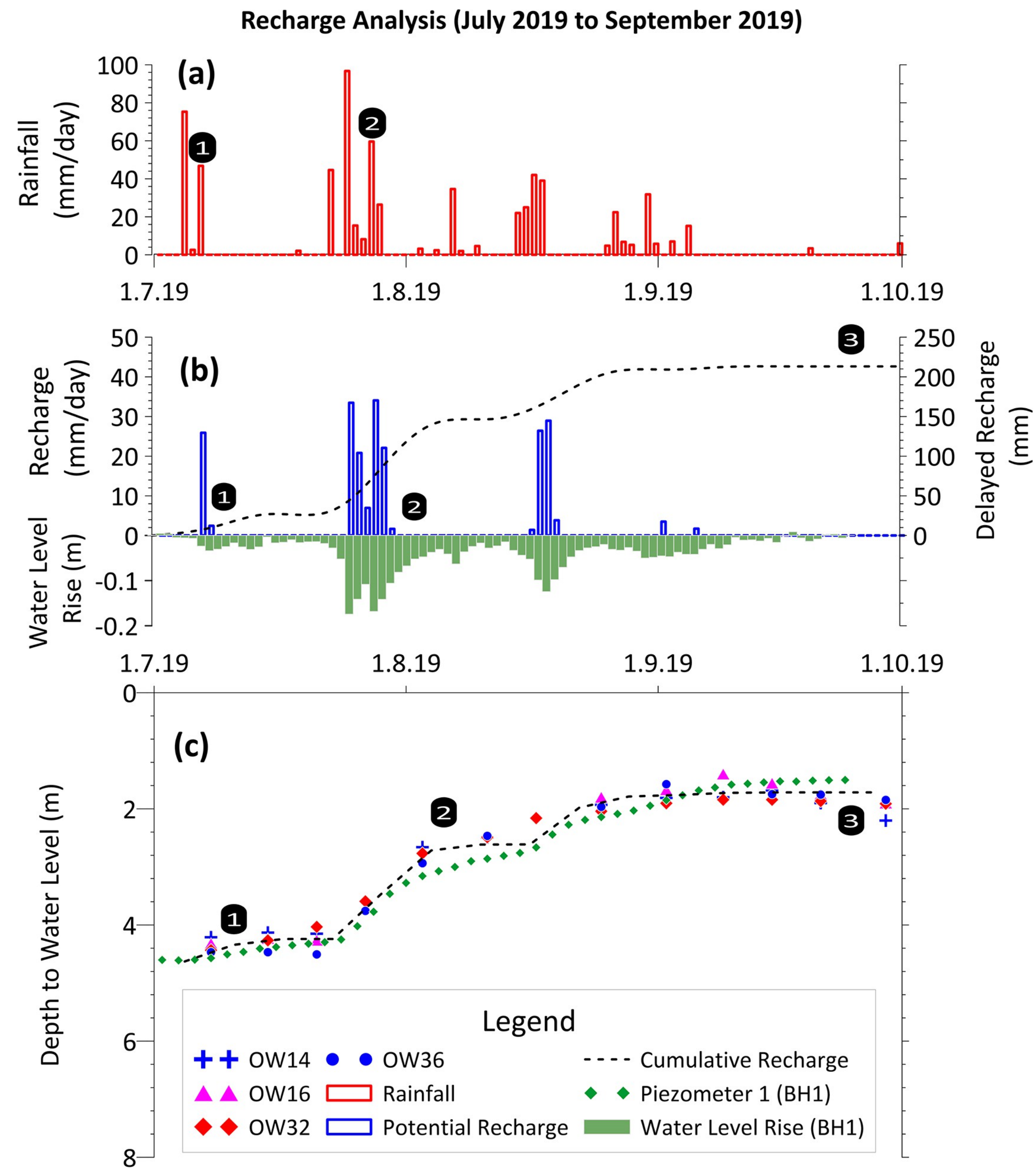

Fig 7. Water table response in Lapodiya watershed due to the estimated potential recharge using (a) rainfall between July 2019 to March 2020, (b) soil water balance based potential recharge and incremental water level rise in BH1 (lower), and (c) observed water table rise in the open wells (OW).

https://doi.org/10.1371/journal.pwat.0000061.g007

matrix. Further, point 3 in Fig 7, where there is no rainfall, indicates abstraction from these wells, which resulted in the decline of water levels.

3.5 Conversion of potential recharge to actual recharge

The objective of this study was to estimate the groundwater recharge in a different land-use conditions so that the information can help farmers use limited groundwater resources efficiently. Using delay factors, potential recharge estimates from the SWB approach were converted to actual recharge at the water table (Eq 5). Further, the cumulative recharge was mapped against the water level (bgl) in various open wells and BH1 in Fig 7. During this period, the annual rainfall and estimated potential recharge were 722 mm and 223 mm, respectively. The conversion of potential recharge into actual recharge and resulting changes in the water table elevation significantly depend on the aquifer's specific yield.

Nine pumping tests were conducted in four large-diameter wells to estimate the specific yield in the field site. The pumping tests were conducted in both wet (i.e., high well storage conditions) and dry (i.e., low well storage conditions) seasons to minimize the impact of well storage and capture the effects of horizontal drillings on estimated aquifer parameters. The large diameter wells are described in S1 Table and S1 Text. The specific yield of 0.07 was deduced from the water table conditions and estimated recharge. The obtained specific yield was also consistent with the specific yield obtained from pumping test analysis. Fig 7C shows that the rise in water levels of W14, W16, W32, W36, and BH1 is close to the estimated actual cumulative recharge on the water table. Further, the average total rise in open well water levels and BH1 during the observation period was 3.10 m. The estimated water table rise using the potential recharge and specific yield is 3.18 m, which further verifies the accuracy of the soil water balance approach in assessing the accurate recharge under semiarid conditions.

3.6 Potential groundwater recharge under variable rainfall conditions

An analysis of the relationship between potential recharge and rainfall for ten years from June 2010 to May 2020 is presented in Fig 8. This recharge estimation is based on agricultural land

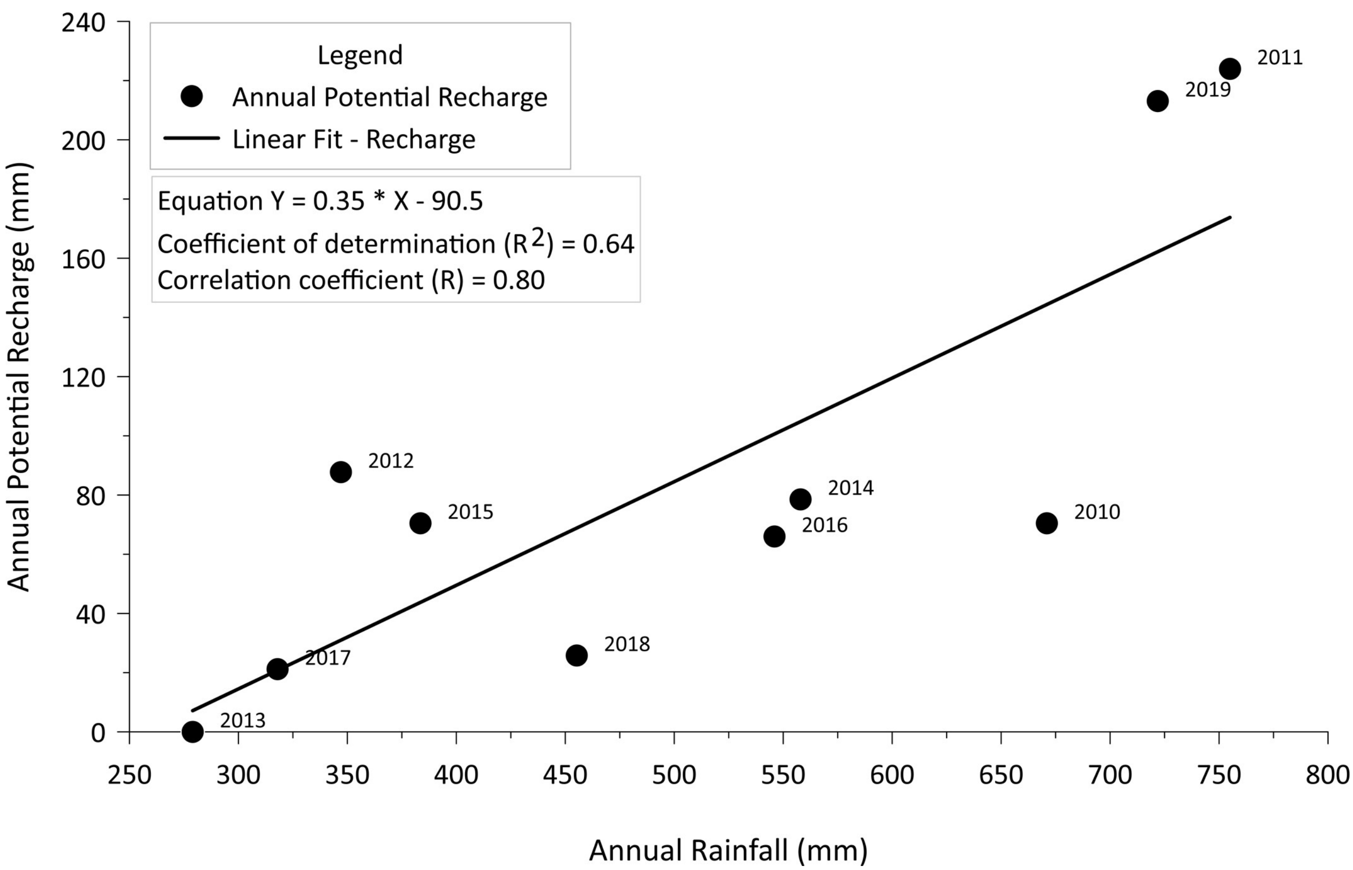

Fig 8. Relationship between annual rainfall and corresponding potential recharge in Lapodiya watershed from 2010 to 2019.

https://doi.org/10.1371/journal.pwat.0000061.g008

Table 5. Annual rainfall variability (depth, distribution) and corresponding potential recharge in Lapodiya watershed from 2010 to 2019.

Rainfall Depth (mm)	Distribution of Rainfall in Years (2010–2019)									
	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
<5.0	21	11	11	12	9	8	20	14	14	11
>5–10.0	9	8	9	10	6	4	7	5	5	9
>10–20.0	8	3	4	8	12	7	10	9	8	2
>20–50.0	8	8	1	2	8	6	9	1	6	11
>50–100.0	1	6	2	0	1	1	0	1	1	3
>100	1	0	0	0	0	0	0	0	0	0
Total Rainfall (mm)	671	755	347	279	558	383.5	546	318	455.3	722
Rainy days	48	36	27	32	36	26	46	30	34	36
Initial SMD (mm)	70	30	70	77	73	70	89	61	86	68
Recharge (mm)	70	224	88	0	78	70	66	21	26	211

https://doi.org/10.1371/journal.pwat.0000061.t005

use with rainfed millet crops each year. The potential recharge for each year was estimated using the previous year's soil moisture deficit at the end of the year as an initial *SMD* for the following year. It is evident from Fig 8 that the estimated potential recharge varies significantly and does not correlate linearly with rainfall depth. The estimated potential recharge over ten years varies between 0 to 224 mm. The mean annual average potential recharge is 86 mm, with over 70% of years having a recharge of between 20 to 90 mm. The mean annual rainfall over these ten years is 503 mm with minimum and maximum values of 279 and 722 mm for 2013 and 2019, respectively. The potential recharge for 2013 was zero, which was also a year with the least annual rainfall and a relatively high soil moisture deficit of 74 mm (Table 5). The impact of a high soil moisture deficit is visible in 2018, where the annual rainfall is 455 mm, and the potential recharge is just 26 mm due to an increased initial soil moisture deficit of 86 mm. In contrast, 2017 received only 318 mm of annual rainfall but contributed 21 mm as potential recharge due to a low initial *SMD* of 61 mm. In 2017, a low SMD allowed the soil to reach field capacity level quickly, thus draining the excess inflows below the soil zone as potential recharge.

Table 5 also presents rainfall intensity and distribution, which plays a significant role in potential recharge estimation. Two cases of low annual rainfall values of 347 mm (2012) and 318 mm (2017) are substantial as they provided the lowest potential recharge. Rainfall in 2012 was distributed between 9th June to 31st August with two events of 73 mm and 36 mm, providing 88 mm as recharge below the soil zone. Similarly, in 2017 the rainfall was distributed between 11th July to 9th September with three events of 54 mm, 88 mm, and 40 mm depth, providing 21 mm of recharge. However, in 2013 where the potential recharge was zero, the rainfall was distributed between 6th June to 22nd September, with the highest rainfall event of 20 mm. Rainfall distributed over a more extended period with a lower intensity than the hydraulic conductivity causes more water loss through evapotranspiration thus limiting the potential recharge.

The highest potential recharges of 224 mm and 211 mm were estimated for 2011 and 2019 respectively, which also have an above-average annual rainfall of 755 mm and 722 mm. Potential recharge was higher in 2011 due to a low initial soil moisture deficit of 60 mm and concentrated rainfall distribution with high-intensity rainfall events. Similarly, in 2019 which also received an above-average rainfall of 722 mm, there was potentially 211 mm of recharge as it was high in magnitude and distributed evenly throughout the season. The analysis of Fig 8 suggests that the potential recharge in the semiarid regions depends on factors including initial soil moisture deficit, rainfall intensity, and its distribution. Annual rainfall only is not a good indicator for estimating recharge.

3.7 Sensitivity analysis

The effect of various soil water balance parameters on computed recharge is presented in Fig 9. Further, Table 6 presents the summary of sensitivity analysis performed. Depending on the relative humidity, wind velocity, and percentage of ground cover, the combined crop coefficient (K_{cm}) can vary between 1.06±0.1. A higher combined crop coefficient results in higher evapotranspiration during the mid-growth stage and hence 11.63% change in potential groundwater recharge. Similarly, a reduced combined crop coefficient produced 10.73% change in potential groundwater recharge due to the reduction in evapotranspiration. Variation in moisture availability in the soil zone, especially under rainfed conditions, results in a variable root depth for the millet crop, which can vary by a range of 0.6±0.15m in the semiarid regions under rainfed conditions. Maximum root growth occurs in the first 40 days, and therefore later rainfall has little impact on the root length. The maximum root depth of 0.75 m represents the condition of a water-stressed region with higher evapotranspiration losses resulting in 15.56% reduction in average annual potential recharge. If the soil is frequently wetted or has regular rainfall in rainfed conditions, the maximum root depth can be reduced to 0.45 m, which restricts the evapotranspiration losses and allows 19.01% more water to the potential recharge. Total available water (TAW) is the amount of water that a crop can extract from its root zone, and its magnitude depends on the field capacity, wilting point, and root depth. Variation in the soil type (texture) can result in different values of TAW in the range of 0.06±0.02. Increased value of TAW results in a 5.65% reduction in average potential recharge, while a reduced value caused a 5.83% higher average potential recharge.

Near-surface soil storage (NSS) is a fraction that varies between zero and one, representing the amount of moisture retained in the near soil surface which is available for the crop. The

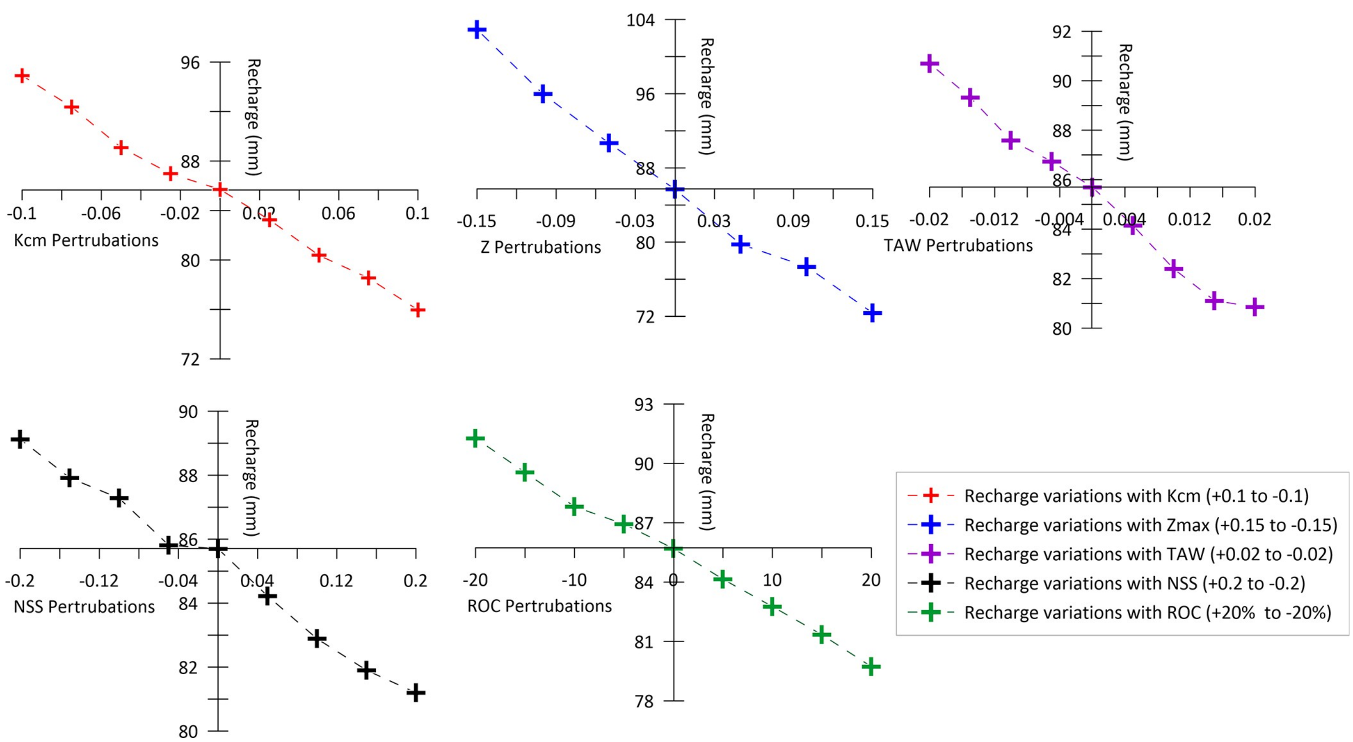

Fig 9. Sensitivity analysis of the soil water balance parameters (horizontal axes- fraction of change) on computed recharge (vertical axes). The range of perturbation for crop coefficient (K_{cm}), maximum root depth (Z_{max}), total available water (TAW), near-surface soil storage (NSS), and runoff coefficient (ROC) is shown in brackets.

https://doi.org/10.1371/journal.pwat.0000061.g009

Table 6. Summary of the relative sensitivity analysis performed on crop parameters (K_{cm} and Z_{max}), soil parameters (TAW, NSS), and runoff coefficient.

Parameters	Base annual recharge (mm/year)	Change in the parameters	Relative change in recharge, (%)
Crop coefficient (K_{cm})	85.7	+0.1	11.36
		-0.1	10.73
Maximum root depth (Z_{max}) (m)	85.7	+0.15	15.56
		-0.15	19.01
Total available water (TAW) (m^3/m^3)	85.7	+0.02	5.65
		-0.02	5.83
Near-surface soil storage (NSS)	85.7	+0.2	5.25
		-0.2	4.0
Runoff coefficient (ROC) (%)	85.7	+20	6.96
		-20	6.50

Note: Relative change in recharge (%) = $[(R_s - R_b)/R_b] \times 100$ where R_s is Simulated annual recharge and R_b base annual recharge.

https://doi.org/10.1371/journal.pwat.0000061.t006

range of *NSS* in the field can vary in the range of 0.25±0.2 based on the soil type. Increased NSS value (0.45) retains more water near the soil surface, resulting in 5.25% lower average potential recharge. However, a lower *NSS* (0.05) provides 4.0% more water to average potential recharge. Similarly, variation in the runoff coefficient directly impacts average potential recharge. An increase in runoff coefficients by 20% results in 6.96% less water annually for potential recharge, and a similar reduction (20%) in the runoff coefficient provides 6.50% more water for potential recharge. Sensitivity analysis suggests that the maximum root depth, runoff coefficient and combined crop coefficient are the most sensitive parameters of the soil water balance approach which is reflected in Fig 9.

4. Discussion

The recharge estimation using the soil water balance method for agricultural land and barren land shows that the change in land use pattern affects the recharge rate. Barren land with natural grass cover experiences less evapotranspiration than agricultural land with a millet crop, and hence the barren land provides more recharge [3]. Recharge studies in semiarid regions with similar climatic conditions suggest that the irrigation return flow could be up to 40% [52]. However, this study suggests that with an efficiently planned irrigation schedule, depth of irrigation and irrigation method, there may be no excess water beyond the soil zone depth.

The impact of rainfall variability is immediately evident on surface water sources. However, its impact on groundwater is complex and long-lasting, often with a time lag between incidence and effect [53]. This study indicates that in semiarid regions, a substantial amount of rainfall is required to reduce a high soil moisture deficit and increase the moisture content of the soil to its field capacity. Further, rainfall variability in semiarid regions is also a significant factor in groundwater recharge and agricultural production. Increased groundwater availability significantly impacts land use patterns and cropped areas [54]. Annual rainfall in the study area for 2017–18 was 318 mm compared to 2018–19 when it was 455.3 mm. The cropped area for irrigation-dependent winter crops increased from 15% to 76% between these two years.

In a hard rock aquifer, groundwater flow is restricted to the fractures and forced to flow along a complex pathway [55]. Therefore, groundwater recharge in these aquifers occurred along the fracture-controlled preferential flow paths [56] with some delay between the potential recharge and actual recharge [53]. This study reinforces the delayed recharge process and identifies the potential delay between the potential recharge and its impact on the water table. However, time to reach the water table can be reduced as saturation level increases in the unsaturated zone and depth to the water table declines. The shallow water table and high potential recharge indicate that the delay in actual recharge could only be attributed to the complex geology comprised of weathered gneiss. Weathered gneiss predominantly has a fracture-based flow mechanism and low permeability, which might be the reason for the delay between potential and actual recharge.

Groundwater recharge in the north western part of India has been estimated using the tritium injection method in a rainfed grassland setting in 1972–1973 and 1994–1995 ([57]); and the Cl mass balance approach and nutrient availability method in rain-fed/irrigated cropland [26]. Median recharge rates in 1972–1973 and 1994–1995 were 35, 43, and 67 mm/year, representing 8, 9, and 14% of precipitation (460, 470, and 491 mm), respectively. Scanlon et al. [26] reported a similar recharge rate of 61–94 mm/year (10–16% of precipitation, 600 mm/year) for rain-fed agriculture of the Jaipur study area. These recharge rates are within the range found in this study (Table 5).

The recharge rate estimated using the soil water balance could be uncertain because errors in all terms accumulate in the recharge rates; however, smaller steps can minimize these errors [18]. More detailed measurement of evapotranspiration and the components of Total Available Water and Total Evaporable Water (Eqs 3 and 4) would allow more accurate estimation and this is an area for further research. As demonstrated in this study, the daily time step, along with detailed consideration of physical processes for both soil and crops, this method is suitable for routine potential recharge estimation in semiarid field conditions. Further, consideration of delayed recharge process, rainfall variability, and land-use change makes this method suitable for actual recharge estimation in various climatic conditions, situations, and locations.

5. Conclusions

The soil water balance method confirms the groundwater recharge dependency on the variability of the rainfall and land use pattern. This study suggests that the annual recharge in semiarid regions can vary significantly due to the erratic rainfall behavior and variability in the land use pattern. Historic rainfall-recharge analysis indicates that the initial soil moisture deficit, intensity, and distribution of monsoon rain are crucial factors for groundwater recharge. The irrigated agricultural land in this semiarid region has limited potential for groundwater recharge due to efficient irrigation methods employed to maximize groundwater use. Barren lands with limited root depth have less evapotranspiration, allowing more water below the soil zone for potential groundwater recharge.

Conversion of potential recharge estimated using SWB to actual groundwater recharge was also achieved using the delayed groundwater recharge process. Further, estimated actual groundwater recharge could also be validated with the observed water levels in the study area, proving the SWB approach's efficacy. Sensitivity analysis suggests that the maximum root depth and crop coefficient significantly impact groundwater recharge. Therefore, crops with shallow roots can help increase groundwater recharge potential in the semiarid regions. The suggested approach could be an alternative to the methods recommended by the Groundwater Estimation Committee (2015) for assessing groundwater resources at the regional scale in India.

Supporting information

S1 Text.
(DOCX)

S1 Table. Details of the large diameters wells used for pumping tests in dry and wet season of 2019.
(DOCX)

Acknowledgments

The authors are grateful to Prof. Ken Rushton for his insights and support during the conceptualization and implementation of this work. The research was funded by NERC-DST (Grant Ref: NE/R003351/1). The CEO of local NGO Gram Vikas Navyuvak Mandal Laporiya gave permission to access the fieldsites. The following people are thanked for their support during the fieldwork: Mr. Jagveer Singh, Sangram Singh, Sanju Devi.

Author Contributions

Conceptualization: Basant Yadav, Alison Parker, Anupma Sharma.

Data curation: Basant Yadav, Suraj Kumar, Jaswant Singh.

Formal analysis: Basant Yadav.

Funding acquisition: Alison Parker, Anupma Sharma.

Methodology: Basant Yadav, Alison Parker.

Supervision: Alison Parker, Anupma Sharma.

Writing – original draft: Basant Yadav.

Writing – review & editing: Alison Parker, Anupma Sharma, Rakesh Sharma, Gopal Krishan, Kristell Le Corre, Pablo Campo Moreno.

References

1. Sophocleous MA. Stream-floodwave propagation through the Great Bend alluvial aquifer, Kansas: field measurements and numerical simulations. Journal of Hydrology. 1991 May 1; 124(3–4):207–28. https://doi.org/10.1016/0022-1694(91)90015-A
2. Garatuza-Payan J, Shuttleworth WJ, Encinas D, McNeil DD, Stewart JB, DeBruin H, et al. Measurement and modelling evaporation for irrigated crops in north-west Mexico. Hydrological processes. 1998 Jul; 12(9):1397–418.
3. Allen RG, Pereira LS, Raes D, Smith M. Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56. Fao, Rome. 1998; 300(9): D05109.
4. De Vries JJ, Simmers I. Groundwater recharge: an overview of processes and challenges. Hydrogeology Journal. 2002 Feb; 10(1):5–17.
5. Lerner DN, Issar A, Simmers I. Groundwater recharge: A guide to understanding and estimating natural recharge. Hannover, West Germany: Verlag Heinz Heise; 1990.
6. Sandström K. Modeling the effects of rainfall variability on groundwater recharge in semi-arid Tanzania. Hydrology Research. 1995 Aug; 26(4–5):313–30.
7. Barnes CJ, Jacobson G, Smith GD. The distributed recharge mechanism in the Australian arid zone. Soil Science Society of America Journal. 1994 Jan; 58(1):31–40. https://doi.org/10.2136/sssaj1994.03615995005800010005x
8. Lloyd JW. A review of aridity and groundwater. Hydrological processes. 1986 Dec; 1(1):63–78.
9. Gupta A, Kamble T, Machiwal D. Comparison of ordinary and Bayesian kriging techniques in depicting rainfall variability in arid and semi-arid regions of north-west India. Environmental Earth Sciences. 2017 Aug; 76(15):1–6.
10. Allison GB, Hughes MW. The use of natural tracers as indicators of soil-water movement in a temperate semi-arid region. Journal of Hydrology. 1983 Jan 1; 60(1–4):157–73.
11. Allison GB, Cook PG, Barnett SR, Walker GR, Jolly ID, Hughes MW. Land clearance and river salinisation in the western Murray Basin, Australia. Journal of Hydrology. 1990 Nov 1; 119(1–4):1–20.

12. Anuraga TS, Ruiz L, Kumar MM, Sekhar M, Leijnse A. Estimating groundwater recharge using land use and soil data: A case study in South India. Agricultural water management. 2006 Jul 16; 84(1–2):65–76.

13. Scanlon BR, Reedy RC, Tachovsky JA. Semiarid unsaturated zone chloride profiles: Archives of past land use change impacts on water resources in the southern High Plains, United States. Water Resources Research. 2007 Jun; 43(6).

14. Zimmermann B, Elsenbeer H. Spatial and temporal variability of soil saturated hydraulic conductivity in gradients of disturbance. Journal of Hydrology. 2008 Oct 30; 361(1–2):78–95.

15. Rushton KR, Eilers VH, Carter RC. Improved soil moisture balance methodology for recharge estimation. Journal of Hydrology. 2006 Mar 1; 318(1–4):379–99.

16. De Silva CS, Rushton KR. Representation of rainfed valley ricefields using a soil–water balance model. agricultural water management. 2008 Mar 1; 95(3):271–82.

17. Hellwig DH. Evaporation of water from sand, 1: Experimental set-up and climatic influences. Journal of hydrology. 1973 Feb 1; 18(2):93–108.

18. Scanlon BR, Healy RW, Cook PG. Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeology journal. 2002 Feb; 10(1):18–39.

19. Kinzelbach W, Aeschbach W. A survey of methods for analysing groundwater recharge in arid and semi-arid regions. Division of Early Warning and Assessment, United Nations Environment Programme; 2002.

20. Fitzsimons VP, Misstear BD. Estimating groundwater recharge through tills: a sensitivity analysis of soil moisture budgets and till properties in Ireland. Hydrogeology Journal. 2006 Apr; 14(4):548–61.

21. Chung IM, Kim NW, Lee J, Sophocleous M. Assessing distributed groundwater recharge rate using integrated surface water-groundwater modelling: application to Mihocheon watershed, South Korea. Hydrogeology Journal. 2010 Aug; 18(5):1253–64.

22. Eilers VH, Carter RC, Rushton KR. A single layer soil water balance model for estimating deep drainage (potential recharge): An application to cropped land in semi-arid North-east Nigeria. Geoderma. 2007 Jun 15; 140(1–2):119–31.

23. Rushton KR, Asaduz Zaman M, Hasan M. Monitoring groundwater heads and estimating recharge in multi-aquifer systems illustrated by an irrigated area in north-west Bangladesh. Sustainable Water Resources Management. 2020 Apr; 6(2):1–2.

24. Gee GW, Hillel D. Groundwater recharge in arid regions: review and critique of estimation methods. Hydrological processes. 1988 Jul; 2(3):255–66.

25. Hendrickx J.M. and Walker G. (1997) Recharge from Precipitation, Chapter 2. In: Simmers I., Ed., Recharge of Phreatic Aquifers in (Semi)-Arid Areas, IAH Contributions to Hydrogeology Series, Taylor and Francis, Balkema, Rotterdam.

26. Scanlon BR, Mukherjee A, Gates J, Reedy RC, Sinha AK. Groundwater recharge in natural dune systems and agricultural ecosystems in the Thar Desert region, Rajasthan, India. Hydrogeology journal. 2010 Jun; 18(4):959–72.

27. Owuor SO, Butterbach-Bahl K, Guzha AC, Rufino MC, Pelster DE, Díaz-Pinés E, et al. Groundwater recharge rates and surface runoff response to land use and land cover changes in semi-arid environments. Ecological Processes. 2016 Dec; 5(1):1–21.

28. Chinnasamy P, Maheshwari B, Dillon P, Purohit R, Dashora Y, Soni P, et al. Estimation of specific yield using water table fluctuations and cropped area in a hardrock aquifer system of Rajasthan, India. Agricultural Water Management. 2018 Apr 1; 202:146–55.

29. Mileham L, Taylor R, Thompson J, Todd M, Tindimugaya C. Impact of rainfall distribution on the parameterisation of a soil-moisture balance model of groundwater recharge in equatorial Africa. Journal of Hydrology. 2008 Sep 15; 359(1–2):46–58.

30. Owor M, Taylor RG, Tindimugaya C, Mwesigwa D. Rainfall intensity and groundwater recharge: empirical evidence from the Upper Nile Basin. Environmental Research Letters. 2009 Sep 30; 4(3):035009.

31. Nasta P, Allocca C, Deidda R, Romano N. Assessing the impact of rainfall seasonality anomalies on catchment-scale water balance components 2. Hydrology and Earth System Sciences Discussions. 2019 Oct 29; 2019:1–39.

32. Parker AH, Nyangoka J, Rodrigues I, Yadav B, Le Corre KS, Campo P, et al. The multiple uses of water derived from managed aquifer recharge systems in Kenya and India. Journal of Water, Sanitation and Hygiene for Development. 2022 Feb; 12(2):208–16.

33. CGWB, Aquifer Systems of India, Government of India, Ministry of Water Resources, Central Ground Water Board, 2012, 22.

34. Singh A, Acharya N, Mohanty UC, Robertson AW, Mishra G. On the predictability of Indian summer monsoon rainfall in general circulation model at different lead time. Dynamics of atmospheres and oceans. 2012 Nov 1; 58:108–27.

35. CGWB. Aquifer Mapping and Ground Water Management. Central Ground Water Board (WR) Western Region Jaipur. 2017. Available from: http://cgwb.gov.in/reportspublished.html

36. Cherlet M, Hutchinson C, Reynolds J, Hill J, Sommer S, Von Maltitz G. World atlas of desertification rethinking land degradation and sustainable land management, Publication Office of the European Union, Luxembourg.

37. Central Ground Water Board. Ground Water Year Book, 2015–16. Ministry of Water Resources, New Delhi, India.

38. Chandramouli C, General R. Census of India 2011. Provisional Population Totals. New Delhi: Government of India. 2011.

39. CGWB. Ground Water Information: Jaipur District, Rajasthan. 2013. Available from: http://www.cgwb.gov.in/District_Profile/Rajasthan/Jaipur.pdf

40. Rajasthan Ground Water Department, Reappraisal of ground water resources of Udaipur District on 31.03.2007. Ground Water Department (GWD), Government of Rajasthan, Jodhpur, India. 2008

41. Rushton KR. Groundwater hydrology: conceptual and computational models. John Wiley & Sons; 2003 Feb 6.

42. Hargreaves GL, Hargreaves GH, Riley JP. Irrigation water requirements for Senegal River basin. Journal of Irrigation and Drainage Engineering. 1985 Sep; 111(3):265–75.

43. Carter RC, Rushton KR, Eilers VH, Hassan M. Modelling with limited data:" Plausibility" as a measure of model reliability. ACTA-UNIVERSITATIS CAROLINAE GEOLOGICA. 2002 Jun(2/3):328–30.

44. Everard M, West H. Livelihood security enhancement though innovative water management in dryland India. Water International. 2021 Jan 2; 46(1):59–82.

45. Yadav B, Patidar N, Sharma A, Panigrahi N, Sharma RK, Loganathan V, et al. Assessment of traditional rainwater harvesting system in barren lands of a semi-arid region: A case study of Rajasthan (India). Journal of Hydrology: Regional Studies. 2022 Aug 1; 42:101149.

46. Jolly ID, Cook PG, Allison GB, Hughes MW. Simultaneous water and solute movement through an unsaturated soil following an increase in recharge. Journal of Hydrology. 1989.

47. Healy RW, Cook PG. Using groundwater levels to estimate recharge. Hydrogeology journal. 2002 Feb; 10(1):91–109.

48. Price M, Low RG, McCann C. Mechanisms of water storage and flow in the unsaturated zone of the Chalk aquifer. Journal of Hydrology. 2000 Jun 12; 233(1–4):54–71.

49. Ghauri S., (2004). Groundwater Trends in the Central Agricultural Region. Resource Management Technical Report 269. Department of Agriculture, Western Australia.

50. O'Reilly AM. Hydrogeology and simulation of the effects of reclaimed-water application in west Orange and southeast Lake Counties, Florida. US Department of the Interior, US Geological Survey; 1998.

51. Lee LJ, Lawrence DS, Price M. Analysis of water-level response to rainfall and implications for recharge pathways in the Chalk aquifer, SE England. Journal of hydrology. 2006 Nov 15; 330(3–4):604–20.

52. Maréchal JC, Dewandel B, Ahmed S, Galeazzi L, Zaidi FK. Combined estimation of specific yield and natural recharge in a semi-arid groundwater basin with irrigated agriculture. Journal of Hydrology. 2006 Sep 30; 329(1–2):281–93.

53. Rathore MS. Groundwater exploration and augmentation efforts in Rajasthan–a review. Institute of Development Studies, Jaipur, India. 2005 Feb.

54. Pathak P, Chourasia AK, Wani SP, Sudi R. Multiple impact of integrated watershed management in low rainfall semi-arid region: A case study from eastern Rajasthan, India. Journal of Water Resource and Protection. 2013; 5(1):27–36.

55. Stiefel JM, Melesse AM, McClain ME, Price RM, Anderson EP, Chauhan NK. Effects of rainwater-harvesting-induced artificial recharge on the groundwater of wells in Rajasthan, India. Hydrogeology Journal. 2009 Dec; 17(8):2061–73.

56. Sukhija BS, Reddy DV, Nagabhushanam P, Hussain S. Recharge processes: piston flow vs preferential flow in semi-arid aquifers of India. Hydrogeology Journal. 2003 Jun; 11(3):387–95.

57. Rangarajan R, Athavale RN. Annual replenishable ground water potential of India—an estimate based on injected tritium studies. Journal of hydrology. 2000 Jun 30; 234(1–2):38–53.