Catena 211 (2022) 105972

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Impact of raised beds on surface runoff and soil loss in Alfisols and Vertisols

Kaushal K. Garg *, K.H. Anantha, Sreenath Dixit, Rajesh Nune, A. Venkataradha, Pawan Wable, Nagaraju Budama, Ramesh Singh

ICRISAT Development Center, ICRISAT, Patancheru 502 324, Hyderabad, India

ARTICLE INFO

Keywords:
Rainfall-runoff relationship
Soil loss
Hydrological monitoring
Raised beds
Flat beds

ABSTRACT

Hydrological monitoring is crucial to designing agricultural water management (AWM) interventions. This study characterizes the soil hydraulic properties of Alfisols and Vertisols and develops rainfall-runoff-soil loss relationships through long-term hydrological monitoring. Two types of landform management techniques, i.e., raised bed and flat bed, were followed in three paired watersheds of 2–5 ha, characterized by deep Vertisols, medium deep Vertisols and Alfisols. Surface runoff and soil loss were monitored at the outlet of the respective watersheds for 8–12 years. In addition, 29 infiltration tests were conducted using a tension disc infiltrometer by applying a suction of −150 mm, −100 mm, −50 mm, and −20 mm. Soil macro porosity and hydraulic conductivity in the raised bed landform were found to be almost double those in the flat beds at −50 mm suction head in both the soil types. Saturated hydraulic conductivity was found higher in Alfisols compared to Vertisols; however, less runoff was generated in Vertisols compared to Alfisols. This phenomenon is largely explained by the high water storage capacity of Vertisols. Runoff generated from both the soils was less than 2% of total rainfall (<500 mm) received in dry years. In normal years (600–900 mm), runoff coefficient for Vertisols ranged from 7–11% of total rainfall compared to 16–17% in the case of Alfisols. However, runoff generated from fallow land was 17% in deep Vertisols due to higher soil moisture content and limited available storage compared to the cropped land. The raised bed method reduced surface runoff by 15–20 mm in Alfisols compared to 35–40 mm in Vertisols. Runoff from the raised beds was significantly lower during light and moderate intensity rainfall compared to the flat bed method; however, this difference was not significant during events of high and very high intensity rainfall. In addition, raised beds reduced soil loss by 30–60% compared to flat beds. The results of this study are useful in designing evidence-based AWM strategies under rainfed conditions.

1. Introduction

There is growing concern over declining availability of resources, water scarcity and land degradation in the drylands that can impede sustainable crop intensification (Fu et al., 2020; Wei et al., 2021; deAraujo et al., 2021). Land degradation is negatively affecting crop yields and their sustainability across the globe (Montgomery, 2007; Meena et al., 2020). The removal of top soil largely through water and wind erosion is one of the major causes of land degradation (FAO and ITPS, 2015; An et al., 2021). Annual soil loss worldwide was estimated at about 75 billion tons (in 1995), causing economic losses of about US$ 600 billion per year, equivalent to US$ 80 per person per year (Pimentel et al., 2010). Soil degradation has been identified as one of the threats that affect the long term sustainability of agricultural systems. Hence much attention has been paid to soil themed strategies by the European Union (CCCEP, 2006; European Parliament, 2006; Moebius-Clune et al., 2016; Bagagiolo et al., 2018; Capello et al., 2019; Bonfante et al., 2020; European Commission, 2020). The 2030 Agenda for Sustainable Development adopted by all UN member countries in 2015 aims to improve the well-being of people while protecting the planet by implementing 17 Sustainable Development Goals (SDGs). Goal 15 on 'Life on Land' is dedicated to combating desertification, halting and reversing land degradation, protecting, restoring and promoting the sustainable use of terrestrial ecosystems (United Nations, 2015).

A number of agricultural water management (AWM) interventions have been designed to control land degradation and enhance moisture availability, especially in the drylands (Kelly, 2014; Garg et al., 2020; Zhang et al., 2020; Garg et al., 2021; Singh et al., 2021a). Raised beds, minimum/zero-tillage, mulching, conservation furrow, field and contour bunding and cultivation across the slope are some of the *in-situ*

* Corresponding author.
E-mail address: k.garg@cgiar.org (K.K. Garg).

https://doi.org/10.1016/j.catena.2021.105972
Received 1 April 2021; Received in revised form 25 October 2021; Accepted 20 December 2021
Available online 28 December 2021

conservation measures being used (Biddoccu et al., 2013; Mhizha and Ndiritu, 2013; Liu et al., 2018; Li et al., 2019; Ebabu et al., 2019; Capello et al., 2019; Bagagiolo et al., 2018; Capello et al., 2020; Singh et al., 2021b; Anantha et al., 2021a; Anantha et al., 2021b). Since 1990, public and private sector agencies in India have invested about US$ 14 billion on these interventions in dryland regions as drought proofing measures (Garg et al., 2011; Garg et al., 2012; Santra and Das, 2013; Singh et al., 2014; Karlberg et al., 2015; Ali et al., 2020; Mondal et al., 2017; Singh et al., 2018; Mondal et al., 2020). Despite these heavy investments, data monitoring and the characterization of rainfall-runoff and rainfall-soil loss relationships is lacking (Glendenning et al., 2012; Aissia et al., 2017). Hydrological assessment in these ecologies is largely dependent on downscaling methods from catchment scale monitoring (river basin scale) to meso-scale watersheds or field scale (Habets et al., 2018; Ahmadi et al., 2019). In addition, the hydrological response of different soils has not been well accounted for while running such models. In both cases, planning and designing of AWM interventions have failed to factor field realities, leading to either over or underutilization of resources.

Alfisols and Vertisols are the major soil types in the drylands. Alfisols cover nearly 33% of the area in the drylands (Pathak et al., 2016) and are mainly prevalent in southern Asia, western and central Africa and South America, particularly northeast Brazil (El-Swaify et al., 1985). Vertisols, also known as black cotton soil, are abundant in India, Sudan, Ethiopia, Australia and several other countries (El-Swaify et al., 1985). Alfisols are often light textured, have poor water holding capacity, shallow effective rooting depth and traditionally support a single crop grown as a monoculture under rainfed situations. Surface sealing, crusting, low soil organic carbon and low soil fertility have been reported in Alfisols (Mullins et al., 1990; Selvaraju et al., 1999; Meena et al., 2020). In contrast, Vertisols are heavy textured, have higher clay content and moderate to high water holding capacity. They develop deep cracks while drying and exhibit slow internal drainage, with infiltration rates between 20 mm/day and 60 mm/day after getting wet (Erkossa et al., 2004; Harmel et al., 2006; Dinka et al., 2013). Hydrological responses in these soils differ due to differences in their water retention capacity and soil hydraulic properties (Pathak et al., 2016). A comprehensive understanding of this phenomenon is lacking while planning and implementing rainwater management interventions.

Against this background, this paper attempts to describe the hydrological processes at play in both soil types under two types of landform management. Our overarching aim is to (i) establish rainfall-runoff and rainfall-soil loss relationships for different soil types in different rainfall years; and (ii) evaluate the impact of raised bed landform on surface runoff and soil loss in the two soil types. We, therefore, followed a paired experimental approach by treating 2–5 ha scale micro-watersheds with two types of landform management, flat beds and raised beds, where surface runoff and soil loss were measured for 8–12 years. In addition, a large number of infiltration experiments were undertaken to characterize the hydraulic properties of Vertisols and Alfisols under both methods.

2. Material and methods

2.1. Site description

ICRISAT is located in Hyderabad in Telangana state of India (17.5192° N; 78.2784° E). The site is unique in that it has both Alfisols and Vertisols which make it easy to study the behavior of two major soil types that dominate the drylands. This study was undertaken in the ICRISAT Heritage watersheds (3 paired watersheds with a land slope of 2–3%) which naturally drain from 2 to 5 ha of the catchment. Of the three, two paired watersheds have Vertisols (named BW1 and BW2) & (BW3 and BW4) and one set has Alfisols (RW1 and RW2) (Table 1). A layer-wise analysis of the physical properties of the soils (texture, field capacity, permanent wilting point, bulk density, porosity) was done in 5–10 locations in each of the micro-watersheds to capture the heterogeneity of the experimental sites. The total catchment, cropping system, landform management, soil depth and other biophysical parameters in the micro-watersheds are presented in Table 1**.**

2.2. Overall field experiment

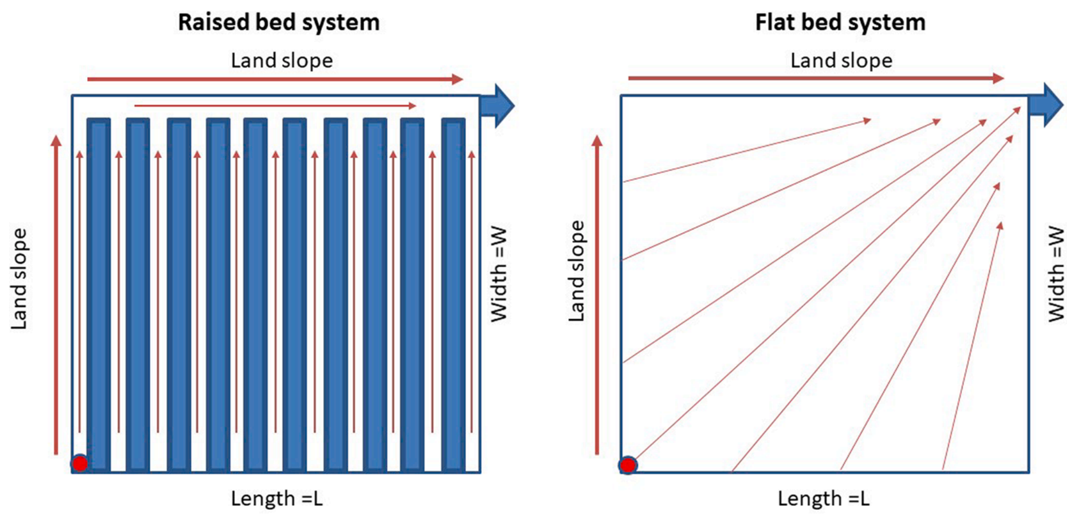
Long-term field experiments were conducted in the experimental watersheds during different time frames, but the data reported is for the 8 to 12-year period (Table 1**)**. All the experiments were undertaken under rainfed conditions and no irrigation was applied. The paired watersheds under this research initiative were characterized as (i) deep Vertisols (BW1 and BW2); (ii) medium deep Vertisols (BW3 and BW4); and (iii) Alfisols (RW1 and RW2). Landscape with a soil depth between 0.90 m and 1.50 m (till it reaches the hard bed) was considered as deep whereas medium deep soil had a depth ranging between 0.50 m and 0.90 m (Pathak et al., 2016). The depth of the soil profile from the top to the parent material (or bed rock) is congenial; root penetration beyond this depth is negligible (Wei and Bing, 2014).

The main purpose of these experiments was to compare hydrological responses between raised bed and flat bed landforms. Fig. 1 shows the schematic representation of both landforms. In the traditional flat bed method of cultivation, the crop is grown under ordinary field conditions. Runoff from the field naturally drains towards the land slope. In a raised bed, the bed is 0.90 m wide and a furrow of 0.60 m is made with a 0.50–0.60% slope using a tropicultor (ICRISAT, 1985; Erkossa et al., 2011, 2014; Pathak et al., 2013). Under raised beds, runoff retention time is extended as water has to flow in a guided manner along the furrow. This helps harvest extra soil moisture and at the same time facilitates the disposal of excess runoff during heavy rainfall events (Erkossa et al., 2011, 2014; Pathak et al., 2016; Anantha et al., 2021a, Anantha et al., 2021b). The raised part of the bed is the crop zone and

Table 1
Cropping systems and landform management in the experimental watersheds.

Soil type	Deep Vertisols		Medium deep Vertisols		Alfisols	
Landform	Raised bed	Flat bed	Raised bed	Flat bed	Raised bed	Flat bed
Watershed	Black soil watershed no. 1 (BW1)	Black soil watershed no. 2 (BW2)	Black soil watershed no. 3 (BW3)	Black soil watershed no. 4 (BW4)	Red soil watershed no. 1 (RW1)	Red soil watershed no. 2 (RW2)
Cropping system	Sorghum /pigeonpea intercrop	*Kharif* fallow (wet season) -*rabi* sorghum (dry season)	Maize /pigeonpea intercrop	Maize /pigeonpea intercrop	Sorghum /pigeonpea or groundnut intercrop	Sorghum /pigeonpea or groundnut intercrop
Experiment period	1997–2008	1997–2008	1997–2006	1997–2006	2002–2009	2002–2009
Catchment (ha)	3.48	3.41	2.33	2.59	1.25	2.00
Soil depth (m)	1.20–1.50	1.20–1.50	0.60–0.75	0.60–0.75	0.90–1.10	0.90–1.10
Hydrological data recorded	Only runoff		Runoff and soil loss		Runoff and soil loss	

Note: BW = Black soil watershed; RW = Red soil watershed; *wet* season: Crops cultivated during monsoon (Jun-Oct); *dry* season: Crops cultivated during post-monsoon (Nov-Mar).



$$Travel\ distance\ (D_i)_{RB} = L_i + W_i \qquad Travel\ distance\ (D_i)_{FB} = \sqrt{L_i^2 + W_i^2}$$

Fig. 1. A schematic representation of raised beds and flat beds. The red dot indicates the most elevated location within the micro-watershed and the red arrows indicate the direction in which the water travels. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the furrow is used for intercultural operations (Fig. 2).

2.2.1. *Field experiment in deep Vertisols (BW1 vs. BW2)*

Vertisols have high clay content and swell during wet periods and develop cracks during dry periods (Pal et al., 2009; Dinka et al., 2013). This contraction and swelling makes these soils difficult to cultivate; therefore farmers leave their land fallow during the rainy season and only cultivate during the dry season (*rabi* in local parlance) using

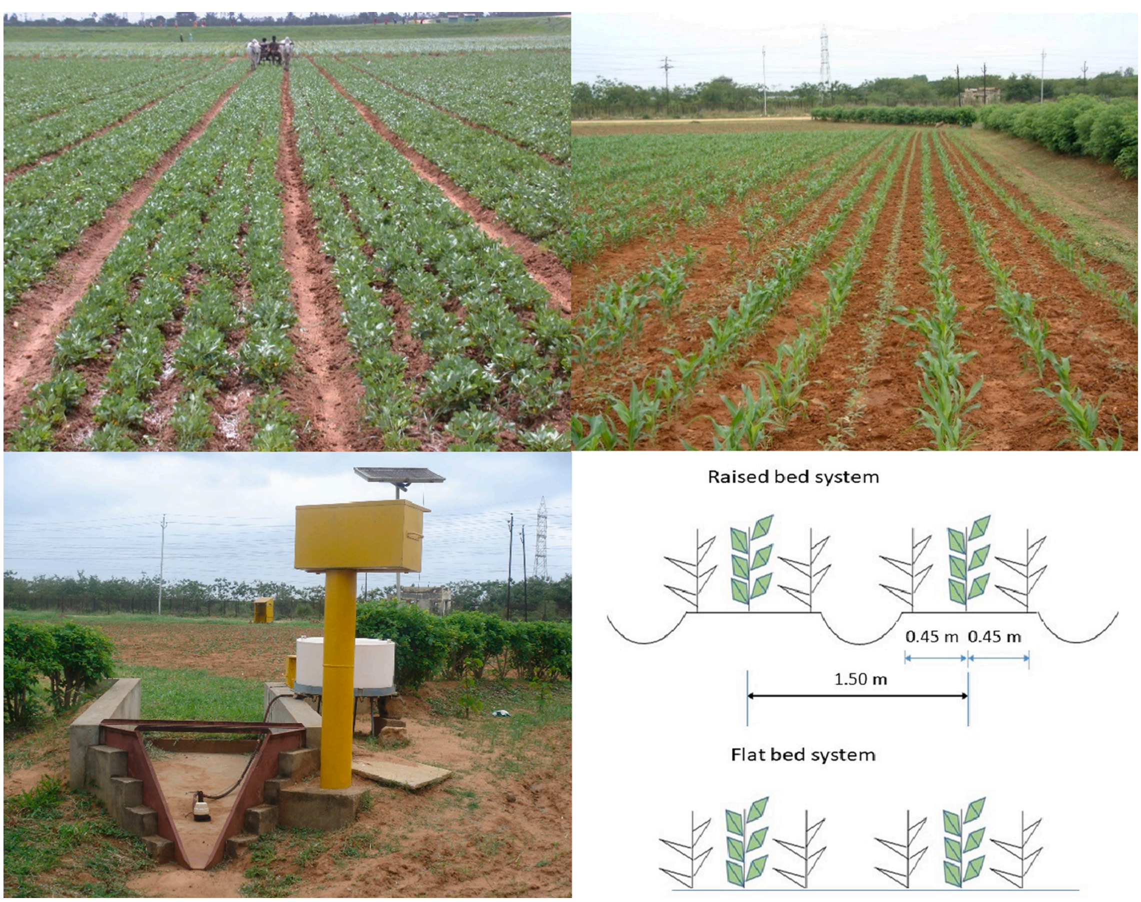


Fig. 2. (clockwise from top left) Groundnut on raised bed; sorghum/pigeonpea intercropping on flat bed; a runoff gauging station and sediment sampling unit installed at the outlet of the Alfisols watershed; and raised beds and flat beds in sorghum/pigeonpea (2:1) intercropping.

residual soil moisture (Rao et al., 2015). Under this experiment, two types of landform management were compared in deep Vertisols: (i) Raised bed representing the improved practice in BW1 and ii) flat bed representing farmers' practice in BW2. Sorghum intercropped with pigeonpea was grown on raised beds during the monsoon in BW1. Sorghum grows in 110 days (Jun-Sep) and pigeonpea (Jun-Feb) is of relatively longer duration in 180 days. Between every two rows of sorghum grown 0.70 m apart, one row of pigeonpea was grown (Fig. 2). The raised beds have remained undisturbed over the last 30 years while the furrows were opened up before every monsoon season. In BW2, only sorghum was cultivated during the post-monsoon period (Oct-Jan) using the flat bed method, and the field was left fallow during the monsoon to represent farmers' practice. Intercultural operations were carried out to keep the fields weed free in both BW1 and BW2.

2.2.2. *Field experiment in medium deep Vertisols (BW3 and BW4)*

In another paired watershed in Vertisols, the landscape had raised beds (BW3) and flat beds (BW4) with the same cropping system, i.e., maize/pigeonpea intercropping. Maize and pigeonpea were sown at the beginning of the monsoon (mid-Jun) in a 2:1 ratio, i.e., one row of pigeonpea between two rows of maize spaced 1.5 m apart. Maize was harvested by the end of October and pigeonpea in February/March. Intercultural operations such as harrowing and hand weeding were undertaken from time to time to keep the fields weed free.

2.2.3. *Field experiment in Alfisols (RW1 and RW2)*

In this experiment, one part of the watershed located in Aflisols was treated with raised beds (RW1) and the other part with flat beds (RW2). Sorghum intercropped with pigeonpea was followed in both landforms. Sowing was completed during 2nd/3rd week of June every year. Intercultural operations such as harrowing and hand weeding were undertaken regularly to keep the fields weed free. Harvesting of the short-duration crop (sorghum) was done in September/October and pigeonpea was harvested in February/March.

2.3. *Data monitoring and analysis*

Table 2 shows the time of measurements of different hydrological parameters along with frequency and methods followed in current study. Throughout the experimental years, the raised beds in the watersheds were kept intact while the furrows were opened using a bullock-drawn tropicultor during sowing. We hypothesized that undisturbed beds may build soil structure over the period and improve soil hydraulic conductivity. To test this hypothesis, we undertook infiltration experiments using a tension disc infiltrometer (TDI) in 2012 (described in section 2.3.1*)*. The impact of raised beds on surface runoff and soil loss in both soil types was analysed through state-of-the-art monitoring for 8–12 years (refer section 2.3.2). Soil moisture availability in topsoil layers is one of the important factors generating surface runoff. If the soil moisture levels are high, there is limited space available to harvest rainwater in form of soil moisture and there is high likelihood to generate surface runoff. Therefore, soil moisture fluctuation and difference in water storage capacity was analysed through periodic soil moisture monitoring for entire crop seasons in respective watersheds between 2018 and 2020 (refer 2.3.2).

2.3.1. *Characterizing soil hydraulic properties in both landforms*

To characterize the hydraulic properties of Vertisols and Alfisols under raised bed and flat bed landforms, TDI tests were undertaken during March-May 2012 after the harvest of *rabi* crops. In Vertisols, 8 TDI tests were undertaken in the raised bed watershed (BW1) and 5 in the flat bed watershed (BW2). In Alfisols, 8 TDI tests were undertaken in the raised bed watershed (RW1) and 8 in the flat bed watershed (RW2). An infiltrometer with a disc radius of 100 mm was used. A retaining ring of 100 mm radius was fixed in the gently cleaned soil surface and a layer of less than 5 mm of sand was spread over the soil surface to ensure proper contact with the disc infiltrometer ring. For each infiltration test, different water tensions (e.g., −150 mm, −120 mm, −100 mm, −50 mm and −20 mm) starting from a higher suction head was imposed; it took nearly 6–7 h to complete a set of measurements. Both transient and steady-state water fluxes were recorded in each test. Soil cores were collected from an adjacent location to determine initial water content in the surface soil.

Sorptivity, a measure of the capacity of the medium to absorb or desorb liquid by capillarity, was estimated from the infiltration experiment. The square root of time transformation on cumulative infiltration is described by Smiles and Knight (1976), as shown in Eq. (1).

$$\frac{I}{\sqrt{t}} = S + A'\sqrt{t} \tag{1}$$

Where, I is the cumulative infiltration and t is time. Sorptivity (S) was determined from the intercept by plotting $\frac{I}{\sqrt{t}}$ against $\sqrt{t}$; saturated hydraulic conductivity (A') was calculated as the slope of the fitted line on the experimental data.

Water movement through macro-pores was estimated using the Watson and Luxmoore (1986) method. Pore radii for the imposed suction were estimated using the capillarity equation (Eq. (2))

$$r = \frac{2\sigma}{\rho g h} \tag{2}$$

where, σ is the surface tension of water, ρ is the density of water, g is the constant acceleration due to gravity, and h is the suction imposed on the tension infiltration disc.

Macro-pore conductivity (K_m) was calculated as the difference between the ponded infiltration rate and infiltration rate at applied suction (Watson and Luxmoore, 1986). Using minimum pore radius (r) and applying Eq. (2) in conjunction with Poiseuille's equation, the maximum number of effective macro-pores per unit area was calculated by Eq. (3):

$$N = \frac{8\mu K_m}{\pi \rho g r^4} \tag{3}$$

Where, μ is the viscosity of water.

Water conducting porosity (Θ_m) was estimated using Eq. (4):

$$\Theta_m = N\pi r^2 \tag{4}$$

Total water conducting porosity (Θ_{mt}) was estimated by summing up Θ_m values for imposed tensions from 0 to −150 mm.

Saturated hydraulic conductivity (K_s) for surface soil (0–10 cm) was obtained by fitting the Gardner's exponential model using unsaturated

Table 2
Hydrological data monitored at different time scale.

Parameter	Time of measurement (year)																								Scale (frequency)	Frequency	Method used
	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020			
Infiltration characteristics																■									Point based	One time (March-May 2012)	Tension disc infiltrometer
Rainfall	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	Hourly & daily	Continuous-Automatic	Weather station
Runoff & soil loss	■	■	■	■	■	■	■	■	■	■	■	■	■												Event wise	Continuous-Automatic	*H-flume* coupled with sediment sampling unit
Soil moisture																						■	■	■	0-0.15 m depth	Weekly	Gravimetric method

hydraulic conductivity function (ref Eq. (5)) to steady-state water fluxes at different supply pressures.

$$K(h) = K_s \exp(bh) \quad (5)$$

2.3.2. Monitoring rainfall, soil moisture, runoff and soil loss

All three experimental sites were located within a radius of one kilometer. A state-of-the art meteorological station (300–900 m from the experimental watersheds) retrieved data on rainfall and other meteorological parameters (maximum and minimum temperature, wind speed, solar radiation and relative humidity) on a daily basis. Soil moisture measurement at surface depth (0–0.15 m) was taken using the gravimetric method. A 50-mm diameter core sampler was used to collect soil samples, whose moisture content was measured at weekly intervals for the select years (2018–2020). Data was analyzed to estimate soil moisture storage over different months in the experimental watersheds.

An *H-flume* and sediment sampling unit was installed at the outlet of the watersheds to monitor surface runoff and collect sediment samples from running water (Fig. 2). A stilling well was placed at the outlet which was hydraulically connected to the *H-flume*. A mechanical stage recorder was used to monitor runoff at two-minute intervals. The stage of the flowing water depth (i.e., height of the water surface) was converted into water volume using standard rating curve for different rainfall events. A rating curve is a graph that shows discharge versus stage for a given point in a stream (Kennedy, 1984). Sediment samples were collected at 30–60-minute intervals using an automatic sample collection unit (Pathak et al., 2004; 2016) and transferred to the laboratory to measure sediment concentration and soil loss for each rainfall event during the monitoring period. Rainfall and runoff measured from the experimental fields were analyzed for different dry, normal and wet years. Going by meteorological classification, a year receiving ± 20% rainfall of the long term average is classified as a normal year; rainfall < 20% of the long term average is a dry/deficit year and rainfall > 20% of the long term average is a wet/excess year (India Meteorological Department, 2010). Runoff response to different intensities of daily rainfall events (mm/day) was also analyzed (light intensity rainfall: <7.5 mm/day; moderate intensity: 7.5–35.5 mm/day; high intensity: 35.6–64.4 mm/day; and very high intensity; >64.5 mm, as per IMD classification).

2.4. Statistical analysis

2.4.1. Regression analysis between event rainfall and surface runoff

Linear regression was performed to establish the relationship between daily rainfall and measured surface runoff under raised bed and flat bed landforms for i) deep Vertisols (BW1 vs BW2); ii) medium deep Vertisols (BW3 vs BW4); and iii) Alfisols (RW1 vs RW2). In this analysis, slope of the regression line indicates the fraction of rainfall partitioned into surface runoff (called as runoff coefficient).

2.4.2. Analysis of variance (AVOVA)

Analysis of Variance (ANOVA) was used to evaluate the differences in mean and variance in hydraulic conductivity measured at different suction heads (TDI experiments) between Alfisols and Vertisols and in raised bed and flat bed landforms. Similarly, the level of significance for runoff and soil loss was evaluated in the two soil types and landforms. Daily, monthly and annual data on runoff and soil loss was used for this analysis. Runoff coefficients estimated for different rainfall intensities were also evaluated for the respective months using z-test and also through a post-hoc test to understand its level of significance. The statistical analysis was done using R-program.

3. Results

3.1. Soil retention and soil hydraulic properties of Vertisols and Alfisols

3.1.1. Soil retention

Soil texture (sand, silt and clay percentage), bulk density, porosity and moisture retention at 0.3 bar and 15 bar measured in Alfisols and Vertisols are shown in Table 3. The sand content in Alfisols was between 61% and 75% and clay content between 18% and 31%. In Vertisols, the sand content was in between 21% and 29% while clay content ranged between 50% and 58%. Soil moisture retention at 0.3 bar was in the range of 0.17–0.22% in Alfisols and 0.33–0.45% (v/v) in Vertisols. Bulk density data showed that the 30-year practice of raised beds increased top soil (0–0.15 m) porosity (55% in raised bed vs 42% in furrow) in Vertisols. Bulk density at 0–0.15 m was 1190 kg/m^3 in raised bed compared to 1550 kg/m^3 in furrows. Bulk density at lower layers (i.e., 0.15–0.30 m and 0.30–0.45 m) ranged from 1330 kg/m^3 to 1360 kg/m^3 in raised beds. A comparison of flat bed and raised bed fields located side by side indicated that long-term raised beds helped improve soil porosity in top soil layers (0–0.15 m). Bulk density in Alfisols ranged between 1390 kg/m^3 and 1460 kg/m^3 across the soil profile.

3.1.2. Soil hydraulic properties

Of the 5–8 experiments conducted, a set of suction heads was applied (-150 mm, −100 mm, −50 mm, −20 mm) in the infiltration tests to ascertain time vs. infiltration rate, time vs. cumulative infiltration and sorptivity for different suction heads (Fig. 3). Infiltration rate (mm/h) at the beginning of the experiment was relatively high due to higher sorptivity and reached a steady state in about an hour's time. Infiltration rate and cumulative infiltration were highly sensitive to the suction applied. Infiltration rate (both transient and steady state) were multiple-folds higher while changing the suction from −150 mm to −20 mm. Cumulative infiltration was higher in Alfisols compared to Vertisols. Infiltration rate at different suction heads was relatively higher in raised beds compared to flat beds. Soil sorptivity was estimated at 1–5 $mm/h^{0.5}$ in Vertisols and 1–10 $mm/h^{0.5}$ in Alfisols.

Fig. 4 shows the steady state infiltration rate measured at different suction heads in both Vertisols and Alfisols in both raised beds and flat beds. The coloured line shows the results of individual TDI experiments. Infiltration rate in raised beds was always higher than in flat beds both in Alfisols and Vertisols. The infiltration rate at −100 mm suction was below 2–5 mm/hour in Vertisols, indicating that the contribution of macro-pores is declining with increasing suction. Infiltration rate increased significantly from −100 mm to −20 mm. The steady state infiltration rate at −20 mm was 40 mm/hour in raised beds compared to 25 mm/hour in flat beds. In Alfisols, infiltration rate at −100 mm suction head ranged between 8 mm/hour and 15 mm/hour in raised beds compared to between 2 mm/hour and 15 mm/hour in flat beds. The steady state infiltration rate at −50 mm in Alfisols ranged from 20 mm/hour to 55 mm/hour in raised beds compared to 2 mm/hour to 25 mm/hour in flat beds.

Table 4 compares saturated hydraulic conductivity in raised bed and flat bed landforms in Vertisols and Alfisols. Saturated hydraulic conductivity (K_s) and constant (b) of Gardner exponential model is summarized for the respective watersheds. There was large variability from location to location in both the soil types and land management treatments. Saturated hydraulic conductivity in Alfisols under raised beds was the highest, with an average of 174 mm/hour (54–339 mm/hour) compared to 64.4 mm/hour under flat beds (3–280 mm/hour). Average saturated hydraulic conductivity in Vertisols under raised beds was 141 mm/hour (69–359 mm/hour) compared to 57 mm/hour (20–150 mm/hour) under the flat bed landform.

Table 5 presents the level of significance ($p < 0.05$) in soil hydraulic conductivity measured at different suction heads. In total, results were obtained from 40 TDI tests at −150 mm suction. No significant difference was found between soil types and landform treatments at −150 mm

Table 3
Soil texture, bulk density, porosity, and moisture retention in different soil layers in Vertisols and Alfisols.

Depth (m)	Vertisols								
	Sand (%)	Silt (%)	Clay (%)	Bulk density (kg/m^3)		Porosity (%)		Moisture retention (v/v)	
				Raised bed	In furrow	Raised bed	In furrow	0.3 bar	15 bar
0–0.15	28	21	52	1190	1550	55	42	0.33	0.25
0.15–0.30	29	21	50	1330	1400	50	47	0.36	0.28
0.30–0.45	21	21	58	1360	1400	49	47	0.45	0.34
Depth (m)	**Alfisols**								
	Sand (%)	Silt (%)	Clay (%)	Bulk density (kg/m^3)		Porosity (%)		Moisture retention (v/v)	
								0.3 bar	15 bar
0–0.15	75	7	18	1390		48		0.17	0.08
0.15–0.30	67	7	26	1450		46		0.19	0.10
0.30–0.45	61	7	31	1460		46		0.22	0.10

suction, as indicated by the *F* value. On the contrary, hydraulic conductivity measured in the experimental watersheds at −100 mm suction and above was found significantly different (F value > $F_{critical}$). Further, the *post-hoc* test indicated significant difference in hydraulic conductivity between raised bed and flat bed landforms at −100 mm, −50 mm and soil saturation stage for Alfisols while the difference in hydraulic conductivity between raised bed and flat bed landforms was significant only at saturation level in Vertisols.

Fig. 5**a and b** compare the macro-pores of different radii contributing to water flow in Vertisols and Alfisols. The radii of macro-pores contributing at −150 mm, −100 mm, −50 mm and −20 mm suction heads are 0.1 mm, 0.15 mm, 0.30 mm and 0.75 mm or lower, respectively. Large variability was observed in the number of macro-pores contributing to the movement of water at different suctions. The experiment showed a maximum of 2000 pores (ranging from 500 to 2000/m^2) of 0.1 mm contributing to the movement of water at −150 mm suction in Vertisols. In Alfisols, these numbers were as high as 4000/m^2. Between 0.2 mm and 0.4 mm radii, the number of macro-pores contributing to the movement of water was less than 200/m^2 in Vertisols and 500/m^2 in Alfisols. Fig. 5**c and d** compare the total water conducting porosities (cm^3/m^3) at different suction heads in Vertisols and Alfisols. In Alfisols, higher water conducting porosity was observed at higher suction compared to that in Vertisols. Total water conducting porosity (Θ_{mt}) below − 100 mm suction was in the range of 10–100 cm^3/m^3 in Vertisols compared to 10–250 cm^3/m^3 in Alfisols. Maximum Θ_{mt} at −50 mm suction in Vertisols was 180 cm^3/m^3 compared to 350 cm^3/m^3 in Alfisols. The value of Θ_{mt} in raised beds was observed to be higher compared to that in flat beds in both Vertisols and Alfisols.

3.2. Rainfall, soil moisture, runoff and soil loss dynamics

3.2.1. Amount of rainfall and variability

Between 1996 and 2020, the study area received between 494 mm and 1473 mm annual rainfall with an average of 897 mm from an average of 50 rainfall events (>2.5 mm/day). Of the total rainfall received in a year, 85% was between June and October, the predominant crop season. Of this, nearly half the events (23) had a rainfall intensity of 2.5–7.5 mm/day (light intensity); 19 with 7.6–35.5 mm/day (moderate intensity); 6 with 35.6–64.4 mm/day (high intensity), and a minimum two events with more than 64.5 mm/day (very high intensity). On an average, the amount of rainfall received from light, moderate, high and very high rainfall events was 135 mm, 340 mm, 200 mm, and 222 mm, respectively.

3.2.2. Soil moisture dynamics

Moisture in the top soil layer (0–0.15 m) in deep Vertisols with sorghum/pigeonpea intercrop (BW1) and fallow-sorghum (BW2) and in Alfisols with sorghum/pigeonpea intercrop (RW1) for an entire year is shown in Fig. 6**a**. Each dot shows soil moisture content (%, v/v) at 5–7-day intervals and daily rainfall (vertical bars). Soil moisture in different watersheds was measured at 0.1–0.4% (v/v) at the beginning of January. It was always the highest in BW2, followed by RW1 and BW1. Minimum soil moisture was recorded in May and June (0.05–0.1%), which reached the highest level by the end of October (0.15–0.35%) and subsequently declined. As BW2 remains fallow during the monsoon season, moisture level builds up and its utilization largely takes place during the post-monsoon season. In the other watersheds, the crops were grown in both Wet (*Kharif*) and dry (*rabi*) seasons with residual moisture being utilized subsequently.

Further, Fig. 6**b** describes the difference in water storage (DWS) capacity (% v/v) of surface soil in the watersheds. This difference is the free space available at any given point of time to bring soil moisture to saturation level. During rain events, it is expected that runoff will be generated after soil surface moisture reaches saturation level. Data on soil physical properties showed that total porosity of the surface soil in BW1, BW2 and RW1 was 55%, 42% and 48%, respectively. The higher DWS value in BW1 followed by RW1 and BW2, implies greater scope to harvest soil moisture in BW1 given any amount of rainfall. Since soil moisture in RW1 and RW2 were being utilized for crop growth, the DWS was relatively low compared to that in BW2 (fallow during monsoon). A comparison of DWS between different months showed that it was highest during May-June, coinciding with summer, and lower in October, coinciding with the end of the monsoon.

3.2.3. Rainfall-runoff and soil loss relationship

Fig. 7 describes the daily rainfall-runoff relationship in two paired Vertisols watersheds and a paired Alfisols watershed under raised bed and flat bed landforms. As expected, the magnitude of runoff increased with increasing rainfall intensity. However, large variability was recorded in runoff generated for the same intensity of rainfall. For example, rainfall at 60 mm/day generated runoff ranging from 5 mm to 50 mm in BW3, indicating event-wise runoff coefficients ranging between 8% and 80%. Similar variations were observed in each experimental watershed both under raised bed and flat bed landforms.

In the deep Vertisols experiment, one part of the watershed (BW1) was treated with raised beds and sorghum cultivated with pigeonpea, whereas other part (BW2) had flat beds which remained fallow during *wet season*. Under this experiment, runoff generated from BW1 was relatively less than from BW2. A regression analysis indicated an average 24% runoff coefficient in raised beds compared to 38% in flat beds (significantly different, $p < 0.05$) for daily rainfall intensity events (Fig. 7**a**).

In another paired watershed of Vertisols, both experimental fields (raised bed BW3 vs. flat bed BW4) were under cropped condition. Regression line shows 41% runoff coefficient in flat bed landform compared to 29% in raised bed landform, i.e., significantly different ($p < 0.05$) (Fig. 7**b**). Similarly, under the third experimental watershed of Alfisols, the runoff coefficients for raised beds and flat beds were 48%

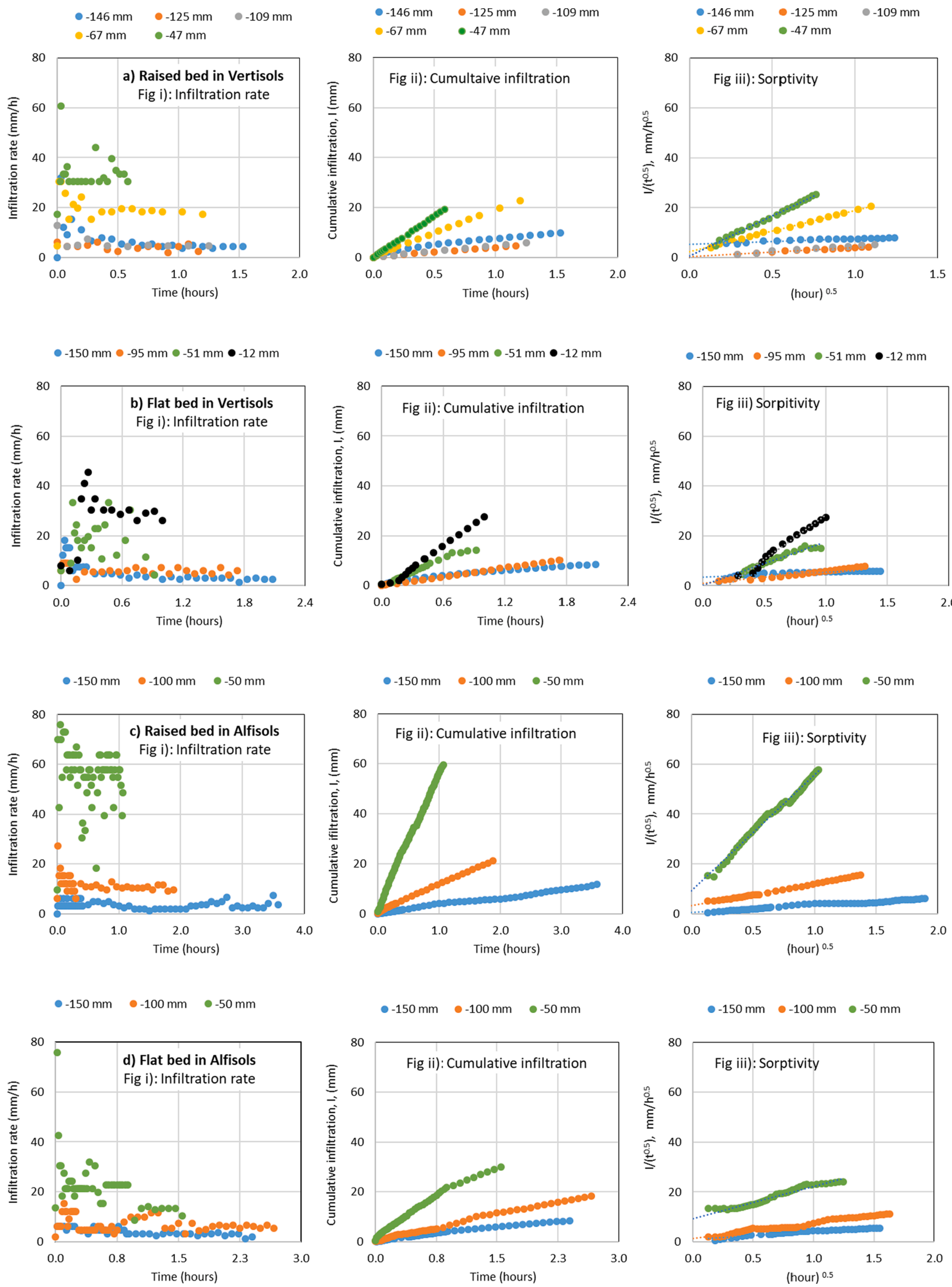


Fig. 3. Infiltration rate, cumulative infiltration and sorptivity for selected TDI experiments in Vertisols and Alfisols.

and 47% (insignificantly different, $p > 0.05$), respectively for daily intensity rainfall (Fig. 7**c**). A comparison of all the six experimental watersheds showed that the highest runoff coefficient was from RW1 and RW2 followed by BW4 and BW2; the lowest was in BW1.

Runoff response to moderate (7.5–35.5 mm/day), high (35.6–64.4 mm/day) and very high (>64.5 mm/day) intensity rainfall events in all the three paired watersheds are summarized in Fig. 8. On an average, runoff from BW1 (raised bed under cropped condition) was 2 mm (σ –

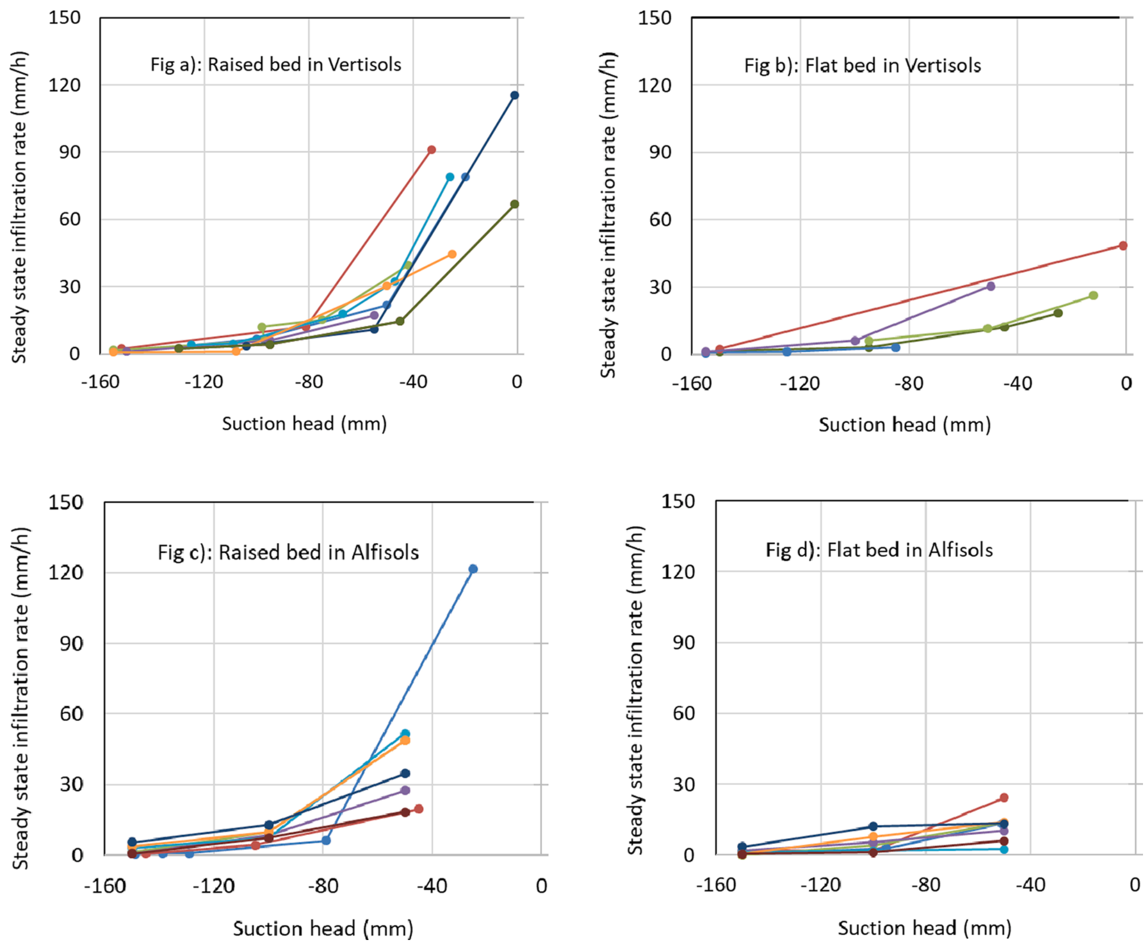


Fig. 4. Steady state infiltration rate measured at different suction heads in raised bed and flat bed fields in Vertisols and Alfisols. The coloured lines represent the different TDI experiments.

Table 4
A comparison of saturated hydraulic conductivity (K_s) in raised bed and flat bed landforms in Vertisols and Alfisols.

TDI tests	Vertisols				Alfisols			
	Raised bed (BW1)		Flat bed (BW2)		Raised bed (RW1)		Flat bed (RW2)	
	K_s (mm/h)	b (–)	K_s (mm/h)	b (–)	K_s (mm/h)	b (–)	K_s (mm/h)	b (–)
1	84	0.29	33	0.23	264	0.39	80	0.49
2	359	0.42	20	0.22	65	0.27	76	0.34
3	124	0.27	50	0.20	250	0.33	51	0.26
4	75	0.27	33	0.19	99	0.26	22	0.15
5	212	0.38	150	0.32	339	0.38	3	0.07
6	84	0.24	–	–	228	0.31	33	0.17
7	121	0.43	–	–	91	0.19	22	0.09
8	69	0.33	–	–	54	0.22	27	0.30
Average	**141**	**0.33**	**57**	**0.23**	**174**	**0.29**	**64.4**	**0.23**

standard deviation = 2 mm), 7 mm (σ = 6 mm) and 19 mm (σ = 7 mm) compared to 5 mm (σ = 2 mm), 13 mm (σ = 8 mm) and 32 mm (σ = 14 mm) in BW2 (flat bed with fallow land) under moderate, high and very high intensity rainfall events, respectively. Under medium deep Vertisols, average runoff was 2 mm (σ = 3 mm), 7 mm (σ = 8 mm) and 21 mm (σ = 18 mm) in BW3 (raised bed with crop) compared to 3 mm (σ = 4 mm), 11 mm (σ = 11 mm) and 27 mm (σ = 17 mm) in BW4 (flat bed with crop) under moderate, high and very high intensity events, respectively. Similarly in Alfisols, 11 mm (σ = 7 mm), 9 mm (σ = 10 mm) and 35 mm (σ = 25 mm) runoff was recorded from RW1 (raised bed) whereas 11 mm (σ = 7 mm), 9 mm (σ = 10 mm) and 34 mm (σ = 21 mm) runoff was recorded from RW2 (flat bed) in response to moderate, high and very high intensity rainfall events, respectively. Overall, the analysis showed declining runoff in raised beds in Vertisols compared to in flat beds.

Statistical analysis (Table 6) further indicates that runoff response from moderate intensity events was significantly different in both soil types ($F = 318 > F_{critical}$) and also among all the three paired experimental watersheds ($p < 0.05$). However, this difference was not significant for high and very high intensity events. Also, runoff generated between BW1 and BW2 was significantly ($p < 0.05$) different for all categories of rainfall intensity events. Under cropped conditions, there was no significant ($p > 0.05$) difference between raised bed and flat bed

Table 5
ANOVA showing the level of significance ($p < 0.05$) in soil hydraulic conductivity at different suction heads.

Suction head	No of tests	Soil types	Landform	F value	F critical	p-value between soil types	p-value between landform methods	Significance level
−150 mm	40	Vertisols	Raised bed Flat bed	1.01	2.87	0.532	0.06	No difference between soil types and landform treatment
		Alfisols	Raised bed Flat bed				0.47	
−100 mm	32	Vertisols	Raised bed Flat bed	3.29	2.95	0.129	0.62	In Alfisols, significance among landform methods
		Alfisols	Raised bed Flat bed				0.03	
−50 mm	32	Vertisols	Raised bed Flat bed	4.89	2.95	0.499	0.15	In Alfisols, significance among landform methods
		Alfisols	Raised bed Flat bed				0.008	
At saturation level	32	Vertisols	Raised bed Flat bed	3.36	2.95	0.572	0.044	Significance among landform methods in both soil types
		Alfisols	Raised bed Flat bed				0.045	

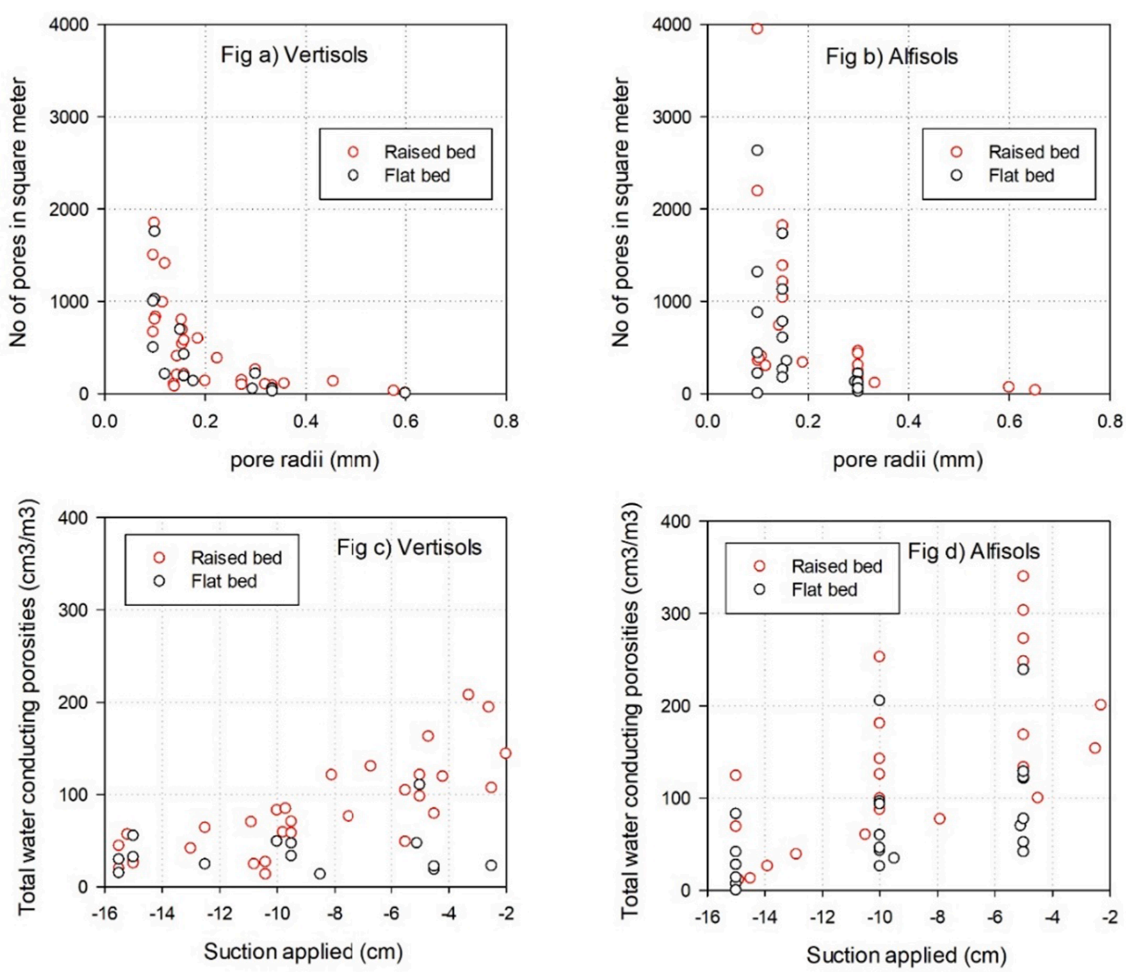


Fig. 5. The distribution of different radii of macro-pores contributing to water flow in **a)** Vertisols and **b)** Alfisols and total water conducting porosity at different rates of suction applied in **c)** Vertisols and **d)** Alfisols.

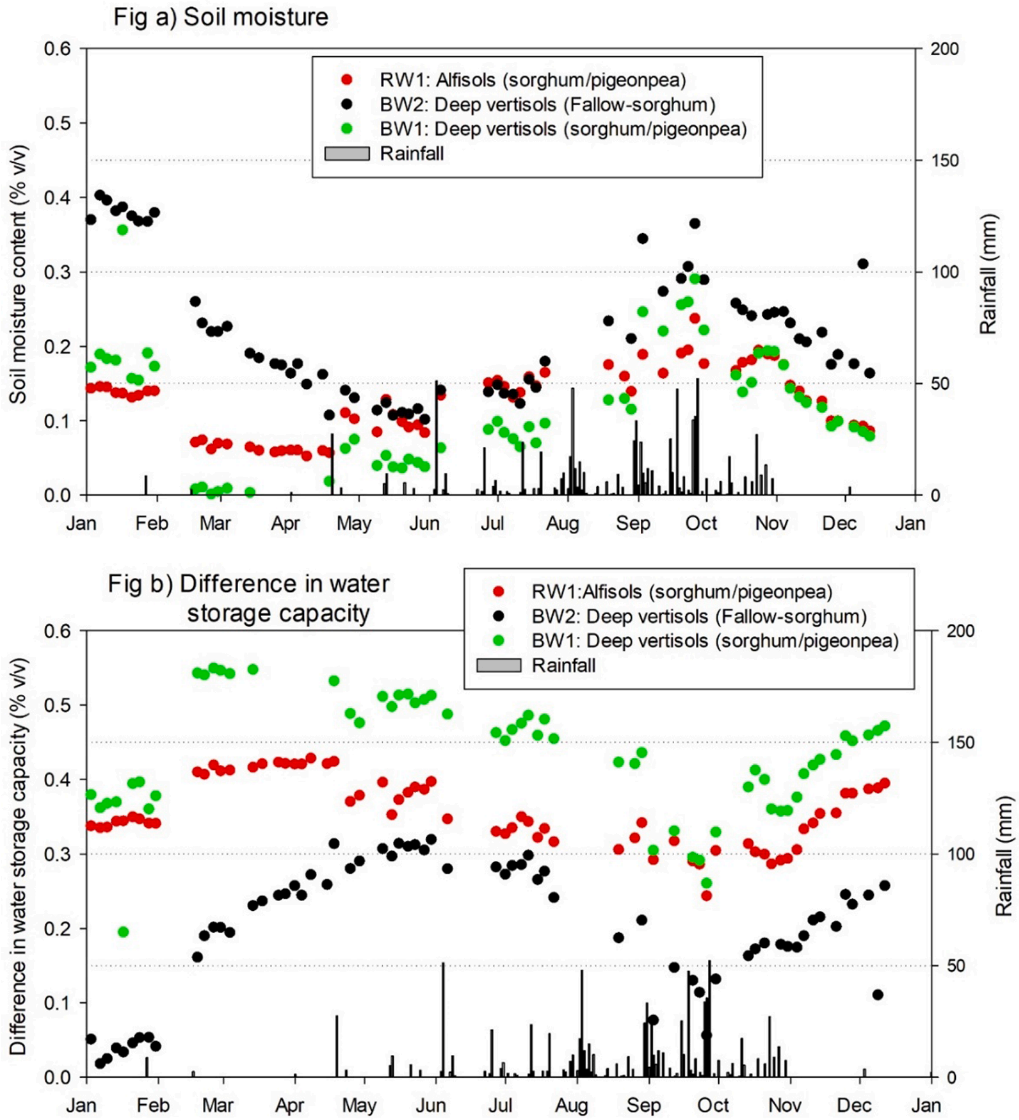


Fig. 6. Layer-wise soil moisture fluctuations in a) Alfisols (sorghum/pigeonpea); b) deep Vertisols (*wet season* fallow- *dry season* sorghum) under flat bed landform; and c) deep Vertisols (sorghum/pigeonpea) under raised bed landform.

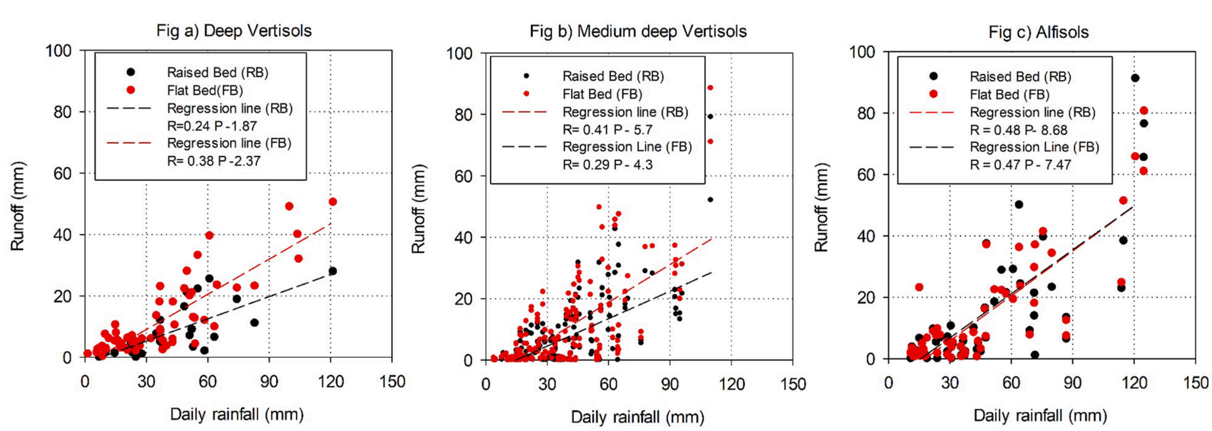


Fig. 7. The relationship between daily rainfall and runoff in a) deep Vertisols (BW1 vs BW2); b) medium deep Vertisols (BW3 vs BW4); and c) Alfisols (RW1 vs RW2) under raised bed and flat bed landforms.

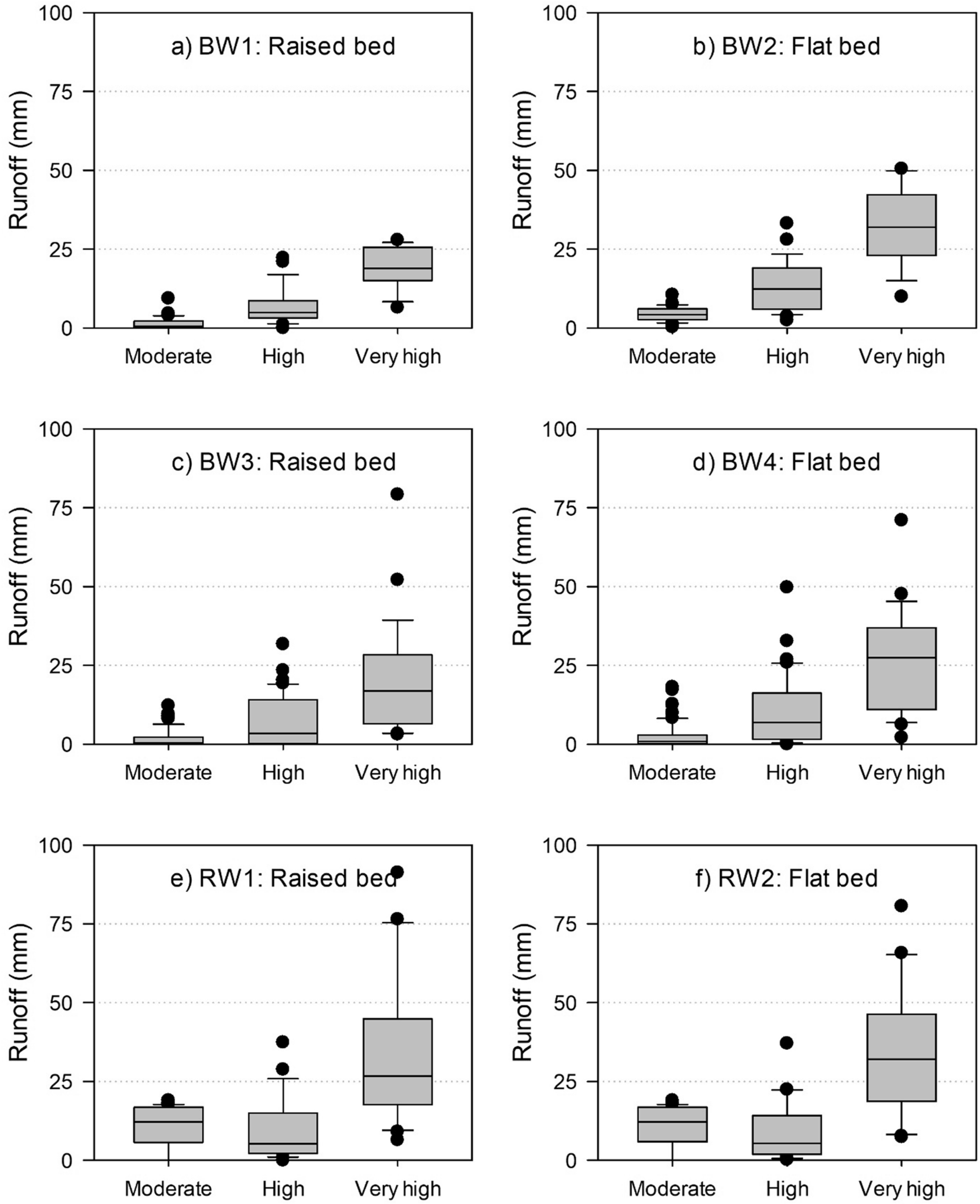


Fig. 8. Runoff response to moderate, high and very high rainfall events in three paired watersheds.

landforms in terms of runoff generation in Vertisols (BW3 vs BW4) and Alfisols (RW1 vs RW2).

Fig. 9 presents cumulative rainfall vs. cumulative runoff from the experimental watersheds for all the monitoring years. Coloured dots in the panels represent different years. Runoff threshold, i.e., cumulative rainfall required to initiate surface runoff, varied from year to year. For example, there was no runoff in 1999 from BW1 despite receiving 600 mm rainfall in the entire year. In 2001, despite receiving the same amount of rainfall, 40 mm cumulative runoff was generated. In 2008, 10 mm runoff was generated with merely 50 mm of cumulative rainfall. Similar observations were recorded in all the experimental watersheds with different amounts of runoff. Further, a comparison between raised bed and flat bed landforms indicated that cumulative runoff was either higher or almost the same in flat beds compared to raised beds. The maximum cumulative runoff recorded during the monitoring period in BW1 was 95 mm compared to 200 mm in BW2 and from BW3 (raised bed) and in BW4 (flat bed) it was 330 mm and 380 mm, respectively. In Alfisols, the maximum cumulative runoff recorded from RW1 (raised bed) and RW 2 (flat bed) was 260 mm and 280 mm, respectively. This difference was statistically significant between BW1 and BW2 ($p < 0.05$) but not significantly different in the other two paired watersheds (RW1 vs. RW2 and BW3 vs.BW4).

The variability in runoff generated can be better understood in terms of rainfall intensity and its distribution. Fig. 10 compares runoff

Table 6
ANOVA showing level of significance ($p < 0.05$) of runoff response in different experimental watersheds.

Rainfall intensity	Watersheds	F-value	Significance between watersheds	Raised bed vs. flat bed (p-value)
Moderate	Deep Vertisols (BW1 and BW2)	$F = 318 > F_{crit} = 3.01$	DV vs MDV: p = 0.018;	p = 0.000
	Medium deep Vertisols (BW3 and BW4)		MDV vs AS: p = 0.000;	p = 0.148
	Alfisols (RW1 and RW2)		DV vs AS: p = 0.000	p = 0.933
High	Deep Vertisols (BW1&BW2)	$F = 0.42 < F_{crit} = 3.03$	DV vs MDV: p = 0.37	p = 0.003
	Medium deep Vertisols (BW3 and BW4)		MDV vs AS: p = 0.70	p = 0.125
	Alfisols (RW1 and RW2)		DV vs AS: p = 0.69	p = 0.872
Very high	Deep Vertisols (BW1 and BW2)	$F = 2.57 < F_{crit} = 3.06$	DV vs MDV: p = 0.35	p = 0.018
	Medium deep Vertisols (BW3 and BW4)		MDV vs AS: p = 0.06	p = 0.286
	Alfisols (RW1 and RW2)		DV vs AS: p = 0.059	p = 0.943

Note: DV = Deep Vertisols (BW1 and BW2); MDV = Medium deep Vertisols (BW3 and BW4); and AS = Alfisols (RW1 and RW2).

response to intensity of rainfall received in 2002 and 2003 in dry and normal years, respectively. A total of 580 mm rainfall was received in 2002 with 44 events of light and moderate intensity (Fig. 10). Due to the uniform distribution and moderate intensity, maximum cumulative runoff in all the experimental watersheds was 30 mm. The year 2003 received 900 mm rainfall from 40 rainfall events and generated 100–210 mm cumulative surface runoff in different watersheds. Of the 40 rainfall events, 6 of high and very high intensity (40–120 mm/day) contributed to runoff generation. With incidence of high to very high intensity rainfall events, about 70–180 mm runoff was generated from different watersheds in response to 600 mm of cumulative rainfall by the middle of the monsoon in 2003.

Runoff response to a selected rainfall event during 2003 is further described on an hourly basis. The rainfall received on 23 July 2003 was 47 mm. Fig. 11 shows the runoff generated at frequent intervals (10–30 min) from deep Vertisols and Alfisols for raised bed and flat bed landforms. The runoff response was quicker in Alfisols compared to Vertisols. Peak runoff was recorded within one hour of the rainfall event in Alfisols whereas the peak in Vertisols was reached between 1.5 and 2 h. In Alfisols, within four hours, 98% of runoff was recorded at the outlet, whereas in Vertisols runoff continued for 9–10 h. During this event, the amount of runoff generated from flat beds was relatively high compared to that from raised beds. More specifically, the response of Alfisols and Vertisols mainly differed in terms of timing of peak flow and total duration of hydrograph which could be understood by differences in soil porosity, total storage capacity and also drainable porosity. Due to differences in water storage capacity of surface soils in the different watersheds, the magnitude of runoff was different. Relatively poor drainable porosity (i.e., macro-porosity near saturation) might have contributed to long recession of hydrograph in Vertisols compared to Alfisols.

Fig. 12 compares cumulative rainfall with cumulative soil loss in all the monitoring years (the coloured dots represent different years) and between the experimental watersheds. Cumulative soil loss in different years was strongly correlated with rainfall. Maximum cumulative soil loss of 3.9 t/ha was observed in BW3 compared to 7.0 t/ha in BW4 and 7.0 t/ha in RW1 compared to 9.0 t/ha in RW2. This demonstrates that soil loss in Alfisols was relatively higher than in Vertisols. The raised beds significantly helped control soil loss compared to flat beds in both Vertisols ($p < 0.05$) and Alfisols ($p < 0.05$). This could be due to the greater distance covered by runoff water from a given location in the field to the outlet point. In flat beds, water moves towards a natural slope whereas in raised beds water is guided along the raised bed with a mild slope of 0.5–0.6% and is safely disposed at the outlet, as shown in Fig. 1. While taking the longer path, the suspended soil particles get settled and the energy dissipates. Therefore, while there is a slight difference in runoff between both landforms, the difference in soil loss is significant.

Table 7 summarizes the runoff generated from all the three soil types under two different landforms in dry, normal, and wet years based on 8–12 years of monitoring. Total data for BW1 and BW2 was available for 8 years in which 3 were dry and 5 were normal, with average monsoonal rainfall of 530 mm and 720 mm, respectively. The 530 mm rainfall received in the dry years generated surface runoff of 2% (12 mm) from raised beds and 4% (19 mm) from flat beds. In normal years, surface runoff generated was 8% (55 mm) from raised beds and 17% (122 mm) from flat beds.

Data for BW3 and BW4 was available for 12 years. Of the 12 years, 3 were dry, 5 were normal, and 4 were wet years with average rainfall of 530 mm, 729 mm and 1101 mm, respectively. Surface runoff generated in dry years was < 2% of total rainfall in both raised beds and flat beds. In normal years, surface runoff from raised beds and flat beds was 7% (53 mm) and 11% (77 mm), respectively. Surface runoff during wet years was 20% (215 mm) from raised beds and 23% (258 mm) from flat beds. In Alfisols (RW1 and RW2), data is available for 8 years, of which 1 was dry (573 mm), 5 were normal (722 mm) and 2 were wet years (986 mm). Runoff generated in dry years was <2% of the rainfall from both flat bed and raised bed land forms, negligible soil loss was recorded. Runoff during normal years was 16% (i.e., 115 mm) and 17% (i.e., 126 mm) under raised bed and flat bed conditions, respectively. During wet years, the surface runoff recorded was 19% (186 mm) and 22% (213 mm) of total rainfall in raised bed and flat bed conditions, respectively. Soil loss from medium deep Vertisols ranged from 1.1 t/ha to 3.1 t/ha in raised beds compared to 2.6 t/ha to 5.2 t/ha in flat beds. Soil loss from Alfisols ranged from 3.0 t/ha to 7.1 t/ha in raised beds compared to 4.5 t/ha to 9.1 t/ha in flat beds. Results showed that raised beds are helpful in reducing soil loss by 1.5 to 2.1 t/ha compare to untreated landscape during normal and wet years.

4. Discussion

4.1. *Influence on available water storage and soil hydraulic conductivity*

Experimental results indicate that raised beds reduce runoff and sediment loss, more so in Vertisols than in Alfisols, particularly during low to moderate intensity rainfall events. However, there is no significant difference in runoff reduction and sediment loss between high and very high intensity events due to landform treatments. Raised beds in Alfisols and Vertisols reduced runoff by 10–30 mm and 25–40 mm, respectively during normal and wet years. Raised beds facilitate better crop growth and protects it from water logged conditions and develops soil structure. It is characterized by a large number of macro-pores and a high infiltration rate compared to flat beds. It was also found that hydraulic conductivity in Alfisols is higher compared to that in Vertisols. Despite this, runoff generated was higher in Alfisols than in Vertisols for the same amount of rainfall. This could be explained by the difference in water storage capacity. Hydraulic conductivity and water storage capacity are the key physical processes that determine runoff response. In an unsaturated state, available water storage capacity (the difference between saturated moisture and current soil moisture) largely influences runoff dynamics, while during excess rainfall, soil hydraulic conductivity influences hydrological processes.

Moisture availability in the top soil surface (0–0.15 m) fluctuated not only due to crop water uptake but also other environmental factors. Soil moisture from the top layer can directly evaporate, bringing soil

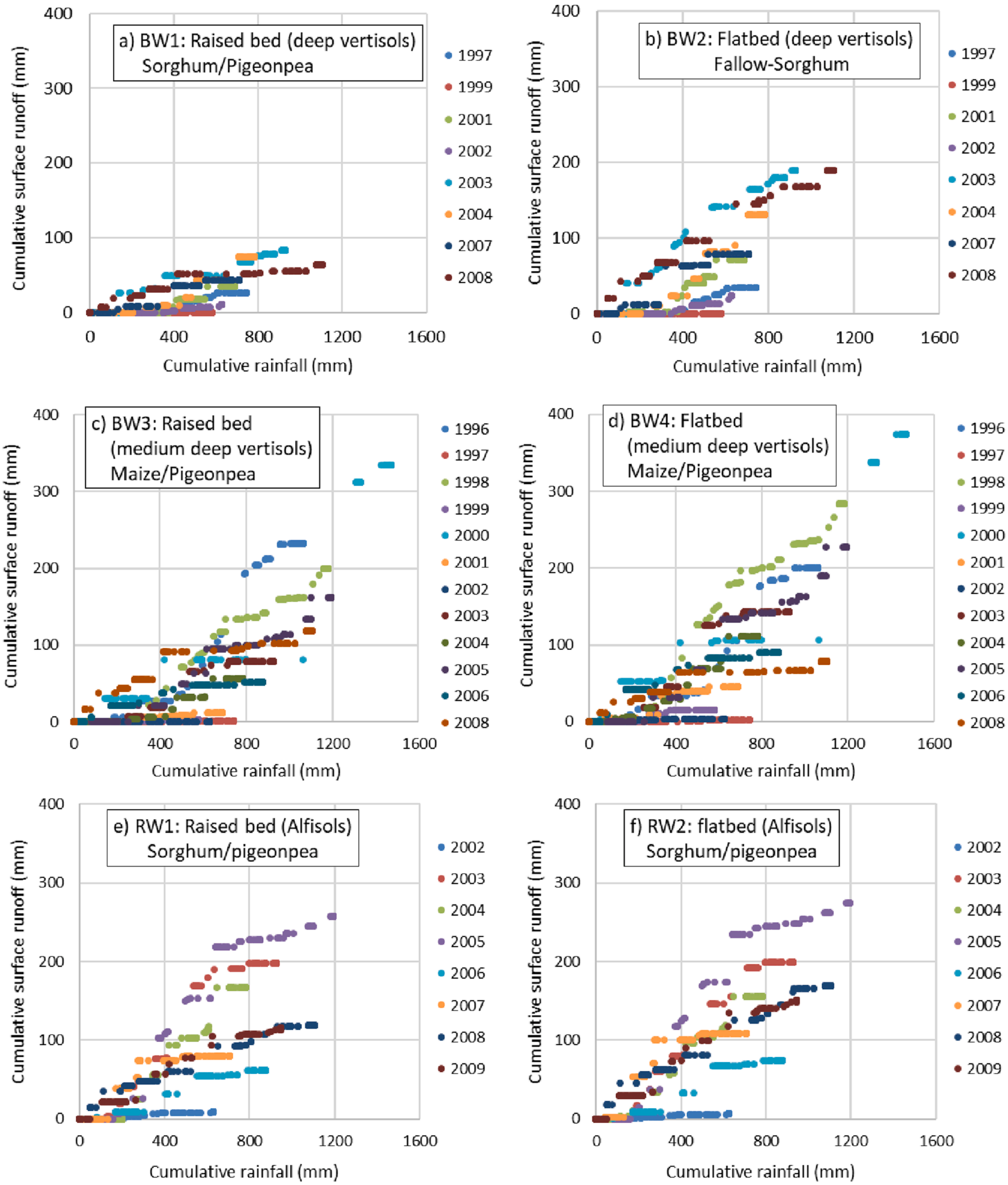


Fig. 9. Cumulative surface runoff generated in response to cumulative rainfall in Vertisols and Alfisols under raised bed and flat bed landforms between 1996 and 2009.

moisture much lower than the permanent wilting point. Vertisols, which are prone to wide and deep cracks, lose soil moisture even up to the extreme dry stage. Under such condition, the rainfall received on the landscape is largely utilized to fill the available storage, which is mostly higher in Vertisols compared to Alfisols. Soil sorptivity also plays an important role when the soil is dry (i.e., before the monsoon).

Runoff generated in Vertisols was found 50% lower than that in Alfisols, especially during normal rainfall years. This difference was nullified during wet years as available storage was filled in both the landforms. Land use too plays an important role in runoff generation. The runoff generated from fallow land was almost double that generated under cropped conditions. While soil moisture in cropped land is usually utilized and creates higher available storage, under fallow conditions there is minimal utilization of soil moisture; so the landscape retains the high soil moisture and creates less available storage resulting in high runoff. Raised beds have a major advantage in terms of controlling soil erosion. Raised beds and furrows allow running water to dissipate its energy and slow it down by offering resistance to the course of its flow. They also guide the runoff towards a safe way of disposal from the field. Raised beds also contributed to reducing soil loss by 30–60% both in Vertisols and Alfisols.

4.2. Comparison with other studies and future scope

Similar to the current study, Kurothe et al. (2015) analyzed the effects of tillage and cropping system on runoff and soil loss using long-term experimental studies in very deep sandy soils of the semi-arid tropics of Western India. They found that various *in-situ* water

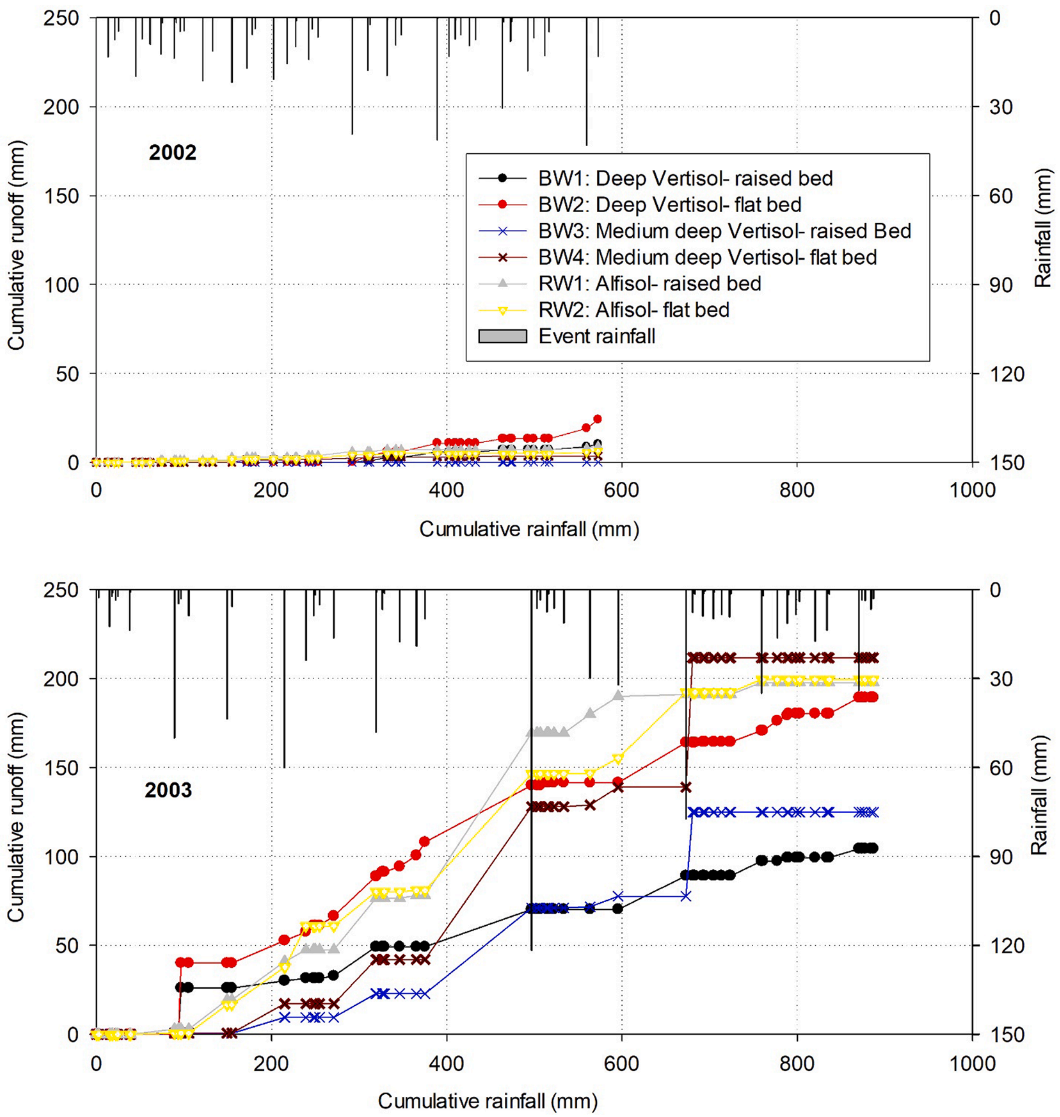


Fig. 10. Cumulative rainfall vs cumulative runoff in 2002 and 2003 in deep Vertisols, medium deep Vertisols and Alfisols under raised bed and flat bed landforms.

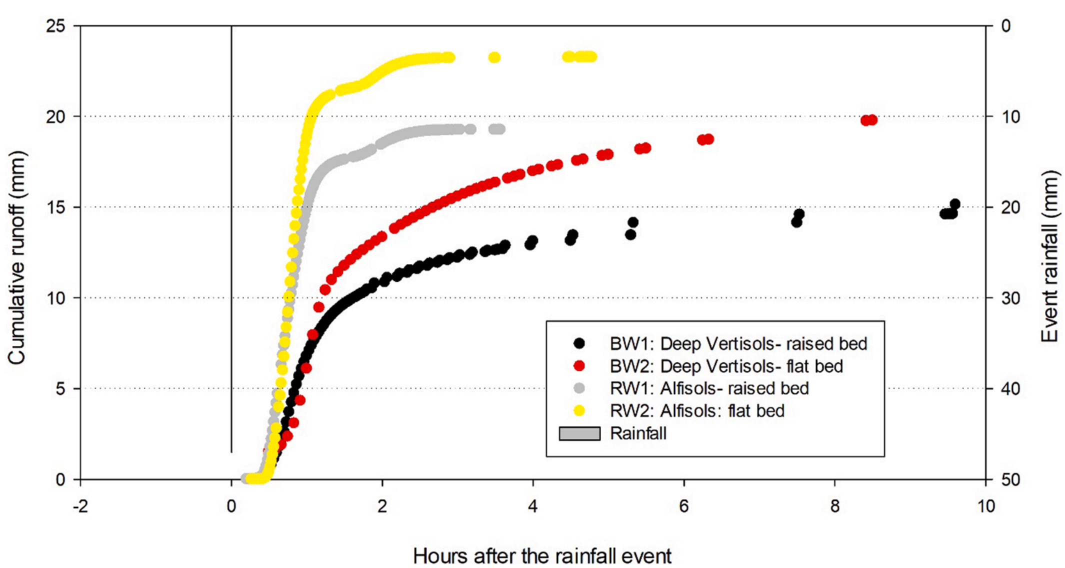


Fig. 11. Cumulative runoff generated in Vertisols and Alfisols for a selected rainfall event in 2003.

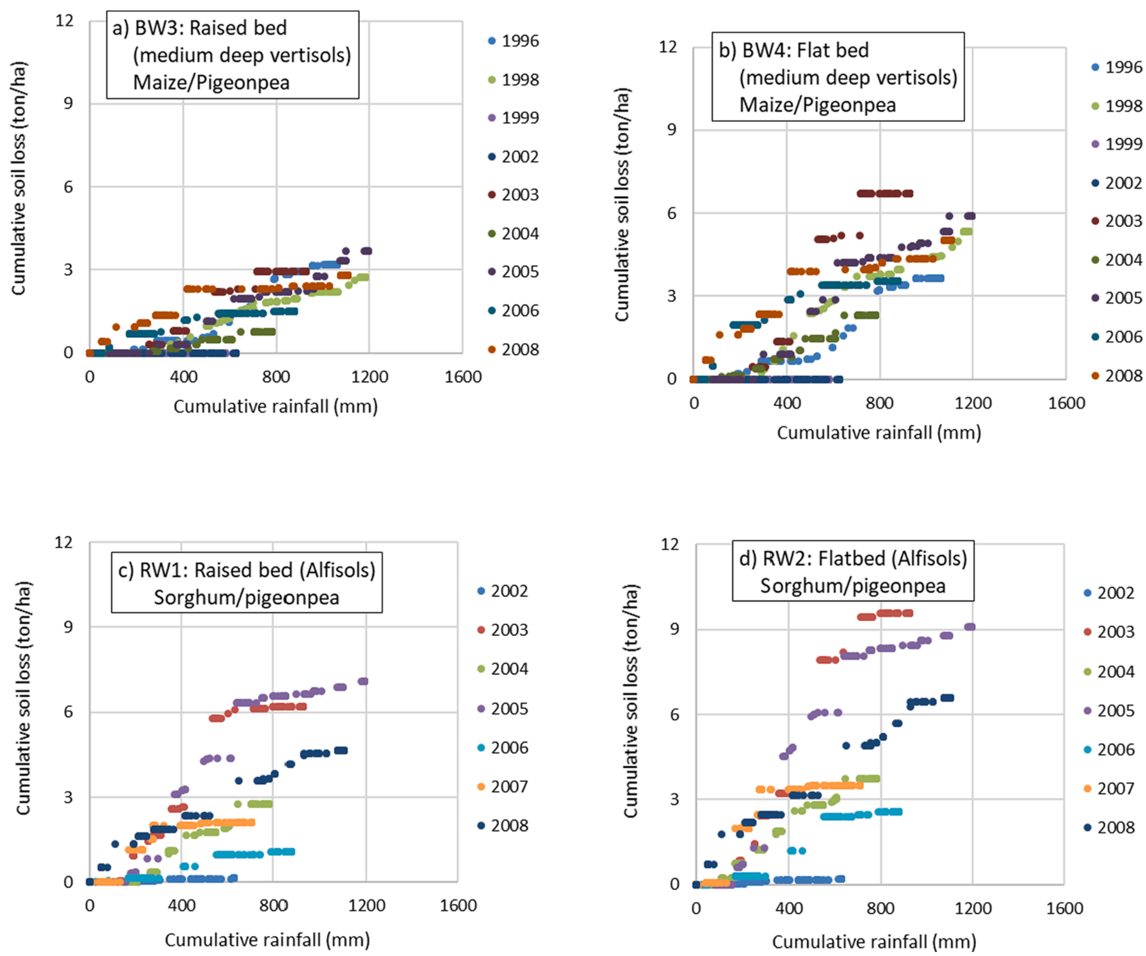


Fig. 12. Cumulative soil loss in response to cumulative rainfall in Vertisols (between 1996 and 2008) and Alfisols (between 2002 and 2008) under raised bed and flat bed landforms.

Table 7
Average runoff and soil loss measured from different experimental watersheds during dry, normal, and wet years. Parentheses shows the runoff in terms of per cent of total rainfall.

Site	Year	No of Years	Rainfall (mm)	Runoff (mm)		Soil loss (t/ha)	
				Raised bed	Flat bed	Raised bed	Flat bed
Deep Vertisols (BW1 vs. BW2)	Dry	3	530	12 (2%)	19 (4%)	–	–
	Normal	5	720	55 (8%)	122 (17%)	–	–
Medium deep Vertisols (BW3 vs. BW4)	Dry	3	530	2 (0%)	9 (2%)	0.0	0.0
	Normal	5	729	53 (7%)	77 (11%)	1.1	2.6
	Wet	4	1101	215 (20%)	258 (23%)	3.1	5.2
Alfisols (RW1 vs. RW2)	Dry	1	573	9 (2%)	6 (1%)	0.1	0.2
	Normal	5	722	115 (16%)	126 (17%)	3.0	4.5
	Wet	2	986	186 (19%)	213 (22%)	7.1	9.1

conservation practices (e.g., ridge farming, no-tillage practices and stubble mulching) reduced surface runoff and soil loss by 16–69% and 32% compared to conventional practices. Pathak et al. (2013) explained that sandy Alfisols which are characterized by high saturated hydraulic conductivity, can generate higher runoff compared to clayey Vertisols with extremely low saturated hydraulic conductivity, especially during high intensity rainfall events. This contrasting hydrological behavior is largely due to differences in soil characteristics. dos Santos et al. (2016) explain that the occurrence of dry spells and the formation of cracks in Vertisols are the most important factors controlling runoff. Dry spells lead to cracks in the expansive soil, which act as preferential flow path leading to high initial abstractions.

Singh et al. (2011) developed a strategy for *in-situ* water conservation in the hilly micro-watershed of Himalaya, India using two years' field data and simulation modeling. A combination of different vegetative measures along with low-cost rainwater harvesting structures reduced soil loss by 75%. Similarly, Wolka et al. (2020) studied the impact of soil and water conservation measures on the steep hill slopes of southwest Ethiopia. Soil bunds effectively reduced surface runoff by 80–92%. Without soil bunds, soil loss between 5 and 43 t/ha was recorded following two years of monitoring, indicating a loss of about 1.3–4 mm soil per year. Soil bunds decreased soil loss by about 96%. Levine et al. (2021) investigated the impact of detainment bunds as a novel strategy to mitigate nutrient and sediment losses in surface runoff from pastures lands in New Zealand. A one-year field study on 55 ha and 20 ha of micro-watersheds showed that detainment bunds decreased annual discharge by 31–43% and enhanced base flow.

Other than runoff, groundwater recharge and evapotranspiration (ET) are the other water balance components that can be influenced by landform management. This paper has focused only on rainfall-runoff relationship. There is scope to study the other water balance components using hydrological modelling tools in addition to strengthening field scale monitoring of groundwater recharge as well as under different rainfall, soil type, slope and landform conditions in order to optimize the use of available natural resources towards sustainable intensification.

4.3. Optimizing AWM interventions based on water balance

Understanding the hydrological response of different soil types has direct implications for designing rainwater management interventions in arid and semi-arid tropics. In the absence of such information, interventions lack adherence to standard protocols/methodologies based on sound hydrological principles. Most of the engineering structures constructed under various public welfare programs have either underutilized or overutilized available resources (Glendenning et al., 2012). Under current practices, only hydraulic designs are sometimes taken into account to decide the strength of structures. However, in the absence of complete hydrological information, there is no clarity on the optimal number of structures to be constructed in different ecologies. As Vertisols and Alfisols cover more than 60% of the land area in arid and semi-arid tropics, the outcome of this research will help different stakeholders take informed decisions while investing in soil and moisture conservation interventions. Besides, a variety of interventions are required to be designed for low, medium and high rainfall zones in order to enhance land and water use efficiency in upland areas with minimal negative impact on downstream. Under a climate change scenario and extreme weather events, a clear understanding of the relationship between rainfall and runoff is key to developing and scaling up appropriate land and water management strategies. This will help rainfed agriculture systems move closer to achieving Sustainable Development Goals.

5. Conclusions

Data generated from long-term field experiments were analyzed under deep Vertisols, medium deep Vertisols and Alfisols to understand the rainfall-runoff-soil loss relationship under two land management forms. Two landforms, raised beds and flat beds, were compared using a paired watershed approach. The experiments ran for a period of 8–12 years, during which rainfall variations in dry, normal and wet years were experienced, leading to the generation of extensive data. The findings from the study are as follows:

- Alfisols are characterized by $<$ 20% clay content and 45–48% porosity while Vertisols have $>$ 50% clay content and 47–55% porosity. Average saturated hydraulic conductivity in Alfisols in raised beds was 174 mm/hour compared to 64 mm/hour in flat beds while in Vertisols they were 141 mm/hour in raised beds and 57 mm/hour in flat beds. Total water conducting porosity at near saturation (-50 mm suction) was 180 cm^3/m^3 in Vertisols compared to 350 cm^3/m^3 in Alfisols.
- Runoff generated in dry years from both the soils was negligible, while in normal years there was a significant difference between Alfisols and Vertisols. In a normal year (about 730 mm rainfall), Alfisols generated about 16–17% surface runoff on an average compared to 7–11% in Vertisols. Runoff generated from deep Vertisols under fallow in a normal year was 17% compared to 8% under cropped conditions on raised beds.
- Raised beds were found to reduce surface runoff by 10–30 mm in Alfisols and 25–40 mm in Vertisols, which is equivalent to one or two supplemental irrigations. This could serve as a drought mitigation strategy in rainfed agriculture in the drylands which are prone to frequent dry spells. More importantly, soil loss was reduced by 30–60% in raised beds compared to flat beds. The average soil loss from Vertisols was 1.1 t/ha under raised beds and 2.6 t/ha under flat beds in a normal year. On the other hand, in Alfisols average soil loss was 3.0 t/ha in raised beds and 4.5 t/ha in flat beds.
- Surface runoff in Alfisols was 30–50% higher than that observed in Vertisols, especially during high rainfall events ($>$50 mm). The difference in surface runoff was not significant during rainfall events of $<$ 50 mm in both the soils. This is likely to be the tipping point of available moisture storage in Alfisols compared to Vertisols. Rainfall intensity events of more than 100 mm were not studied.
- The results of the study will be useful in designing a robust, soil-specific rainwater management strategy to optimize the use of natural resources and deal with the challenges posed by climate change in the drylands.

Declaration of Competing Interest

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

Acknowledgements

The authors thank the CGIAR Research Program on Water, Land and Ecosystems and TIGR^{2}ESS project for partially supporting the cost of the lead author's time for analyzing long-term data and drafting the manuscript.

References

Ahmadi, M., Baharak, M., Ahmadi, H., Moeini, A., Zehtabiyan, G.R., 2019. Assessment of climate change impact on surface runoff, statistical downscaling and hydrological modeling. Phys. Chem. Earth. 14, 102800.
Aissia, M.A.B., Chebana, F., Ouarda, T.B.M.J., 2017. Multivariate missing data in hydrology – Review and applications. Adv. Water Resour. 110, 299–309.
Ali, S., Sethy, B.K., Parandiyal, A.K., Kumar, A., Singh, R.K., Somasundaram, J., Mina, B. L., 2020. Long-term effects of rainwater conservation measure on improving yield, runoff use efficiency and soil properties of horti-pastoral system on the degraded ravine lands of India. Agric. Water Manag. 233, 106068. https://doi.org/10.1016/j.agwat.2020.106068.
An, J., Wu, Y., Wu, X., Wang, L., Xiao, P., 2021. Soil aggregate loss affected by raindrop impact and runoff under surface hydrologic conditions within contour ridge systems. Soil Tillage Res. 209, 104937.
Anantha, K.H., Garg, K.K., Petrie, C.P., Dixit, S., 2021a. Seeking sustainable pathways for fostering agricultural transformation in peninsular India. Environ. Res. Lett. 16, 044032. https://doi.org/10.1088/1748-9326/abed7b.
Anantha, K.H., Garg, K.K., Barron, J., Dixit, S., Venkataradha, A., Singh, R., Whitbread, A.M., 2021b. Impact of best management practices on sustainable crop production and climate resilience in smallholder farming systems of South Asia. Agric. Syst. 194, 103276.
Bagagiolo, G., Biddoccu, M., Rabino, D., Cavallo, E., 2018. Effects of rows arrangement, soil management, and rainfall characteristics on water and soil losses in Italian sloping vineyards. Environ. Res. 166, 690–704. https://doi.org/10.1016/j.envres.2018.06.048.
Biddoccu, M., Ferraris, S., Cavallo, E., Opsi, F., Previati, M., Canone, D., 2013. Hillslope Vineyard Rainfall-Runoff Measurements in Relation to Soil Infiltration and Water Content. Proc. Environ. Sci. 19, 351–360. https://doi.org/10.1016/j.proenv.2013.06.040.
Bonfante, A., Basile, A., Bouma, J., 2020. Targeting the soil quality and soil health concepts when aiming for the United Nations Sustainable Development Goals and the EU Green Deal. Soil 6 (2), 453–466.
Capello, G., Biddoccu, M., Cavallo, E., 2020. Permanent cover for soil and water conservation in mechanized vineyards: A study case in Piedmont, NW Italy. Italian J. Agronomy 15 (4), 323–331.
Capello, G., Biddoccu, M., Ferraris, S., Cavallo, E., 2019. Effect of tractor passes on hydrological and soil erosion processes in tilled and grassed vineyards. Water 11, 2118. https://doi.org/10.3390/w11102118.
Communication from the Commission to the Council, the European Parliament, the European economic and social Committee and the Committee of the Regions. 2006. Thematic Strategy for Soil Protection; CEC: Brussels, Belgium, p. 130.
deAraujo, H.F.P., Machado, C.C.C., Pareyn, F.G.C., Nascimento, N.F.F.d., Araújo, L.D.A., Borges, L.A.d.A.P., Santos, B.A., Beirigo, R.M., Vasconcellos, A., Dias, B.d.O., Alvarado, F., Silva, J.M.C.d., 2021. A sustainable agricultural landscape model for tropical drylands. Land Use Policy 100, 104913. https://doi.org/10.1016/j.landusepol.2020.104913.

Dinka, T.M., Morgan, C.L.S., McInnes, K.J., Kishné, A.S., Harmel, R.D., 2013. Shrink–swell behavior of soil across a Vertisol catena. J. Hydrol. 476, 352–359.
dos Santos, J.C.N., de Andrade, E.M., Guerreiro, M.J.S., Medeiros, P.H.A., de Queiroz Palácio, H.A., de Araújo Neto, J.R., 2016. Effect of dry spells and soil cracking on runoff generation in a semiarid micro watershed under land use change. J. Hydrol. 541, 1057–1066.
Ebabu, K., Tsunekawa, A., Haregeweyn, N., Adgo, E., Meshesha, D.T., Aklog, D., Masunaga, T., Tsubo, M., Sultan, D., Fenta, A.A., Yibeltal, M., 2019. Effects of land use and sustainable land management practices on runoff and soil loss in the Upper Blue Nile basin, Ethiopia. Sci. Total Environ. 648, 1462–1475.
El-Swaify, S.A., Pathak, P., Rego, T.J., Singh, S., 1985. Soil management for optimized productivity under rained conditions in the semi-arid tropics. In: Stewart, B.A. (Ed.), Advances in Soil Science, vol. 1. Springer-Verlag, New York, pp. 1–64.
Erkossa, T., Gizaw, A., Stahr, K., 2004. Land preparation methods efficiency on the highland vertisols of Ethiopia. Irrig. Drain. 53 (1), 69–75.
Erkossa, T., Haileslassie, A., MacAlister, C., 2014. Enhancing farming system water productivity through alternative land use and water management in vertisol areas of Ethiopian Blue Nile Basin (Abay). Agric. Water Manag. 132, 120–128.
Erkossa, T., Menker, M., Betrie, G.D., 2011. Effects of bed width and planting date on water productivity of wheat grown on Vertisols in the Ethiopian Highlands. Irrig. Drain. 60 (5), 635–643.
European Commission, 2020. Caring for soil is caring for life. Independent Expert Report. Directorate-General for Research and Innovation & Directorate-General for Agriculture and Rural Development. European Commission. DoI: 10.2777/918775.
European Parliament, 2006. Proposal for a Directive of the European Parliament and of the Council Establishing a Framework for the Protection of Soil and Amending Directive 2004/35/EC; CEC: Brussels, Belgium.
FAO & ITPS., 2015. Status of the World's Soil Resources (Main Report); FAO: Rome, Italy, p. 608.
Fu, B., Stafford-Smith, M., Wang, Y., Wu, B., Yu, X., Lv, N., Ojima, D.S., Lv, Y., Fu, C., Liu, Y.u., Niu, S., Zhang, Y., Zeng, H., Liu, Y., Liu, Y., Feng, X., Zhang, L.u., Wei, Y., Xu, Z., Li, F., Cui, X., Diop, S., Chen, X.i., 2020. The Global-DEP conceptual framework — research on dryland ecosystems to promote sustainability. Current Opinion Environ. Sustain. 48, 17–28.
Garg, K.K., Anantha, K.H., Venkataradha, A., Dixit, S., Singh, R., Ragab, R., 2021. Impact of rainwater harvesting on hydrological processes in a fragile watershed of South Asia, Groundwater (*in press*). https://doi.org/10.1111/gwat.13099.
Garg, K.K., Karlberg, L., Barron, J., Wani, S.P., Rockstrom, J., 2011. Assessing impacts of agricultural water intervention in the Kothapally watershed, Southern India. Hydrol. Process. 26, 387–404.
Garg, K.K., Singh, R., Anantha, K.H., Singh, A.K., Akuraju, V.R., Barron, J., Dev, I., Tewari, R.K., Wani, S.P., Dhyani, S.K., Dixit, S., 2020. Building climate resilience in degraded agricultural landscapes through water management: A case study of Bundelkhand region, Central India. J. Hydrol. 591, 125592. https://doi.org/10.1016/j.jhydrol.2020.125592.
Garg, K.K., Wani, S.P., Barron, J., Karlberg, L., Rockstrom, J., 2012. Up-scaling potential impacts on water flows from agricultural water interventions: opportunities and trade-offs in the Osman Sagar catchment, Musi sub-basin, India. Hydrol. Processes. 27 (26), 3905–3921.
Glendenning, C.J., van Ogtrop, F.F., Mishra, A.K., Vervoort, R.W., 2012. Balancing watershed and local scale impacts of rain water harvesting in India—a review. Agric. Water Manage. 107, 1–13.
Habets, F., Molénat, J., Carluer, N., Douez, O., Leenhardt, D., 2018. The cumulative impacts of small reservoirs on hydrology: A review. Sci. Total Environ. 643, 850–867.
Harmel, R.D., Richardson, C.W., King, K.W., Allen, P.M., 2006. Runoff and soil loss relationships for the Texas Blackland Prairies ecoregion. J. Hydrol. 331 (3-4), 471–483.
ICRISAT (International Crops Research Institute for the Semi Arid Tropics), 1985. The Tropicultor operator's manual: field operations. Patancheru, AP. 502324 India, ICRISAT.
India Meteorological Department. 2010. Annual Report, India Meteorological Department, Pune, Ministry of Earth Science, Government of India.
Karlberg, L., Garg, K.K., Barron, J., Wani, S.P., 2015. Impacts of agricultural water interventions on farm income: an example from the Kothapally watershed, India. Agric. Syst. 136, 30–38.
Kelly, P., 2014. What to do when we run out of water. Nature Clim. Change 4 (5), 314–316.
Kennedy, E.J., 1984. Discharge ratings at gaging stations: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 3 US Government Printing Office. p. 5.
Kurothe, R.S., Kumar, G., Singh, R., Singh, H.B., Tiwari, S.P., Vishwakarma, A.K., Sena, D.R., Pande, V.C., 2015. Effect of tillage and cropping systems on runoff, soil loss and crop yields under semiarid rainfed agriculture in India. Soil Tillage Res. 140, 126–134.
Levine, B., Horne, D., Burkitt, L., Tanner, C., Sukias, J., Condron, L., Paterson, J., 2021. The ability of detainment bunds to decrease surface runoff leaving pastoral catchments: Investigating a novel approach to agricultural stormwater management. Agric. Water Manag. 243, 106423. https://doi.org/10.1016/j.agwat.2020.106423.
Li, W., Xiong, L.i., Wang, C., Liao, Y., Wu, W., 2019. Optimized ridge–furrow with plastic film mulching system to use precipitation efficiently for winter wheat production in dry semi–humid areas. Agric. Water Manag. 218, 211–221.
Liu, G., Zuo, Y., Zhang, Q., Yang, L., Zhao, E., Liang, L., Tong, Y., 2018. Ridge-furrow with plastic film and straw mulch increases water availability and wheat production on the Loess Plateau. Sci. Rep. 8, 6503.
Meena, R.S., Lal, R., Yadav, G.S., 2020. Long-term impacts of topsoil depth and amendments on soil physical and hydrological properties of an Alfisol in central Ohio, USA. Geoderma 363, 114164. https://doi.org/10.1016/j.geoderma.2019.114164.
Mhizha, A., Ndiritu, J.G., 2013. Assessing crop yield benefits from in situ rainwater harvesting through contour ridges in semi-arid Zimbabwe. Phys. Chem. Earth, Parts A/B/C 66, 123–130.
Moebius-Clune, B.N., Moebius-Clune, D. J., Gugino, B.K., Idowu, O.J., Schindelbeck, R. R., Ristow, A.J., et al., 2016. Comprehensive assessment of soil health: The Cornell Framework Manual, Edition 3.1, Cornell Univ., Ithaca, NY.
Mondal, B., Loganandhan, N., Patil, S.L., Raizada, A., Kumar, S., Bagdi, G.L., 2020. Institutional performance and participatory paradigms: Comparing two groups of watersheds in semi-arid region of India. Int. Soil Water Conserv. Res. 8 (2), 164–172.
Mondal, B., Singh, A., Singh, S.D., Kalra, B.S., Samal, P., Sinha, M.K., Ramajayam, D., Kumar, S., 2017. Augmentation of water resources potential and cropping intensification through watershed programs. Water Environ. Res. 90 (2), 101–109.
Montgomery, D.R., 2007. Soil erosion and agricultural sustainability. Proc. Natl. Acad. Sci. USA 104 (33), 13268–13272.
Mullins, C.E., Mac Leod, D.A., Northcote, K.H., Tisdall, J.M., Young, I.M., 1990. Hardsetting soils: behaviour, occurrence, occurrence and management. Adv. Soil Sci. 11, 37–99.
Pal, D.K., Bhattacharyya, T., Chandran, P., Ray, S.K., Satyavathi, P.L.A., Durge, S.L., Raja, P., Maurya, U.K., 2009. Vertisols (cracking clay soils) in a climosequence of Peninsular India: Evidence for Holocene climate changes. Quat. Int. 209 (1-2), 6–21.
Pathak, P., Chandrasekhar, K., Wani, S.P., Sudi, R.R., Budama, N., 2016. Integrated runoff and soil loss monitoring unit for small agricultural watersheds. Comput. Electron. Agric. 128, 50–57.
Pathak, P., Sudi, R., Wani, S.P., Sahrawat, K.L., 2013. Hydrological behavior of Alfisols and Vertisols in the semi-arid zone: Implications for soil and water management. Agric. Water Manag. 118, 12–21.
Pathak, P., Wani, S.P., Singh, P., Sudi, R., 2004. Sediment flow behaviour from small agricultural watersheds. Agric. Water Manag. 67 (2), 105–117.
Pimentel, D., Whitecraft, M., Scott, Z.R., Zhao, L., Satkiewicz, P., Scott, T.J., Phillips, J., Szimak, D., Singh, G., Gonzalez, D.O., Moe, T.L., 2010. Will Limited Land, Water, and Energy Control Human Population Numbers in the Future? Hum Ecol. 38 (5), 599–611.
Nageswara Rao, V., Meinke, H., Craufurd, P.Q., Parsons, D., Kropff, M.J., Anten, N.P.R., Wani, S.P., Rego, T.J., 2015. Strategic double cropping on Vertisols: A viable rainfed cropping option in the Indian SAT to increase productivity and reduce risk. Eur. J. Agron. 62, 26–37.
Santra, P., Das, B.S., 2013. Modeling runoff from an agricultural watershed of western catchment of Chilika lake through ArcSWAT. J. Hydro-Environ. Res. 7 (4), 261–269.
Selvaraju, R., Subbian, P., Balasubramanian, A., Lal, R., 1999. Land configuration and soil nutrient management options for sustainable crop production on Alfisols and Vertisols of southern peninsular India. Soil Tillage Res. 52, 203–216.
Singh, C., Rahman, A., Srinivas, A., Bazaz, A., 2018. Risks and responses in rural India: Implications for local climate change adaptation action. Clim. Risk Manage. 21, 52–68.
Singh, R., Garg, K.K., Wani, S.P., Tewari, R.K., Dhyani, S.K., 2014. Impact of water management interventions on hydrology and ecosystem services in Garhkundar - Dabar watershed of Bundelkhand region, Central India. J. Hydrol. 509, 132–149.
Singh, R.K., Panda, R.K., Satapathy, K.K., Ngachan, S.V., 2011. Simulation of runoff and sediment yield from a hilly watershed in the eastern Himalaya, India using the WEPP model. J. Hydrol. 405 (3-4), 261–276.
Singh, S.P., Mahapatra, B.S., Pramanick, B., Yadav, V.R., 2021a. Effect of irrigation levels, planting methods and mulching on nutrient uptake, yield, quality, water and fertilizer productivity of field mustard (Brassica rapa L.) under sandy loam soil. Agric. Water Manage. 244, 106539.
Singh, R., Garg, K.K., Anantha, K.H., Venkataradha, A., Dev, I., Dixit, S., Dhyani, S.K., 2021b. Building resilient agricultural system through groundwater management interventions in degraded landscapes of Bundelkhand region, Central India. J. Hydrol.: Regional Stud. 37, 100929.
Smiles, D.E., Knight, J.H., 1976. A note on the use of the Philip infiltration equation. Soil Res. 14 (1), 103. https://doi.org/10.1071/SR9760103.
United Nations, 2015. Resolution adopted by the General Assembly on 25 September 2015, Transforming our world: the 2030 Agenda for Sustainable Development. United Nations.
Watson, K.W., Luxmoore, R.J., 1986. Estimating Macroporosity in a Forest Watershed by use of a Tension Infiltrometer. Soil Sci. Soc. Am. J. 50, 578.
Wei, H., Bing, C.S., 2014. Can soil water measurements at a certain depth be used to estimate mean soil water content of a soil profile at a point or at a hillslope scale? J. Hydrol. 516, 67–75.
Wei, Y., Wu, S., Jiang, C., Feng, X., 2021. Managing supply and demand of ecosystem services in dryland catchments. Current Opinion Environ. Sustain. 48, 10–16.
Wolka, K., Biazin, B., Martinsen, V., Mulder, J., 2020. Soil and water conservation management on hill slopes in southwest Ethiopia. I. Effects of soil bunds on surface runoff, erosion and loss of nutrients. Sci. Total Environ. 757, 142877.
Zhang, F., Guo, S., Liu, X., Wang, Y., Engel, B.A., Guo, P., 2020. Towards sustainable water management in an arid agricultural region: A multi-level multi-objective stochastic approach. Agric. Syst. 182, 102848.