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Hydrological behavior of Alfisols and Vertisols in the semi-arid zone: Implications for soil and water management

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ABSTRACT

Understanding of the hydrological behavior of soils is a prerequisite for developing appropriate soil and water management practices. Such information for Alfisols and Vertisols, the two major soils in the semi-arid tropics (SATs), is scanty especially from a long-term perspective. In this paper, we describe and discuss results from long-term (from 1976 to 2010) hydrological studies conducted on small agricultural watersheds on Vertisols and Alfisols at the ICRISAT Center, Patancheru, India. The hydrological behavior of soils are characterized in terms of runoff volume, peak runoff rate, number of runoff events, soil loss, sediment concentration and deep drainage loss under different rainfall, crop cover and soil moisture conditions to aid in developing effective soil and water management practices. We also provide details on the effects of annual and monthly rainfall on the hydrological behavior of these soils in different rainfall regions. The results show that Alfisols and Vertisols in the SATs have very contrasting hydrological behavior. Several findings emerging from our studies, are rather unexpected. For example, the sandy Alfisols with higher saturated hydrological conductivity generated higher runoff compared to the clayey Vertisols with extremely low saturated hydraulic conductivity. The undesirable early season runoff from Alfisols is higher than from Vertisols. The contribution of 1–2 big storms to annual runoff and soil loss was high on both soils. The contrasting hydrological behavior of these two soils is due to differences in soil characteristics such as crusting, sealing and low structural stability in Alfisols; and the presence of cracks during the early season and formation of micro-cracks during rainless periods in Vertisols. The results suggest that the information from the long-term hydrological studies is useful for determining appropriate soil and water management practices and strategies in different rainfall regions.

1. Introduction

Alfisols and Vertisols are the major soil orders in the semi-arid tropics (SATs). Alfisols, the most abundant soils in SATs, cover nearly 33%. They occur extensively in southern Asia, western and central Africa, and many parts of South America, particularly north-east Brazil. Vertisols are the deep black soils, generally called black cotton soils, which are abundant in India, Sudan, Ethiopia, Australia and several other countries (El-Swaify et al., 1985). In most semi-arid regions, average annual rainfall seem enough to produce one or two crops per year; however, rainfall pattern are highly erratic with frequent dry periods within the rainy season (Virmani et al., 1991). The soil-related constraints combined with a SAT environment result in uncertainties and considerable risk to agricultural systems. This does not help farmers to invest in land development, use of high yielding varieties, fertilizers, and other inputs. As a result, the current agricultural productivity on these soils in most SAT regions remains low. Also, with the current land use system, the rainfall use efficiency of the production systems is low, ranging from 35 to 55%; and thus annually a large percentage of annual rainfall is lost as surface runoff, evaporation and deep drainage (Pathak et al., 2009). Groundwater levels are depleting fast, and most rural rain-fed areas are facing general water scarcity (Rockström et al., 2007). Though the problem of water shortages and land degradation has been there in the past, the pace of natural resource degradation has greatly increased in recent times. Thus, for these soils in the SATs, new strategies and more appropriate soil and water management systems, which combine the effective conservation and utilization of soil and water resources in production systems that increase productivity and assure dependable harvest, are required.

To develop appropriate and more effective soil and water management strategies and practices, a better understanding of the hydrological behavior of these soils is important (Purandara and Kumar, 2003). Several researchers (Assouline, 2004; Arnold et al., 2005; Shainberg, 1992; Tarchitzky et al., 1984) have studied Alfisols and Vertisols with some key features (crusting and sealing on Alfisols and cracks formation on Vertisols) that have strong influence on their hydrological behavior. However, the majority of the

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Table 1
Background information on Alfisol and Vertisol watersheds at the ICRISAT research station Patancheru, India.

Soil type	Watershed name	Area (ha)	Slope (%)	Land and water management system	Crops and cropping system
Vertisols	BW1	3.41	2.15	Broadbed and furrow system at 0.6% slope with grassed waterways	Maize, sorghum intercrop with pigeonpea or sequential with chickpea and sunflower
	BW3A	3.82	2.05	Broadbed and furrow system at 0.6% slope with grassed waterways	
Alfisols	RW2	2.80	2.10	Broadbed and furrow system at 0.6% slope with grassed waterways	Sorghum intercrop with pigeonpea, groundnut and castor
	RW3C	3.15	2.25	Broadbed and furrow system at 0.6% slope with grassed waterways	

studies reported in the literature were either from small plots, or from simulated rainfall experiments (Stolte et al., 1997; Helalia et al., 1988; Philip, 1998). The hydrological information from SAT Alfisols and Vertisols from large plots/small watersheds and from long-term studies is still scanty. Scientists at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India have conducted long-term hydrological studies on small agricultural watersheds on both Vertisols and Alfisols. Based on the results from these long-term studies, this paper aims to discuss the hydrological behavior of the widely contrasting Alfisols and Vertisols. We discuss the influence of rainfall, crop cover and typical characteristics of Alfisols and Vertisols on their hydrological behavior. We also discuss the results on hydrological behavior of these two soil types with emphasis on using the results for hydrological modeling, and developing effective soil and water management strategies and practices for water management in different rainfall regions of the SATs.

2. Materials and methods

2.1. Description of experimental sites

The long-term hydrological studies were conducted on four small agricultural watersheds, two on Vertisols (BW1 and BW3A) and two on Alfisols (RW2 and RW3C) at the ICRISAT Center, near Hyderabad, India (17°36′N, 78°16′E, 545 m altitude). Brief relevant details on these watersheds are given in Table 1. In all four watersheds, we used the broadbed and furrow (BBF) system of land and water management along with improved crop production technologies. The broadbed and furrow system of land management consists of a relatively flat bed approximately 90 cm wide and shallow furrows 60 cm wide. The BBF system has a slope of 0.6%.

The mean annual rainfall at the experimental area is about 892 mm; the average minimum temperature is 17 °C and maximum temperature is 32 °C. Rainfall is variable spatially and temporally; and often occurs in high intensity. During the experimental period (1976–2010), the annual rainfall ranged from 558 mm to 1473 mm with a coefficient of variation (CV) of 25.2% (Fig. 1). Such erratic rainfall results in spells of excess moisture and drought during the crop-growing period. About 80% of the annual rainfall occurs during four months (June–September) termed rainy season, and this period is used for growing crops under rainfed conditions. The post-rainy season (October–January) is dry and the days are cool and short. A feature of the climate at the ICRISAT center is the high annual potential evapotranspiration (mean annual value of 1807 mm) with highest values during the summer months prior to the onset of the rainy season.

2.2. Soils at the experimental site

2.2.1. Vertisols

The Vertisols at the experimental watersheds are deep black soils, belonging to the very fine, clayey, montmorillonitic, calcareous hyperthermia family of Typic Pellusterts (Table 2) (Virmani et al., 1991). The soil is self-mulching and exhibits cracking and swelling; and becomes hard when dry and sticky when wet. Because of the prevailing 2:1 clay type and the relatively high clay content, the soils have a very low saturated hydraulic conductivity (Table 3). Under dry conditions, these soils develop deep and wide cracks, reflecting substantial shrinkage. These cracks greatly influence the infiltration and runoff behavior of soils particularly during the early periods of the rainy season.

2.2.2. Alfisols

The Alfisols at the experimental watersheds are medium deep red soils; and belong to the fine, kaolinitic, isohyperthermic member of the family of Udic Rhodustalfs (El-Swaify et al., 1985). Some of the major physical and chemical characteristics of the soils at

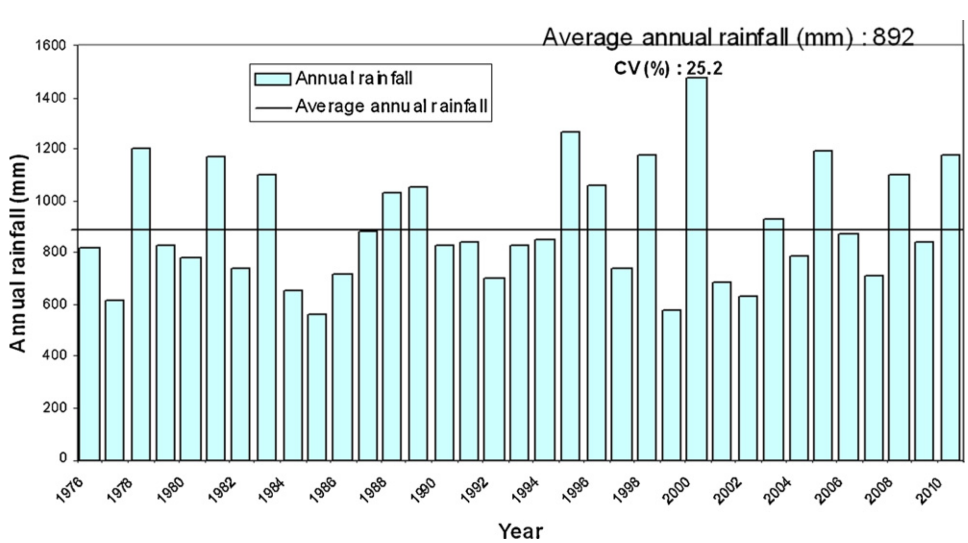

Fig. 1. Long term annual rainfall during the study period (1976–2010) at the ICRISAT Center, Patancheru, India.

Table 2
Major characteristics of Vertisols in the experimental watersheds at the ICRISAT farm in Patancheru, India, 1976.

Soil depth (cm)	Clay sand (<0.002 mm)	Silt (0.050–0.002 mm)	Sand (2–0.05 mm)	Coarse fragments (>2 mm)	Moisture holding capacity (%)		Bulk density ($g\,cm^{-3}$)
					0.03 MPa	1.5 MPa	
0–15	51.7	20.8	21.5	6	31.0	19.5	1.20
15–30	53.9	20.5	19.6	6	32.2	19.7	1.30
30–60	55.5	19.8	18.7	6	33.5	20.2	1.40
60–90	58.0	20.1	15.9	6	34.4	20.0	1.40
90–120	61.2	20.0	11.8	7	34.3	20.0	1.42

Soil depth (cm)	Organic carbon (%)	pH (1:2:5) H_2O suspension	EC (1:2:5) H_2O suspension (dS/m)	Exchangeable sodium (%)	Base saturation (%)	Clay fraction mineralogy[a]			
						AM	KK	MI	SM
0–15	0.27	8.1	0.10	34.9	93	4	14	7	64
15–30	0.17	8.5	0.15	35.0	93	6	13	7	65
30–60	0.16	8.5	0.20	35.5	94	5	13	7	66
60–90	0.16	8.4	0.20	44.6	93	5	13	7	68
90–120	0.15	8.4	0.25	49.1	92	5	13	7	67

[a] AM = amphibole; K = kaolinite; MI = mica; SM = smectite.

Table 3
Saturated hydraulic conductivity of Alfisols and Vertisols in the experimental watersheds at the ICRISAT Center, Patancheru, India, 1976.

Soil depth (cm)	Alfisols ($mm\,h^{-1}$)	Vertisols ($mm\,h^{-1}$)
0–15	17.1	0.60
15–30	6.7	0.35
30–60	6.1	0.33
60–90	8.3	0.21
90–120	–	0.22

the experimental site are given in Table 4. These soils have very low water retention characteristics; and they have mechanical impedance-related problems in the soil profile that restrict crop root development and proliferation. The soil has an unstable structure mainly due to low contents of fine (clay-sized) particles and inactivity of the prevailing clay minerals (mostly kaolin). A major consequence of the lack or non-stability of aggregation is the tendency of these soils to display rapid surface sealing following rainfall and crusting with subsequent drying. This characteristic greatly influences the infiltration, runoff and soil loss behavior of these soils. Sub-surface layers are very hard and compact, and possess relatively lower saturated hydraulic conductivity (Table 3). The soils are very low in organic matter and the depth of these soils in the experimental watersheds range from 90 to 110 cm.

Fig. 2. Hydrological gauging units and automatic weather station installed at RW2 Alfisol watershed at the ICRISAT research station, Patancheru, India.

2.3. Measurements and analysis

Weather data in the watersheds during the study period (1976–2010) are given in Fig. 2. Rainfall was measured using both fabricated reinforced plastic (FRP) rain gauges and self-recording rain gauges. Rainfall from the FRP rain gauge was measured using calibrated glass measuring jar daily once at 08:30 h. Continuous monitoring of rainfall was done with a tipping bucket rain gauge

Table 4
Major characteristics of Alfisols in the experimental watersheds at the ICRISAT farm in Patancheru, India, 1976.

Soil depth (cm)	Clay sand (<0.002 mm)	Silt (0.050–0.002 mm)	Sand (2–0.05 mm)	Coarse fragments (>2 mm)	Moisture holding capacity (%)		Bulk density ($g\,cm^{-3}$)
					0.03 MPa	1.5 MPa	
0–15	13.2	6.1	75.7	5.0	13	7.2	1.50
15–30	22.3	9.7	63.0	6.0	18	10.1	1.58
30–60	31.1	9.0	51.9	8.0	21	12.3	1.59
60–90	38.3	8.8	41.9	12.0	23	14.2	1.46

Soil depth (cm)	Organic carbon (%)	pH (1:2:5) H_2O suspension	EC (1:2:5) H_2O suspension (dS/m)	CEC NH_4OA_c (cmol/kg)	Base saturation (%)	Clay fraction mineralogy[a]				
						AM	KK	MI	SM	QZ
0–15	0.53	6.5	0.1	6.2	70	11	37	11	17	15
15–30	0.52	6.6	0.1	10.4	67	12	37	10	19	14
30–60	0.57	6.7	0.1	12.1	68	14	37	10	23	13
60–90	0.45	6.5	0.1	12.3	74	12	38	11	20	16

[a] AM = amphibole; K = kaolinite; MI = mica; SM = smectite; QZ = quartz.

Fig. 3. Microprocessor-based runoff sampler used for collecting runoff samples to estimate soil loss from experimental watersheds at the ICRISAT Center during 1996–2010.

having a bucket resolution of 0.254 mm per tip. The numbers of tips vs. time data are stored in the data logger and reported as rainfall in mm at a 4-min interval.

In all four watersheds, surface runoff was measured by using hydraulic structures and water-stage-level recorders (mechanical clock-chart type stage level recorders) from 1976 to 2000; and digital automatic runoff recorders (Thalimedes) from 2001 to 2010. In the mechanical stage level recorders, the runoff charts of 24-h time-scale with 4 min least count on time-interval, were used. These charts were digitized and stage vs. time values obtained, were used to calculate runoff volume and peak runoff rate. In case of digital runoff recorder, the changes in the water level are transferred via a float cable and counter weight system to the float pulley on the shaft encoder unit. In the digital runoff recorder, the sampling and logging intervals of stage was set to 1 and 5 min intervals, respectively. The stage vs. time graph was subsequently processed to obtain the runoff rates and volume.

For measuring soil loss, runoff samples from all runoff events were collected using sediment samplers (Fig. 3). From 1976 to 1995, a time integrating runoff sampler (Pathak, 1991) and from 1996 to 2010 a microprocessor based automatic runoff samplers (Pathak and Sudi, 2004) were used for collecting runoff samples at all four watersheds. These automatic runoff samplers collected and stored the runoff samples in separate containers at 10-min time intervals through out the runoff events. These samples were analyzed in laboratory for sediment concentration of eroded soil material. The concentration values were used to prepare sediment concentration vs. time graph, which was superimposed on the runoff hydrograph. Each runoff event hydrograph was divided into 10-min time segments. For each hydrograph segment, the soil loss was computed by multiplying the segment runoff volume with sediment concentration. The total soil loss for a runoff event was determined by adding these segment values.

In all watersheds during 1976–1995, soil moisture measurements were taken up to 120 cm depth using neutron probe. For the past few years (1995–2010), the soil moisture measurements are made using the Time Domain Reflectometer (TDR). The annual deep drainage from all four watersheds was determined using the following equation:

$$D = R - RU - ET - E \pm \Delta SM$$

where D = annual deep drainage in mm; R = measured annual rainfall in mm; RU = measured annual runoff in mm; ET = annual evapotranspiration in mm estimated by using the crop and water balance model of Ritchie (1998); E = annual evaporation loss (during non cropping season) in mm estimated by using the crop and water balance model of Ritchie (1998); ΔSM = measured annual change in profile soil moisture in mm.

The calibrated and tested model of Ritchie was used to estimate the daily and annual soil evaporation, plant transpiration, evapotranspiration (soil evaporation + plant transpiration) and changes in profile moisture. The measured values of soil profile moisture and runoff were used to check and improve the accuracy of the model. The model first estimates the potential soil evaporation and plant transpiration, which are adjusted as per the potential supply of moisture in different soil layers. The data on daily rainfall, maximum and minimum temperatures, solar radiation, initial water content, maximum available water holding capacity, lower limit of water extraction, standard values of crop specific leaf area index and light interception coefficient, stage-I and stage-II evaporation coefficients were used for running the model.

3. Results and discussion

3.1. Runoff behavior of Alfisols and Vertisols

3.1.1. Annual runoff and peak runoff rate

Large differences were found in the mean values of annual runoff volume between the Alfisol and Vertisol watersheds (Table 5). The mean annual runoff volume in Alfisol watersheds is 69% higher compared to those in Vertisol watersheds. However, the peak runoff is slightly higher in Vertisol watersheds compared to that in Alfisol watersheds. The mean annual runoff volume recorded from Alfisol and Vertisol watersheds is rather unexpected. Alfisols relatively sandy in texture with higher saturated hydraulic conductivity (Table 3) compared to the Vertisols, generated much higher runoff volumes compared to Vertisols high in clay and very low saturated hydraulic conductivity (Table 3).

Several factors are likely responsible for the relatively higher runoff from Alfisols compared to Vertisols. Alfisols have non-stable soil structure, which enhances the soil tendency to develop surface seals that reduce infiltration and profile recharge even under moderate or mild rains. The surface seal hardens into crusts during the intermittent dry periods, which further influences the runoff behavior of Alfisols. Also because of low structural stability, there is much faster reduction in soil surface roughness due to rainfall impact. This contributes to fast decline in surface depression storage, resulting in relatively higher runoff. On Alfisols and associated soils, several others (Assouline, 2004; Assouline and Mualem, 1997; Tarchitzky et al., 1984; Valentin and Bresson, 1992; Helalia et al., 1988) have studied the formation of crusting and sealing and their influence on infiltration, runoff, evaporation loss and other parameters; and the results reported are similar to the results obtained in the present study. On the other hand, Vertisols have much better structural stability, resulting in a slow and gradual decline in depression storage capacity due to the rain impact. Moreover, the presence of large cracks during the early part of the rainy season and formation of micro-cracks during the rainless period (within the rainy season) in Vertisols, leads to high infiltration and surface depression storage during the subsequent rains. These typical soil properties contribute significantly to reducing runoff on Vertisols. Arnold et al. (2005), Krohn and Slosson (1980) and Lin et al. (1998) reported similar results on the influence of cracks in reducing runoff and soil loss on Vertisols and associated soils.

3.1.2. Monthly and daily runoff

The data on mean monthly runoff from Alfisols and Vertisols show a very contrasting trend (Fig. 4). During all the rainy months, the mean monthly runoff from Alfisols was higher than from

Table 5
Mean annual rainfall, runoff, soil loss and peak runoff rate in the Alfisol and Vertisol watersheds at the ICRISAT Center, Patancheru, India, 1976–2010.

Soil type and watersheds	Mean annual rainfall (mm)	Mean annual runoff		Peak runoff rate ($m^3 s^{-1} ha^{-1}$)	Mean annual soil loss ($t ha^{-1}$)
		Runoff (mm)	Runoff as % of rainfall		
Alfisol watersheds with BBF system	890	199.7	22.4	0.21	4.76
SD	205	136	–	–	1.90
SE±	79	62	–	–	0.81
CV%	27	46	–	–	28.2
Vertisol watersheds with BBF system	894	117.8	13.2	0.25	1.68
SD	193	83	–	–	1.76
SE±	38	16	–	–	0.51
CV%	23	73	–	–	106

Vertisols. In the first two months viz. June and July, the mean monthly runoff from Alfisols was relatively higher than Vertisols. For example in the month of June, the mean monthly runoff from Vertisols was only 1% compared to 12% in Alfisols. The monthly runoff data clearly shows that the early runoff in Alfisol watersheds is higher than in Vertisol watersheds. However, with progress in the rainy season, the relative differences in the runoff between Alfisols and Vertisols gradually decline. The high early season runoff from Alfisols is undesirable because most of the times during these periods, the soil is dry and the top layer (0–30 cm) is not even near field capacity. In the case of Vertisols, the early season runoff is low and most of the runoff occurs during the months of August and September when the soil profile is near field capacity.

The results on the contrasting behavior of individual runoff events from Alfisols and Vertisols during the early part of the rainy season (Fig. 5) clearly showed that the runoff from Alfisols is higher than from Vertisols. This reconfirms the monthly runoff trend that the early season runoff from Alfisols is higher than from Vertisols. On Alfisols, the problems of crusting and sealing are encountered more during the early part of the growing season when the crop canopy is not fully developed. This reduces the infiltration considerably, leading to higher runoff on Alfisols particularly during the early part of the season. Assouline (2004) and Hussein et al. (2010) also reported similar results on the influence of raindrop impact and vegetative cover on crust formation and infiltration. However, the reverse trend in runoff was observed from the events, which occur under extremely wet soil conditions (soil moisture at field capacity or higher) during the later part of the rainy season. Under such conditions, the runoff from Vertisol watersheds was significantly higher than from Alfisol watersheds (Fig. 6). The runoff from Vertisols under extremely wet soil conditions (higher than field capacity) is mainly determined by their very low saturated hydraulic conductivity (Table 3). This leads to very high runoff on Vertisols under such moisture condition. Due to this, on Vertisols, the monthly runoff during August and September is substantially higher and the runoff gap between Alfisols and Vertisols is considerably reduced (Fig. 4). These results support the trends in monthly runoff from Alfisols and Vertisols.

3.1.3. Runoff under dry soil conditions

Occurrence of runoff under dry soil moisture conditions is highly undesirable. The runoff behavior of Vertisols and Alfisols when the top 30 soil layer was dry (below field capacity), is indeed contrasting. During the early parts of the rainy season (June and July), very low runoff was recorded on the Vertisols when the top 30 cm

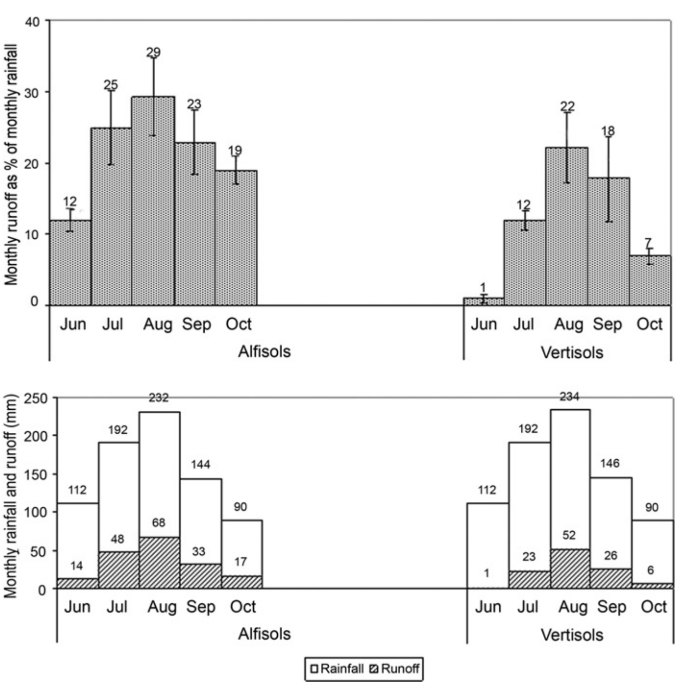

Fig. 4. Mean values of monthly runoff characteristics of Vertisol and Alfisol watersheds at the ICRISAT Center during 1976–2010.

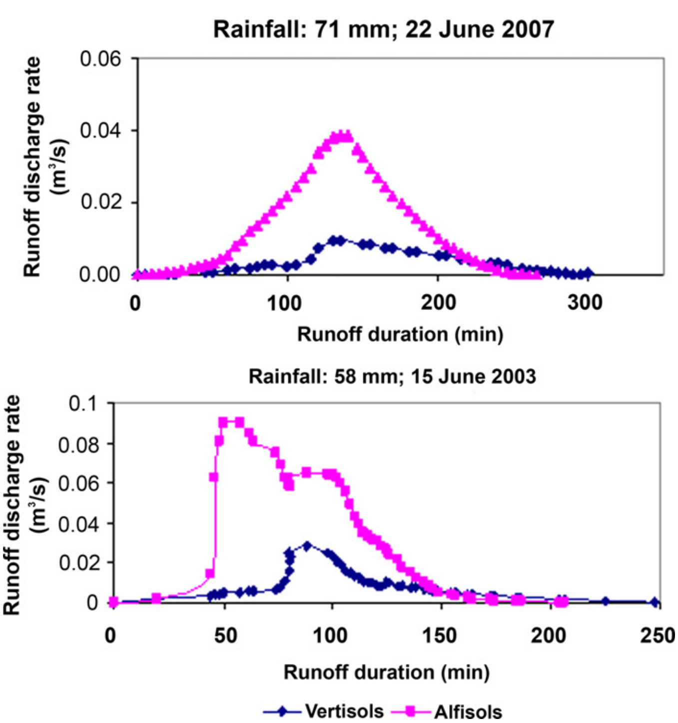

Fig. 5. Trends in runoff events under dry soil conditions during the early part of the rainy season in the Alfisol watershed (RW2) and the Vertisol watershed (BW1) at the ICRISAT Center, Patancheru, India.

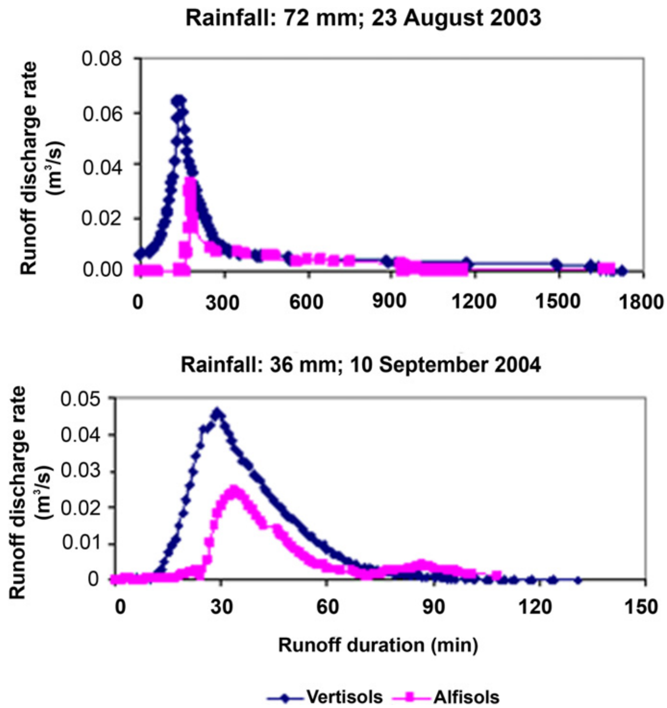

Fig. 6. Trends in runoff events under extremely wet soil conditions (soil moisture at field capacity or even higher) during the later part of the rainy season in the Alfisol watershed (RW2) and the Vertisol watershed (BW1) at the ICRISAT Center, Patancheru, India.

soil profile was below field capacity. The high initial infiltration rate, good surface retention storage due to rough soil surface and the presence of abundant large and micro-cracks under dry soil conditions mainly lead to low runoff. This suggests that on Vertisols, the benefits from the implementation of improved soil and water management practices via additional infiltration of water are rather low.

On the other hand on Alfisols, a substantial amount of runoff (53 mm) was recorded even when the top 30 cm soil profile has not yet reached field capacity. This runoff under dry soil conditions was primarily due to low infiltration rate because of crusting and sealing of the surface layer, and the presence of very low surface roughness storage (fast reduction in soil surface roughness following rains, due to low structural stability of the soil). This is undesirable because often the crops on these Alfisols suffer from moisture stress particularly during the early parts of the cropping season. Therefore, for the Alfisols substantial benefits can be obtained by controlling such early season runoff through appropriate soil and water management practices such as mulching, conservation agriculture, contour cultivation with conservation furrows and additional shallow inter-cultivations.

3.1.4. Big runoff events

The contribution of a few big runoff events to annual runoff and soil loss recorded from Alfisol and Vertisol watersheds are high (Table 6). A close examination of the individual annual runoff events reveals that in most of the years, 1–2 big runoff events account for more than 72% of the annual runoff and 74% of annual soil loss on Vertisols. In the case of Alfisols, these events account for more than 63% of the annual runoff and 69% of the annual soil loss. Further examination of the rainfall events with higher weighted mean rainfall intensities for various years indicated that these big runoff and soil loss producing events were not necessarily those with highest rainfall intensities, but were those with large amounts of total rainfall, particularly received while the soils were still moist from

Table 6
The contribution of 1 or 2 big runoff events to annual runoff and soil loss in Alfisol and Vertisol watersheds with broadbed and furrow (BBF) systems at the ICRISAT Center, Patancheru, India, 1976–2010.

	Contribution of 1–2 big runoff events annually		
	Contribution to annual rainfall (%)	Contribution to annual runoff (%)	Contribution to annual soil loss (%)
Vertisol watersheds with BBF system	14.0	49–91[a] (73[b])	51–89 (74)
Alfisol watersheds with BBF system	14.2	40–79 (62)	42–84 (68)

[a] Range of values.
[b] Mean values.

the previous rainfall events. However, the contribution of these big rainfall events to annual runoff and soil loss is relatively lower on Alfisols than on Vertisols. This is primarily due to a greater number of runoff events occurring on Alfisols than on Vertisols, each season (Table 7). These results suggest that a proper management of big rainfall events is crucial for effectively controlling the runoff and soil loss on these two soil types.

3.1.5. Annual runoff during low, medium and high rainfall years

During the past 35 years (1976–2010) of the study, the annual rainfall at the experimental sites varied from 580 to 1473 mm (Fig. 1). When the individual-year runoff and soil loss results from the Alfisol and Vertisol were closely examined, a pattern emerged. The hydrological behavior of these soils varied considerably during different years; and it was greatly influenced by the total annual rainfall. The hydrological behavior of Alfisols and Vertisols during low rainfall years (annual rainfall <750 mm), medium rainfall years (annual rainfall 750–900 mm) and high rainfall years (annual rainfall >900 mm) were contrastingly different (Fig. 7).

As expected, with increase in the annual rainfall, the annual runoff increased substantially on both Alfisols and Vertisols. However, the relative increase in runoff is much higher on Vertisols than on Alfisols (Fig. 7). For example, the mean annual runoff on Vertisols increased 15 times (from 2 to 30% annual runoff recorded during low to high rainfall years); while on the Alfisols, it increased only 1.8 times (from 16 to 29% annual runoff recorded during low to high rainfall years).

The annual rainfall greatly influences water loss through deep drainage from both Alfisols and Vertisols (Fig. 7). As expected, the deep drainage loss increased with increase in the annual rainfall in both soils. During all the years, the deep drainage losses were substantially higher in Alfisols compared to Vertisols. This indicates a greater groundwater recharge and its availability in Alfisols compared to Vertisols. The relatively higher deep drainage loss in Alfisols is primarily due to low water holding capacity of the soil profile, and relatively higher saturated hydraulic conductivity (Tables 3 and 4) compared to Vertisols, which have higher water-holding capacity and extremely low saturated hydraulic conductivity (Tables 2 and 3) and very poor internal profile drainage.

Table 7
Selected hydrological characteristics of Alfisol and Vertisol watersheds at the ICRISAT Center, Patancheru, India, 1976–2010.

Hydrological parameters	Alfisol watersheds	Vertisol watersheds
Average number of annual runoff events	12	8
Annual runoff range as % of rainfall	6–32	0–34
Annual soil loss range ($t\,ha^{-1}$)	1.21–6.20	0–3.29
Mean sediment concentration in runoff ($g\,L^{-1}$)	2.36	1.39

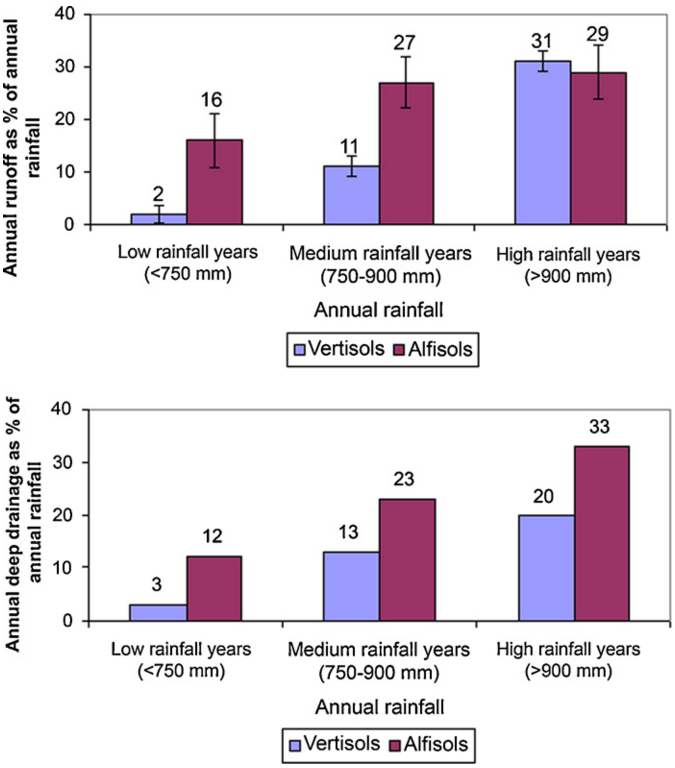

Fig. 7. Annual runoff and deep drainage losses in Vertisol and Alfisol watersheds during low, medium and high rainfall years (1976–2010) at the ICRISAT Center, Patancheru, India.

During the low rainfall years (<750 mm annual rainfall), the mean annual runoff from Vertisols was low (Fig. 7). On an average, the annual runoff from Vertisol watersheds was only 2% of the annual rainfall. In fact, there were years, when the annual runoff on Vertisols was almost zero. These results suggest that in low rainfall areas of SATs, the Vertisols may generate low annual runoff. During the low rainfall years, the deep drainage loss from Vertisols was also very low (Fig. 7). The mean annual deep drainage loss was 3% of the mean annual rainfall, clearly indicating a poor groundwater recharge in Vertisols in low rainfall areas in the SAT regions. In contrast, on Alfisols substantial annual runoff and deep drainage took place even during the low rainfall years. The mean annual runoff from Alfisols was 16% of annual rainfall, which is eight times higher than that observed on Vertisols. Similarly, on Alfisols, about 12% of the mean annual rainfall was lost as deep drainage, which is about 4 times higher than on the Vertisols. These results show that for Alfisols, even in low rainfall areas, there are good prospects of runoff water harvesting and groundwater availability.

During the medium annual rainfall years (750–900 mm annual rainfall), the mean annual runoff on Vertisols was moderate (Fig. 7). On Vertisols, the average annual runoff was about 10% of the annual rainfall. From this, it follows that in the medium rainfall regions of Vertisols, there are low to medium prospects of runoff harvesting. In medium rainfall areas on Vertisols, about 13% of the annual rainfall is as deep drainage (Fig. 7). These results indicate only moderate prospects of groundwater recharge and availability in such regions. In contrast, on Alfisols much higher annual runoff and deep drainage took place during the medium rainfall years (Fig. 7). The mean annual runoff on Alfisols is 26% that of annual rainfall, which is 2.6 times higher than that on Vertisols. Similar trend can be seen for water loss through deep drainage. These results imply that for Alfisols in the medium rainfall areas, there are very good prospects of runoff water harvesting and groundwater availability.

During the high annual rainfall years (>900 mm annual rainfall), a different trend in runoff behavior of Vertisols and Alfisols is seen (Fig. 7). During these years, the Vertisols generated higher annual runoff compared to Alfisols. It would appear that because of high rainfall, most of the time the soil stayed wet, leading to very low infiltration and high runoff. These results suggest that in the high rainfall areas, Vertisols may generate high annual runoff and hence very good prospects of harvesting runoff water. In high rainfall areas on Vertisols, deep drainage losses are higher but not of the magnitude of surface runoff. This is because under extremely wet soil conditions (moisture level at field capacity and above), the internal profile drainage of the Vertisols is poor due to very low saturated hydraulic conductivity of different soil layers (Table 3). This leads to low deep drainage losses on Vertisols. In contrast, Alfisols in high rainfall years recorded very high annual runoff and deep drainage; and about 62% of the annual rainfall is lost through runoff plus deep drainage. These results show very high prospects of runoff water harvesting and groundwater availability on Alfisols in the high rainfall areas of the SATs. However, high runoff on both soils results in serious soil erosion and often waterlogging problems.

3.2. Soil loss and sediment concentration from Alfisol and Vertisol watersheds

The results on mean annual soil loss and sediment concentration recorded in Alfisol and Vertisol watersheds during 1976–2010 (Tables 5 and 6) showed a large difference in both the mean annual soil loss and sediment concentration between these two soils. In Alfisols, the mean annual soil loss was about 3.0 times higher (4.62 vs. 1.63 t ha^{-1}/annum) compared to Vertisols. The mean sediment concentration in runoff water for Alfisols was 1.69 times (2.35 vs. 1.39 g l^{-1}) that of Vertisols (Table 7). This indicates that the Alfisols are more susceptible to soil erosion than the Vertisols. This is undesirable, since most of Alfisols in SAT regions are poor in terms of physical, chemical and biological soil health parameters (El-Swaify et al., 1985). Any further land degradation due to soil erosion is undesirable and may eventually lead to low as well as unstable agricultural productivity. On the other hand, the mean soil loss recorded from Vertisol watersheds was relatively low. Since most of the SAT Vertisols are generally quite deep with relatively better soil health, a low level of soil erosion may not pose any immediate serious threat to agricultural productivity.

3.2.1. Effect of crop cover on sediment concentration

On both Alfisols and Vertisols, crop cover had significant effects on sediment concentrations in runoff water (Fig. 8). The mean sediment concentration in runoff water was high during the early parts of cropping season, when the crop cover was low. During August and September, when the crop cover was highest, the mean sediment concentration in runoff water was lowest (almost half that recorded during the early part of the season). On both soils, the sediment concentration gradually decreased with the increase in crop cover during the crop-growing season. Crops at the experimental watersheds are normally planted during the 2nd or 3rd week of June and harvested in the 1st or 2nd week of October. The crop cover gradually increases from June and reaches a peak in the month of August or September (ICRISAT, 1984). This trend in the sediment concentration was similar in both Alfisol and Vertisol watersheds. However, the sediment concentration in runoff was always higher on Alfisols than that on Vertisols. This reconfirms that in the SAT regions Alfisols are more prone to soil erosion than Vertisols; and emphasizes the need to controlling soil erosion on Alfisols.

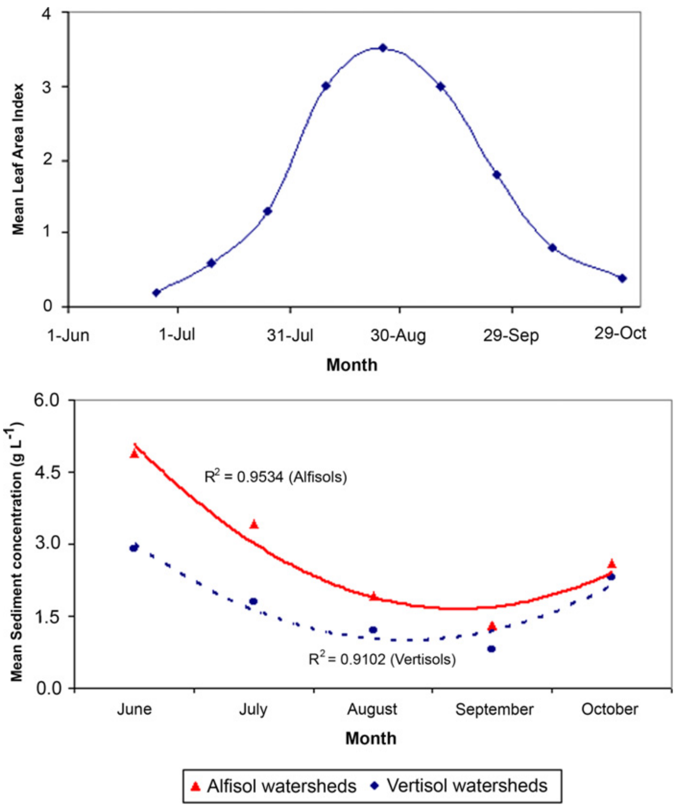

Fig. 8. Effects of crop canopy on sediment concentration in runoff water on Alfisol and Vertisol watersheds at the ICRISAT Center, Patancheru, India.

4. Implications of hydrological behavior for hydrological models and soil and water management

4.1. Implications for soil and water management

Although in the semi-arid tropics of India, Alfisols and Vertisols often occur in close proximity, their hydrological behavior is strikingly different; and obviously, different soil and water management practices are needed for their effective use for agricultural production and maintenance of environmental quality. The hydrological behavior of these two soils is influenced by the rainfall and soil characteristics and preceding soil moisture conditions. Soil crusting, sealing, low structural stability, formation of cracks, and other properties have strong influence on their hydrological behavior.

Evidence from this as well from our research in 12 other on-farm watersheds located in the low, medium and high rainfall areas, suggest that distinct hydrological behavior of these two soil types has important implications for developing effective soil and water management strategies and practices based on the annual rainfall (Pathak et al., 2010). Although the study on the 12 on-farm watersheds was conducted only for 3 years (2008–2010), the hydrological behavior of Alfisol and Vertisol watersheds of low, medium and high rainfall areas was quite similar to that of the long-term on-station watersheds during low, medium and high rainfall years (Pathak et al., 2010). Evidently, the optimum soil and water management practices vary in low, medium and high rainfall areas of the SAT regions.

4.1.1. Vertisols and Alfisols in low rainfall regions (<750 mm annual rainfall)

In low rainfall region, the annual runoff on the SAT Vertisols is expectedly very low and hence there would be a low potential for runoff water harvesting in surface storage structures. This implies that in these regions, the construction of water harvesting structures or related interventions may not be so effective. As the runoff on Vertisols is very low, there may not be much advantage in improving the infiltration into the soil. Very low loss of water through deep drainage in Vertisols in low rainfall implies low prospects of groundwater recharge and availability. Soil loss does not seem a serious problem in the SAT Vertisols of low rainfall regions as low annual soil losses are expected from Vertisols. In low rainfall regions, the annual runoff from Alfisols is expectedly moderate, resulting in a moderate potential of runoff harvesting. Since in the low rainfall regions, droughts are common, the benefits from runoff water harvesting and supplemental irrigation is expectedly rewarding in increasing and sustaining crop yields on these soils. There is need to control the early season runoff, particularly when these soils are dry through appropriate soil and water management interventions. This is more important in low rainfall regions where moisture stress is common during the growing season. Annual deep drainage from Alfisols in the low rainfall regions is apparently moderate; and thus even in the low rainfall regions, there is moderate potential of groundwater recharge and its availability for increasing agricultural productivity on these soils. In low rainfall areas crop covers are effective in reducing soil loss on both Alfisols and Vertisols.

4.1.2. Vertisols and Alfisols in medium rainfall regions (750–900 mm annual rainfall)

Vertisols in the medium rainfall regions generate low to moderate annual runoff, mostly in the later part of the rainy season, implying low to moderate prospects of harvesting runoff water. However, since most of the runoff occurs during the later part of the rainy season, water availability and its usefulness for the rainy season crops is limited. Nevertheless, the stored runoff can be utilized as pre-sowing irrigation for the post-rainy season crops. In the medium rainfall regions of Vertisols, excellent responses to pre-sowing irrigation have been recorded (Pathak et al., 2009). Also in these regions, the deep drainage on Vertisols is low to moderate; and hence low to moderate potential of groundwater recharge and availability. Moreover, not much benefit will likely accrue by increasing rainwater infiltration as most of the runoff occurs when the top 30 cm soil profile is near field capacity. In such situations, the soil and water management systems should focus more on improving waterlogging and drainage problems by a safe disposal of excess runoff. In the medium rainfall regions, high annual runoff from Alfisols, indicates good prospects of runoff water harvesting. In such region, the occurrence of droughts and moisture stress are common features in Alfisols and the use of stored runoff water as supplemental irrigation during the rainy season would be beneficial to the crops. An excessive early season runoff particularly occurs on Alfisols when the soils are dry, and this needs to be managed through appropriate soil and water management practices such as contour cultivation along with conservation furrows, mulching and conservation agriculture. Moderate to high annual deep drainage losses from Alfisols suggest good prospects of groundwater availability. On Alfisols, high annual soil loss occurs even in the medium rainfall regions. Crop cover alone may not be sufficient for controlling soil erosion, and thus there is a need for support by appropriate soil and water management interventions. The soil and water management practices such as contour cultivation along with conservation furrows, contour bund with gated outlets, mulching and conservation agriculture could be effective in controlling soil loss as well as runoff from Alfisols. In medium rainfall region, the contribution of big runoff events with annual runoff and soil loss on Alfisols and Vertisols is quite high. Therefore, proper management of big events through in situ and ex situ soil and water

Fig. 9. The broadbed and furrow system with groundnut crop (inset showing broadbed and furrow and its formation).

conservation measures is crucial for effectively controlling the high runoff and soil loss on these two soils.

4.1.3. Vertisols and Alfisols in high rainfall regions (>900 mm annual rainfall)

Extremely high annual runoff from Vertisols in high rainfall regions provides a high potential for runoff water harvesting. In such region, the focus of soil and water management system should be a safe disposal of the excess runoff without causing soil erosion, and to reduce the waterlogging problem, which often affects agricultural productivity. On Vertisols, the deep drainage loss is expectedly moderate, suggesting a moderate potential of groundwater recharge and availability. In high rainfall regions, the annual runoff from Alfisols is high; and thus an excellent potential for runoff water harvesting. In such region, soil moisture does not appear to be a major issue and the soil and water management system should focus on a safe disposal of excess runoff without causing soil erosion. For such situations, the soil and water management practices such as broadbed and furrow with drain, narrow ridge and furrow on grade with graded bund could be useful for safe disposal of excess runoff thereby reducing the waterlogging conditions in soils. The broadbed and furrow system consists of 95 cm wide beds separated by 55 cm wide furrows, which drain into grassed waterways (Fig. 9). In this system, the furrows are laid out on a grade of 0.4–0.8% for optimum performance. The raised bed portion acts as an in situ “bund” to ensure soil stability; and the shallow furrow (15 cm deep) provides surface drainage to promote aeration and prevent waterlogging of crops growing on the bed. The design of this system is quite flexible for accommodating crops and cropping systems with widely differing row spacing requirements. The basic principle of graded narrow ridge and furrow is quite similar to that of broadbed and furrow system, except that the ridges where crops are planted are quite narrow (35 cm). The dimension of the furrow and its grade are similar to that of broadbed and furrow system. Since the stability of narrow ridge and furrow system during heavy rains are questionable, it needs to be supported by graded bunds at horizontal intervals of 70–100 m depending upon the slope and rainfall.

The annual deep drainage loss from Alfisols is expectedly very high, which provides an excellent opportunity for groundwater recharge and availability. On both Alfisols and Vertisols, there is potential for high soil loss, and a good crop cover would only provide a limited control of soil erosion. For such regions, soil and water management system must focus on reducing soil loss. This is particularly important for Alfisols since most of the SAT Alfisols are already in a degraded state.

4.2. Implications for hydrological models

The long-term hydrological data summarized in this paper, clearly show a profound influence of some key features of Alfisols (crusting and sealing) and Vertisols (cracks formation) on runoff volume, peak runoff rate, soil loss, deep drainage and other hydrological components. The results also suggest that the influence of these key soil features on various hydrological parameters is quite complex, and varies considerably with soil moisture, rainfall, wetting and drying cycle, crop canopy and other variables. Past research (Ahuja and Swartzendruber, 1992; Arnold et al., 2005; Assouline, 2004; Hoogmoed and Bouma, 1980; Vandevaere et al., 1988; Wakindiki and Ben-Hur, 2002) has also emphasized the role of these key soil features in influencing the hydrology of soils. However, most of results reported are from studies made on small plots (Assouline and Mualem, 2003; Helalia et al., 1988; Krohn and Slosson, 1980; Tarchitzky et al., 1984). Based on our results and those from others (Stolte et al., 1997; Smith et al., 1999), we propose that for Vertisols and Alfisols, the hydrological models employed must consider the influence of key soil features and characteristics on hydrological components. Currently, most of the major hydrological and other crop models (Neitsch et al., 2005; Jones et al., 2003; Ritchie, 1998) do not adequately account for the influence of these key soil features on hydrological parameters. There is an obvious need to consider the influence of key soil features of Alfisols and Vertisols while developing hydrological models for these and related soils. This would help considerably in improving the performance of the hydrological models in predicting hydrological components.

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