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Effect of slope position and depth on hydraulic and physical properties of soils in north-western tract of India

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ABSTRACT

The undulating topographies and changing depth can influence soil physical and hydraulic property by affecting runoff, drainage, microclimate, and water erosion in the North-western tract of India. These facts warrant suggesting suitable strategies to alleviate degradation of soil hydraulic and physical properties and devise suitable agricultural management practices in the tract. Keeping in view these points, the hypothesis of the investigation was to evaluate the effect of slope position and depth on soil physical and hydraulic properties in the tract. Therefore, the investigation was undertaken to examine the effect of slope position and depth on hydraulic and physical properties of soils in the tract. The study was carried out at Kokowal -Majari, Bhadiar, Jhunewal and Binewal watersheds located in district Hoshiarpur, Punjab. The mean values of maximum water holding capacity for 3- slope positions varied from 40.1 to 44.5 per cent for Kokowal, Majari and Binewal. Whereas, it varied from 39.8 to 44.4 per cent and 40.0 to 44.8 per cent at Dallewal and Bhadiar respectively. These were higher on the lower slope position over the upper and middle slope positions at all depths and locations. The infiltration rate was lower on middle and lower slope position than that at the upper slop position at locations Kokowal –Majari and Binewal. The per cent proportion of sand and silt content decreased with (average of all locations) and clay content increased with increase in depth (average of all locations). The saturated hydraulic conductivity was higher on middle and lower slope positions than that at upper slope position at locations Kokowal, Majari and Binewal. The mean weight diameters were higher on middle and lower slope position over the upper slope position at all locations. The modulus of rupture increased with increase in depth, irrespective of slope position. The different indices of soil erodiblity such as dispersion ratio, erosion ratio and clay ratios decreased with increase in depth of soil. The different soil hydraulic and physical properties were influenced either by slope position or depth and combination of both.

Keywords: Arable watersheds, summit, mid ad toe slope, hydro-physical properties

INRODUCTION

The variation in slope gradient and position has a major impact on soil erosion, which causes significant loss of finer soil particles (Carroll *et al.*, 2000). Wang *et al.*, (2001) moreover, considered topography as the dominant factor influencing soil property variation by affecting runoff, drainage, and microclimate and water erosion. In addition, other soil properties such as particle-size distribution and organic matter content vary substantially with slope position (Wang *et al.*, 2001; Mulugeta and Sheleme, 2010).

The slope position as one of the major topographical parameter has a significant indirect influence on soil physical and hydrological properties by controlling the soil water movement. This also results in water erosion and carries away eroded material (Khormali, 2007; Begum *et al.*, 2010; Arora *et al.*, 2023). In this regard, the different hill slope erosion process affects physical properties of soils on their upper horizons.

However, the soil hydraulic and physical properties are important soil quality indicator for sustainable soil management practices in the North-western tract of India (Chandel *et al*., 2018). These are known to control and characterize the various saturated and unsaturated flows in soils (Dorner *et al*., 2010). The various agricultural management practices (Arora *et al*., 2023), topographic positions (Patra *et al*., 2019; Singh *et al*., 2022) and environmental factors affect soil hydraulic and physical properties. In addition, these affect relevant processes dynamically and thereby, cause movement and retention of water, solutes, nutrients and pollutants. However, a little change in soils textural composition under undulating or changing field topographies can change soil hydraulic properties (Bodner *et al.*, 2008; Singh, 2010). Whereas, lack of knowledge regarding varying soil physical properties and pore-size distribution under different slope positions and crop-rotations may lead to poor predictions. This suggests understanding of soil hydraulic and physical properties prove helpful in proper calibration, validation of hydrological models and proposing suitable land management strategies in the tract (Singh, 2010).

The different slope positions are the important influential factors in affecting the soil hydraulic and physical properties due to changes introduced by soil pore system and hydraulic conductivity (Singh, 2010). The undulating topographies also lead to increased runoff and soil erosion resulting in larger variability of soil hydraulic and physical properties (Chandel and Hadda, 2019). Therefore, there is a need to propose suitable strategies to alleviate degradation of soil hydraulic and physical properties and recommend suitable agricultural management practices in the tract. Keeping these points in view, the objective of the investigation was to examine the effect of slope position and depth on hydraulic and physical properties of soils in North-western tract of India.

MATERIALS AND METHODS

The present investigation was conducted on Kokowal-Majari and Bhadiar watershed(s) in Hoshiarpur district of Punjab.

Climate

The study area is situated in agro climatic zone-I of Punjab. According to the Thornthwaite climatic classification, the study area has a semi- arid to sub-humid climate (Singh 1979). The mean annual rainfall of the area is 1000±150 mm which constitutes the major source of water in the area. The rainfall pattern follows bimodal distribution with a mean monthly rainfall highest in July and lowest in November. About 80 per cent and 20 per cent of the total annual rainfall is received in months of June to September (summer season) and in October to March (winter season) respectively. The monsoon rains (June - September) are received in 20 to 30 storms, of which 8 to 12 storms produce runoff and overland flow (Hadda and Sur 1986). However, 2 to 3 rainstorms occur with an average intensity greater than 120 mm h^{-1} in the tract (Hadda and Sur 1986).

Of the total annual rainfall, 91 per cent was received during months of June to September (Summer monsoon months) whereas only 9 per cent was received during the month of October to March (Winter months) in the year 2003. Similarly, of the total annual rainfall, about 80 per cent was received during summer months and 20 per cent during winter months, in the year 2005. Similarly in year 2008, of the total annual rainfall, about 92 per cent was received in summer months and only 8 per cent was received during winter months (Singh, 2010).

The mean-maximum temperature varies from 18.6°C in January to 39.1°C in May and mean-minimum temperature from 5.2°C in December to 24.7°C in June. The high temperature and desiccating winds in May to June months create scarcity of fodder due to grazing and browsing of trees, bushes and grasses by cattle. Due to high temperatures and low humidity in these months, vegetation cover is very sparse.

Geology and Geomorphological Features

The lower Shiwaliks have grey to light grey micaceous fine to medium sandstone occasionally mixed with pseudo- conglomerates containing pebbles of calcareous clay and shale (Mahajan *et al*., 2000). The geology of the area consists mainly of alluvial detritus derived from sub-serial wastes of mountains, swept down by rivers, streams, rocks and deposits from the Upper Miocene to the Lower Pleistocene age (Wadia, 1976). The soils of the area are represented by the great groups of Ustorthents, Ustipsamments and Haplustalfs. The predominant minerals present in these soils are Illite, Smectite, Kaolinite and Chlorite (Singh, 1979). A variety of heavy minerals like Garnet, Tourmaline and Biotite etc. have also been reported in the area (Sur *et al*., 1998).

The fluvial action of seasonal ephemeral streams (torrents), erosion and deposition are the three main geomorphological processes responsible in the development of the tract (Sur and Ghuman, 1994). The processes are strongly influenced by the relief and climate and the soil profiles are being constantly modified due to these processes even today. However, the erosion of sediments from the hilly portions and their deposition in the lower and toe slopes is continuously modifying the original profiles.

The important watershed related parameters of Kokowal–Majari–Jhunewal is described in Table 1. The watershed is located at an elevation of 355 at MSL, the size of the watershed is 40 hectares and slope steepness is 4.25 per cent.

Soil sampling

Soil samples from 0-15, 15-30, and 30-60 cm depth, from upper, middle and lower slope positions were collected from 5- sites viz; Majari, Kokowal, Binewal, Dallewal and Bhadiar. However, each location (site), 3-replications were considered and which varied in the slope steepness from 0 to 5 per cent. The samples were taken as per standards procedures and analysed for their chemical and physical characteristics as per the procedures described below.

Soil organic Carbon

Soil organic carbon (SOC) was determined with wet digestion potassium dichromat (Walkley and Black, 1934) procedure.

Table 1. Important watershed related parameters at Kokowal-Majari-Jhunewal*

Parameters	Range
Elevation (MSL, m)	355
Size of watershed (ha)	40
Average width (m)	470
Maximum length (m)	605
Average slope steepness (per cent)	4.25
Perimeter (m)	1623.9
Total no. of streams / gullies	183
Total length of streams / gullies (km)	3.7
Length to width ratio	1.3
Channel slope (per cent)	1
Time of concentration (minute)	9.3

*Adapted from Singh (2004)

Hydrologic and physical Parameters

The saturated hydraulic conductivity (Ks) was determined by constant head method (Reynolds, Elrick, and Youngs 2002). However, bulk density (Db) was determined by core method (Blake and Hartge, 1986). Infiltration rate (IR) was determined by double ring infiltrometers (Reynolds, Elrick, and Youngs, 2002) by maintaining 3- replications. However, the particle size analysis was carried out as per the International Pipette Method of Day (1965). The maximum water holding capacity (MWHC, per cent) was determined by using the method of Richard (1954).

Per cent proportion of sand silt and clay

The per cent proportion of sand content decreased from surface (0-15cm) depth to sub-surface (15-30) and (30-60 cm) depth respectively at a location (Table 4). Whereas, the per cent proportion of silt did not vary much with increase in depth of soil at a location. However, the per cent proportion of clay increase with increase in depth of soil i.e. 0-15, 15-0 and 30-60 cm respectively. The different types of soil textures noticed at surface to sub-surface layers of soils are clay loam to loam at a depth and location in the area.

Soil erodibility

The formulae used to compute clay ratio, dispersion ratio and erosion ratio are described below as indirect indices of soil erodibility.

Erodibility index	Formula	Author
Clay ratio	% sand+ % silt % clay	(Bouyoucos 1935)
Dispersion ratio	%(silt + clay) in undispersed soil % (silt + clay) in dispersed soil	(Middleton 1930)
Erosion ratio	dispersion ratio % clay / moisture equivalent	(Middleton 1930)

Aggregate size distribution

Aggregate size distribution was determined by wet sieving method as described by Yoder (1936). The mean weight diameter (MWD) was computed as described below.

$$MWD = \frac{\sum_{i=1}^{n} diwi}{\sum_{i=1}^{n} wi} \quad (1)$$

Where, di is mean diameter of ith size fraction in mm; n is number of sieve sizes and wi is weight of aggregates occurring in the ith size fraction in g.

Modulus of rupture

Modulus of rupture was determined by using the procedure described by Richards (1953). It was computed from the following formula:

$$\text{Modulus of rupture (S)} = \frac{3FL}{2bd^2} \quad (2)$$

Where,

S is modulus of rupture (dyne/cm^2)

F is breaking force in dyne = W × 980

W is weight of water (gm)

L is distance between two lower bars or briquette and support (cm)

b is width of briquette (cm)

d is thickness of briquette (cm)

Depth distribution of Modulus of Rupture (MOR) under different slope positions and locations is described in Table 7. On an average, the MOR increases with the increase in depth, irrespective of slope position. However, the average values of MOR increased significantly from the upper slope position to the lower slope position both in surface and sub-surface layers of the soils.

RESULTS AND DISCUSSION

Organic Carbon

The information on organic carbon content in soil surface layer at upper, middle and lower slope position is presented in Table 2. The mean (average of 3- slope positions) per cent soil organic C content varied from 0.31 to o.74 at all locations. The per cent Organic C content differed at upper, middle and lower slope position(s) at all the locations. In general, the organic C content decreased from lower to middle and then from middle to upper slope position at all locations. For example, the organic carbon content was 0.87, 0.85 and 0.51 per cent at lower, middle and upper slope position respectively at Bhadiar.

Maximum water holding capacity

The information on depth distribution of maximum water holding capacity on upper, middle and lower slope positions at different locations is described in Table 3. The mean values of maximum water holding capacity for 3- slope positions varied from 40.1 to 44.5 per cent for Kokowal, Majari and Binewal. Whereas, it varied from 39.8 to 44.4 per cent and 40.0 to 44.8 per cent at Dallewal and Bhadiar respectively. These were higher on the lower slope position over the upper and middle slope positions at all depths and locations. This was noticed higher at lower slope position over other slope positions due to higher clay content. However, Hadda *et al*. (2001) and Singh (2004) observed similar relationships in between maximum water holding capacity and clay content ($R^2 = 0.98$ and $R^2 = 0.97$ respectively) for soils of sub-surface compared to surface layers. Singh (2008) reported that increase in finer particles and organic carbon content on the lower slope position could increase the maximum water holding capacity in the tract. The study by Magdic *et al*. (2022) suggested that a higher percentage of clay fractions were found on upper land slope position, which was related positively with water retention in the soils. However, the main cause attributed for the retention of soil moisture at the particular slope is mainly influenced by soil properties (primarily the soil texture) compared to the land slope position.

Table 2. Per cent soil organic carbon in soil surface depth (0-15cm) as affected by slope position at different locations

Location	Slope position			Mean±SD
	Upper	Middle	Lower	
Majari	0.26±0.02	0.33±0.02	0.34±0.01	0.31±0.02
Kokowal	0.27±0.01	0.31±0.01	0.35±0.02	0.31±0.01
Binewal	0.38±0.01	0.40±0.01	0.41±0.02	0.40±0.01
Dallewal	0.38±0.02	0.39±0.04	0.40±0.01	0.39±0.02
Bhadiar	0.51±0.005	0.85±0.04	0.87±0.005	0.74±0.02

Table 3. Maximum water holding capacity (%) as affected by different slope positions at different locations and depths in Hoshiarpur

Location	Slope position	Soil Depth (cm)			Mean ± SD
		0-15	15-30	30-60	
Majari	Upper	38.3±0.2	40.0±0.2	42.0±0.1	40.1±0.2
	Middle	36.4±0.6	43.2±0.5	45.0±0.4	41.5±0.5
	Lower	40.4±0.4	45.4±0.4	47.6±0.5	44.5±0.4
	Mean±SD	38.4±0.4	42.9±0.4	44.9±0.3	-
Kokowal	Upper	38.3±0.5	40.0±0.4	42.0±0.3	40.1±0.4
	Middle	36.8±1.1	43.1±0.3	45.1±0.3	41.7±0.6
	Lower	40.5±0.4	45.3±0.4	47.8±0.2	44.5±0.3
	Mean±SD	38.5±0.7	42.8±0.4	45.0±0.3	-
Binewal	Upper	38.3±0.3	39.9±0.4	42.1±0.2	40.1±0.3
	Middle	36.4±0.7	43.1±0.3	45.2±0.2	41.6±0.4
	Lower	40.4±0.2	45.4±0.2	47.7±0.4	44.5±0.3
	Mean±SD	38.4±0.4	42.8±0.3	45.0±0.3	-
Dallewal	Upper	38.0±0.4	39.8±0.4	41.5±0.4	39.8±0.4
	Middle	35.9±0.6	42.9±0.3	44.9±0.1	41.2±0.3
	Lower	40.2±0.3	45.2±0.3	47.7±0.4	44.4±0.3
	Mean±SD	38.0±0.4	42.6±0.3	44.7±0.3	-
Bhadiar	Upper	38.1±0.4	40.2±0.2	41.6±0.5	40.0±0.4
	Middle	36.2±0.5	43.1±0.9	45.2±0.4	41.5±0.6
	Lower	40.8±0.2	45.7±0.4	48.0±0.3	44.8±0.3
	Mean±SD	38.4±0.4	43.0±0.5	44.9±0.4	-

Bulk density

The bulk density decreased from upper to middle then from middle to lower slope position(s) at a location (Table 4). The mean values of bulk density at different locations followed the trend: Binewal> Dallewal> Majari>Bhadiar> Kokowal. The removal of finer particles by the runoff process from the upper slope to the lower slope resulted in higher contents of coarser particles, resulting in the variation of bulk density at different slope positions. The variation of soil moisture at different slope positions combined with soil compaction resulting from tractor- traffic may also dynamically affect the bulk density. Lin *et al.* (2018) found a lower bulk density at the lower slope position than at the upper and middle-slope positions. Ma *et al*. (2019) concluded that the differences in bulk density at different slope positions were due to the washing of surface soil by runoff from the upper and middle slope positions. The study of Raoff (2011) noticed bulk density values of soils were increased with increase in slope steepness. The variation in bulk density from upper slope to lower slope position might be attributed by the removal of fine particles through runoff process and left the high contents of coarser particles. In addition, this may be caused by the variation of soil moisture at different slope positions combined with soil compaction resulting from tractor –traffic may also dynamically affect bulk density. However, Mao *et al*. (2019) found differences in bulk density at different slope positions This can be attributed due to the washing of surface soil by runoff from the upper and middle slope positions but the deposition of washed soil particles at the lower slope position did not significantly reduce the bulk density. The water uptake increases the bulk density near the

Table 4. The effect of slope position on bulk density (Mg/m^3) at different locations in Hoshiarpur

Location	Slope position			Mean±SD
	Upper	Middle	Lower	
Majari	1.51±0.1	1.46±0.1	1.43±0.01	1.47±0.07
Kokowal	1.50±0.03	1.45±0.02	1.41±0.02	1.45±0.02
Binewal	1.52±0.005	1.48±0.02	1.46±0.03	1.49±0.02
Dallewal	1.51±0.01	1.47±0.02	1.45±0.1	1.48±0.04
Bhadiar	1.50±0.01	1.46±0.02	1.43±0.01	1.46±0.01

Table 5. Per cent proportion of sand, silt, and clay at different location(s) and depth(s)

Location	Soil depth (cm)	Sand	Silt	Clay	Texture
			Percent		
Majari	0-15	43.8±1.0	31.0±1.0	24.9±0.3	L
	15-30	39.1±0.8	34.4±0.5	26.3±0.4	Cl l
	30-60	34.0±0.4	34.8±0.4	31.0±1.0	Cl l
Kokowal	0-15	40.6±0.3	36.8±0.6	22.3±0.2	L
	15-30	38.4±0.5	36.0±0.3	25.3±0.4	Cl l
	30-60	34.3±0.8	35.9±1.1	29.6±0.7	Cl l
Binewal	0-15	35.4±0.6	35.7±0.9	28.5±0.7	Cl l
	15-30	28.3±0.6	34.5±0.6	37.0±0.3	Cl l
	30-60	24.5±0.6	34.5±0.6	40.9±0.4	Cl l
Dallewal	0-15	44.0±2.5	35.8±1.0	19.8±1.0	L
	15-30	35.3±0.4	34.8±1.1	30.0±1.0	Cl l
	30-60	33.4±1.2	34.1±0.4	32.4±0.7	Cl l
Bhadiar	0-15	46.0±1.1	36.8±0.3	16.6±0.7	L
	15-30	39.6±1.0	36.2±0.4	23.8±0.2	L
	30-60	34.0±1.3	35.2±0.5	30.5±0.7	Cl l

roots of the plants due to adhesion to the soils. The study of Magdic *et al*. (2022) showed that the sand content indicated a positive and better correlation with bulk density (r=0.60), while clay content negatively related with bulk density (r=0.41) for Stagnosol soils. The study further indicated that a soil profile located at the upper slope position, which has higher clay content, has a lower bulk density.

Sand, silt and clay

The per cent proportion of sand, silt and clay varied with soil depths (average of all 5 locations for each soil layer i.e. 0-15, 15-30 and 30-60 cm) (Average values drawn from Table 5). At soil depth of 0-15 cm, per cent proportion of sand, silt and clay was 41.96, 35.22 and 22.42 respectively (mean of 5 locations). However, for next soil layer, 15-30 cm, the per cent proportion of sand, silt and clay was 36.08, 35.18 and 30.4 respectively (mean of 5 locations). Similarly, in the next layer of 30-60cm, the per cent proportion of sand silt and clay was 32.04, 32.9 and 32.88 respectively (mean of 5 locations). The per cent proportion of sand decreased with depth (0 to 15 cm) which is 41.96 to 36.08 (15-30 cm) and further decreased from 36.08 to 32.04 (30 to 60 cm). Similarly, per cent of silt also decreased with depth (0-15cm), that is 35.22 to 35.18 (15-30 cm) and from 35.18 to 32.90 (30 to 60 cm) respectively. Whereas, per cent proportion of clay increased from 22.42 (0-15 cm) to 30.4 (15-30 cm), and then from 30.4 (15-30cm) to 32.88 (30-60 cm). These variations in sand, silt and clay proportions with depth might be attributed due to undulating topographies and mechanical cutting of the soil layers by water erosion process mainly caused by intense and short duration rainstorms received in summer monsoon months (Hadda and Sur, 1986; Singh, 2010). In addition, several authors contended that silt particles are more susceptible to moving down the land slope than the clay and sand particles by water erosion. (Torri *et al*., 1997; Cerdan *et al*., 2010).

Saturated hydraulic conductivity

The saturated hydraulic conductivities were higher on the middle and lower slope position than that in the upper slope position, irrespective of soil depth at all locations (Table 6). However, among all locations, Dallewal has the highest values of saturated hydraulic conductivity i.e. 0.24, 0.26, 0.29 cm h^{-1}, while Majari has lowest values of saturated hydraulic conductivity i.e. 0.19, 0.22, 0.23 cm h^{-1} at upper, middle and lower slope position(s) respectively. The increase of saturated hydraulic conductivity in lower slope than that in the upper slope position is attributed to the presence of higher clay content. The surface soil layer showed higher saturated hydraulic conductivity irrespective of slope position and locations. Singh (2004) showed similar results at Kokowal-Majari-Jhunewal watershed located in district Hoshiarpur. However, Study of Rao of (2011) indicated that saturated hydraulic conductivity decreased with increase in slope gradient. The saturated hydraulic conductivity was significantly reduced at lower slope position that might have occurred due to higher clay content

Table 6. Effect of slope position on saturated hydraulic conductivity (cm h^{-1}) at different locations and depths

Location	Slope position	Soil Depth (cm)			Mean ± SD
		0-15	15-30	30-60	
Majari	Upper	0.23±0.02	0.19±0.01	0.16±0.01	0.19±0.01
	Middle	0.26±0.02	0.22±0.01	0.19±0.01	0.22±0.01
	Lower	0.28±0.02	0.22±0.01	0.20±0.02	0.23±0.02
	Mean±SD	0.26±0.02	0.21±0.01	0.18±0.01	-
Kokowal	Upper	0.25±0.01	0.21±0.01	0.20±0.02	0.22±0.01
	Middle	0.29±0.01	0.22±0.02	0.21±0.03	0.24±0.02
	Lower	0.30±0.02	0.23±0.02	0.22±0.04	0.25±0.02
	Mean±SD	0.28±0.01	0.22±0.02	0.21±0.03	-
Binewal	Upper	0.24±0.01	0.19±0.02	0.18±0.03	0.20±0.02
	Middle	0.27±0.02	0.21±0.02	0.18±0.03	0.22±0.03
	Lower	0.29±0.01	0.23±0.01	0.20±0.03	0.24±0.01
	Mean±SD	0.26±0.01	0.21±0.02	0.19±0.03	-
Dallewal	Upper	0.29±0.01	0.26±0.01	0.19±0.02	0.24±0.01
	Middle	0.31±0.02	0.27±0.02	0.20±0.01	0.26±0.02
	Lower	0.32±0.02	0.28±0.01	0.20±0.01	0.27±0.01
	Mean±SD	0.31±0.02	0.27±0.01	0.20±0.01	-
Bhadiar	Upper	0.28±0.02	0.23±0.03	0.19±0.02	0.23±0.02
	Middle	0.28±0.01	0.23±0.02	0.19±0.04	0.23±0.02
	Lower	0.33±0.02	0.28±0.01	0.21±0.03	0.27±0.02
	Mean±SD	0.30±0.02	0.25±0.02	0.20±0.03	-

(Bodner *et al.*, 2008). In addition, the study area falls in higher rainfall region, where large volume of overland flow was reported (Hadda and Sur 1987). In addition, the water erosion, soil compaction and surface sealing, ultimately reduced pore-size and conductivity at the lower slope position (Cameira *et al.*, 2003; Biddocu *et al.*, 2016).

Infiltration rate

The infiltration rate as a function of time for upper, middle and lower slope positions at Bhadiar is shown in Fig. 1. For Bhadiar site, the infiltration rate was observed to be lower by 10 and 30 per cent in middle and lower slope position as compared with upper slope position for first 2 minutes. But in the lapse of further 15 minutes, the infiltration rate was observed to be lower by 20 per cent and 28 per cent on middle and lower slope position than that at the upper slope position. The large differences observed in the infiltration rate, in first 5-25 minutes may be attributed due to the presence of more organic matter content in surface layers than that in

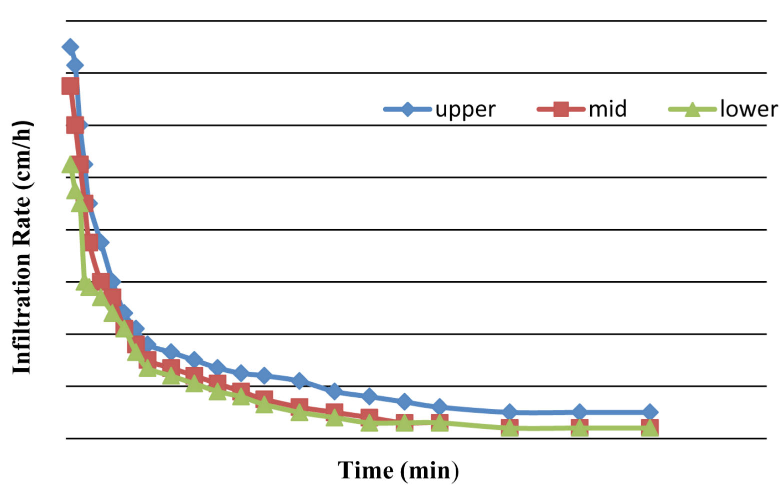

Fig. 1. Infiltration rate as a function of time for different slope positions at Bhadiar

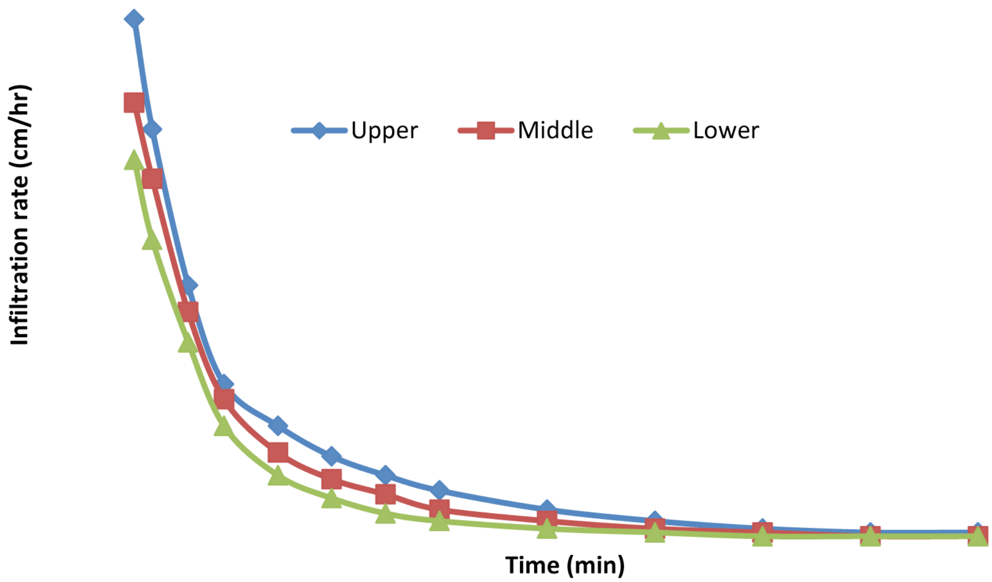

Fig. 2. Infiltration rate as a function of time for different slope positions at Kokowal-Majari-Jhunewal (Source: Singh, 2004)

the sub-surface layers. The steep decline in infiltration rate in further 5-30 minutes onwards is as per the expectations because of increase in wetted length of hydraulic gradient with time. It was observed that lower slope position showed less infiltration rate than that at the upper slope position. This may be due to the presence of more clay content in lower slope position over the upper slope position. Bradford *et al*. (1987) revealed that reduction in infiltration rate might be due to seal formation but the extent of seal formation depends upon the texture and porosity of soils. Some authors had found that soil surface conditions such as roughness, structure, vegetation and rock fragment cover affect the infiltration rates, runoff and soil erosion (Papy and Douyer, 1991; Auzet *et al.* 1995).

The infiltration rate was 15.9 and 26.8 per cent lower on middle and lower slope position than that on upper slope position for first 5 minutes at Kokowal –Majari (Fig. 2). However, after the lapse of further 15 minutes, the infiltration rate was lower by 10.3 and 22.1 per cent in middle and lower slope position than that in upper slope position. The large differences observed in the infiltration rate, in first 5-20 minutes may be attributed due to the presence of more organic matter content in surface layers than that in sub-surface layers. The steep decline in infiltration rate in further 5-30 minutes onwards was as per the expectation because of increase in wetted length of hydraulic gradient with time. It was observed that lower slope position showed less infiltration rate than that in upper slope position. This may attributed due to the presence of more clay content in lower slope position than that in upper slope position (Singh, 2004).

The cumulative infiltration as a function of time for upper, middle and lower slope positions at Bhadiar (Fig. 3). The cumulative infiltration was lower by 10 and 30 per cent in middle and lower slope position as compared with upper slope position for first 2 minutes. But after 250 minutes, the cumulative infiltration was lower by 30.7 and 34.2 per cent on middle and lower slope position than that on upper slope position. The cumulative infiltration increased with cumulative time at decreasing rate, irrespective of the slope position.

Aggregate size distribution

The mean weight diameter of aggregates (MWD) for upper, middle and lower slope positions is presented in Table 7. The MWD increased by 13.6 and 15.9 per cent for the middle and lower slope position over the upper slope position at Majari. However, at Kokowal, MWD increased by 14.9 and 23.4 per cent at middle and lower slope position respectively, than that in the upper slope position. Whereas, the MWD increased by 23.3 and 41.9 per cent in middle and lower slope position over the upper slope position at Binewal. The MWD increased by 19.6 and 34.8 per cent in middle and lower slope position over the upper slope position at

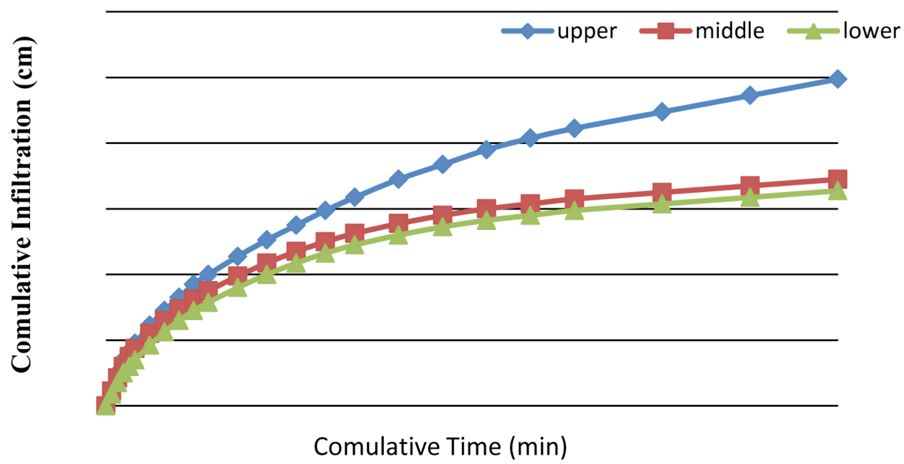

Fig. 3. Cumulative infiltration as a function of cumulative time for different slope positions as Bhadiar

Table 7. Mean weight diameter (mm) of aggregates as affected by slope position at different locations and depths in Hoshiarpur

Location	Slope position	Soil Depth (cm)			Mean ± SD
		0-15	15-30	30-60	
Majari	Upper	0.51±0.02	0.44±0.02	0.38±0.02	0.44±0.02
	Middle	0.62±0.03	0.46±0.02	0.42±0.02	0.50±0.02
	Lower	0.69±0.02	0.46±0.02	0.39±0.03	0.51±0.02
	Mean±SD	0.61±0.02	0.45±0.02	0.40±0.02	-
Kokowal	Upper	0.52±0.02	0.46±0.01	0.43±0.02	0.47±0.02
	Middle	0.66±0.02	0.50±0.02	0.46±0.03	0.54±0.02
	Lower	0.72±0.02	0.54±0.02	0.48±0.02	0.58±0.02
	Mean±SD	0.63±0.02	0.50±0.02	0.46±0.02	-
Binewal	Upper	0.49±0.02	0.43±0.03	0.38±0.02	0.43±0.02
	Middle	0.63±0.06	0.51±0.02	0.45±0.04	0.53±0.04
	Lower	0.72±0.03	0.58±0.04	0.54±0.03	0.61±0.03
	Mean±SD	0.61±0.03	0.51±0.03	0.46±0.03	-
Dallewal	Upper	0.51±0.02	0.42±0.03	0.37±0.02	0.43±0.02
	Middle	0.61±0.02	0.45±0.03	0.41±0.02	0.49±0.02
	Lower	0.67±0.03	0.48±0.03	0.41±0.04	0.52±0.03
	Mean±SD	0.60±0.02	0.45±0.03	0.40±0.03	-
Bhadiar	Upper	0.53±0.02	0.45±0.02	0.40±0.02	0.46±0.02
	Middle	0.67±0.03	0.53±0.02	0.45±0.03	0.55±0.02
	Lower	0.73±0.03	0.59±0.05	0.54±0.03	0.62±0.04
	Mean±SD	0.64±0.02	0.52±0.03	0.47±0.02	-

Dallewal. Generally, a decrease in aggregate size was observed with increase in depth. The clay content increased with depth, but on the other hand clay by itself is not sufficient to maintain the aggregate stability (Singh, 2010). The aggregates attain stability only when they are incorporated with organic matter and other polysaccharides (Narayana and Shah, 1966). The breakdown of aggregates leads to the displacement of small soil particles forming a more continuous structure that creates a surface seal or surface crust (Ramos *et al.,* 2003).

Modulus of rupture

The modulus of rupture increased with increase in depth of soil, irrespective of slope position and location (Table 8). It was observed that the lower slope position had higher value of modulus of rupture than that in the upper and middle slope position. The modulus of rupture (MOR) increased by 56.5 and 96.9 per cent on middle and lower slope position over the upper slope position at Majari. Whereas, MOR increased by 59.4 and 90.7 per cent

Table 8. Effect of slope position on Modulus of Rupture (× 10^4dyne cm^{-2}) at different locations and depths in Hoshiarpur

Location	Slope position	Soil Depth (cm)			Mean ± SD
		0-15	15-30	30-60	
Majari	Upper	20.0±2.5	33.2±1.4	41.2±1.0	31.5±1.6
	Middle	34.9±3.6	52.9±4.2	60.8±1.4	49.3±6.5
	Lower	40.4±3.4	67.7±2.6	77.8±2.8	61.9±3.0
	Mean±SD	31.5±6.6	51.3±2.8	59.9±1.7	-
Kokowal	Upper	19.5±2.4	32.7±2.5	39.7±3.1	30.6±2.7
	Middle	38.3±6.3	49.6±2.1	58.6±2.2	48.8±3.6
	Lower	38.9±6.0	64.3±3.5	72.1±1.8	58.4±3.8
	Mean±SD	32.2±4.9	48.9±2.7	56.8±2.4	-
Binewal	Upper	26.4±3.3	33.8±1.7	43.0±4.5	34.4±3.2
	Middle	37.4±5.1	54.9±4.2	62.2±3.3	51.5±4.2
	Lower	45.1±2.6	66.4±5.7	81.2±2.7	64.3±3.7
	Mean±SD	36.3±3.7	51.7±3.9	62.2±3.5	-
Dallewal	Upper	19.9±3.0	32.1±0.8	40.2±0.4	30.7±1.4
	Middle	32.0±3.7	51.3±3.0	60.8±1.4	48.0±2.7
	Lower	36.9±5.2	62.8±1.0	69.1±2.8	56.3±3.0
	Mean±SD	29.6±4.0	48.7±1.6	56.7±1.5	-
Bhadiar	Upper	19.0±2.07	30.8±0.5	39.5±1.2	29.7±1.3
	Middle	32.6±5.3	48.9±6.3	59.6±2.8	47.0±4.8
	Lower	35.5±5.2	61.6±2.0	68.4±2.3	55.2±3.1
	Mean±SD	29.0±4.2	47.1±2.9	55.8±2.1	-

on middle and lower land slope position than that on upper slope position at Dallewal. The MOR increased in middle and lower slope position over the upper land slope position by 49.6 and 86.7 per cent at Binewal. However, the MOR increased by 20.3 and 85.5 per cent in middle and lower slope position over upper slope position at Bhadiar.

Soil erodibility

With the increase in depth of soil, 0-15 cm to 15-30 cm, the dispersion ratio decreased from 0.60 to 0.47, 0.67 to 0.44, 0.49 to 0.40, 0.66 to 0.53 and 0.75 to 0.52 for Majari, Kokowal, Binewal, Dallewal and Bhadiar locations respectively (Table 9). Whereas, mean value of dispersion ratio was highest at Bhadiar

Table 9. Dispersion ratio, clay ratio and erosion ratio at different locations and depths

Location	Soil Depth (cm)			Mean ± SD
	0-15	15-30	30-60	
		Dispersion ratio		
Majari	0.60±0.02	0.52±0.02	0.47±0.02	0.53±0.02
Kokowal	0.67±0.03	0.54±0.02	0.44±0.03	0.55±0.02
Binewal	0.49±0.01	0.45±0.04	0.40±0.02	0.45±0.02
Dallewal	0.66±0.02	0.62±0.03	0.53±0.02	0.60±0.02
Bhadiar	0.75±0.03	0.61±0.04	0.52±0.03	0.62±0.03
		Clay ratio		
Majari	3.0±0.20	2.8±0.12	2.2±0.45	2.7±0.26
Kokowal	3.5±0.10	2.9±0.15	2.4±0.26	2.9±0.17
Binewal	2.5±0.39	1.7±0.16	1.4±0.17	1.9±0.24
Dallewal	4.0±0.50	2.3±0.36	2.1±0.48	2.9±0.45
Bhadiar	5.0±0.66	3.2±0.27	2.3±0.41	3.5±0.45
		Erosion ratio		
Majari	19.4±3.8	13.8±4.4	11.6±3.7	14.9±4.0
Kokowal	19.4±5.5	14.9±4.5	10.9±1.6	15.1±3.9
Binewal	18.9±0.6	13.2±4.0	8.8±1.4	13.6±2.0
Dallewal	20.2±2.7	13.9±1.9	8.9±1.6	14.3±2.0
Bhadiar	21.8±0.4	16.8±1.9	11.2±1.2	16.6±1.2

(0.62) and lowest at Binewal (0.45). Similarly with increase in soil layer from 0-15 cm to 30-60 cm, the clay ratio decreased from 3.0 to 2.2, 3.5 to 2.4, 2.5 to 1.4, 4.0 to 2.0 and 5.0 to 2.3 at Majari, Kokowal, Binewal, Dallewal and Bhadiar locations respectively. The similar trend was observed with erosion ratio at different locations. However, with increase in soil depth layer from 0-15 cm to 15-30 cm, the erosion ratio decreased from 19.4 to 11.6, 19.4 to 10.9, 18.9 to 8.8, 20.2 to 8.9 and 21.8 to 11.2 for Majari, Kokowal, Binewal, Dallewal and Bhadiar locations respectively.

Chandra and De (1978) reported that dispersion ratio appeared to be better index of erodibility than that erosion ratio in explaining the erosion behavior of sandy soils. Whereas, Kahlon (1996) observed that dispersion ratio and silt/clay ratio were most suitable erodibility indices under simulated rainfall conditions in the tract. However, the study by Mukhi (1988) while studying Vertisols soils of Karnatka observed that erosion ratio was better index of soil erodibility than the dispersion ratio. Whereas, the study by Sharma and Bhatia (2003) concluded that both the erosion ratio and dispersion ratio are equally good indices of soil erodibility.

CONCLUSION

The slope position i.e. the relative height along the hill slope position has a significant indirect effect on soil hydraulic and physical properties by affecting the movement of water and eroded material in the hill slope by the process of water erosion (Khoramail *et al.*, 2007; Begum *et al.*, 2010). In addition, water erosion is a serious problem in the tract due to receipt of intense and short duration rainstorms, highly erodible soils, undulating and irregular slopes and structure less soils. Ecological degradation in the tract is the resultant of continued over-exploitation and mismanagement of land and soil resources by overgrazing, deforestation and clearance of vegetation for the agricultural purposes, irrespective of slope and topography (Kukal *et al.*, 2004). Therefore, aim of the investigation was to evaluate how the slope position and depth can affect the physical and hydraulic properties of soils in the tract. The different in magnitude and variation of soil hydraulic and physical properties such as maximum water holding capacity, bulk density, saturated hydraulic conductivity, infiltration rate, per cent proportion of sand, silt and clay, and modulus of rupture and soil erodibility were affected either by slope position or depth and combination of both. These, were further associated through the processes of drainage, runoff, and microclimate and water erosion in the tract. In addition, hill slope hydrology in agricultural watersheds or catchments is complex due to variety of hydro-pedological processes and field management possibilities. Therefore, in future studies must be conducted to understand the hill slope hydrology, soil morphological and physical properties in relation to water erosion and field management practices in the arable watersheds located in the tract.

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