

SPATIAL VARIABILITY OF SOIL PHYSICOCHEMICAL PROPERTIES IN HILL TORRENT COMMAND AREAS OF PUNJAB, PAKISTAN

M. Asif¹, K. Mubeen^{1*}, S. Ahmed², N. Sarwar³, A. Wasaya³, T. A. Yasir³, A. Ghaffar¹, M. Aziz¹, A. Matloob⁴, S. Ahmad⁵, M. Ahmad⁶, W. Hassan⁵ and M. Shehzad⁸

¹ Department of Agronomy, Faculty of Agriculture and Environmental Sciences, Muhammad Nawaz Shareef University of Agriculture Multan, Multan, Punjab, Pakistan

² Department of Agricultural Engineering, Muhammad Nawaz Shareef University of Agriculture Multan, Multan, Punjab, Pakistan

³ Institute of Agronomy, Bahauddin Zakariya University Multan, Multan, Punjab, Pakistan

⁴ Department of Climate Change, Faculty of Agriculture and Environmental Sciences, Muhammad Nawaz Shareef University of Agriculture Multan, Multan, Punjab, Pakistan

⁵ Department of Soil and Environmental Sciences, Faculty of Agriculture and Environmental Sciences, Muhammad Nawaz Shareef University of Agriculture Multan, Multan, Punjab, Pakistan

⁶ Agricultural Engineering, Ghazi University Dera Ghazi Khan, Dera Ghazi Khan, Punjab, Pakistan

⁸ Department of Agronomy, Faculty of Agriculture, University of Poonch Rawalakot, Rawalakot, AJK, Pakistan

* Corresponding author's email: khurram.mubeen@mnsuam.edu.pk

ABSTRACT

Soils in arid to semi-arid areas, which receive hill torrents in many countries around the world, are continually under threat of soil loss, rendering fertile and productive lands barren over time. Mapping of soil properties contributes to better management practices leading to enhanced crop production. This study examines the influence of altitude on the physico-chemical qualities of soil in 13 hill torrent affected regions of Dera Ghazi Khan and Rajanpur from the Sulaiman range. 351 soil samples from 3 soil depths (0–15 cm), (16–30 cm), and (31–45 cm) were taken at three altitudes of each hill torrent command area. Portable GPS coordinates were collected for each elevation and hill torrent location. Physico-chemical soil parameters were determined using standard procedures. For this investigation, a representation of soil parameters was created using the ArcGIS 10.2 software. The soil was sandy in the upper elevated command areas of most of the hill torrents except Pitok and gradually became loamy to clay loam in the lower command areas. Other soil attributes were better at higher elevations except for total nitrogen, which probably leached under heavy hill torrent flows. Bulk density ranged between 1.56 in upper slope of Sanghar to 1.36 in lower slope of Zangi; interaction of Soil pH ranged from 8.81 in Vidor at upper elevation at upper 15 cm soil depth to 7.9 in Chachar at lower elevation and 31–45 cm soil depth. Whereas, interaction of organic matter ranged from 1.23% in Suri Shumali at upper elevation with upper 15 cm soil depth to 0.15% in Suri Janobi at lower elevation with 31–45 cm soil depth. With increasing soil depth from the surface, up to 45 cm, the soil properties worsened in terms of supporting plant growth based on soil texture and likely presence of hard plough pan. There were marked differences for various soil fertility parameters across soil depths and hill torrent sites. Moreover, good crop production is possible in hill torrent command areas of Punjab, Pakistan.

Keywords: Spate irrigation, soil properties; geospatial analysis; hill torrent, GPS, GIS

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0>)

<https://doi.org/10.36899/JAPS.2026.4.0090>

Published first online May 01, 2026

INTRODUCTION

Around the globe, many countries like Malaysia, Afghanistan, Sudan, Eritrea, Ethiopia, Kenya, Algeria, Libya, Morocco, Somalia, Yemen, Tunisia, Pakistan, Myanmar, Oman, parts of China etc. are affected by seasonal flooding and hill torrents affects soil productivity. Soil quality reflects the capability to sustain biological productivity, promote growth and maintain environmental quality (Doran *et al.*, 1996; Wubie and Assen, 2020). The topographic factors such as position, slope and gradients are also responsible for changing the local climatic conditions, which may further influence the soil properties (Jakšić *et al.*, 2021). The topography is among the important factors responsible for the induction of quality changes (Jing *et al.*, 2011). The impact of topographic changes on soil properties might be the combined result of

erosion and deposition, water dynamics and slope aspects (Van Oost *et al.*, 2000). It is also reported that processes in the upper positions also affect the soil properties at the lower positions of the slopes (Hons, 2004).

The soil and water losses also increased with increasing slope gradients. The nutrients are eroded from the upper slopes and accumulate downside of the slopes, leading to more nutrients on the lower side (Alemayehu, 2007). Similarly, it's reported that soil available phosphorus was negatively affected by the altitude gradient (Pourbabaei *et al.*, 2020). The impact of topographic conditions on variations in soil properties has been witnessed in many studies (Gessler *et al.*, 2000; Wolde *et al.*, 2007; Amuyou and Kotingo, 2015). The response of physical soil properties to varying altitude showed that base saturation percentage and sand (%) increase while clay and silt (%) decrease with increasing altitude gradient.

Soil organic matter is vital for agricultural productivity due to its better nutrient holding, supplying and water holding capacity (Jakšić *et al.*, 2021). It also binds mineral particles into aggregates and improves the aeration through better porosity. It acts as a major source of nitrogen in unfertilized soils (Asmamaw and Mohamed, 2013). The soil organic matter is positively related to the rainfall and negatively with the temperature (Pourbabaei *et al.*, 2020). Higher altitudes generally receive more rainfall, which enhances the leaching of base cations and consequently leads to lower soil pH values (Tsui *et al.*, 2004). The proportion of soil particles varies across the slope gradient due to selective removal. The higher sand and silt contents were obtained in steep gradients; however, flat slopes were occupied with clay particles. Variations in soil particle distribution along the slope influence water-holding capacity; lower slopes, with higher clay content, receive runoff from upper slopes and therefore retain greater subsurface moisture (Asmamaw and Mohamed, 2013). The low clay contents at higher slopes in comparison with lower slopes have been witnessed in the results reported by Ofori *et al.*, (2013). It was also concluded that proportion of sand particles in soil texture also affects the soil organic matter contents at various altitude (Esmailzadeh *et al.*, 2011). The pH, potassium, phosphorus and total nitrogen values were also high on the gentle slope and low on the steeper slope (Aytenew, 2015; Wubie and Assen, 2020). Soil properties like pH, base saturation and exchangeable basic cations are important to investigate soil nutrient status (Brady and Weil, 2017).

The comparison of mean bulk density and mean total porosity of cultivated land across various slope gradients revealed that mean bulk density gradually declined and mean total porosity increased with steep to gentle slope. The phosphorus, soil bulk density, sand and available water holding capacity of the topsoil was negatively affected by the slope angle. The opposite trend was recorded for silt, soil organic matter, total nitrogen and potassium (Sangchyoswat and Yost, 2002). Soil properties strongly influence crop yield, making cultivation dependent on slope gradient. Yields decline on steeper slopes, though crop sensitivity varies; grains are generally better suited to sloping land, whereas wheat performs poorly under such conditions (Rahman *et al.*, 2015). Out of the various physical and chemical properties, the sand content was the major component to produce variations in the biomass yield (Zhao *et al.*, 2007). Hill torrent water flows carry soil/sediments/silt from the mountainous catchment areas, which flow towards command areas and settle there in varying depths over time.

Already reported studies in hill torrent hit ecologies covered hydrological modelling (Yasin, 2015) irrigation water sources (Ahmad *et al.*, 2016), strip intercrops (Amin *et al.*, 2019), soil water conservation through tillage frequency, yield and benefit cost ratio in chickpea (Mubeen *et al.*, 2023) and arugula (Nawaz *et al.*, 2023). Studying different hill torrent locations will help us to explain how erosion and deposition create spatial variability in soil fertility and productivity. Analyzing soils under various elevations and depths reveal how topography influences soil development, nutrient distribution, rooting conditions and crop suitability. However, information on soil physico-chemical properties across depths and elevations in hill torrent command areas of Punjab, Pakistan, is limited. Therefore, we hypothesized that soil properties vary with hill torrent location, elevation, and depth, ultimately affecting crop productivity. This study was conducted to evaluate variations in soil properties at different depths across upper, middle, and lower command areas of hill torrents in Punjab, Pakistan, to support sustainable land and water management decisions.

MATERIALS AND METHODS

Study area: The study was conducted in hill torrent affected (spate irrigated) areas of Dera Ghazi (DG) Khan and Rajanpur districts of Punjab, Pakistan during the years 2019-20, which are occasionally affected by hill torrents coming from Sulaiman range. There are 13 major hill torrents in DG Khan and Rajanpur districts named as: Kaura (1), Vohva (2), Sanghar (3), Suri Lund (4), Sakhi Sarwar (5), Vidor (6), Mithawan (7), Kaha (8), Chachar (9), Pitok (10), Suri Shumali (11), Zangi (12) and Suri Janobi (13). The study consisted of soil characteristics of these 13 major hill torrent areas of both the districts. The study area is also referred to as "Pachadh" that lies between Sulaiman Mountains and Kachhi Canal (between latitude 31 08.742 ° N to 29 48.668° N and longitude 70 24.861° E to 70 20. 570° E and district Rajanpur lies between latitude 29 33.104 ° N to 28 38.859° N and longitude 70 02.705° E to 69 47.307° E) and falls

under the administrative control of DG Khan and Rajanpur Districts, respectively. The study area of District DG Khan has arid climate and erratic rainfall pattern and received 25 years return period discharge of 2238 cumecs (Yasin *et al.*, 2015). The mountainous landscape of area causes speedy water run-off from hills and deep storage in soil providing enough moisture to crop in dry seasons (Mehari *et al.*, 2005).

Physico-chemical analysis

Soil Sampling: The soil samples from upper, middle and lower slope positions were collected from 13 locations as shown in Figure 1. The minimum distance selected though varied but maintained at least above 1 km between upper to middle and middle to lower elevation. The sampling depth was 0-15 cm, 16-30 cm and 31-45 cm. In total 351 samples ($13 \times 3 \times 3 \times 3$) were collected for various physical and chemical analysis. The bulk density was measured by core method as described by Rai (2015). The bulk density along with moisture contents was measured as

$$\text{Bulk density} = \frac{\text{Oven dry weight of soil sample}}{\text{Volume of soil sample}}$$

The soil texture class was measured using hydrometer method (Bouyouces, 1962). The following formula was used for calculation of the silt plus clay

$$\% (\text{Silt} + \text{Clay}) = (R_{sc} - R_b) \times \frac{100}{\text{Oven} - \text{dry soil (g)}}$$

The following equation was used to measure % clay

$$\% \text{Clay} = (R_{sc} - R_b) \times \frac{100}{\text{Oven dry soil (g)}}$$

The percentage of the silt was recorded as

$$\% \text{Silt} = \% (\text{Silt} + \text{Clay}) - (\% \text{clay})$$

The % of the sand was measured according to the given equation

$$\% \text{Sand} = \frac{\text{Sand weight}}{\text{Oven dry soil (g)}} \times 100$$

The soil textural class was found using USDA textural triangle.

The electrode of the pH meter was inserted in soil water suspension and reading on pH meter was noted for various samples. The electrodes were properly cleaned and immersed in the solution and reading was noted 0.01. The electrical conductivity values reflect the salts concentration in the water samples. Similar to pH, the electrical conductivity of the water samples was determined with EC meter following procedures laid out by Richards (1954) in Agriculture Handbook No. 60.

The exchangeable sodium contents in soil were determined using flame photometer as per given formula:

$$C1V1 = C2V2$$

C1 represents the concentration of stock solution (ppm), V1 is volume of stock solution to be taken (ml), C2 is Concentration of Na to be required (ppm) and V2 is total volume to be required (ml)

$$\text{Therefore, } C2 = \frac{V1 \times C1}{V2}$$

It is also necessary to reduce the chances of the choking (United States Salinity Laboratory Staff, 1954.). The sodium concentration was determined according to the given equation

$$Na (\text{ppm}) = R \times \text{Dilution factor}$$

The R represents the flame photometer reading in concentration mode.

Soil organic matter was determined as per given equation

$$\text{Organic matter (\%)} = \frac{10}{\text{Blank}} (\text{Blank} - \text{Reading}) \times \frac{0.003 \times 100}{\text{Weight of soil}}$$

Total N was determined by taking 05 g of the well-prepared soil in digestion tube. The blank sample was also run simultaneously. The following equation was used for determination of the total nitrogen

$$\text{Total Nitrogen (kg ha}^{-1}\text{)} = \frac{R(\text{Titer reading} - \text{Blank reading}) \times \text{Normality of the acid} \times \text{Atomic weight of N} \times 100}{\text{Sample weight (g)} \times 1000}$$

Available phosphorus reading was taken at 880 nm wavelength on spectrophotometer (Olsen *et al.*, 1954).

Available potassium was determined in ppm by flame photometer using graph readings (United States Salinity Laboratory Staff, 1954) according to the given equation

$$\text{Extractable K (ppm)} = \text{Reading (ppm)} \times 20$$

The saturation percentage was determined according to the procedure laid out by United States Salinity Laboratory Staff (1954) according to given equation

$$\text{Saturation \%age} = \frac{\text{Loss in weight of soil}}{\text{Oven dried weight of soil}} \times 100$$

The water holding capacity (% moisture retained at 1/3 bars) was determined using pressure plate apparatus method according to the given equation

$$\begin{aligned} \text{Moisture retained} &= \frac{\text{Water lost due to oven drying}}{\text{Weight of oven dry soil}} \times 100 \\ &= \frac{(A - B) - (B - C)}{(B - C)} \times 100 \end{aligned}$$

A represents the weight of moist soil + aluminum tin, B is the weight of oven dry soil+tin and C is the weight of empty tin.

Experimental Design and Statistical Analysis: The experiment data collected was arranged as randomized complete block design with a split split plot arrangement. The slope position (upper, middle and lower) was allocated to the main plot and sampling depths (0-15 cm, 16-30 cm and 31-45 cm) were allocated in sub-plot. The statistical analysis was conducted using Statistix 8.1. A variance analysis was done to evaluate the significance of treatments. LSD test was used to determine the significance of treatment means at $p \leq 0.05$ (Steel *et al.*, 1997).

Geospatial analysis: The geographic information system (GIS) was used for geospatial analysis. Environmental Systems Research Institute develops and maintains the ArcGIS family of client software, server software, and services (ESRI). ArcGIS Desktop supports mapping and visualization in both 2D and 3D. For this investigation, a representation of soil parameters was created using the ArcGIS 10.2 software. Thirty-nine sample locations, three from each of thirteen sites, were used to estimate the values of relevant parameters at unknown points to produce a smooth raster. District and tehsil administrative boundary shape files were added to the ArcGIS software, followed by the addition of data points containing longitude and latitude, as well as soil parameters bulk density, soil texture, pH, EC (dS/m), exchangeable sodium (meq/100mg), OM (percentage), available P (ppm) and extractable K (ppm). The tabular data was translated into xy point data and saved as a shape file including point vector data. Visualizations of each soil parameter were made for each depth, i.e. 0 to 15 cm, 16 to 30 cm, and 31 to 45 cm. The basic interpolation technique known as inverse distance weighting (IDW) was used to estimate soil properties at unknown locations to generate a continuous raster surface. The IDW is one of the most used techniques for estimating unknown values at known locations. The inverse distance weightage technique algorithm is described by equations 1.1 and 1.2 below.

$$z_x = \sum_{i=1}^N \lambda_i z_i \quad (1.1)$$

Where,

z_i = Observations at N points ($i=1, 2, \dots, N$)

λ_i = Weights given to i^{th} sample point based on the distance between the known value to the point in question.

$$\lambda_i = \frac{\frac{1}{d_i^p}}{\sum_{i=1}^N \frac{1}{d_i^p}} \quad (1.2)$$

Where,

d_i = The distance between i^{th} sample point and the unsampled point.

p = The power variable.

In the IDW estimation algorithm in the present study z values refer to soil parameters. At 90m grid of generated raster surfaces, the calculations were performed. Around 9 sizeable watersheds in both the districts were noted (Figure 1). A 90 m resolution digital elevation model was used to delineate the watersheds and their stream networks.

RESULTS

Bulk density: Significant variations in soil bulk density values due to slope positions were recorded for all locations except Suri Janobi, Pitok and Vohva. The maximum bulk density among significantly different locations was recorded in upper slope position which gradually decreased from upper slope position to lower slope position except in Suri Shumali in which middle slope position had maximum bulk density values. The highest bulk density (1.56) was recorded in the upper slope position of Sanghar and the lowest (1.36) was recorded in lower slope position of Zangi (Table 1).

Soil texture: It was noted that generally at upper soil depth (0-15 cm) soil texture was more with sandy loam properties in upper and middle command areas of the hill torrents. Up to 30 cm soil depth, Suri Janobi soil was clay loam at the upper, middle and lower slope positions (Table 2). However, an increase in sampling depth beyond 30 cm showed that soil was dominated by clay particles. The soil of Pitok was dominated by sandy loam texture up to 15 cm and further increase in sampling depth showed that soil was loam to clay loam. The soil of Kaura in upper 0-15 cm was sandy loam across slope, while 16-30 cm and 31-45 cm depth was loamy with high silt particles. The soil texture of Vohva location

was sandy loam irrespective of sampling depths and slope positions. The soil texture of Mithawan changed from sandy loam to clay loam and clay from surface to downward. The upper soil surface of Chachar (up to 15 cm) was loam which changed to clay loam and clay by increasing the depth from 16-30 cm to 31-45 cm. The upper soil surface (up to 15 cm) from Kaha was sandy loam which generally changed to loam and clay loam at deeper soil layers. However, at lower elevation, the dominant soil texture with 15 cm soil depth across hill torrent locations under study was recorded to be loamy, in general.

Soil pH: The interactive effects of elevation and depth were significant only for Chachar and Vidor locations. However, higher reduction was witnessed for middle and lower sampling core at Chachar (Figure 2). The highest values of pH in Vidor were recorded in upper slope position at 0-15 cm depth (E1 × D1) and lowest pH values were gained in lower slope position and 31-45 cm depth (E3 × D3) (Table 10). The impact of elevation on pH was significant for all the locations except Pitok, Kaura, Suri Shumali and Sakhi Sarwar (Table 3).

Electrical conductivity: The interaction between elevation and sampling depth for EC was significant only for Suri Shumali, Vohva, Chachar, Vidor, Suri Lund and Sanghar. The highest EC values in these locations were recorded from upper slope position at 0-15 cm depth (E1 × D1). However, the minimum values in Suri Shumali, Vohva, Suri Lund and Sanghar were recorded from lower slope position and 31-45 cm depth (E3 × D3). Whereas the middle slope position at 31-45 cm depth (E2 × D3) for Chachar and lower slope position at 31-45 cm depth (E3 × D3) for Vidor and Suri Lund resulted in statistically lowest EC values (Table 10). The EC values in upper, middle and lower slopes ranged from 0.43-3.04, 0.37-3.00 and 0.32-2.81, respectively at various locations. The decline in EC was observed by increasing the depth of sampling in all locations except for Kaura (Figure 3). The EC values of upper, middle and lower depths ranged from 0.57-3.29, 0.34-2.95 and 0.21-2.61, respectively (Table 4).

Exchangeable sodium: There was a gradual decline in ES values by increasing the depth of sampling across all elevations. The trend was consistent for Suri Janobi, Suri Shumali, Chachar, Vidor, Suri Lund and Sanghar (Figure 4). The data presented in Table 5 demonstrated the significant interactions between elevation and sampling depth for exchangeable sodium in Suri Janobi, Kaura, Suri Shumali, Vohva, Chachar, Vidor, Suri Lund and Sanghar. The ES values in Kaura initially decreased from surface to 30 cm depth (D1 to D2) but again increased in 31-45 cm soil layer (D3) irrespective of the slope position. Therefore, the maximum ES values in the upper, middle and lower elevation of Kaura were recorded from D3. This is unique characteristic of soil of Kaura compared with the soils of other locations. At same depth (D1), the ES values significantly reduced by moving downward from upper to lower elevations in Suri Janobi and Chachar. While in D2 (16-30 cm) and D3 (31-45 cm), the variations at various slopes were minor in these above locations.

Organic matter: The interaction of elevation and depth remained significant only for Suri Janobi, Suri Shumali, Vohva, Mithawan, Chachar, Kaha and Zangi locations. In these locations, the organic matter contents reduced with increasing sampling depth across all the elevations (Figure 5). In upper, middle and lower elevations, the organic matter contents in Suri Janobi reduced from 0.69 to 0.42 across sampling depth. In upper elevation in Suri Shumali, Vohva, Mithawan, Chachar, Kaha and Zangi, the organic matter reduced from 0.99 to 0.86%, 0.46 to 0.28%, 0.60 to 0.36%, 0.34 to 0.25%, 0.59 to 0.35% and 0.35 to 0.24%, respectively. Likewise, there were non-significant variations in organic matter in interaction across all the slopes at D2 in Kaha and Zangi. The organic matter contents in upper and middle slope at D1 were statistically similar in interaction in Suri Shumali and Mithawan. Statistically similar values were recorded for D2 and D3 in middle and lower elevations of Vohva (Table 6).

Total nitrogen: Increase in sampling depth resulted in a significant reduction in the total nitrogen contents at upper elevation in Suri Janobi, Suri Shumali, Kaha, Zangi and Sanghar. The interaction effect of the elevation and sampling depths on total nitrogen was significant for most of the locations except Pitok, Kaura, Chachar and Sakhi Sarwar. The highest values of total nitrogen were observed in upper elevation (E1) and upper soil layer (0-15 cm) for the locations Suri Janobi, Suri Shumali, Vohva, Kaha, Zangi, Suri Lund and Sanghar. The decrease in total nitrogen with increasing sampling depth was also observed in both middle and lower elevations (Table 7).

Available phosphorus: The interactive effects of elevation and depth were significant for all the locations except Kaura, Vohva and Sanghar. The available phosphorus was reduced in response to increasing depth irrespective of slope elevation (Figure 6). The maximum values in all the locations were obtained at the upper slope (E1) with D1 sampling depth (0-15 cm) and minimum were recorded from lower slope (E3) with D3 sampling depth (31-45 cm). Among the locations, Pitok had the highest available phosphorus contents at upper elevation at D1 (0-15 cm) and lowest was recorded from Zangi at lower elevation at D3 (31-45 cm). The available phosphorus at middle and lower slope at D1 (0-15 cm) was statistically similar in Pitok and Mithawan. The increase in sampling depth from D2 to D3 (16-30 cm to 31-45 cm) at middle and lower slope did not produce significant differences with each other at Mithawan. The increase in sampling

depth from D1 to D2 (0-15 cm to 16-30 cm) in upper slope area also resulted in similar values for available phosphorus at Mithawan. The phosphorus contents obtained from D3 (31-45 cm) were statistically similar at both upper and middle slopes at Chachar, Zangi and Sakhi Sarwar (Table 8).

Extractable potassium: Interactive effect of elevations and sampling depth for extractable potassium was significant for all the locations except Suri Janobi. Except for Kaura, all the locations exhibited the highest value of extractable potassium in upper slope with D1 sampling depth (0-15 cm). However, the Kaura location at upper slope represented the highest value with D3 sampling depth (31-45 cm) and lowest in sampling depth D2 (16-30 cm). The extractable potassium value decreased across slope from upper to lower elevation and within sampling depth (Figure 7). However, the reduction in extractable potassium was less from upper to lower slope in comparison with reduction based on sampling depth. The values of extractable potassium achieved from D2 (16-30 cm), both at middle and lower elevations were statistically similar for location Pitok. Similar trends were also recorded in Kaura, Vohva, Mithawan and Zangi (Table 9).

Saturation percentage: Interactive effect of elevations and sampling depth was significant for SP at 04 locations i.e. Suri Shumali, Zangi, Vidor and Sanghar out of 13 locations (Table 10). The SP gradually increased with increasing sampling depth in upper, middle and lower elevation except Kaura which showed non-significant variations. At D3 (31-45 cm sampling depth) there was an increase in SP value over D1 (0-15 cm) in all locations except Kaura. The overall minimum SP values were observed in Vohva and maximum witnessed in Suri Janobi irrespective of the elevations and sampling depths. The location Sanghar exhibited the highest variations in SP across elevations and locations. Kaura exhibited the lowest variation across varying elevations and soil depths (Table 11).

Soil water holding capacity: The interaction between slope positions and sampling depth was significant only for Vidor location (Table 10). The highest water holding capacity was recorded at lower slope position and 31-45 cm sampling depth (E3 × D3). The results showed significant variations in water holding capacity of the soil across the slope positions for all the locations except Vohva, Zangi, and Suri Lund. The water holding capacity of soil was low in upper slope positions, which gradually increased toward middle and lower slope position. However, variation in soil depth could not bring significant variation for soil water holding capacity in Vohva hill torrent area only (Table 12).

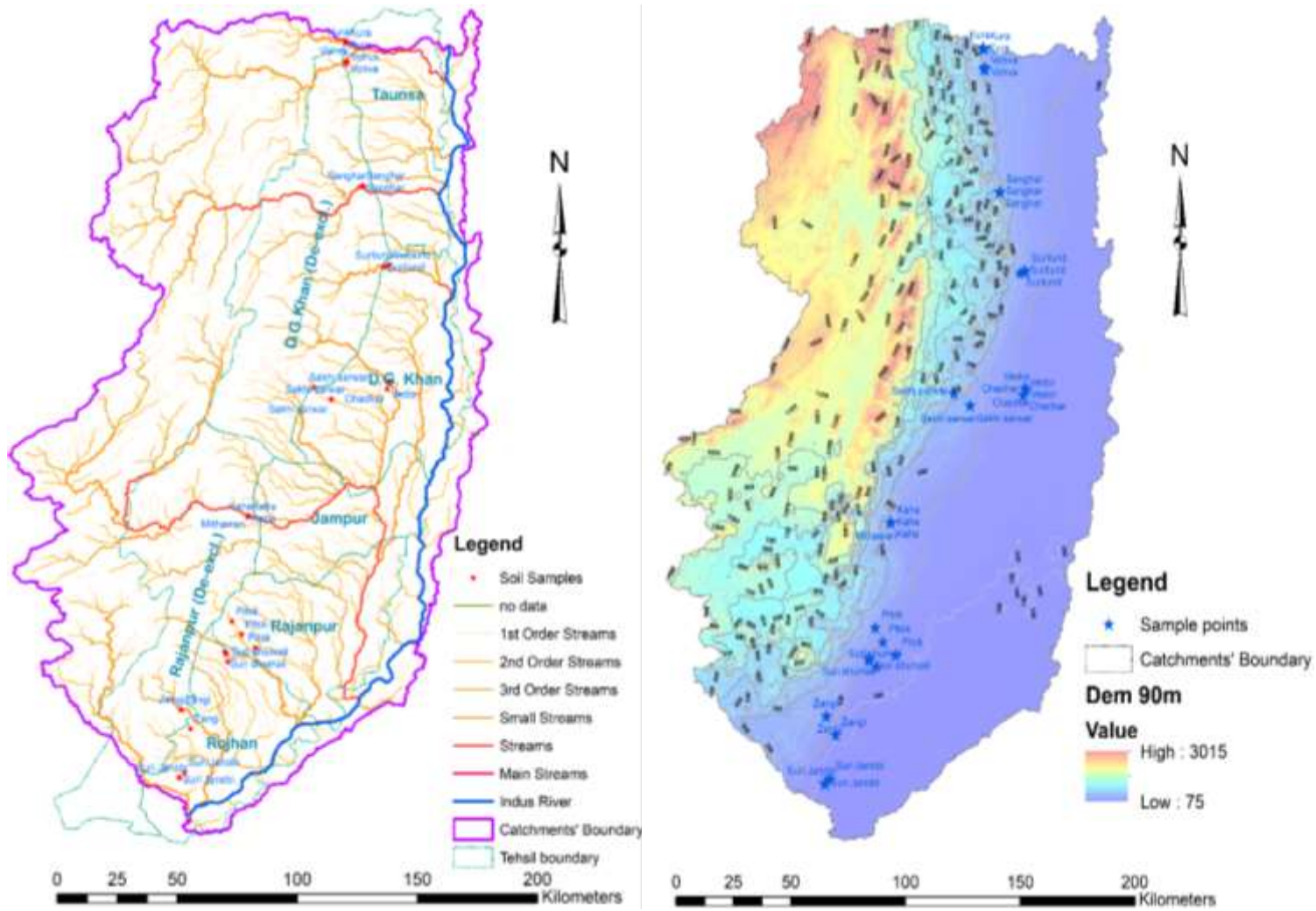


Figure 1. Study area (Watershed, Stream network, Contour lines) in the hill torrent affected region of DG Khan and Rajanpur Districts Punjab, Pakistan.

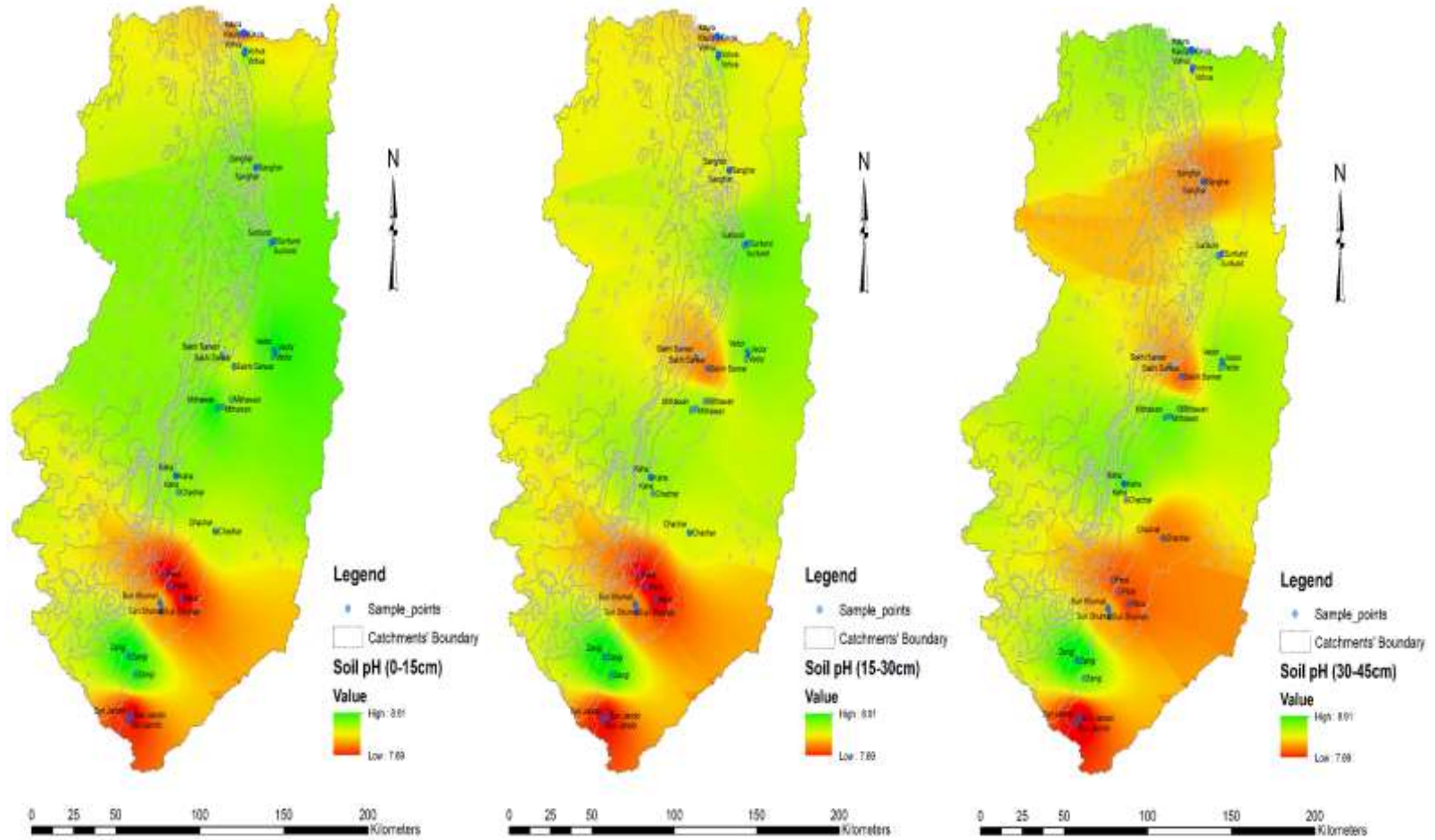


Figure 2. Spatial variability in soil pH at various sampling depths of 13 hill torrents of Punjab, Pakistan.

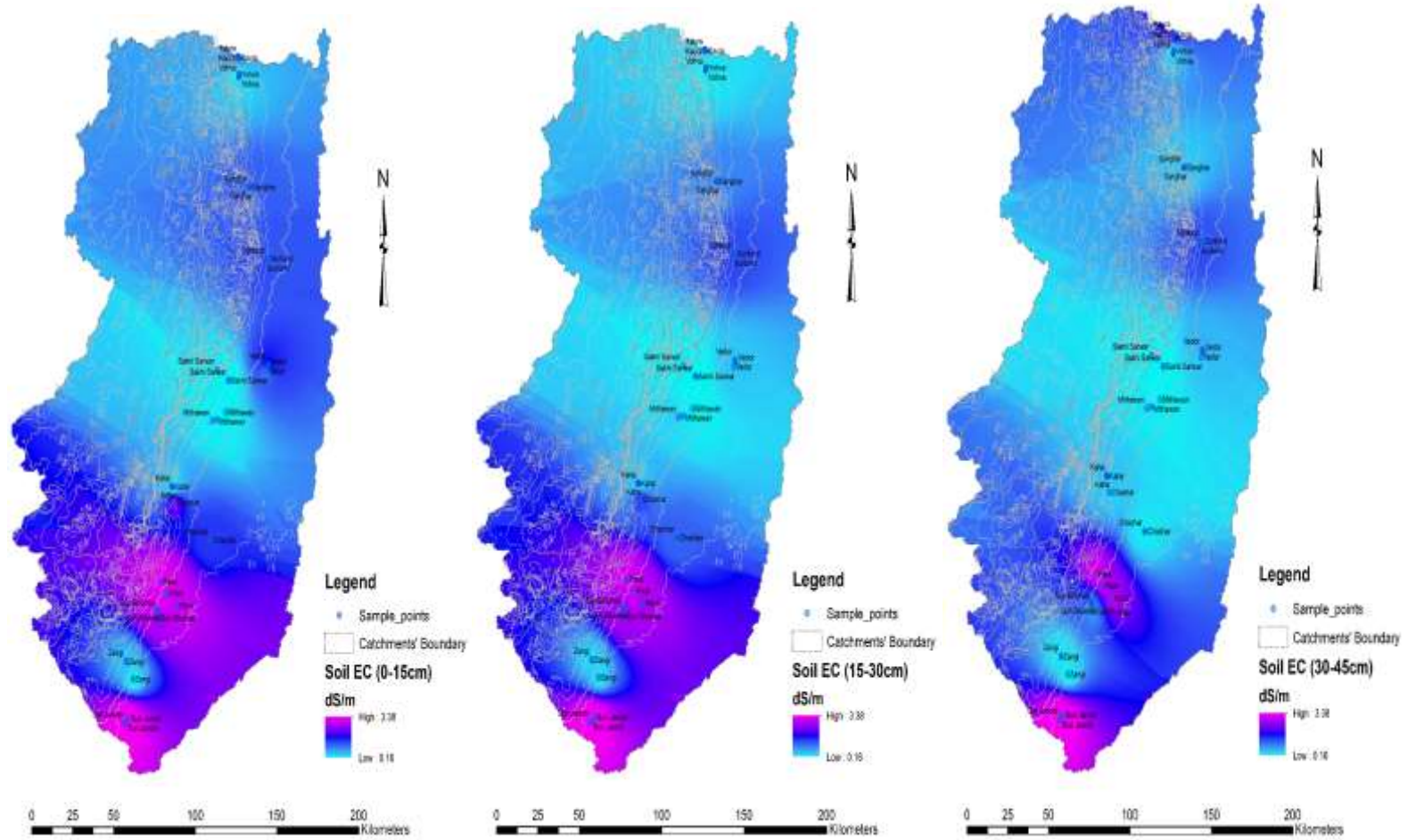


Figure 3. Spatial variability in soil EC at various sampling depths of 13 hill torrents of Punjab, Pakistan.

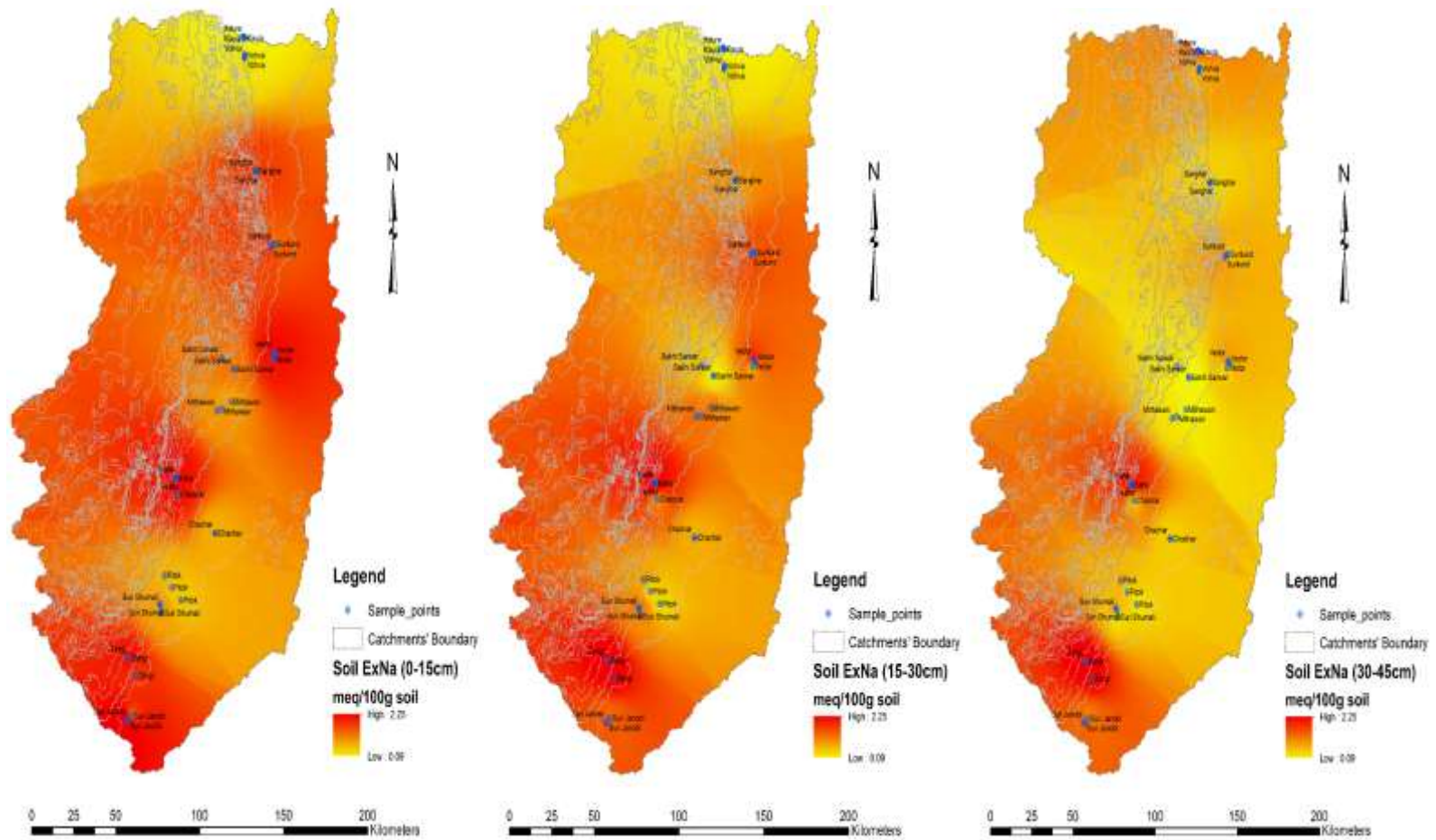


Figure 4. Spatial variability in Exchangeable Sodium (meq/100 g soil) at various sampling depths of 13 hill torrents of Punjab, Pakistan.

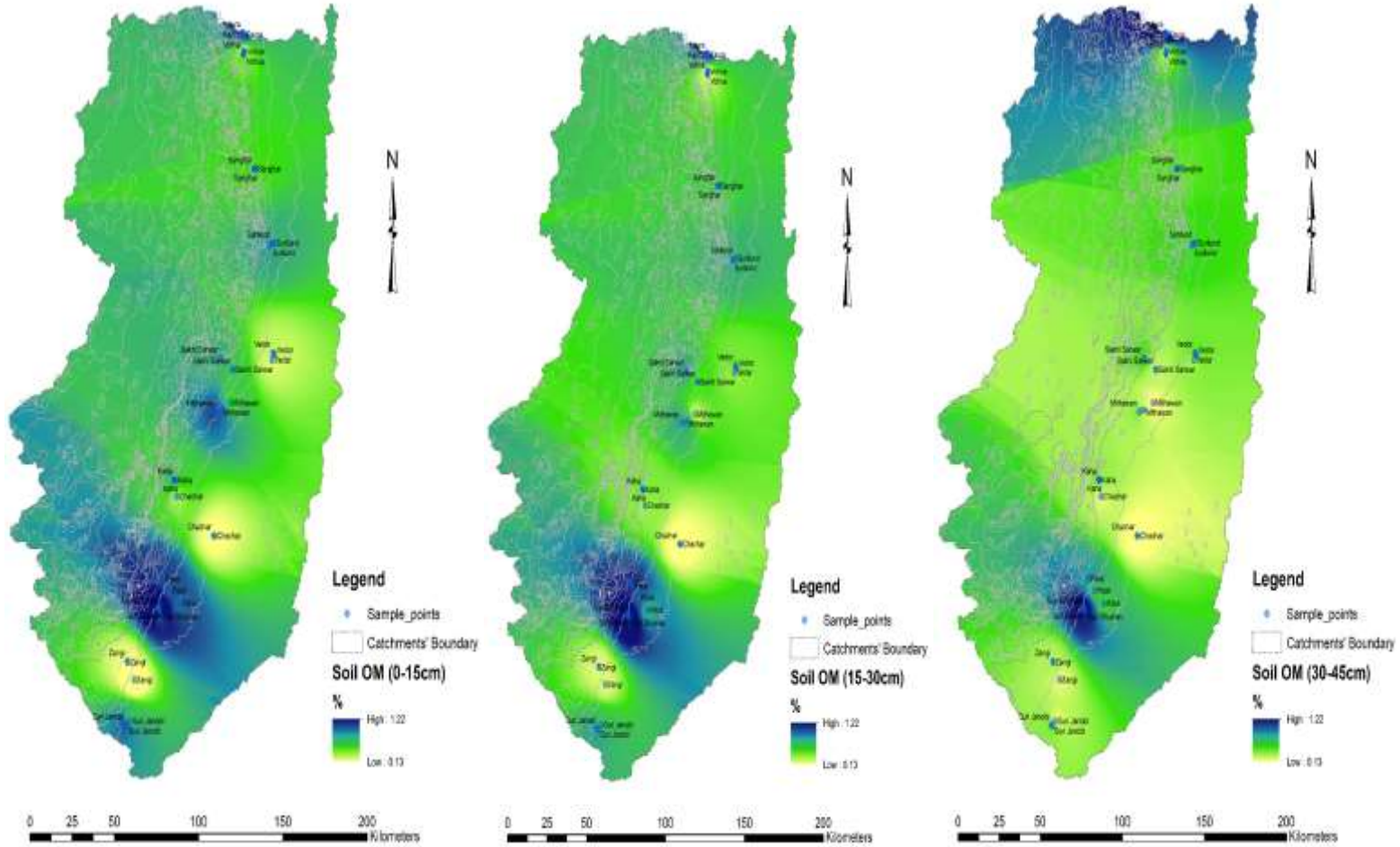


Figure 5. Spatial variability in Soil OM (%) at various sampling depths of 13 hill torrents of Punjab, Pakistan.

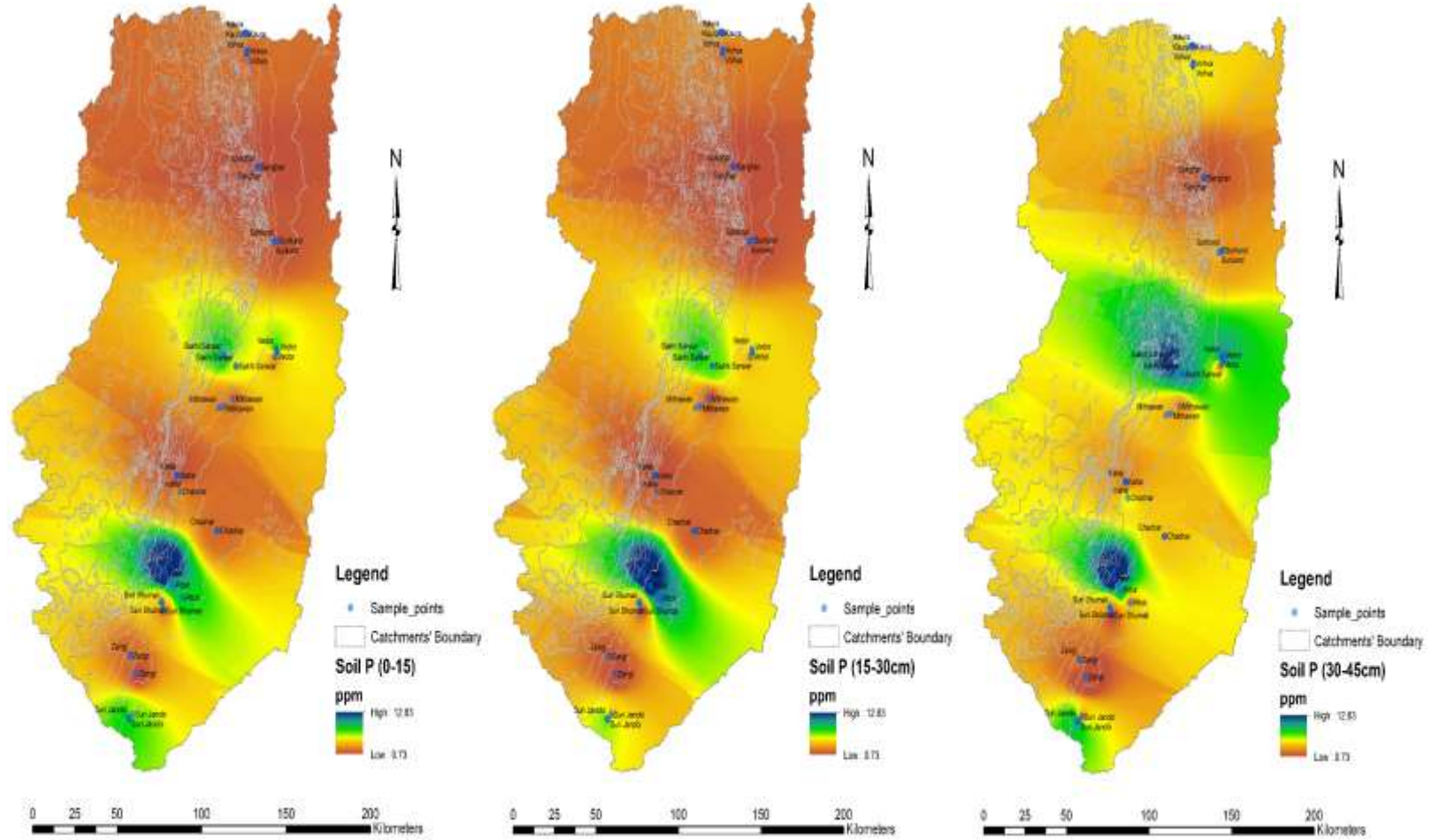


Figure 6. Spatial variability in Soil Available P at various sampling depths of 13 hill torrents of Punjab, Pakistan.

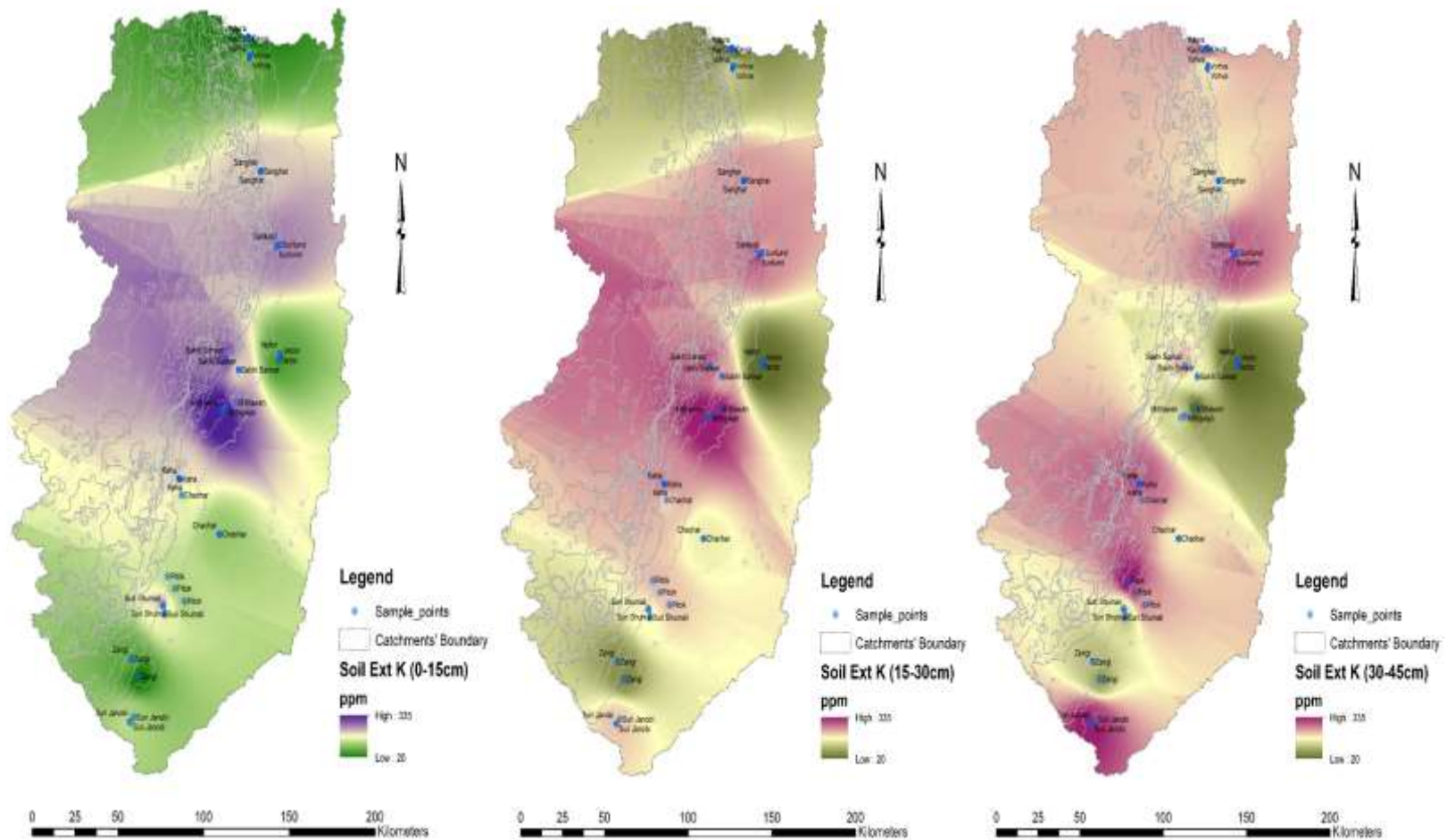


Figure 7. Spatial variability in Soil Ext K (ppm) at various sampling depths of 13 hill torrents of Punjab, Pakistan.

Table 1. Variation in soil bulk density (g cm⁻³) at 0-15 cm soil depth across slope positions in 13 major hill torrents areas of Punjab, Pakistan

Slope position	Hill Torrent Location / Area												
	Suri Janobi	Pitok	Kaura	Suri Shumali	Vohva	Mithawan	Chachar	Kaha	Zangi	Sakhi Sarwar	Vidor	Suri Lund	Sanghar
Upper	1.48	1.49	1.54 a	1.46 b	1.47	1.52 a	1.54 a	1.52 a	1.51 a	1.55 a	1.54 a	1.55 a	1.56 a
Middle	1.49	1.50	1.47 c	1.48 a	1.46	1.46 b	1.48 b	1.47 b	1.41 b	1.49 b	1.48 b	1.49 b	1.49 b
Lower	1.50	1.50	1.51 b	1.45 b	1.45	1.39 c	1.44 c	1.44 c	1.36 c	1.46 b	1.46 b	1.47 b	1.47 b
LSD	NS	NS	0.02	0.01	NS	0.28	0.02	0.02	0.03	0.03	0.04	0.04	0.52

Different letters within a column indicate significant differences at the 5% probability level according to LSD test.

NS= Non-Significant

Table 2. Soil textural class across soil elevations, soil depths and hill torrent locations in Punjab Pakistan.

Elevation	Soil Depth (cm)	Hill Torrent Location / Area												
		Suri Janobi	Pitok	Kaura	Suri Shumali	Vohva	Mithawan	Chachar	Kaha	Zangi	Sakhi Sarwar	Vidor	Suri Lund	Sanghar
Upper	0-15	*CL	*SL	SL	SL	SL	SL	*L	SL	*S	SL	SL	SL	SL
	16-30	CL	L	L	L	SL	CL	L	L	L	L	SL	CL	L
	31-45	*C	CL	L	L	SL	C	CL	CL	L	CL	L	C	L
Middle	0-15	CL	SL	SL	SL	SL	SL	L	L	SL	L	SL	L	SL
	16-30	CL	L	L	L	SL	C	CL	L	L	CL	SL	C	L
	31-45	C	CL	L	L	SL	C	CL	CL	L	C	L	C	L
Lower	0-15	CL	L	SL	L	SL	L	L	L	L	L	SL	L	SL
	16-30	CL	CL	L	L	SL	C	CL	CL	L	CL	SL	C	L
	31-45	C	C	L	CL	SL	C	CL	C	C	C	CL	C	C

*CL: Clayey loam; C: Clayey; SL: Sandy loam; L: Loam; S: Sandy

Table 3. Soil pH across elevation and sampling depths in 13 major hill torrent areas of Punjab, Pakistan

Treatments	Hill Torrent Location / Area												
	Suri Janobi	Pitok	Kaura	Suri Shumali	Vohva	Mithawan	Chachar	Kaha	Zangi	Sakhi Sarwar	Vidor	Suri Lund	Sanghar
Elevation (E) means across depth													
E1	7.95 a	7.91	8.23	8.14	8.42 a	8.54 a	8.37 a	8.53 a	8.73 a	8.18	8.61 a	8.55 a	8.38 a
E2	7.93 b	7.85	8.25	8.13	8.34 b	8.47 b	8.27 b	8.46 ab	8.65 b	8.20	8.50 ab	8.41 b	8.32 ab
E3	7.88 c	7.85	8.24	8.11	8.33 b	8.46 b	8.20 c	8.43 b	8.55 c	8.12	8.46 b	8.41 b	8.22 b
LSD value at 5%	0.022	NS	NS	NS	0.027	0.046	0.039	0.077	0.061	NS	0.108	0.079	0.109
Soil Depth (D) means across elevation													

D1	8.01 a	7.89	8.09 b	8.19 a	8.51 a	8.67 a	8.52 a	8.58 a	8.81 a	8.51 a	8.76 a	8.66 a	8.66 a
D2	7.95 a	7.89	8.09 b	8.11 ab	8.40 b	8.42 b	8.34 b	8.47 b	8.67 b	8.14 b	8.50 b	8.48 b	8.33 b
D3	7.80 b	7.83	8.54 a	8.08 b	8.17 c	8.37 c	7.99 c	8.37 c	8.45 c	7.85 c	8.31 c	8.23 c	7.93 c
LSD value at 5%	0.090	NS	0.087	0.080	0.030	0.048	0.056	0.069	0.052	0.094	0.050	0.083	0.087
E×D	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Different letters within a column indicate significant differences at the 5% probability level according to LSD test.

NS= Non-Significant; E1 = Upper slope position; E2 = Middle slope position; E3 = Lower slope position; D1 = 0-15 cm depth; D2 = 16-30 cm depth; D3 = 31-45 cm depth

Table 4. Soil EC (ds m⁻¹) across slope and sampling depths in 13 major hill torrent areas of Punjab, Pakistan.

Treatments	Hill Torrent Location / Area												
	Suri Janobi	Pitok	Kaura	Suri Shumali	Vohva	Mithawan	Chachar	Kaha	Zangi	Sakhi Sarwar	Vidor	Suri Lund	Sanghar
E1 × D1	2.25 a	1.00	0.56 c	1.04 a	0.78 a	1.06	1.79 a	1.98	1.88	1.29	1.92 a	1.91 a	1.80 a
E1 × D2	1.08 d	0.78	0.47 cd	0.97 ab	0.51 bc	0.97	0.84 c	1.53	1.53	0.48	1.51 c	1.12 c	1.08 c
E1 × D3	0.84 f	0.48	0.94 a	0.53 d	0.48 bc	0.24	0.34 f	1.20	1.33	0.24	0.57 e	0.66 e	0.46 e
E2 × D1	2.13 b	0.86	0.44 d	1.04 a	0.69 a	1.07	1.10 b	1.86	1.77	1.26	1.78 b	1.25 b	1.47 b
E2 × D2	1.02 de	0.51	0.23 e	0.93 b	0.51 bc	0.87	0.71 d	1.50	1.49	0.50	0.83 d	1.15 c	0.87 d
E2 × D3	0.79 f	0.36	0.83 b	0.36 e	0.45 c	0.23	0.32 fg	1.19	1.23	0.17	0.45 f	0.45 f	0.34 f
E3 × D1	1.34 c	0.85	0.44 d	1.02 ab	0.52 bc	0.98	0.91 c	1.86	1.63	1.22	1.75 b	1.26 b	1.44 b
E3 × D2	0.98 e	0.50	0.06 f	0.82 c	0.58 b	0.93	0.56 e	1.42	1.43	0.27	0.63 e	0.99 d	0.46 e
E3 × D3	0.63 g	0.26	0.77 b	0.17 f	0.43 c	0.15	0.25 g	1.15	1.17	0.12	0.21 g	0.29 g	0.18 g
LSD value at 5%	0.093	NS	0.114	0.094	0.099	NS	0.090	NS	NS	NS	0.106	0.065	0.092

Different letters within a column indicate significant differences at the 5% level according to LSD test.

NS= non-significant; E1 = Upper slope position; E2 = Middle slope position; E3 = Lower slope position; D1 = 0-15 cm depth; D2 = 16-30 cm depth; D3 = 31-45 cm depth

Table 5. Exchangeable sodium (meq / 100 g soil) across slope and sampling depths in 13 major hill torrent areas of Punjab, Pakistan.

Treatments	Hill Torrent Location / Area												
	Suri Janobi	Pitok	Kaura	Suri Shumali	Vohva	Mithawan	Chachar	Kaha	Zangi	Sakhi Sarwar	Vidor	Suri Lund	Sanghar
E1 × D1	1.05 a	0.94	1.00	1.23 a	0.82 a	0.93 a	0.50 a	1.02 a	0.52 a	0.75	0.50	0.82	0.70
E1 × D2	0.61 cd	0.76	0.83	0.90 b	0.31 bc	0.57 b	0.34 d	0.41 cd	0.27 bc	0.59	0.42	0.57	0.51
E1 × D3	0.41 f	0.48	1.22	0.85 bc	0.25 d	0.30 c	0.18 g	0.34 d	0.25 c	0.37	0.34	0.41	0.41
E2 × D1	0.71 b	0.90	0.93	1.20 a	0.35 b	0.87 a	0.43 b	0.53 b	0.31 b	0.70	0.44	0.74	0.61
E2 × D2	0.59 d	0.58	0.75	0.90 b	0.27 cd	0.57 b	0.25 e	0.37 d	0.27 bc	0.43	0.36	0.56	0.48
E2 × D3	0.22 g	0.38	1.21	0.78 c	0.24 d	0.19 d	0.16 gh	0.27 e	0.24 c	0.25	0.33	0.38	0.35
E3 × D1	0.63 c	0.87	0.93	0.91 b	0.35 b	0.62 a	0.38 c	0.47 bc	0.28 bc	0.64	0.43	0.70	0.53
E3 × D2	0.47 e	0.54	0.71	0.90 b	0.26 d	0.30 c	0.21 f	0.36 d	0.27 bc	0.42	0.34	0.53	0.46
E3 × D3	0.15 h	0.30	1.11	0.76 c	0.24 d	0.15 d	0.15 h	0.23 e	0.18 d	0.20	0.24	0.36	0.27
LSD value at 5%	0.037	NS	NS	0.111	0.049	0.069	0.019	0.061	0.058	NS	NS	NS	NS

Different letters within a column indicate significant differences at the 5% probability level according to LSD test.

NS= Non-Significant; E1 = Upper slope position; E2 = Middle slope position; E3 = Lower slope position; D1 = 0-15 cm depth; D2 = 16-30 cm depth; D3 = 31-45 cm depth

Table 6. Organic matter (%) across slope and sampling depths in 13 major hill torrent areas of Punjab, Pakistan.

Treatments	Hill Torrent Location / Area												
	Suri Janobi	Pitok	Kaura	Suri Shumali	Vohva	Mithawan	Chachar	Kaha	Zangi	Sakhi Sarwar	Vidor	Suri Lund	Sanghar
E1 × D1	1.05 a	0.94	1.00	1.23 a	0.82 a	0.93 a	0.50 a	1.02 a	0.52 a	0.75	0.50	0.82	0.70
E1 × D2	0.61 cd	0.76	0.83	0.90 b	0.31 bc	0.57 b	0.34 d	0.41 cd	0.27 bc	0.59	0.42	0.57	0.51
E1 × D3	0.41 f	0.48	1.22	0.85 bc	0.25 d	0.30 c	0.18 g	0.34 d	0.25 c	0.37	0.34	0.41	0.41
E2 × D1	0.71 b	0.90	0.93	1.20 a	0.35 b	0.87 a	0.43 b	0.53 b	0.31 b	0.70	0.44	0.74	0.61
E2 × D2	0.59 d	0.58	0.75	0.90 b	0.27 cd	0.57 b	0.25 e	0.37 d	0.27 bc	0.43	0.36	0.56	0.48
E2 × D3	0.22 g	0.38	1.21	0.78 c	0.24 d	0.19 d	0.16 gh	0.27 e	0.24 c	0.25	0.33	0.38	0.35
E3 × D1	0.63 c	0.87	0.93	0.91 b	0.35 b	0.62 a	0.38 c	0.47 bc	0.28 bc	0.64	0.43	0.70	0.53
E3 × D2	0.47 e	0.54	0.71	0.90 b	0.26 d	0.30 c	0.21 f	0.36 d	0.27 bc	0.42	0.34	0.53	0.46
E3 × D3	0.15 h	0.30	1.11	0.76 c	0.24 d	0.15 d	0.15 h	0.23 e	0.18 d	0.20	0.24	0.36	0.27
LSD value at 5%	0.037	NS	NS	0.111	0.049	0.069	0.019	0.061	0.058	NS	NS	NS	NS

Different letters within a column indicate significant differences at the 5% probability level; according to LSD test.

NS= Non-Significant; E1 = Upper slope position; E2 = Middle slope position; E3 = Lower slope position; D1 = 0-15 cm depth; D2 = 16-30 cm depth; D3 = 31-45 cm depth

Table 7. Total nitrogen (ppm) across slope and sampling depths in 13 major hill torrent areas of Punjab, Pakistan.

Treatments	Hill Torrent Location / Area												
	Suri Janobi	Pitok	Kaura	Suri Shumali	Vohva	Mithawan	Chachar	Kaha	Zangi	Sakhi Sarwar	Vidor	Suri Lund	Sanghar
E1 × D1	0.041 a	0.022	0.035	0.041 a	0.025 a	0.038 a	0.046	0.051 a	0.025 a	0.046	0.061 a	0.027 a	0.054 a
E1 × D2	0.016 c	0.043	0.025	0.029 d	0.021 bc	0.030 d	0.029	0.021 d	0.017 d	0.049	0.045 b	0.013 c	0.031 b
E1 × D3	0.012 ef	0.061	0.032	0.021 f	0.017 de	0.019 f	0.015	0.017 f	0.009 g	0.028	0.042 b	0.012 cd	0.021 c
E2 × D1	0.018 b	0.046	0.031	0.037 b	0.022 b	0.035 b	0.044	0.026 b	0.021 b	0.045	0.060 a	0.019 b	0.035 b
E2 × D2	0.013 d	0.037	0.024	0.028 d	0.018 d	0.022 e	0.028	0.019 e	0.013 e	0.035	0.045 b	0.014 c	0.030 b
E2 × D3	0.012 f	0.057	0.032	0.019 g	0.017 e	0.013 g	0.021	0.013 h	0.008 h	0.023	0.037 c	0.012 cd	0.013 d
E3 × D1	0.018 b	0.046	0.026	0.035 c	0.021 bc	0.032 c	0.031	0.024 c	0.019 c	0.044	0.045 b	0.014 c	0.032 b
E3 × D2	0.013 de	0.034	0.035	0.026 e	0.017 e	0.021 e	0.015	0.018 f	0.011 f	0.028	0.046 b	0.013 c	0.024 c
E3 × D3	0.012 ef	0.054	0.025	0.018 h	0.012 f	0.010 h	0.019	0.012 i	0.007 i	0.020	0.036 c	0.009 d	0.013 d
LSD value at 5%	0.001	NS	NS	0.001	0.001	0.001	NS	0.001	0.0005	NS	0.003	0.004	0.006

Different letters within a column indicate significant differences at the 5% probability level according to LSD test.

NS= Non-Significant; E1 = Upper slope position; E2 = Middle slope position; E3 = Lower slope position; D1 = 0-15 cm depth; D2 = 16-30 cm depth; D3 = 31-45 cm depth

Table 8. Available phosphorus (ppm) across slope and sampling depths in 13 major hill torrent areas of Punjab, Pakistan

Treatments	Hill Torrent Location / Area												
	Suri Janobi	Pitok	Kaura	Suri Shumali	Vohva	Mithawan	Chachar	Kaha	Zangi	Sakhi Sarwar	Vidor	Suri Lund	Sanghar
E1 × D1	7.18 a	12.85 a	3.39	4.12 a	2.31	2.74 a	3.14 a	2.34 a	2.61 a	6.53 a	6.90 a	2.40 a	1.88
E1 × D2	3.15 d	5.44 c	2.62	2.44 d	1.84	2.41 a	1.74 d	1.60 d	1.64 c	3.33 d	2.58 d	1.56 cd	1.62
E1 × D3	2.08 g	2.59 e	1.93	1.56 f	1.59	1.45 b	1.57 e	1.34 fg	1.25 e	2.27 f	2.23 e	1.44 cd	1.31
E2 × D1	5.09 b	6.76 b	2.67	3.56 b	2.17	2.66 a	2.57 b	1.77 b	2.48 b	5.55 b	3.78 b	1.96 b	1.78
E2 × D2	2.83 e	5.39 c	2.11	1.91 e	1.78	1.69 b	1.60 e	1.43 e	1.53 d	3.26 d	2.53 d	1.53 cd	1.38
E2 × D3	1.88 h	1.88 f	1.29	1.33 g	1.50	1.37 b	1.50 e	1.30 g	1.19 e	2.18 f	2.04 f	1.39 cd	1.13
E3 × D1	4.74 c	6.53 b	2.67	2.73 c	2.21	2.65 a	2.29 c	1.68 c	1.68 c	3.84 c	2.72 c	1.60 c	1.67
E3 × D2	2.29 f	4.32 d	1.81	1.74 f	1.66	1.55 b	1.58 e	1.39 ef	1.23 e	2.80 e	2.20 e	1.39 cd	1.37
E3 × D3	1.25 i	1.54 f	1.39	1.12 h	1.53	1.36 b	1.35 f	1.17 h	0.81 f	1.89 g	1.23 g	1.32 d	1.05
LSD value at 5%	0.075	0.486	NS	0.176	NS	0.352	0.119	0.071	0.106	0.117	0.134	0.256	NS

Different letters within a column indicate significant differences at the 5% probability level according to LD test.

NS= Non-Significant; E1 = Upper slope position; E2 = Middle slope position; E3 = Lower slope position; D1 = 0-15 cm depth; D2 = 16-30 cm depth; D3 = 31-45 cm depth

Table 9. Extractable potassium (ppm) across slope and sampling depths in 13 major hill torrent areas of Punjab, Pakistan.

Treatments	Hill Torrent Location / Area												
	Suri Janobi	Pitok	Kaura	Suri Shumali	Vohva	Mithawan	Chachar	Kaha	Zangi	Sakhi Sarwar	Vidor	Suri Lund	Sanghar
E1 × D1	176.00	179.00 a	96.00 d	248.00 a	156.00 a	336.00 a	188.00 a	228.00 a	170.00 a	289.67 a	146.00 a	266.00 a	236.00 a
E1 × D2	162.67	163.00 c	32.00 g	148.00 d	117.00 c	239.67 c	151.00 cd	192.00 c	84.00 c	202.00 d	55.00 d	229.00 d	215.00 b
E1 × D3	150.33	158.00 d	136.00 a	81.00 f	98.00 d	72.00 f	108.00 e	164.00 e	57.67 e	101.00 g	23.00 g	144.00 g	105.67 e
E2 × D1	176.00	169.00 b	58.00 e	202.00 b	137.00 b	336.00 a	167.00 b	228.00 a	104.00 b	233.00 b	126.00 b	255.00 b	232.00 a
E2 × D2	154.33	160.00 cd	30.00 g	136.00 e	110.00 c	221.00 d	146.00 d	180.33 d	74.00 d	184.00 e	48.67 e	181.00 e	165.00 c
E2 × D3	144.00	124.00 e	118.00 b	67.00 g	85.00 e	52.00 f	92.00 f	114.00 f	55.33 e	96.00 h	26.67 g	135.00 h	80.00 f
E3 × D1	162.00	169.00 b	39.00 f	186.00 c	131.00 b	258.00 b	157.00 c	209.00 b	89.00 c	218.00 c	119.00 c	249.00 c	218.00 b
E3 × D2	152.67	159.00 cd	29.00 g	136.00 e	108.00 c	219.33 d	113.00 e	167.00 e	68.00 d	154.00 f	31.00 f	151.00 f	147.00 d
E3 × D3	124.67	105.33 f	113.67 c	59.00 g	65.00 f	23.00 g	80.00 g	101.00 g	44.00 f	57.00 i	17.67 h	99.00 i	70.00 g
LSD value at 5%	NS	4.95	3.91	10.49	9.71	5.40	7.62	6.58	7.01	3.36	4.09	4.51	7.08

Different letters within a column indicate significant differences at the 5% probability level according to LSD test.

NS= Non-Significant; E1 = Upper slope position; E2 = Middle slope position; E3 = Lower slope position; D1 = 0-15 cm depth; D2 = 16-30 cm depth; D3 = 31-45 cm depth

Table 10. Interactive effect of elevation and sampling depth on soil pH, EC, Saturation %, water holding capacity in 13 major hill torrent areas of Punjab, Pakistan.

Treatments	Hill Torrent Location / Area												
	Soil pH		Soil EC						Saturation %age (SP)				Soil water holding capacity (%)
	Chachar	Vidor	Suri Shumali	Vohva	Chachar	Vidor	Suri Lund	Sanghar	Suri Shumali	Zangi	Vidor	Sanghar	Vidor
E1 × D1	8.55a	8.81 a	3.34 a	0.80 a	2.51 a	1.97 a	1.68 a	1.75 a	26.67 e	19.33 h	24.67 d	20.33 f	12.2 de
E1 × D2	8.40 bc	8.67 b	2.46 bc	0.46 d	1.25 cd	0.71 c	1.38	1.08 c	30.00 d	32.33 e	23.00 d	36.33 d	11.9 e

Different letters within a column indicate significant differences at the 5% probability level according to LSD test.

NS= Non-Significant; E1 = Upper slope position; E2 = Middle slope position; E3 = Lower slope position; D1 = 0-15 cm depth; D2 = 16-30 cm depth; D3 = 31-45 cm depth

Table 12. Effect of elevation and sampling depth on soil water holding capacity (% moisture at 1/3 bars) in 13 major hill torrent areas of Punjab, Pakistan.

Treatments	Hill Torrent Location / Area												
	Suri Janobi	Pitok	Kaura	Suri Shumali	Vohva	Mithawan	Chachar	Kaha	Zangi	Sakhi Sarwar	Vidor	Suri Lund	Sanghar
Elevation (E) means across depth													
E1	24.4 c	19.6 b	16.3 b	17.1 b	12.9	19.3 b	20.4 b	20.1 b	16.4	19.8 c	14.0 c	18.9	17.7 b
E2	27.6 b	23.1 a	17.3 ab	18.2 ab	12.2	21.9 a	22.4 a	21.6 ab	16.9	23.1 b	16.2 b	20.4	19.7 a
E3	29.1 a	24.0 a	18.2 a	20.9 a	14.0	24.0 a	23.7 a	22.8 a	17.8	24.6 a	17.6 a	20.9	20.2 a
LSD value at 5%	1.02	2.36	1.10	3.28	NS	2.42	1.60	1.78	NS	1.35	1.00	NS	0.75
Depth (D) means across elevation													
D1	24.4 b	17.9 c	18.5 a	15.2 c	13.1	16.2 c	18.1 b	16.3 b	14.7 b	16.7 b	12.3 c	14.9 b	13.1 c
D2	27.3 ab	22.9 b	19.1 a	18.5 b	12.4	22.5 b	23.3 a	23.1 a	17.1 ab	24.1 a	13.3 b	21.7 a	20.5 b
D3	29.3 b	25.8 a	14.2 b	22.5 a	13.6	26.6 a	25.3 a	25.0 a	19.4 a	26.5 a	22.3 a	23.5 a	24.0 a
LSD value at 5%	4.00	2.38	1.82	1.94	NS	1.76	2.65	2.69	3.22	2.53	0.76	4.35	1.61
E×D	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

Different letters within a column indicate significant differences at the 5% probability level according to LSD test.

NS= Non-Significant; E1 = Upper slope position; E2 = Middle slope position; E3 = Lower slope position; D1 = 0-15 cm depth; D2 = 16-30 cm depth; D3 = 31-45 cm depth

DISCUSSION

Steady increase in bulk density (BD) in most of the hill torrent locations in Punjab from upper elevation to lower elevation may be attributed to reduced porosity and more soil compaction (Jiao *et al.*, 2020), probably due to a reduction in hill torrent run off velocity in lower elevation areas, though it varies with demography of each hill torrent. Moreover, the sandy or sandy loam soils in upper hill torrent locations like Pitok, Kaura, Suri Shumali, Vohva, Mithawan, Kaha, Zangi, Sakhi Sarwar, Vidor, Suri Lund and Sanghar are easily washed away causing water channels widening and sediment transport downstream with high vulnerability to erosion on slopy lands. Clayey soils (Mithawan and Suri Lund in middle and lower command areas in deeper soil layers i.e. 16 to 45 cm) are more resistant to detachment due to strong cohesion of fine particles prone to run-off driven erosion. This causes the variability in sand, silt and clay across soil depths (Zheng *et al.*, 2015). The organic carbon declines with the slope gradient from higher to lower elevation position, which might be result of high sand contents on lower side which promote leaching on this side (Wubie and Assen, 2020).

Except for Pitok, Kaura, Suri Shumali, and Sakhi Sarwar, all locations showing significant pH fluctuation, which might be due to parent material of rocks and soil throughout elevation and sampling depths in different hill torrent locations in Punjab. The significant reductions in pH values from every successive sampling towards the lower slope recorded in Suri Janobi, Chachar and Zangi. The maximum pH values among locations recorded at Zangi at upper, middle and lower slope might be due to differences in soil parent material (Sun *et al.*, 2021, Awoonor and Dogbey, 2021). Decrease in electrical conductivity across elevation and depth may be due to inherent salinity level of soil with less vegetation. Moreover, at higher soil depth as the soil is more compact with hardly any disturbance hence higher EC is evident. The decrease in EC down the slope might be due to the result of the reduction in clay contents (Munny *et al.*, 2021)

The unique trend of ES in Kaura might be due to variations in parental material, catchment span, flow path complexity, free intake design. ESP of land in arid and semi-arid regions falls between 1-5% (Laker and Nortjé, 2019). Among the hill torrent locations, Kaha, Zangi and Suri Janobi have high ESP values but still are in safer limits. Variable ESP values were recorded under moderate to steep slope (Aytenew, 2015; Seenivasan *et al.*, 2015). Lower organic matter content in lower elevation of hill torrent areas could be partly due to continuous / repeated tillage for cropping. While reduced organic matter across increasing depth could be due to reduced plant litter and biological activity. Although a threshold level for soil organic matter cannot be set but 1.0 to 5.6% was proposed as an optimal range (Hijbeek, 2017). Organic matter decreased from 3.36 to 1.60% in grass and 2.62 to 1.16% in garden field due to slope gradient from upper position to lower (Mogs and Holden, 2008). The downward decrease in organic matter contents in the soil at various altitudes was also confirmed by the results of Wani *et al.* (2017).

The low nitrogen contents in lower slope position might be a result of increased leaching losses due to deposition of coarse particles and less slope in lower position also makes it vulnerable to leaching losses. A decline in total nitrogen from higher to lower elevation positions was observed (Wubie and Assen, 2020). The decreasing trend in nitrogen along the slope gradient has also been confirmed in the findings reported by Mogs and Holden (2008). Reduction in available P because of increasing soil depth in hill torrent location across slope elevation may be attributed to low organic matter which is concentrated near the surface. Additionally, limited leaching at higher elevations and inputs from decaying vegetation / organic matter can increase measurable available P. Available phosphorus was maximum in upper slope position and minimum in lower slope position (Awoonor and Dogbey, 2021). The soil organic carbon was positive while soil available phosphorus was negatively affected by the altitude gradient (Sierra *et al.*, 2017; Pourbabaei *et al.*, 2020).

Highest extractable K in upper slopes and soil layer (0-15 cm) can be attributed to greater weathering of K bearing minerals on steeper gradients, limited downward leaching because of shallow soils and intermittent intense runoff, accumulation of fine mineral and organic residues at the surface, enhanced input from decaying vegetation, and reduced soil erosion relative to deeper layers which together concentrate exchangeable K in the topsoil. While reduction in extractable K across slope and soil depth among most of the hill torrent locations could be due to downward leaching of K during rainfall and runoff, dilution in deeper layers with lower organic matter and clay content, uptake by vegetation concentrated near the surface, erosion and removal of fine K-rich topsoil on steeper slopes, and limited K replenishment at depth due to slower mineral weathering and fewer biological inputs. Range of various recorded parameters was small in middle slope (Liu *et al.*, 2020a) however, no such trend appeared in current study.

The increase in soil saturation %age across soil depths was observed in present investigation which may be the result of differences in the relative proportion of sand, silt and clay particles. With increased soil depth, saturation percentage increases due to increased percolation and organic matter at lower depth. Moreover, saturation percentage relates directly with soil texture. Likewise, lower elevation has more clay and clay loam content hence more saturation percentage compared to upper command areas. The saturation %age depends upon the soil texture being maximum in clay loam, silt loam and clay soils followed by sandy loam to clay loam and very sandy loam soils. Since there is a

selective removal of the soil particles during the runoff process from higher to lower slope position (Li and Lindstrom, 2001), it resulted in differences in saturation %age along the slope. Maximum soil water holding capacity evident at lower slope position, gradually decreased to middle, and upper slope position. However, contrasting results were reported from the study conducted by Liu *et al.* (2020b). Water holding capacity of the soil was decreased with increasing soil depth (Bhavya *et al.*, 2018; Wang *et al.*, 2022). The tillage practices that can modify the bulk density also brings changes in infiltration rate and water holding capacity (Kuzucu and Dökmen, 2015).

Conclusions: Study concluded that soil fertility was generally higher in upper soil layers and upper slope positions compared with deeper layers and lower slopes. As soil properties varied with hill torrent location, slope and depth, site-specific and sustainable nutrient management is proposed for hill torrents farmers. Similarly, breaking soil hardpans can further enhance infiltration, enrich groundwater, improve biological activity in deeper layers and expand the rhizosphere for better crop productivity. Lastly, the generated maps can guide farmers for fertilizer application and management strategies to optimize inputs and assess soil and environmental impacts.

Author contributions Data collection, Wrote original draft prepared by MA; Conceptualization, Supervision by KM; Validation, Software by SA; Writing – review & editing by NS, AW and AG; Statistical analysis by TAY; Draft reviewed by MA; Conceptualization, Methodology by AM; Data curation by SA; research goals determined by MA; Methodology, visualization by WH; Data curation, methodology; visualization by MS. All authors read and approved the final manuscript.

Funding: No funding was received to conduct this study.

Data availability: The datasets used during the current study are available from the corresponding author on reasonable request.

Declarations: “All authors have read, understood, and have complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the Instructions for Authors”

Conflicts of interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Clinical trial number: Not applicable

REFERENCES

- Ahmad, M., M. Arshad, M.J.M. Cheema and R. Ahmad (2016). Comparison of available water resources for irrigation mithawan hill torrent command area of Dera Ghazi Khan, Pakistan. Pak. J. Agric. Sci. 53: 233-240. 10.21162/PAKJAS/16.4570
- Alemayehu, K. (2007). Effects of different land use systems and topography on selected soil properties at Delbo watershed, Wolayta zone, southern Ethiopia. MSc thesis, Hawasa University, Hawasa, Ethiopia.
- Amin, J., K. Mubeen, M. Ahmad, M. Aziz and M. Arif (2019). Strip intercropping system of chickpea, lentil and arugula crop as a promising option in spate irrigated area of Punjab Pakistan. Asian J. Agri. Bio. 7(2):224-233. <https://www.cabidigitallibrary.org/doi/pdf/10.5555/20203305431>
- Amuyou, U.A. and K.E. Kotingo (2015). Toposequence analysis of soil properties of an agricultural field in the Obudu Mountain slopes, cross river state-Nigeria. Eur. J. Phys. Agric. Sci. 3(1):1-11. <https://www.idpublications.org/wp-content/uploads/2015/01/TOPOSEQUENCE-ANALYSIS-OF-SOIL-PROPERTIES-OF-AN-AGRICULTURAL-FIELD-IN-THE-OBUDU-MOUNTAIN-SLOPES.pdf>
- Asmamaw, L.B. and A.A. Mohammed (2013). Effects of slope gradient and changes in land use/cover on selected soil physico-biochemical properties of the Gerado catchment, north-eastern Ethiopia. Int. J. Env. Stud. 70(1): 111-125. 10.1080/00207233.2012.751167
- Awoonor, J.K. and B.F. Dogbey (2021). An assessment of soil variability along a toposequence in the tropical moist semi-deciduous forest of Ghana. Open J. Soil Sci. 11: 448-477. [10.4236/ojss.2021.119023](https://doi.org/10.4236/ojss.2021.119023)
- Aytenew, M. (2015). Effect of slope gradient on selected soil physicochemical properties of Dawja watershed in Enebse Sar Midir District, Amhara National Regional State. Ameri. J. Sci. Ind. Res. 6(4): 74-81. [10.5251/ajsir.2015.6.4.74.81](https://doi.org/10.5251/ajsir.2015.6.4.74.81)
- Bhavya, V.P., K.S. Anil, A. Ashok, M. Shivanna and K.M. Shiva (2018). Changes in soil physical properties as a result of different land use systems with depth. Int. J. Curr. Microbiol. Appl. Sci. 7(1): 323-327. [10.20546/ijemas.2018.701.035](https://doi.org/10.20546/ijemas.2018.701.035)

- Bouyoucos, G.J. (1962). Hydrometer method improved for making particle size analysis of soils. *Agron. J.* 53: 464-465. <http://dx.doi.org/10.2134/agronj1962.00021962005400050028x>
- Brady, N.C. and R.R. Weil. (2017). *The nature and properties of soils*. 15th Ed. Pearson Education, ISBN 978-0133254488.
- Doran, J.W., T.B. Parkin and A.J. Jones (1996). Quantitative indicators of soil quality: a minimum data set. *Methods for Assessing Soil Quality*: 25–37. <https://doi.org/10.2136/sssaspecpub49.c2>
- Esmailzadeh, O., S.M. Hosseini and M. Tabari (2011). Relationship between soil seed bank and above-ground vegetation of a mixed-deciduous temperate forest in northern Iran. *J. Agric. Sci. Tech.* 13(3): 411-424. <https://jast.modares.ac.ir/article-23-9196-en.pdf>
- Gessler, P.E., O.A. Chadwick, F. Chamran, L. Althouse and K. Holmes (2000). Modeling soil-landscape and ecosystem properties using terrain attributes. *Soil Sci. Soc. Am. J.* 64: 2046–2056. <https://doi.org/10.2136/sssaj2000.6462046x>
- Hijbeek, R. (2017). On the role of soil organic matter for crop production in European arable farming (Doctoral dissertation, Wageningen University and Research). [10.18174/421022](https://doi.org/10.18174/421022)
- Hons, D.J.K.B.S. (2004). Changes in soil properties due to topography, tillage and time in the guelph soil catena at the Ontario benchmark, Doctoral Dissertation, Carleton University, Ottawa, Canada. [10.22215/etd/2004-05836](https://doi.org/10.22215/etd/2004-05836)
- Jakšić, S., J. Ninkov, S. Milić, J. Vasin, M. Živanov, D. Jakšić and V. Komlen (2021). Influence of slope gradient and aspect on soil organic carbon content in the region of Niš, Serbia. *Sust.* 13: 8332. <https://doi.org/10.3390/su13158332>
- Jiao, S., J. Li, Y. Li, Z. Xu, B. Kong, Y. Li and Y. Shen (2020). Variation of soil organic carbon and physical properties in relation to land uses in the Yellow River Delta, China. *Sci. Rep.* 10(1): 1-12. <https://doi.org/10.1038/s41598-020-77303-8>
- Jing, W.J., X. Yue, Y. Hui-Chun, Y.S. Chong and F.H. Yuan (2011). Effects of land use and soil management particles on soil fertility quality in north china cities urban fringe. *Afr. J. Agric. Res.* 6(11): 2059–2065. <https://doi.org/10.5897/AJAR11.174>
- Khan, F., Z. Hayat, W. Ahmad, M. Ramzan, Z. Shah, M. Sharif, I.A. Mian and M. Hanif (2013). Effect of slope position on physico-chemical properties of eroded soil. *Soil Env.* 32: 22–28.
- Kuzucu, M. and F. Dökmen (2015). The effects of tillage on soil water content in dry areas. *Agric. Agric. Sci. Proc.* 4: 126-132. [10.1016/j.aaspro.2015.03.015](https://doi.org/10.1016/j.aaspro.2015.03.015)
- Laker, M.C. and G.P. Nortjé (2019). Review of existing knowledge on soil crusting in South Africa. *Adv. Agron.* 155: 189-242. [10.1016/bs.agron.2019.01.002](https://doi.org/10.1016/bs.agron.2019.01.002)
- Li, Y. and M.J. Lindstrom (2001). Evaluating soil quality—soil redistribution relationship on terraces and steep hillslope. *Soil Sci. Soc. Am. J.* 65(5):1500–1508. <https://doi.org/10.2136/sssaj2001.6551500x>
- Liu, R., Y. Pan, H. Bao, S. Liang, Y. Jiang, H. Tu, J. Nong and W. Huang (2020a). Variations in soil physico-chemical properties along slope position gradient in secondary vegetation of the hilly region, guilin, southwest china. *Sust.* 12(4): 1-16. [10.3390/su12041303](https://doi.org/10.3390/su12041303)
- Liu, Y., Y. Bing, Q. Kaibin, Y. Tinghui and P. Xueyong (2020b). Ecohydrological functions of soil and the influencing factors of different slope positions in Huangguogan citrus orchards. *J. Appl. Env. Biol.* 26 (3): 649-657. [10.19675/j.cnki.1006-687x.2019.07016](https://doi.org/10.19675/j.cnki.1006-687x.2019.07016)
- Mehari, A., H. Depeweg and B. Schultz (2005). Hydraulic performance evaluation of the Wadi Laba spate irrigation system in Eritrea. *Irrig. Drain.* 54 (4): 389-406. [10.1002/ird.200](https://doi.org/10.1002/ird.200)
- Mogs, A. and N.M. Holden (2008). Soil fertility in relation to slope position and agricultural land use: A case study of Umbulo catchment in southern Ethiopia. *Environ. Mgmt.* 42(5): 753-763. [10.1007/s00267-008-9157-8](https://doi.org/10.1007/s00267-008-9157-8)
- Mubeen, K., O. Farooq, N. Sarwar, M. Ibrahim, M. Ali, H.M. Ijaz, M. Aziz, R.M. Ikram and F. Nawaz (2023). Tillage practices affect rhizospheric moisture availability and performance of chickpea (*Cicer arietinum* L.) cultivars under spate irrigation in Punjab, Pakistan. *J. Arbl. Crops Mktg.* 05 (02):81-94. [10.33687/jacm.005.02.5141](https://doi.org/10.33687/jacm.005.02.5141)
- Munny, N.N., M.Z. Khan and M.D. Hanif (2021). Vertical distribution of soil properties and organic carbon under different land use systems in saline soils of Bangladesh. *Environ. Chall.* 4: 100097. [10.1016/j.envc.2021.100097](https://doi.org/10.1016/j.envc.2021.100097)
- Nawaz, F., K. Mubeen, R.M. Ikram, M.U. Jamshaid, M. Aziz, F. Ehsan, A. Khaliq and S. Irshad (2023). Tillage practices affect soil moisture conservation and productivity of Arugula (*Eruca sativa* L.) in Hill torrent affected areas of Punjab. *Int. J. Agric. Ext.* 11 (03): 307-318. DOI: 10.33687/ijae.011.03.4954
- Ofori, E., E.T. Atakora, N. Kyei-Baffour and B.O. Antwi (2013). Relationship between landscape positions and selected soil properties at a Sawah site in Ghana. *Afr. J. Agric. Res.* 8(27): 3646-3652. [10.5897/AJAR12.150](https://doi.org/10.5897/AJAR12.150)
- Olsen, S.R., C.V. Cole, F.S. Watanabe and L.A. Dean (1954). Estimation of available phosphorus in soils by extraction with sodium bicarbonate. *USDA Circ.* 939. [urn:oclc:record:1045362203](https://nvlpubs.lib.umn.edu/urn:oclc:record:1045362203)

- Pourbabaei, H., A. Salehi, S.S. Ebrahimi and F. Khodaparast (2020). Variations of soil physicochemical properties and vegetation cover under different altitudinal gradient, western Hyrcanean forest, north of Iran. *J. FRST Sci.* 66(4): 159-169. [10.17221/136/2019-JFS](https://doi.org/10.17221/136/2019-JFS)
- Rahman, U.O., M. Rashid, R. Kausar, S. Alvi and R. Hussain (2015). Slope gradient and vegetation cover effects on the runoff and sediment yield in hillslope agriculture. *Turk. J. Agric. Food Sci. Tech.* 3(6): 478-483. [10.24925/turjaf.v3i6.478-483.292](https://doi.org/10.24925/turjaf.v3i6.478-483.292)
- Rai, H.K. (2015). Determination of Bulk Density of Soil by Core Method. National training on climate resilient soil management strategies for sustainable agriculture. Department of Soil Science & Agricultural Chemistry Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur 482 004 (M.P.) https://research.csiro.au/pacsoils/wp-content/uploads/sites/404/2021/11/Training_Bulk-Density_DL-Antille.pdf
- Sangchyoswat, R. and R.S. Yost (2002). Predicting soil properties from landscape attributes with a geographic information system. *CMU J.* 1(3): 257–272. https://cmuj.cmu.ac.th/uploads/journal_list_index/372177208.pdf
- Seenivasan, R., V. Prasath and R. Mohanraj (2015). Restoration of sodic soils involving chemical and biological amendments and phytoremediation by *Eucalyptus camaldulensis* in a semiarid region. *Environ. Geochem. Hlth.* 37(3): 575-586. [10.1007/s10653-014-9674-8](https://doi.org/10.1007/s10653-014-9674-8).
- Sierra, C.A., M. Muller, H. Metzler, S. Manzoni and S.E. Trumbore (2017). The muddle of ages, turnover, transit, and residence times in the carbon cycle. *Glob. Chg. Biol.* 23: 1763–1773. <https://doi.org/10.1111/gcb.13556>
- Steel, R.G.D., J.H. Torrie and D.A. Dickey (1997). Principles and Procedures of Statistics, a biometrical approach. 3rd Ed. McGraw Hill, Inc. Book Co. New York, USA. pp: 352-358. ISBN 0070610282, 9780070610286
- Sun, S., G. Zhang, T. He, S. Song and X. Chu (2021). Effects of landscape positions and landscape types on soil properties and chlorophyll content of citrus in a sloping orchard in the three gorges reservoir area, China. *Sust.* 13: 4288. <https://doi.org/10.3390/su13084288>.
- Tsui, C.C., Z.S. Chen and C.F. Hsieh (2004). Relationships between soil properties and slope position in a lowland rain forest of southern Taiwan. *Geoderma.* 123: 131–142. [10.1016/j.geoderma.2004.01.031](https://doi.org/10.1016/j.geoderma.2004.01.031)
- United States Salinity Laboratory Staff. (1954). Diagnosis and improvement of saline and alkali soils. USDA Handbook 60. Washington, D.C. USA. <https://doi.org/10.2134/agronj1954.00021962004600060019x>
- Van Oost, K., G. Govers and P. Desmet (2000). Evaluating the effects of changes in landscape structure on soil erosion by water and tillage. *Landsc. Ecol.* 15 (6): 577-589. [10.1023/A:1008198215674](https://doi.org/10.1023/A:1008198215674)
- Wang, M.H., L.M. Huang and C.B. Chen (2022). Difference in soil water holding capacity and the influencing factors under different land use types in the alpine region of Tibet, China. *Ying Yong Sheng tai xue bao. Chinese J. Appl. Ecol.* 33(12): 3287-3293. [10.13287/j.1001-9332.202212.012](https://doi.org/10.13287/j.1001-9332.202212.012)
- Wani, S.A., G.R. Najjar, B.A. Padder, F. Akhter and S. Chand (2017). Altitudinal and depth-wise variation of soil physico-chemical properties and available nutrients of pear orchards in Jammu & Kashmir, India. *Chem. Sci. Rev. Lett.* 6(23): 1638-1645. ISSN 2278-6783.
- Wolde, M., E. Veldkamp, H. Mitiku, J. Nyssen, B. Muys and G. Kindeya (2007). Effectiveness of enclosures to degraded soils as a result of overgrazing in Tigray, Ethiopia. *J. Arid Env.* 69: 270–284. [10.1016/j.jaridenv.2006.10.009](https://doi.org/10.1016/j.jaridenv.2006.10.009)
- Wubie, M.A. and M. Assen (2020). Effects of land cover changes and slope gradient on soil quality in the Gumara watershed, Lake Tana basin of North–West Ethiopia. *Model. Earth Sys. Env.* 6(1): 85-97. [10.1007/s40808-019-00660-5](https://doi.org/10.1007/s40808-019-00660-5)
- Yasin, Z. (2015). Hydrological and hydraulic analysis of Mithawan hill torrent for water resource development. MSc thesis, University of Engineering and Technology, Lahore, Pakistan. <https://cewre.edu.pk/web/wp-content/uploads/2021/02/MSc-317.-2015-Zeeshan-Yasin.pdf>
- Yasin, Z., G. Nabi and S.M. Randhawa (2015). Modeling of hill torrent using HEC Geo-HMS and HEC-HMS models: A case study of Mithawan watershed. *Pak. J. Meteorol.* 11(22): 1-11.
- Zhao, H., J. Cui, R. Zhou, T. Zhang, X. Zhao and S. Drake (2007). Soil properties, crop productivity and irrigation effects on five croplands of Inner Mongolia. *Soil Till. Res.*, 93(2):346-355. <https://doi.org/10.1016/j.still.2006.05.009>
- Zheng, H., J. Gao, Y. Teng, C. Feng and M. Tian (2015). Temporal variations in soil moisture for three typical vegetation types in Inner Mongolia, Northern China. *PLOS One.* 10(3): e0118964. doi:10.1371/journal.pone.0118964.