AGRICULTURAL SCIENCE AND TECHNOLOGY, VOL.18, No 3, pp 47-55, 2026
Published by Faculty of Agriculture, Trakia University, Bulgaria
ISSN 1313-8820 (print)
ISSN 1314-412X (online)
http://www.agriscitech.eu
DOI: 10.15547/ast.2026.03.031

Agriculture and Environment

Slope-position effects soil hydraulic and physical properties in Northeastern Nigeria

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(Manuscript received 4 December 2025; accepted for publication 14 July 2026)

Abstract. *Understanding how soil slope positions influence soil hydraulic and physical properties is crucial for sustainable land and water management, particularly in regions vulnerable to erosion and water scarcity. This study evaluated the effects of slope position on soil hydraulic and physical properties in northeastern Nigeria. Nine soil profile pits were made along an upper–middle–lower slope sequence, and soil samples were collected and analyzed for particle size distribution, bulk density (BD), total porosity (TP), saturated hydraulic conductivity (Ksat) and plant-available water content (AWC). Results showed that sand dominated across slope positions, with values decreasing with soil depth, while silt and clay increased downslope. BD values ranged from 1.36 -1.75 g cm^{-3}, indicating moderate compaction. Soil TP (32-47%) generally increased with soil depth and was inversely related to BD. Mean Ksat ranged from 2.14 cm/hr (middle slope) to 3.09 cm/hr (upper slope), decreasing consistently with depth. Available water content varied between 0.29 and 0.37 cm^3 cm^{-3}, increasing with decreasing slope position. These variations suggest that upper slopes favor rapid infiltration and drainage but risk moisture deficits, while middle and lower slopes retain more water but are prone to waterlogging and reduced aeration. The findings highlight the strong topographic control on soil hydrological behavior, emphasizing the need for slope-specific management practices such as organic matter amendment on upper slopes and improved drainage on lower slopes to optimize soil moisture and prevent land degradation.*

Keywords: Toposequence, bulk density, soil variability, water retention, land management

Introduction

Soil is a vital natural resource essential for sustaining life, due to its ability to control Earth's ecosystem functions and provide food, feed and fiber for human existence (Robinson et al., 2017; Liu et al. 2020). Topography plays a crucial role in shaping the physical, chemical and biological properties of soil as well as influencing vegetation growth and distribution (Awoonor and Dogbey, 2021; Belayneh et al., 2021). Agricultural landscapes often vary in terrain, and such variations influence water infiltration, runoff, soil erosion and sedimentation processes. Among the key topographic variables affecting ecosystem functions is slope position, which exerts a significant effect on soil physicochemical characteristics (Markos, 2020). The position along a slope, whether at the summit, midslope, or footslope, affects soil's morphological features, such as clay content, organic carbon, total nitrogen, phosphorus and potassium levels (Awoonor and Dogbey, 2021; Belayneh et al., 2021). These variations arise because slope position influences water movement, soil erosion and sediment deposition, all of which shape soil fertility and structure (Khan et al., 2013; Gou et al., 2015; Maren et al., 2015).

Slope position also affects microclimatic conditions, species composition and vegetation establishment, thereby influencing soil quality and ecosystem processes (Liu et al., 2020). Therefore, studying the impact of soil depth and topography on soil hydraulic and physical properties is critically important for both hydrology and agriculture. In agriculture, this knowledge helps optimize land use by identifying which areas are most suitable for cultivation, and which require conservation or alternative uses. It informs decisions on crop selection, irrigation practices and fertilizer application by highlighting how water and nutrients move through soils of varying depth and slope (Liu et al., 2020). This leads to more efficient resource use, improved crop yields and reduced input costs. Therefore, the objectives of this study include: (i) to evaluate the effect of slope positions on selected hydraulic properties. (ii) to assess the impact of topography on soil physical properties in the study area. Understanding these interactions is key to preventing land degradation, controlling erosion and protecting water resources. Moreover, climate change is increasing rainfall and drought patterns, making it even more essential to manage landscapes wisely based on their topographic and soil characteristics.

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Material and methods

Description of the study area

Location and extent

The study was carried out in an arable land in Damare, located within Girei Local Government Area of Adamawa State (Figure 1), Nigeria. Adamawa State lies in the Northeastern part of the country and shares boundaries with Borno State to the North, Taraba State to the South, Gombe State to the West and the Republic of Cameroon to the East. The area is geographically located at latitude 9°19'51"N and longitude 12°22'36"E, covering a total land area of approximately 36,917 km², which makes Adamawa the fourth-largest state in Nigeria in terms of landmass (National Bureau of Statistics, 2021). The state falls within the Guinea Savanna ecological zone, characterized by a mix of grassland and woodland vegetation that supports both agricultural and pastoral activities.

Physiography and geology

Topographically, Adamawa State presents a diverse landscape that transitions from the highlands in the Southeastern part to the lowlands of the Benue River Basin in the Northwest. This physiographic variation reflects the influence of both the Basement Complex formations and the sedimentary basins associated with the Benue Trough (Ajiboye and Adegoke, 2014). Geologically, Girei and its environs form part of the Nigerian Basement Complex, which lies within the West African Shield: a vast geological formation extending across West Africa (Ajiboye and Adegoke, 2014). The Basement Complex comprises crystalline rocks such as granite, gneiss, schist and quartzite, formed during the Precambrian era through processes of metamorphism, folding, faulting and intrusion (Ajiboye and Adegoke, 2014).

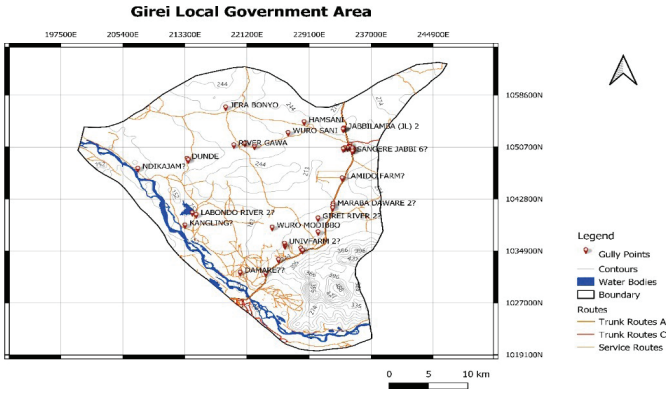

Figure 1. Map of Girei Local Government Showing the Study Area (Damare)

In addition to the Basement Complex, Girei is also influenced by the Benue Trough, a major sedimentary basin containing formations such as shale, sandstone and limestone that were deposited during the Cretaceous and Tertiary periods. These sedimentary layers provide valuable insights into the depositional history and paleogeological evolution of the area while also influencing the hydrogeological characteristics and groundwater potential of the region (Ajiboye and Adegoke, 2014). Overall, the geological and physiographic composition of the Girei area reflects a complex interaction between the Nigerian Basement Complex and the Benue Trough formations, resulting in a landscape of significant scientific, environmental and hydrological relevance.

Drainage

The drainage system in the Girei area is characterized by a complex network of streams and rivers that drain the surrounding highlands and valleys. These watercourses are mainly seasonal, with flow patterns strongly influenced by the annual rainfall distribution. During the rainy season, rivers and streams often overflow their banks, leading to flooding in low-lying areas. However, during the dry season, most of these water bodies dry up, leaving behind dry channels and exposed alluvial deposits (Mustapha et al., 2017). The alluvial soils formed by these periodic floodwaters are generally fertile and suitable for agricultural production, supporting the livelihoods of local farming communities in the region.

Climate and vegetation

The climate of Damare, Girei, is tropical monsoonal, characterized by two distinct seasons: the wet and dry seasons. The rainy season typically begins in May and lasts until October, while the dry season extends from November to April (Adamawa State Planning Commission, 2025). The area receives an average annual rainfall of about 1,400 mm, with peak precipitation usually occurring in August and September. Mean annual temperature hovers around 27°C, although it varies slightly with the seasons (Adamawa State Planning Commission, 2025). The vegetation of the area is characterized by a mixture of grasses, scattered shrubs and few deciduous trees. This vegetation type represents a transitional ecosystem between the dense Southern Forests and the open Sudan Savanna to the North, supporting both crop cultivation and livestock grazing (Zemba and Yusuf, 2020). The natural vegetation cover has, however, been significantly altered due to human activities such as farming, fuelwood collection and settlement expansion, which have led to fragmentation and degradation of the original Savanna landscape.

Reconnaissance Field Survey

A reconnaissance field survey was carried out across the study area to identify suitable locations for the study. The survey aimed to further delineate the area into distinct slope-based mapping units using Digital Terrain Modelling (DTM) derived from ArcGIS software. A Global Positioning System (GPS) was employed to record the coordinates of sampling points and to aid in accurate mapping of the study sites. This preliminary survey facilitated the classification of the terrain into three slope positions: Upper Slope, Middle Slope and Lower Slope for soil profile studies (Soil Survey Staff, 2010).

Profile Description, Soil Sampling and Preparation

Fieldwork involved the excavation of nine soil profile pits, with three pits dug per slope position identified as Upper slope

(Profile I–III), Medium slope (Profile I–III) and Lower Slope (Profile I–III). Each profile pit measured 2 meters in length, 2 meters in width and 2 meters in depth. Two sets of soil samples were collected from each identified pedogenic horizon. Soil samples were collected from the bottom upward and this was done to avoid soil sample contamination. The first set consisted of soil samples used for particle size analysis, while the second set comprised of undisturbed core samples for physical and hydraulic measurements such as bulk density, saturated hydraulic conductivity and moisture retention in the laboratory. Disturbed samples were air-dried and ground using a wooden pestle and mortar. The grounded soil samples were sieved through a 2 mm mesh sieve. The soil sample was properly packaged in a labeled paper bag for onward laboratory analysis.

Laboratory analyses

Following the collection and preparation of soil samples, disturbed and undisturbed soils were available for physical, chemical and hydraulic measurements. The parameters were measured following standard laboratory procedures. Particle size distribution was determined using bouyoucous hydrometer method by measuring the rate at which soil particles settle in a suspension, based on Stokes's law and the proportion of sand, silt and clay was estimated: as outlined by Gee and Bauder (1986). Soil bulk density was determined using the core method, which entails oven-drying to constant weight, as described by Blake and Hartge (1986). Soil saturated hydraulic conductivity was measured using a constant head permeameter method as described by Reynolds et al. (2002). Moisture retention was determined using a pressure plate membrane, at 0.33 bar for FC and 15 bar for PWP while the difference between FC and PWP yield PAWC, as described by Klute (1986). Total porosity of the samples was obtained via calculation using the measured values of bulk density and the assumed particle density for mineral soils (Agbenin, 1995) as follows:

$$Tp = 1 - \frac{pb}{bd} \times 100) \quad (1)$$

Tp = 1 - × 100)
Where Tp=total porosity
pb=particle density
bd=bulk density

Statistical analysis

Descriptive statistics were used to assess the normal distribution of the measured soil parameters as outlined by Agbenin (1995). Analysis of Variance (ANOVA) was equally carried out and means were separated using Least Significant Difference at 5% probability level. All statistical analyses were carried out using Statistix Software version 14.

Results and discussion

Effects of slope positions on soil particle sizes

Results of the particle size distribution of the slope positions are shown in Table 1-4. The textural classes of the slope positions ranged from sand at surface horizons to silty clay loam at the subsurface horizons. The results indicate that sand fraction dominated both the surface and subsurface horizons of the slope positions. The mean sand percentages of the slope positions ranged from 61.67% to 77.33%. The dominance of sand in the slope positions might be attributed to climate of arid and semi-arid regions which promote the transportation of sediments across thousands of kilometers, depositing it at the tail of the wind (Imadojemu et al., 2017). The high sand fraction might also be connected to the parent material of the soil (Kehali and Kibebew, 2017). The results of the study are concomitant with previous findings of Belayneh et al. (2021) who reported high sand percentages. It was observed that the sand fraction of the soil decreased with increasing soil depth across the slope positions, probably due to the transport of finer particles (silt and clay) downward by water. Sand percentage (mean 76.61%) was higher at the upper slope and decreased down the slope (Table 4). The high sands proportion at the upper slope is in harmony with the previous reports by Kehali and Kibebew (2017); Aweke (2021) and Belayneh et al. (2021). The authors attributed the buildup of sand to the selective removal of fine particles such as silt and clay due to faster water erosion, leaving behind sand fraction of the soil.

The silt content of the slope positions ranged from 3.40% in the middle slope to 15.40% in the lower slope. However, the percent of silt does not follow a constant trend with slope position and soil depths. The observed low silt content at upper and middle slope positions is concomitant with the results reported by Ajiboye et al. (2012) while investigating the soils of Kampe-Omi River Basin, Kogi State Nigeria. Generally, silt reduced with soil depth at upper and middle slope whereas it increased with depth at the lower slope. This might be ascribed to the effect of force of gravity and overland flow which transport particles downhill; where slope becomes concave or gentler (foot slope), flow velocity drops and finer particles (silt and clay) settle and accumulate in the sub-soil (Ajiboye et al., 2012). The clay component of the soils in the slope positions increased with soil depth, and the middle slope had the highest mean clay fraction (21.41%) compared to the remaining slope positions of the study.

The increase of Clay with depth in most slope positions indicates possible clay migration by eluviation and illuviation actions. Additionally, it might be partly associated with deposition by runoff from the adjacent uplands and partly to the low erosion status of the soil at the present level of cultivation (Imadojemu et al., 2017). The trend is in conformity with a previous report by Imadojemu et al. (2017). However, it is contrary to the findings of Imadojemu et al. (2017) who reported higher clay fraction at surface soils of Northeast Nigeria. Results of the study also showed that clay had the lowest percentage among the remaining soil fractions. This is probably a product of the inherent parent material from which the soil was formed (Brady and Weil, 2017).

Significant difference ($p \leq 0.05$) was recorded among sand, silt and clay fractions. Coefficient of variation for sand, silt and clay across the slope positions showed moderate variation as

per Wilding (1985) (Table 4). This agrees with earlier report of Imadojemu et al. (2017) but contradicts the findings of Imadojemu et al. (2017) who reported high variation. In general sense, the findings of this study imply that the accumulation of finer materials combined with slower drainage due to high silt and clay at lower slope might lead to a state of saturation, which limits oxygen availability to roots, reduces root respiration, increases the potential for anaerobic conditions, and may cause root diseases (Getahun et al., 2020). These conditions might reduce crop yields leading to decline in profit of farm ventures.

Effects of slope positions on soil bulk density

The bulk density values for the studied soils are presented in Tables 1-4. The mean BD values ranged from 1.36 g cm^{-3} to 1.75 g cm^{-3}. The values were irregularly distributed across the profiles and slope positions, and had an almost equal distribution pattern in the studied pedons. The BDs obtained in the present study are generally considered safe for roots penetration because penetration is restricted in soils having values > 1.75 g cm^{-3} (Donahue et al., 1990). However, good plant growth is best at BD bellow 1.40 g cm^{-3} for clay soils and 1.60 g cm^{-3} for sandy soils (Ajiboye et al., 2012). Nevertheless, surface horizons of the slope positions in this study recorded high BD values.

The high BD values observed at the surface horizons of the slope positions might be attributed to frequent grazing and the use of heavy farm machinery for cultivation. The upper slope had the highest mean BD (1.59 g cm^{-3}) compared to middle and lower slope positions (Table 4). The high BD at the upper slope position indicated high level of compaction which could reduce roots penetration (Getahun et al., 2020). The coefficient of variation across the slope positions showed low variation (4.01%) as per Wilding (1985). This result is in harmony with earlier findings of Getahun et al. (2020) who reported low variation at foot slope while working with soils of Awo-omamma in Imo State, Nigeria.

Generally, surface soils of the slope positions had high BD values. This scenario has profound implications for both hydrology and agriculture. From a hydrological perspective, it can reduce soil total porosity and pore connectivity, leading to lower infiltration and saturated hydraulic conductivity, greater runoff, erosion and waterlogging in flat areas (Radford et al., 2024). Agriculturally, compacted soils restrict root penetration, limit access to water and nutrients, reduce aeration and reduce microbial activity, thereby lowering crop yields and water use efficiency (Hamza and Anderson, 2005; Kay et al., 2024). Additionally, higher bulk density increases mechanical resistance to tillage and exacerbates soil erosion due to reduced vegetative cover. Overall, compaction compromises soil health, reduces agricultural productivity and disrupts natural hydrological processes, making it a critical factor in sustainable land management.

Effects of slope positions on total porosity

The total porosity for the slope positions is presented in Tables 1-4. It ranged from 32.00%-47.00% at upper slope, 33.00%-46.00% at the middle slope and 36.00%-46.00% at the lower slope position. The TP across the slope positions is rated low (Malgwi, 2007). However, the soils of the area are good for agriculture (having TP between 45-50%) according to Kachynskii (1965). The low TP in the present study is in agreement with a previous study by Zata et al. (2020). According to Malgwi, (2007), soils having porosity of 45-50% by volume are good for agricultural use. It is interesting to know that Malgwi (2007) also reported similar TP values in the soils of Zaria, Kaduna State. In the study carried out by Pantami (2017), soil TP<50% was obtained. The results were attributed to clogging of pore spaces by transported finer materials from the upstream.

Soil TP increased with soil depth across the slope positions. In some soils, total porosity may appear to increase with depth, especially within the surface horizons, mainly due to surface compaction or crusting from raindrop impact, tillage or trampling that reduces pore space at the topsoil compared to the underlying layers (Armenise et al., 2018). Similarly, aggregate breakdown and infilling of pores by fine particles at the surface can further reduce macro-pores, while deeper horizons may retain more stable pore networks (Fox et al., 2004). In addition, differences in parent material or textural contrasts can result in inherently higher porosity in subsurface layers. Since porosity is inversely related to BD, any reduction in BD below the compacted surface horizon will increase total porosity, although over greater depths, the weight of overlying soil often leads to reduction of soil TP (Oklahoma State University Extension, 2020).

The middle slope position recorded the highest mean TP (43.30%) followed by the lower slope (41.96%) and the upper slope (37.69%). The higher sand content and the lower BD at the middle slope might account for the higher TP at the middle slope. Confirming the results of the present study, Yasin and Yulnafatmawita (2018) and Aweke (2021), in their separate studies, reported higher TP at the soils of the lower slope position compared to the higher slope position. The observed variation might be attributed to cultivation differences in the field. The coefficient of variation was low across the slope positions in the study. Results of the study showed compacted surface layer which reduces with soil depth. This scenario hampers infiltration and root penetration from surface layer; hence, reducing the overall performance of crops.

Effects of slope positions on plant available water content

Both slope and soil depth affected plant available water content in the present study (Tables 1-4). The mean AWC for the soil profiles ranged from 0.34-0.36 cm^3 cm^{-3} at the middle slope, 0.29-0.31 cm^3 cm^{-3} at the upper slope and 0.33-0.37 cm^3 cm^{-3} at the lower slope position. Soil AWC increased with decreasing slope position. However, middle slope had higher AWC compared to upper and lower slope positions or mapping units. The result is consistent with findings by Belayneh et al. (2021) who, in their separate studies, observed notable differences among the soil samples from various slope positions. Plant AWC generally increases with decreasing of slope because lower slope positions accumulate finer particles, organic matter and deeper soils through erosion and deposition processes, thereby enhancing soil water retention and crop

water supply compared with shallow, coarse-textured upslope soils (Zhang et al., 2023).

Agriculturally, this gradient means crops at toe-slopes often experience higher yields due to greater and more stable water and nutrient availability, despite risks of waterlogging and nutrient accumulation necessitating drainage or input adjustments. Meanwhile, at upslope, crops face greater drought stress needing conservation practices (Zhang et al., 2020). Hydrologically, greater AWC downslope alters infiltration, runoff and subsurface flow, serving as temporary water storage zones that can attenuate or prolong downstream discharge, but saturation may increase susceptibility to flooding, nutrient leaching and even slope instability under extreme rainfall (Zhang et al., 2020). Thus, slope-driven variations in AWC create distinct agricultural opportunities and hydrological risks that call for site-specific soil and water management strategies.

Effects of slope positions on saturated hydraulic conductivity

The saturated hydraulic conductivity (Ksat) of the mapping units is shown in Tables 1-4. The results indicate that the Ksat were within the ranges of 2.08-4.35 cm/hr at the upper slope position, 1.34-3.54 cm/hr at the middle slope and 2.29-3.54 cm/hr at the lower slope positions. All the slope positions of the study showed a decreasing pattern in Ksat with soil depth. Soil Ksat generally decreases with increase of soil depth because of changes in soil texture, structure, bulk density and organic matter content. Surface horizons usually have higher Ksat due to the presence of well-developed soil structure, higher porosity, root channels, bio-pores and organic matter, which promote rapid water transmission (Jarvis, 2007). With depth, soils tend to become more compacted and denser due to overburden pressure, reducing macro-porosity; thus, lowering water conductivity (Lin et al., 1999).

The results of this study are in harmony with the findings by Lin et al. (1999) who observed that the hydraulic conductivity of Vertisols reduced with soil depth. The authors attributed the decrease to the collapse of macro-pores and higher clay content in subsoils. Jarvis (2007) similarly noted that the abundance of bio-pores and root activity in topsoil greatly enhanced Ksat, while their absence at greater depth reduced conductivity. However, the trend observed in this study contradicts a previous report by Ghimire et al. (2012) who found that in some sandy profiles, subsoil horizons exhibited higher Ksat than the surface layer. The authors attributed the scenario to the presence of course-textured materials at higher soil depth. Again, Bouma and Dekker (1978) reported that in structured clay soils, certain subsoil horizons with strong crack networks maintained relatively high conductivity compared to the compacted plow layer above. These exceptions indicate that while the general trend is a decrease in Ksat with depth, local factors such as texture stratification, cracking and preferential flow pathways may alter the pattern.

The upper slope position had the highest mean Ksat (3.09 cm/hr) followed by the lower slope (2.94 cm/hr) and the middle slope position (2.14 cm/hr). Upper slope soils are typically coarser-textured and are better drained because erosion selectively removes fine particles and organic matter downslope, leaving behind sandy or loamy surface horizons that enhance pore connectivity and water movement (Wilding and Drees, 1983; Gessler et al., 2000). In addition, soils at upper slopes often have lower bulk density and stronger aggregate stability, which support greater macro-porosity and infiltration rates (Nyberg, 1995). By contrast, middle and lower slope positions tend to accumulate finer particles (silt and clay) and organic matter through depositional processes, which reduce Ksat by clogging macro-pores and increasing water-holding capacity but restricting percolation (Flanagan et al., 2013). All the slope positions showed medium variability in terms of Ksat in the study.

The variation of Ksat along slope positions has important consequences for water dynamics and crop production. At the upper slope, higher Ksat promotes rapid infiltration and drainage, which reduces surface runoff and erosion risk but can also increase the leaching of nutrients beyond the root zone, leading to low water availability for crops during dry periods (Nyberg, 1995; Lin et al., 2006). In the middle and lower slope positions, where Ksat is lower, reduced infiltration and higher water retention may favor moisture availability in the short term but increase risks of waterlogging, soil crusting and runoff generation, which can reduce crop productivity and enhance erosion and sediment transport downslope (Gessler et al., 2000; Flanagan et al., 2013). From a hydrological perspective, these contrasts create variable recharge, runoff and erosion patterns across the landscape, influencing watershed hydrology and nutrient cycling. Agriculturally, the results highlight the need for slope-specific management: such as drainage at lower slopes to prevent waterlogging and soil amendments (e.g., organic matter, biochar) at upper slopes to improve water retention and reduce nutrient leaching.

Table 1. Soil Physical and Hydraulic Properties of Upper Slope

Depth (cm)	Sand	Silt	Clay (%)	Text. Class	BD (g cm^{-3})	Porosity (%)	FC	PWP	AWC (cm^3 cm^{-3})	Ks (cm/hr)
	→						→			
Profile 1 (Elevation 486 m)										
0 – 43	84.00	9.40	6.60	S	1.59	38.00	0.36	0.05	0.31	5.16
43 - 76	88.00	7.40	4.60	S	1.65	36.00	0.34	0.05	0.28	3.05
76 - 195	60.00	8.00	32.00	SCL	1.50	41.00	0.42	0.08	0.34	0.36
Mean	**77.33**	**8.27**	**14.4**	**-**	**1.58**	**38.33**	**0.37**	**0.06**	**0.31**	**2.86**
SD	**12.36**	**0.84**	**12.47**	**-**	**0.061**	**1.63**	**3.40**	**0.014**	**0.025**	**1.96**

Profile 2 (Elevation 374 m)										
0 – 24	89.00	5.00	6.00	S	1.66	35.00	0.34	0.04	0.29	3.10
24 – 56	86.00	9.40	4.60	S	1.72	33.00	0.34	0.04	0.29	2.27
56 - 100	70.00	6.40	23.60	SCL	1.43	44.00	0.43	0.07	0.36	1.87
100 – 177	50.40	11.20	38.40	SC	1.36	47.00	0.47	0.09	0.38	1.06
Mean	**73.85**	**8.00**	**18.15**	**-**	**1.54**	**39.75**	**0.39**	**0.06**	**0.33**	**2.08**
SD	**11.36**	**0.75**	**12.01**	**-**	**0.015**	**1.53**	**3.22**	**0.012**	**0.019**	**1.00**
Profile 3 (Elevation 361 m)										
0 – 33	88.00	6.00	6.00	S	1.69	34.00	0.33	0.05	0.29	6.08
33 – 63	89.00	7.40	3.60	S	1.75	32.00	0.31	0.04	0.27	6.47
63 - 185	50.00	9.00	41.00	SC	1.55	39.00	0.41	0.08	0.33	0.49
Mean	**75.67**	**5.60**	**12.65**	**-**	**1.66**	**35.00**	**0.35**	**0.06**	**0.29**	**4.35**
SD	**12.03**	**0.82**	**12.41**	**-**	**0.02**	**1.35**	**0.32**	**0.011**	**0.012**	**1.12**

BD=bulk density, FC=field capacity, PWP=permanent wilting point, AWC=available water content, Ksat=saturated hydraulic conductivity, SC=sandy Clay, SCL=sandy clay loam, S=sand

Table 2. Soil Physical and Hydraulic Properties of Middle Slope

Depth (cm)	Sand	Silt	Clay (%)	Text. Class	BD (g cm^{-3})	Porosity (%)	FC	PWP	AWC (cm^3 cm^{-3})	Ksat (cm/hr)
Profile 1 (Elevation 463 m)										
0 – 29.5	79.00	9.40	11.60	LS	1.52	41.54	0.39	0.05	0.34	3.26
29.5 - 65	70.00	8.40	21.60	SLC	1.46	43.85	0.42	0.07	0.35	1.69
65 - 99	66.00	7.40	26.60	SCL	1.40	46.15	0.44	0.07	0.37	1.75
99 - 187	59.00	3.40	37.60	SCL	1.63	37.31	0.38	0.07	0.31	0.51
Mean	**68.50**	**7.15**	**24.35**	**-**	**1.50**	**42.21**	**0.63**	**0.06**	**0.34**	**1.80**
SD	**7.23**	**1.92**	**9.39**	**-**	**0.01**	**5.09**	**0.012**	**0.001**	**0.022**	**0.091**
Profile 2 (Elevation 460 m)										
0 – 63	62.00	10.40	27.60	SCL	1.39	46.54	0.45	0.08	0.37	1.54
63 – 88	60.00	11.40	28.60	SCL	1.44	44.62	0.42	0.07	0.35	1.09
88 - 195	63.00	10.40	26.60	SCL	1.42	45.38	0.43	0.07	0.36	1.40
Mean	**61.67**	**10.73**	**27.60**	**-**	**1.42**	**45.51**	**0.43**	**0.07**	**0.36**	**1.34**
SD	**7.22**	**1.78**	**10.00**	**-**	**0.02**	**5.11**	**0.02**	**0.002**	**0.011**	**0.12**
Profile 3 (Elevation 460 m)										
0 – 35	88.00	7.40	4.60	S	1.72	33.85	0.32	0.04	0.28	5.91
35 – 85	72.00	6.40	21.60	SCL	1.40	46.15	0.44	0.07	0.37	2.37
85 - 195	62.00	12.40	25.60	SCL	1.39	46.54	0.44	0.07	0.37	1.52
Mean	**74.00**	**8.73**	**17.27**	**-**	**1.50**	**42.18**	**0.40**	**0.06**	**0.34**	**3.27**
SD	**6.93**	**1.25**	**12.01**	**-**	**0.02**	**5.13**	**0.013**	**0.001**	**0.021**	**1.09**

BD=bulk density, FC=field capacity, PWP=permanent wilting point, AWC=available water content, Ksat=saturated hydraulic conductivity, LS=loamy sand,SCL=sandy clay loam, S=sand

Table 3. Soil Physical and Hydraulic Properties of Lower Slope

Depth (cm)	Sand	Silt	Clay (%)	Text. Class	BD (g cm^{-3})	Porosity (%)	FC	PWP	AWC (cm^3 cm^{-3})	Ksat (cm/hr)
Profile 1 (Elevation 438 m)										
0 – 23	85.00	9.00	6.00	S	1.65	36.53	0.35	0.05	0.30	5.23
23 - 95	75.00	15.40	9.60	LS	1.57	39.62	0.37	0.04	0.33	2.24
95 - 190	60.00	9.40	30.60	SCL	1.39	46.54	0.44	0.08	0.36	1.43
Mean	**73.33**	**11.27**	**15.14**	**-**	**1.54**	**40.89**	**0.38**	**0.06**	**0.33**	**2.99**
SD	**7.22**	**1.23**	**2.01**	**-**	**0.11**	**4.18**	**0.01**	**0.002**	**0.001**	**1.22**

Profile 2 (Elevation 426 m)										
0 – 27	84.00	5.00	11.00	LS	1.54	40.77	0.43	0.06	0.37	7.38
27 – 88	64.40	6.00	29.60	SCL	1.42	45.38	0.44	0.08	0.36	1.53
88 - 185	64.00	12.00	24.00	SCL	1.38	46.92	0.44	0.07	0.37	1.72
Mean	**70.67**	**7.67**	**21.53**	**-**	**1.45**	**44.36**	**0.44**	**0.07**	**0.37**	**3.54**
SD	**6.25**	**1.34**		**-**	**0.12**	**3.19**	**0.02**	**0.001**	**0.001**	**2.01**
Profile 3 (Elevation 407 m)										
0 – 20	86.00	5.40	7.70	S	1.66	36.15	0.35	0.05	0.30	4.48
20 – 70	80.00	7.40	12.60	LS	1.55	40.38	0.38	0.05	0.33	3.01
70 - 175	61.00	10.40	28.60	SCL	1.42	45.38	0.44	0.08	0.36	1.30
Mean	**75.67**	**7.73**	**16.30**	**-**	**1.54**	**40.64**	**0.39**	**0.07**	**0.33**	**2.29**
SD	**6.33**	**1.11**		**-**	**0.22**	**3.22**	**0.01**	**0.03**	**0.002**	**2.01**

BD=bulk density, FC=field capacity, PWP=permanent wilting point, AWC=available water content, Ksat=saturated hydraulic conductivity, LS=loamy sand,SCL=sandy clay loam, S=sand

Table 4. Variability of Soil Physical Properties expressed in CV across the Study Areas

Location	Sand	Silt	Clay (%)	BD (g cm^{-3})	Porosity (%)	FC	PWP	AWC (cm^3 cm^{-3})	Ksat (cm/hr)
Upper Slope	75.61^a	15.06^a	15.06^b	1.59^a	37.69^a	0.37^a	0.06^a	0.31^a	3.09^a
Middle Slope	68.06^b	8.87^b	21.41^a	1.47^a	43.30^a	0.49^a	0.06^a	0.35^a	2.14^a
Lower Slope	52.22^c	8.89^b	17.66^b	1.51^a	41.96^a	0.40^a	0.07^a	0.34^a	2.94^a
G. Mean	**65.29**	**10.94**	**18.04**	**1.52**	**40.98**	**0.42**	**0.06**	**0.33**	**2.72**
STDEV.	**9.75**	**2.91**	**2.61**	**0.05**	**2.39**	**0.05**	**0.00**	**0.02**	**0.42**
CV (%)	**18.28**	**32.61**	**17.69**	**4.01**	**7.15**	**14.86**	**1.00**	**6.25**	**18.75**

BD=bulk density, FC=field capacity, PWP=permanent wilting point, AWC=available water content, Ksat=saturated hydraulic conductivity, CV=coefficient of variation

Conclusion

This study showed that soil hydraulic and physical properties vary with slope position and depth. Upper slope soils were coarser-textured, had higher saturated hydraulic conductivity and lower available water capacity, reflecting enhanced drainage but reduced moisture retention. In contrast, middle and lower slope positions accumulated finer particles, higher clay and silt fractions, and showed lower saturated hydraulic conductivity but greater plant-available water. This implies a waterlogged condition, nutrient accumulation and soil structural instability. Soil bulk density values were generally within the acceptable agronomic thresholds, but surface compaction was evident across the toposequence, with negative implications on total porosity and infiltration. The observed reduction of saturated hydraulic conductivity with depth confirmed the influence of reduced macro-porosity, organic matter and root activity in subsoil layers. Collectively, the findings highlight the strong control of slope dynamics on soil hydraulic and physical properties, reinforcing the importance of topographic context in soil and water management. This study recommends that upper slope positions be amended with organic matter to improve water retention and reduce nutrient leaching. Meanwhile, adequate drainage and reduced tillage should be adopted at the middle and lower slope positions to reduce waterlogging and compaction. Also, subsoiling should be implemented to alleviate surface compaction and enhance infiltration, particularly in cultivated areas with high soil bulk density.

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