Advances in Agriculture and Biology (2026) 9(1): 100-114
DOI: https://doi.org/10.63072/aab.26007
https://aabinternational.com/
ISSN: 3079-174X

RESEARCH PAPER

Toposequence controls of hydro-pedological properties of Vertisols for sustainable soil and water management in humid tropical Nigeria

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Key Message: Downslope, Nigerian vertisols hold enough moisture to sustain crops for three weeks without rain, but heavy rains cause poor drainage that chokes roots. However, critically low phosphorus prevents crops from using stored water. Solutions must balance retention and outflow while replenishing nutrients via runoff capture, fertility improvement, and flow adjustment to achieve climate resilience.

Abstract

Though wet tropical regions face mounting pressure from shifting climates, insight into soil water management remains sparse. This research examined soil properties governing water movement and storage within vertisols derived from the Ilaro Formation beneath southwestern Nigeria's forests. Across Idogo in Ogun State, soil samples were collected from lower, mid-, and upper slopes, naming the units Yewa, Sepeti, and Lapaleke respectively. Each segment revealed morphological patterns before lab tests determined texture, chemical nutrients, saturated hydraulic conductivity (Ksat), and available water capacity (AWC). Water retention was mapped under varying pressures, showing clay responses during wetting-drying cycles. Water movement tied closely to topographic position. Clay levels ranged from 22.3% to 65.4%, and soil cracks indicated swelling minerals. Water flow spanned very slow (0.12 cm/hr) to 2.45 cm/hr. Surface layers transmitted water faster (1.24–2.45 cm/hr) while deeper zones remained below 0.86 cm/hr. Available moisture held steady at 0.10–0.16 cm/cm. Root-accessible water ranged from 150 mm to 240 mm. Wet conditions caused seasonal saturation on lower slopes (Yewa series), where groundwater reached <50 m below surface during rains. Phosphorus was extremely low (1.4–4.6 mg/kg), yet base saturation exceeded 86%, and organic carbon was moderate (1.3–5.5%). Despite limited field operation windows, these soils held sufficient water to shield crops during droughts. Challenges include poor drainage, tight moisture limits, and nutrient-water interactions. For smarter management under changing climates, four elements are emphasized: continuous soil moisture tracking to guide irrigation timing; raised beds to reduce flooding damage; targeted phosphorus fertilizer to boost crop response during water scarcity; and catchment-scale runoff collection. Results point toward sustainable water management in tropical vertisols, offering practical insights for small-holder farmers adapting to climate shifts across West Africa. © 2026 The Author(s)

Keywords: Climate-smart agriculture, Humid tropical soils, Plant available water, Saturated hydraulic conductivity, Vertisols, Water management

Citation: Ande, O. T., Nurudeen, O. O., Are, K. S., Odunjo, T. E., Ankes, O. J., Ogunweide, T. A., Zubair, A. O., & Ndakotsu, J. (2026). Toposequence controls of hydro-pedological properties of Vertisols for sustainable soil and water management in humid tropical Nigeria. *Advances in Agriculture and Biology, 9*(1), 100–114. https://doi.org/10.63072/aab.26007

Introduction

Across the globe, shifts in climate now challenge how communities secure enough food, especially where farming relies on steady access to water and healthy soils (Lal, 2020; IPCC, 2022). Because higher heat levels arrive alongside erratic rains and stronger storms, areas near the equator often bear greater risks - particularly when resources for adjustment are scarce (Wheeler & von Braun, 2013; Rockström et al., 2020). In sub-Saharan Africa, most crops depend entirely on seasonal rainfall, while hunger rates remain high - a combination that grows riskier as forecasts show less predictable wet periods and longer stretches without rain during key growth phases (Niang et al., 2014; Sultan & Gaetani, 2016). Water stored in soil becomes a key when adapting to shifting climates. From rainfall, the soil holds what plants later draw upon through drought periods (Vereecken et al., 2016; Robinson et al., 2019). Because of how it retains moisture, moves fluid, or limits flow, each soil layer behaves differently. These traits - retention, conductivity, and usable volume - shape its role in farming under stress (Assouline & Or, 2014; Minasny & McBratney, 2018). When planning agriculture that withstands extremes, such details guide better choices (Lipper et al., 2014; Campbell et al., 2014).

Vertisols as soil types rich in smectite clays stand out in how they manage water flow (Ahmad, 1996; Driessen et al., 2001). When moisture rises, swelling clay particles

shut off fissures, slowing down water entry - sometimes leading to pooling (Arnold et al., 2015). As these soils lose water, shrinking generates deep cracks that act as fast lanes for drainage (Grebby et al., 2020; Tang et al., 2021). This shifting structure alters fluid paths repeatedly over time (Kutílek, 2004). Such behaviour brings benefits alongside difficulties depending on context (Pal et al., 2012). Water availability tends to be strong in vertisols - often holding between 150 and 250 millimeters within rooting depths - helping plants endure dry periods lasting up to a month (Dinka & Lascano, 2012). Despite that benefit, working these soils brings challenges: the window for field operations is tight due to rapid texture changes. When wet, swelling restricts internal flow, leading to ponding issues (Lombin & Esu, 1988). Runoff becomes more likely under heavy rain (Kahlown et al., 2005; Kumar et al., 2020). With crop yield in focus, adaptation, and lower emissions defines climate-smart farming (FAO, 2013; Lipper et al., 2014). On Vertisols such approaches show up through reduced soil disturbance - alongside managed outflow patterns - not fixed watering cycles but timed ones, combined planning of nutrients with moisture flow, rain collection methods included (Kahlown et al., 2005; Hobbs et al., 2008; Geerts & Raes, 2009; Rockström et al., 2010; Sadras et al., 2016).

Across Nigeria, where millions depend on farming, access to reliable water is a growing concern. Though home to fertile lands like Vertisols - found over different rock layers - their potential stays largely untapped. With rising heat and shifting rains expected in coming decades, crop yields face mounting risks. Most farmers rely solely on seasonal downpours, leaving livelihoods exposed when weather patterns change. These deep black clays, known for swelling and shrinking, appear in regions shaped by ancient sediment deposits. Past studies highlight both their promise and complexity under changing climate conditions. Southwest Nigeria sees key cocoa farming on Vertisols formed from the Ilaro Formation (Ayorinde et al., 2015), though details about how these soils handle water are still unclear. Where rains fall heavily - between 1300 and 2000 mm each year - the forest belt creates conditions that test soil drainage during wet phases, then shift abruptly into short droughts (Oguntunde et al., 2017). Beginning with morphological observations, this research examined Vertisols from the Ilaro Formation in southwest Nigeria to better understand their combined soil and water behaviour. Specifically, the objectives of this study were to: (i) study the hydrological properties of representative Vertisols along a defined toposequence, (ii) quantify soil-water storage potential and drainage characteristics, (iii) assess the interactions between soil fertility status and plant-available water capacity, and (iv) develop an integrated, toposequence-specific framework for climate-smart Vertisol management.

Materials and Methods

Description of the study area

Located in Ogun State, Nigeria, the research took place in Idogo village (6.62° N, 3.11° E), part of the lowland rainforest region (Fig. 1). Humid tropical conditions define the area, where rains fall in two main phases each year - peaks seen between June and July, then again from September into October - with about 1300 millimeters annually. Following these wet periods, a distinct dry stretch spans November through March. Temperatures typically move between 23 °C and 32 °C across months, while humidity stays consistently above 75% on average yearly. Evaporation potential reaches 1200 to 1400 mm, contributing to seasonal water shortages when rainfall pauses, including brief dry intervals sometimes observed in August (Oguntunde et al., 2017). Below the surface, layers of sedimentary rock form the Ilaro Formation - dating back to the Paleocene and Eocene periods - within the broader sequence of the Dahomey Basin, as noted by Jones & Hockey (1964), followed later by findings from Omatsola & Adegoke (1981). Shale makes up most of these rock deposits. Rising slightly above sea level between 50 and 100 meters, the land shows a softly rolling pattern. From higher ground with inclines of 2–4 percent, it gradually descends toward shallow valleys where water flows only at certain times of year. Secondary growth, abandoned plots, and farmland now cover much of what once was natural woodland. Cocoa trees grow across wide stretches, usually alongside plantains, sometimes with yams or maize appearing between them. In certain zones, rows of teak rise above smaller farms where families raise staples for their own needs. Cassava shows up frequently beneath the shade of taller crops, part of a mixed approach to growing food.

Designing surveys and choosing toposequences

Starting at higher ground near exposed shale, the study area stretches downward toward intermittent stream zones. Running about 1.2 kilometers, it moves across terrain marked by a thirty-five-meter change in height. To include diverse soil and water patterns, researchers followed this natural sequence down the slope. Early field checks confirmed a suitable path where human impact remained limited. Across the transect, spacing between investigation sites ranged from 100 to 150 meters, where both auger borings and small test pits were analyzed. Forty-two auger locations together with ten mini-pits helped locate shifts in soil layers while spotting typical profile examples. From these early observations emerged three separate zones linked to landform position. One sits high on the ridge - Lapaleke soils appear there. Mid-slope areas showed consistent patterns tied to Sepeti-type materials. Lower ground revealed deeper deposits assigned to the Yewa group. In every zone, full-size study pits measuring 2 by 1.5 meters at surface and reaching two meters down allowed close examination.

Soil sampling

From every genetic horizon, three intact soil samples were taken with stainless steel rings holding 100 cm^3. Around 3 kilograms of loose soil followed from each layer, packed into fresh polyethylene sacks. Sealing came next, then labelling and transfer toward the testing facility.

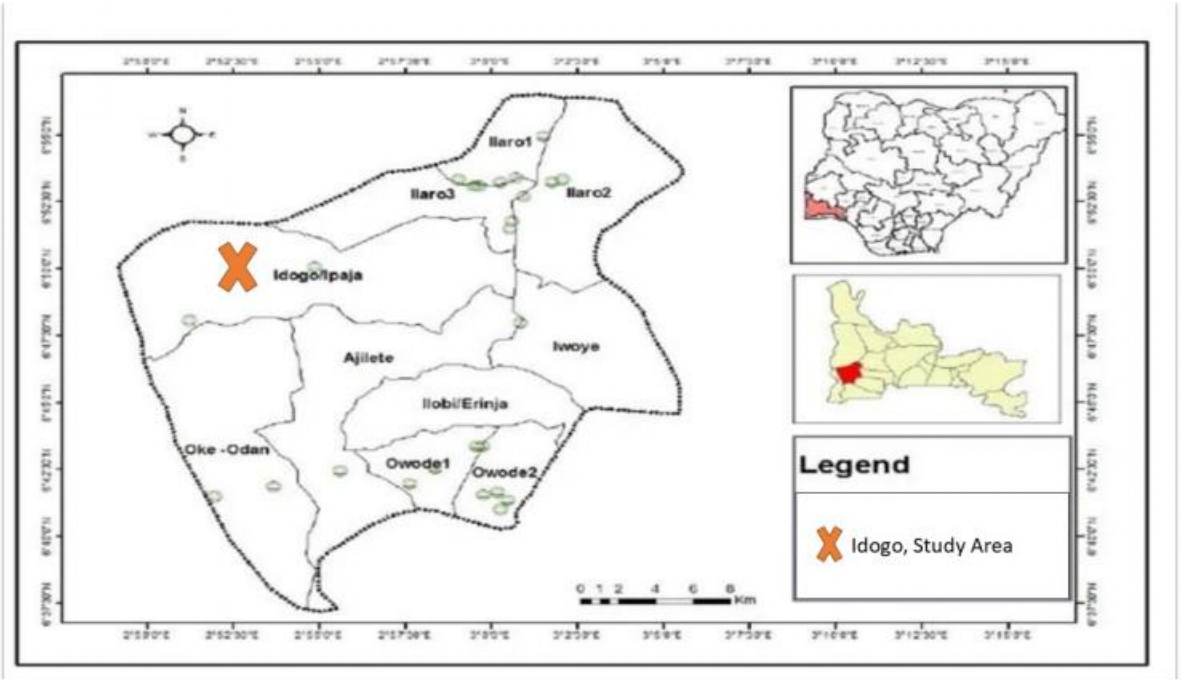


Fig. 1 Maps of Nigeria, Ogun State, and Yewa South Local Government Area showing Idogo (the study area).

Field morphological description

Soil morphological characteristics were documented using methods outlined by FAO (2006); Schoeneberger et al. (2012). Horizon names together with their depths formed part of the recorded data. While moisture levels remained high, colour readings were taken by comparing samples to Munsell charts. Texture estimates came first through tactile assessment; later confirmed via lab-based grain sizing. Regarding structure, notes captured form, scale, and how distinct each aggregate appeared. When soils were damp or saturated, firmness and workability were assessed carefully. Root traces - how numerous they seemed and how thick - were noted at every layer. Open spaces allowing fluid movement received attention during inspection. Signs of chemical reduction-oxidation processes showed up as discoloured patches or hardened mineral masses. In certain layers, shrinking-swelling behaviour revealed itself through fissures, polished surfaces, uneven ground patterns - measurements followed where visible. Unusual elements like limestone bits, broken bedrock pieces, or human-made debris rounded out the list.

Laboratory analyses

Sample preparation

After air-drying over one week under ambient conditions, disturbed soil specimens sat exposed to open air within room temperature. Breaking apart clumps happened carefully by means of a wooden cylinder rolled across the material. A two-millimeter mesh made of corrosion-resistant metal filtered out finer particles from coarser fragments. Remaining below-two-millimeter grains were reserved strictly for subsequent examination involving texture and composition testing.

Physical properties

To find the particle sizes, the hydrometer technique was used (Gee & Or, 2002). For sorting soil types, the USDA textural triangle chart was adopted. Measuring the bulk density of the soil was through the core sampling approach described by Grossman & Reinsch (2002). With that data, total porosity got calculated using the relationship between particle density (PD = 2.65 g/cm^3) and bulk density, BD: (1 – BD/PD). From intact soil cores, saturated hydraulicconductivity (Ksat) was assessed through the constant head permeameter technique (Klute & Dirksen, 1986). To examine water retention behaviour, both tension tables and pressure plates on unaltered core samples were used (Dane & Hopmans, 2002). Instead of summing values, available water capacity (AWC) emerged from subtracting water content at permanent wilting point (-1500 kPa) from that at field capacity (-33 kPa), following Cassel & Nielsen (1986). Estimating plant-accessible water reserves relied upon procedures outlined by Driessen et al. (2001).

Chemical properties

With a 1:1 mix, soil pH measurements took place in water, also repeated using 1 M KCl (Thomas, 1996). The Walkley-Black procedure, relying on dichromate oxidation, assessed organic carbon (Nelson & Sommers, 1996). Through micro-Kjeldahl processing - digestion followed by distillation - total nitrogen levels were measured (Bremner, 1996). To recover available phosphorus, researchers applied Bray-1 extractant (0.03 M NH_4F plus 0.025 M HCl), then quantified it via colorimetry based on molybdenum blue development (Bray & Kurtz, 1945; Kuo, 1996). One molar ammonium acetate at neutral pH removed exchangeable calcium,

magnesium, potassium, and sodium ions, following Thomas (1982). To recover acidic components like aluminum and hydrogen, a separate fraction used potassium chloride extractant; titrating that solution with dilute sodium hydroxide gave the acidity level, per the same source. The effective ability of soil to hold cations added together basic and acidic fractions - this total defined ECEC. From those values came base occupancy: how much of the retention sites held nutrient cations instead of acid ones. That proportion transformed into percent terms through division and multiplication by one hundred. For trace elements such as iron, manganese, copper, zinc, extraction occurred via diluted hydrochloric acid treatment based on Jackson (1962); readings then emerged using light absorbance methods tuned to each metal.

Hydrological parameters calculation

From water retention measurements, the soil moisture curve emerged through fitting to the van Genuchten (1980) equation by way of nonlinear regression. RETC software, Version 6.0 powered the computational process behind these fits. Water retention data helped estimate unsaturated hydraulic conductivity through the Mualem (1976) approach within RETC. The software applied that method to derive flow characteristics under varying moisture conditions. Parameters from retention curves fed into the calculations instead of direct measurements. Model implementation followed standard procedures coded in the program. Predictions relied on pore-size distribution inferred from suction behaviour. Flow estimates emerged from theoretical linkages between saturation and permeability. RETC handled computations using established numerical routines. Drainage class assessment was based on morphology (depth to redoximorphic features), position on toposequence, and Ksat values measured, in accordance with Soil Survey Staff (2022) criteria. In line with the following equation, simple water balance was estimated for the growing season:

$$\Delta S = P - ET - R - D$$

Where ΔS is change in soil water storage, P is precipitation, ET is evapotranspiration, R is runoff, and D is deep drainage. Evapotranspiration was estimated using the FAO Penman-Monteith method (Allen et al., 1998) with local climate data obtained from Nigeria Meteorological Agency, Ilaro in Ogun State, Nigeria.

Building farming methods that work with changing climate

Starting with soil and water traits, a method for managing Vertisols under changing climates took shape - focused on saving water. Instead of just adding inputs, it looked at how fields drain, timing extra watering when rain falls short. Rather than treating nutrients alone, their link with moisture got attention. At larger scales, whole watershed actions became part of the picture. Each piece faced testing through practical lenses: better yields, stronger adaptability, lower greenhouse gases. The study was conducted at Idogo village (6.62° N, 3.11° E) in Ogun State, southwestern Nigeria (Fig. 1). The area experiences a humid tropical climate with a bimodal rainfall pattern (approximately 1300 mm annually) that peaks in June - July and September - October. The dry season runs from November through March. Temperatures range from 23°C to 32°C, and the average relative humidity stays above 75%. Potential evapotranspiration averages 1200 - 1400 mm, which drives a seasonal water deficit during dry spells (Oguntunde et al., 2017). The underlying geology consists of sedimentary rocks from the Ilaro Formation (Paleocene to Eocene), part of the Dahomey Basin succession (Jones & Hockey, 1964). The gently undulating landscape (50 - 100 m elevation) slopes from the upper sections down to seasonal streams. The natural vegetation has been altered to support agricultural land use, primarily cocoa plantations intercropped with plantains, cassava, and other food crops.

Survey design and toposequence selection

A toposequence approach was adopted to account for soil and hydrological variability across the landscape. Reconnaissance surveys identified a 1.2-kilometer transect that spanned an elevation change of approximately 35 meters, running from the upper slope position near shale outcrops down to the lower slope. A schematic diagram of the toposequence is presented in Fig. 2. A grid survey was completed with auger borings and mini-pits at 100 to 150-meter intervals. A total of 42 boreholes and 10 mini-pits were examined to establish soil boundaries. Based on landscape position, three main mapping units were identified: Lapaleke series (upper slope), Sepeti series (middle slope), and Yewa series (lower slope). A modal profile pit (2 m × 1.5 m × 2 m depth) was excavated in each unit for detailed characterization.

Field morphological description

Morphological properties were described following standard FAO (2006) and National Cooperative Soil Survey guidelines (Schoeneberger et al., 2012). Horizon depths, Munsell soil colour, texture, structure, consistence, root distribution, and redoximorphic features were recorded. Also noted were vertic characteristics such as cracks, slickensides, and gilgai microrelief.

Soil sampling

Three undisturbed core samples were taken from each genetic horizon using 100 cm^3 stainless steel core rings. Approximately 3 kg of disturbed soil was collected per horizon, placed in polyethylene bags, and transported to the laboratory. The undisturbed core samples were used to determine soil bulk density and other physical properties, while the disturbed samples were prepared for subsequent physical and chemical analyses. In the laboratory, soil samples were air-dried at room temperature, gently crushed, and passed through a 2 mm sieve to remove stones, roots, and other coarse fragments. The processed samples were then stored in properly labelled containers for further laboratory analysis.

Laboratory procedures

Sample preparation

Disturbed soil samples were air-dried at 25–28°C for 7–10 days, gently crushed with a wooden roller, and passed through a 2 mm sieve to separate the fine earth fraction for analysis.

Physical properties

Particle size distribution was determined using the hydrometer method (Gee and Or, 2002), and textures were classified with the USDA textural triangle. Bulk density was calculated using the core method (Grossman & Reinsch, 2002). Total porosity was calculated from bulk density, assuming a particle density of 2.65 g cm^{-3}. Saturated hydraulic conductivity Ksat was measured on undisturbed cores using a constant head permeameter (Klute & Dirksen, 1986). Water retention was determined using a tension table and pressure plate apparatus (Dane & Hopmans, 2002). Available water capacity (AWC) was calculated as the difference between volumetric water content at -33 kPa and -1500 kPa (Cassel & Nielsen, 1986).

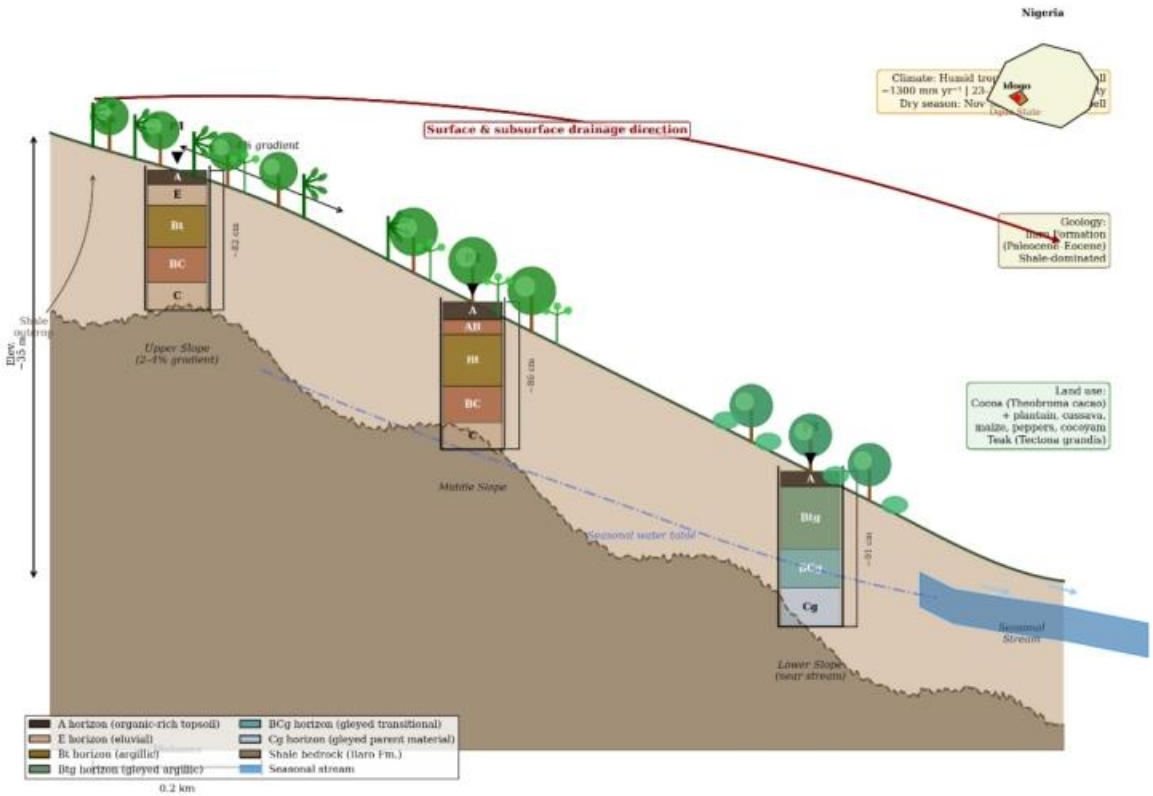


Fig. 2 Toposequence of Idogo village showing soil profile variations

Chemical properties

Soil pH was measured in 1:1 soil-water and 1:1 soil-1 M KCl suspensions (Thomas, 1996). Organic carbon was analyzed using the Walkley-Black dichromate wet oxidation method (Nelson & Sommers, 1996), and total nitrogen was analyzed by the micro-Kjeldahl method (Bremner, 1996). Available phosphorus was extracted using the Bray-1 method (Bray & Kurtz, 1945) and measured colorimetrically. Exchangeable bases (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) were extracted using 1 M ammonium acetate at pH 7.0 (Thomas, 1982). We calculated effective cation exchange capacity (ECEC) by summing exchangeable bases and exchangeable acidity. Micronutrients (Fe, Mn, Cu, Zn) were extracted with 0.1 M HCl and measured using atomic absorption spectrophotometry. Exchangeable acidity was determined through titration, while soil texture was assessed using the hydrometer method. All chemical analyses were performed following standard laboratory procedures, with appropriate reagents and calibrated instruments used to ensure analytical accuracy. The results were expressed on an oven-dry soil weight basis for consistency and comparison among soil horizons.

Hydrological calculations

Water retention data were fitted to the van Genuchten (1980) model using RETC software (Version 6.0), and unsaturated hydraulic conductivity was estimated using the Mualem (1976) model. The seasonal water balance was estimated using the equation:

$$\Delta S = P - ET - R - D$$

Where ΔS is the change in soil water storage, P is precipitation, ET is evapotranspiration, R is runoff, and D is drainage. We calculated ET using the FAO Penman-Monteith method (Allen et al., 1998) with local meteorological data.

Statistical analysis

Descriptive statistics (mean, range, standard deviation, coefficient of variation) were calculated for all soil properties. Analysis of variance (ANOVA) was used to test for significant differences among mapping units and horizons within the different soil profiles. Pearson correlation analysis was performed to explore relationships between soil properties. All these statistical analyses were performed using SPSS version 25.0.

Results

Toposequence characteristics and mapping units

Across the toposequence, changes in landscape position unfolded alongside shifts in slope steepness, water movement patterns, and soil structure. Found at different points along this sequence, each of the three mapping units displays distinct traits detailed in Table 1. Below 35 cm depth, reddish soil patterns revealed strong drainage in the Lapaleke group found uphill. Mid-slope areas held the Sepeti type, where signs of moisture buildup started deeper, past 69 cm down. Sitting low, the Yewa soils showed weak water movement - faint colour shifts near the top 34 cm, along with wetness that comes and goes through the year.

Morphological properties

The morphological characteristics of the studied soil profiles varied considerably with depth and landscape position. The lower-slope profile was characterized by a dark clay loam surface horizon overlying predominantly clayey subsurface horizons. The soil structure changed from moderate fine granular at the surface to strong coarse angular blocky with depth, accompanied by increasing hardness and firmness. Mottling became more pronounced in the deeper horizons, while slickensides, manganese concretions, calcium carbonate nodules, and weathered shale were also observed. These features indicate considerable clay accumulation, periodic wetness, and advanced pedogenic development in the lower-slope position (Table 2). The middle-slope profile had a dark, organic-rich surface horizon with abundant fine roots and organic debris. The surface soil was loamy and friable, whereas the underlying horizons were mainly sandy clay loam and clay. Subsurface horizons exhibited strong angular blocky structures and became increasingly hard, firm, sticky, and plastic with depth. Distinct mottles and slickensides were common in the deeper horizons, suggesting restricted drainage and shrink swell activity. The occurrence of Fe–Mn concretions in the upper subsurface horizon further reflects periodic redox conditions (Table 3). The upper-slope profile was dominated by clay loam at the surface and clay in the underlying horizons. The surface horizons had strong angular blocky structures, while the deeper horizons were extremely hard, very firm, very plastic, and very sticky. Mottling increased substantially with depth, becoming prominent in the Bt horizons. Slickensides were common throughout the subsurface, and a columnar structure was observed in the Bt3 horizon. Fe–Mn concretions, together with the gray coloration of the deepest horizon, indicate prolonged or periodic wetness and restricted drainage. The presence of strong structural development and slickensides also indicates significant clay movement and shrink–swell processes within the profile (Table 4).

Table 1 Selected morphological and physical characteristics of the mapped soil series

Mapping unit	Landscape position	Slope (%)	Elevation (m)	Drainage class	Depth to mottles (cm)	Depth to carbonates (cm)	Gilgai expression
Lapaleke series	Upper slope	2–4	82–95	Well drained	35–55	None observed	Moderate
Sepeti series	Middle slope	1–2	68–81	Well drained	69–120	None observed	Weak
Yewa series	Lower slope	0–1	53–67	Somewhat poorly drained	34–87	130–165	Strong

Table 2 Morphological description of Yewa Series (IDOGO PIT 1) - lower slope

Horizon	Depth (cm)	Color (moist)	Texture	Structure	Consistency	Roots	Redox features	Special features
Ao	0–3	7.5YR 3/1	Clay loam	Moderate fine granular	Slightly hard, friable	Many fine fibrous	None	Many decaying leaves, fine cracks
A1	3–34	7.5YR 5/1	Clay	Strong medium angular blocky	Very hard, very firm, plastic, sticky	Common fine	Few faint mottles	Soft Mn concretions, slickensides, cracks
B	34–87	Variegated	Clay	Strong coarse angular blocky	Extremely hard, very firm	Few very fine	Common distinct mottles	Hard Fe-Mn concretions
Bk1	87–	Variegate	Clay	Strong coarse	Extremely	Few fine	Common	Soft Mn nodules,

	130	d		angular blocky	hard, very firm		distinct mottles	Ca carbonate nodules, slickensides
Bk2	130–165	Variegated	Sandy clay	Weak coarse subangular blocky	Very hard, firm	Very few	Few distinct mottles	Weathered shale, quartz grains, Ca nodules
2C	165–185	Variegated	Clay	Massive	Extremely hard, very firm	None	Few faint mottles	Mn nodules, Ca nodules

Mn = Manganese; Ca = Calcium

Table 3 Morphological description of Sepeti Series (IDOGO PIT 2) - middle slope

Horizon	Depth (cm)	Color (moist)	Texture	Structure	Consistence	Roots	Redox features	Special features
Ap	0–10	10YR 3/2 (very dark gray)	Loam	Weak fine granular	Loose, very friable, non-sticky, non-plastic	Abundant fine	None	Abundant organic debris
A	10–20	7.5YR 2.5/2 (very dark brown) to 7.5YR 4/2 (brown)	Sandy clay loam	Moderate medium subangular blocky	Slightly hard, friable, slightly sticky, slightly plastic	Common fine	None	Soft Fe-Mn concretions
Bw1	20–69	7.5YR 5/2 (brown) with 7.5YR 5/8 (strong brown) mottles	Clay	Strong medium angular blocky	Very hard, firm, very sticky, very plastic	Few fine	Common distinct mottles	Slickensides
Bw2	69–120	7.5YR 5/2 to 7.5YR 5/8 (brown to strong brown)	Clay	Strong coarse angular blocky	Extremely hard, very firm, very sticky, very plastic	Very few fine	Common distinct mottles	Common slickensides
Bw3	120–160	7.5YR 5/2 to 7.5YR 5/8 (brown to strong brown)	Clay loam	Moderate coarse subangular blocky	Very hard, firm, sticky, plastic	None	Few distinct mottles	Few slickensides

Mn = Manganese; Ca = Calcium

Table 4 Morphological description of Lapaleke Series (IDOGO PIT 4) - upper slope

Horizon	Depth (cm)	Color (moist)	Texture	Structure	Consistency	Roots	Redox features	Special features
A	0–5	7.5YR 2.5/2 (very dark brown)	Clay loam	Strong fine angular blocky	Slightly hard, friable, slightly plastic, slightly sticky	Many fine	None	Gilgai microrelief
AB	5–20	7.5YR 2.5/2 (very dark brown)	Clay loam	Strong medium angular blocky	Hard, firm, plastic, sticky	Common fine	Few fine distinct	Slickensides
Bt1	20–35	7.5YR 4/2 (brown)	Clay	Strong coarse angular blocky	Extremely hard, very firm, very plastic, very sticky	Few fine	Common distinct	Common slickensides
Bt2	35–55	7.5YR 6/8 (reddish yellow)	Clay	Strong coarse angular blocky	Extremely hard, very firm, very plastic, very	Few fine	Many prominent	Common slickensides

					sticky			
Bt3	55–100	7.5YR 5/8 (strong brown)	Clay	Moderate coarse angular blocky	Extremely hard, very firm, very plastic, very sticky	Very few fine	Many prominent	Columnar structure
Bt4	100–120	7.5YR 6/1 (gray)	Clay	Strong coarse angular blocky	Extremely hard, very firm, very plastic, very sticky	None	Common prominent	Hard Fe-Mn concretions, slickensides

AB = Angular blocky; Mn = Manganese; Ca = Calcium

Soil physical and hydraulic properties

The textural and hydraulic properties of the different soils along the toposequence are presented in Table 5. Water movement through soil depends on physical traits like how tightly packed particles are, called Bulk density (BD). Pore spaces between grains matter too; total porosity (TP) shows how much air or water fits inside. When pores connect well, water moves freely - that's where saturated hydraulic conductivity (Ksat) comes in. This value reflects speed when all gaps fill with water. Saturated water content (θs) is linked. After drainage stops under gravity, what remains defines field capacity (θfc). Even then, plants struggle once levels drop further to the permanent wilting point (θpwp). The gap between θfc and θpwp gives available water capacity (AWC) indicates usable reserves for roots. Though particle size analysis revealed notable differences in clay levels across mappung units and depths, statistical significance emerged at p less than 0.05. Highest values appeared in the Sepeti series - peaking at 65.4 percent within its Bw1 layer. In contrast, Lapaleke maintained steadier proportions, ranging between 33.4 and 45.4 percent throughout profiles. Clay peaked deepest down in Yewa, hitting 55.4 percent toward lower layers. Between 13.5 and 35.5 percent silt occurred widely, hinting at intermediate breakdown of minerals. Lighter compaction marked topsoil zones; measurements fell from 1.04 to 1.09 g/cm^3 where life activity enriched surface beds. Deep down, bulk density grew steadily, hitting 1.61 g cm^{-3} between 130 and 165 cm in the Yewa soil type. In contrast, the Lapaleke showed lighter packing from top to bottom - likely tied to its stable framework and richer plant remains. Pores made up anywhere from 39.2% to 60.8% of total volume, shrinking as density rose. Near the surface, open spaces passed 58%, allowing air flow and roots to move freely. Lower layers held less space overall; still, more than four-tenths stayed porous across most levels.

Though shallow layers allowed fair flow, deeper zones slowed water sharply. Where roots opened paths and soil stayed loose, rates reached up to 2.45 cm/hr. Below, tight layers cut permeability fast - some below 0.9 cm each hour. In Yewa soils, the slowdown was most extreme: just 0.12 to 0.24 cm hourly beneath. These wet-prone profiles match earlier drainage labels. On steeper rises, Lapaleke earth moved moisture a bit faster down below, clocking 0.33 to 0.67 cm every hour. Elevation here links to freer downward passage. Looking further at Table 5, the way soil holds water becomes clear. Ranging between 0.46 and 0.59 cm^3 cm^{-3}, saturated water content shows maximum storage. Field capacity sits lower, moving from 0.32 to 0.43 cm^3 cm^{-3}. Permanent wilting point appears even less, spanning 0.18 to 0.28 cm^3 cm^{-3}. Because of their texture - rich in clay - and ability to expand when wet, these soils hold more water at saturation.

Water available to plants fell between 0.10 and 0.16 cm^3 per cm^3 of soil, peaking in the top layers of Lapaleke where it reached 0.15 to 0.16 cm^3 cm^{-3}, while dipping as low as 0.10 cm^3 cm^{-3} in deeper parts of Yewa profiles. Though clay-rich, these numbers sit mid-range - shaped not by texture alone but by how much moisture stays after drainage versus what remains when crops can no longer absorb it. Starting at 100 cm deep, the Yewa soil held 128 mm of usable water for plants, though values shifted between 110 and 140 mm depending on layer differences. Moving to Sepeti soils, stored water reached 132 mm, fluctuating from 125 to 140 mm across horizons. Lastly, Lapaleke showed the highest capacity - 150 mm available, with measurements spanning 145 to 160 mm when accounting for vertical change. Rooting depth at 150 cm in cocoa plots raised stored water amounts - Yewa soils held 184 mm. In contrast, Sepeti reached 192 mm. Meanwhile, Lapaleke peaked at 215 mm. The observed variations in soil physical and hydraulic properties reflect differences in landscape position, soil development, and horizon characteristics across the toposequence. The higher clay content and bulk density in subsurface horizons contributed to reduced pore connectivity and lower saturated hydraulic conductivity, particularly in the Yewa series. Conversely, the relatively favorable pore distribution and hydraulic conductivity observed in Lapaleke soils suggest better conditions for water infiltration and root penetration. Differences in available water capacity and cumulative water storage further indicate variations in the capacity of the three soil series to support crop water requirements.

Water retention curve parameters

Table 6 shows Van Genuchten parameter values obtained by fitting to measured water retention data. The soil water retention curves (SWRC) also are shown in Fig. 3. The SWRCs for the Yewa, Sepeti, and Lapaleke series show distinct changes in moisture flow across horizons. Water retention was lower in the above surface horizon while clayey subsoils have higher moisture contents. However, water content after gravity pull and permanent wilting point values change in values with depth, reflecting textural and structural differences along the toposequence. Higher up in the soil profile, the α value - linked to when

air starts moving into pores - was larger, between 0.024 and 0.032 cm^{-1}, compared to deeper layers where it sat at 0.009 to 0.015 cm^{-1}; this shift suggests surface soils release water from large openings under weaker pull. Pore spread patterns, captured by n, varied from 1.16 to 1.35, leaning toward greater consistency near the top, meaning pore widths there differ less from one another. The θr and θs parameters also varied among the soil horizons, indicating differences in residual and saturated water contents across the studied soil series. Higher θs values in the subsurface horizons may be attributed to increased clay content and the greater capacity of fine pores to retain water. In contrast, lower θs values in surface horizons reflect their relatively coarser texture and reduced water-holding capacity. The variation in the Van Genuchten parameters further highlights the influence of soil texture, pore-size distribution, and structural characteristics on water retention behaviour. These differences suggest that soil depth and horizon development play important roles in regulating water availability and movement within the soil profile.

Table 5 Physical and hydraulic properties of the studied soil profiles

Profile/Series	Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Textural class	BD (g cm^{-3})
Yewa	A_o	0–3	33.7	22.0	44.3	Clay	1.06
	A_1	3–34	47.7	30.0	22.3	Loam	1.42
	B	34–87	37.7	16.9	45.4	Clay	1.52
	Bk_1	87–130	31.1	27.5	41.4	Clay	1.56
	Bk_2	130–165	35.1	17.5	47.4	Clay	1.61
	2C	165–185	35.1	9.5	55.4	Clay	1.58
Sepeti	Ap	0–10	45.1	15.5	39.4	Sandy clay	1.04
	A	10–20	29.1	25.5	45.4	Clay	1.33
	Bw_1	20–69	21.1	13.5	65.4	Clay	1.36
	Bw_2	69–120	23.1	27.5	49.4	Clay	1.35
	Bw_3	120–160	27.1	21.5	51.4	Clay	1.44
Lapaleke	A	0–5	37.1	27.5	35.4	Clay loam	1.09
	AB	5–20	37.1	29.5	33.4	Clay loam	1.09
	Bt_1	20–35	37.1	23.5	39.4	Clay loam	1.17
	Bt_2	35–55	27.1	27.5	45.4	Clay	1.34
	Bt_3	55–100	27.1	35.5	37.4	Clay loam	1.32
	Bt_4	100–120	31.1	23.5	45.4	Clay	1.42

BD = Bulk density

Table 5 Continued

Profile/Series	Horizon	TP (%)	Ksat (cm h^{-1})	θs (cm^3 cm^{-3})	θfc (cm^3cm^{-3})	θ pwp (cm^3cm^{-3})	AWC (cm^3 cm^{-3})
Yewa	A_o	60.0	2.45	0.58	0.41	0.28	0.13
	A_1	46.4	0.86	0.48	0.32	0.18	0.14
	B	42.6	0.24	0.51	0.35	0.23	0.12
	Bk_1	41.1	0.18	0.49	0.36	0.22	0.14
	Bk_2	39.2	0.12	0.46	0.33	0.22	0.11
	2C	40.4	0.15	0.47	0.32	0.22	0.10
Sepeti	Ap	60.8	2.18	0.59	0.40	0.28	0.12
	A	49.8	0.92	0.52	0.37	0.24	0.13
	Bw_1	48.7	0.31	0.53	0.38	0.25	0.13
	Bw_2	49.1	0.28	0.52	0.39	0.25	0.14
	Bw_3	45.7	0.21	0.49	0.36	0.23	0.13
Lapaleke	A	58.9	1.86	0.57	0.42	0.27	0.15
	AB	58.9	1.24	0.57	0.43	0.27	0.16
	Bt_1	55.8	0.67	0.55	0.40	0.26	0.14
	Bt_2	49.4	0.42	0.51	0.37	0.23	0.14
	Bt_3	50.2	0.54	0.52	0.40	0.24	0.16
	Bt_4	46.4	0.33	0.49	0.35	0.22	0.13

TP = Total porosity; Ksat = Saturated hydraulic conductivity; θs = Saturated water content; θfc = Field capacity water content; θpwp = Permanent wilting point water content; AWC = Available water capacity

Table 6 Van Genuchten water retention parameters for representative horizons

Profile	Horizon	θr (cm^3 cm^{-3})	θs (cm^3 cm^{-3})	α (cm^{-1})	n	m	R^2
Yewa	Ao	0.12	0.58	0.024	1.28	0.219	0.991
Yewa	B	0.15	0.51	0.011	1.19	0.160	0.987
Sepeti	Ap	0.13	0.59	0.028	1.31	0.237	0.993
Sepeti	Bw1	0.16	0.53	0.009	1.16	0.138	0.985
Lapaleke	A	0.11	0.57	0.032	1.35	0.259	0.994
Lapaleke	Bt2	0.14	0.51	0.015	1.22	0.180	0.989

θr = Residual water content; θs = Saturated water content; α = Inverse of air-entry pressure (cm^{-1}); n = Pore-size distribution index; m = Shape parameter (where m = 1 – 1/n); R^2 = Coefficient of determination for the fitted van Genuchten (1980) model

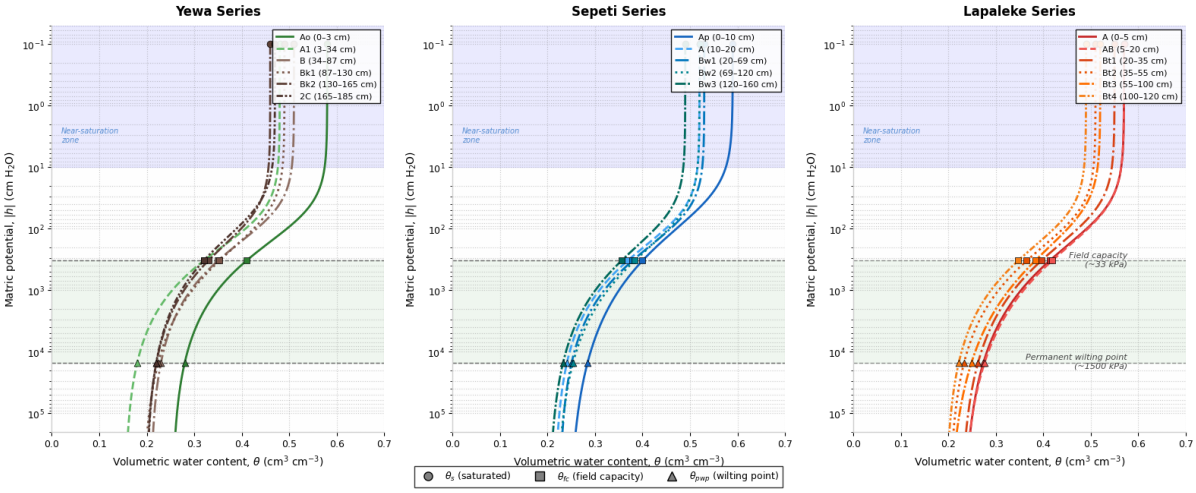


Fig. 3 Soil water retention curves of the soils across the toposequence

Chemical properties of the soils along the toposequence

Table 7 displays the levels of various chemical characteristics, along with micronutrient amounts. Though detailed, the data reflect consistent patterns across samples. Each value corresponds to a specific property measured under controlled conditions. Noticeable differences appear in trace element concentrations. These results build on earlier measurements reported in prior studies. This table captures essential details without oversimplifying the complexity involved. From strongly acidic levels (5.02) in Yewa subsoil up to slightly alkaline readings (7.79) in the Yewa Bk2 layer - where carbonates occurred - pH values shifted noticeably. In contrast, the Lapaleke soil series recorded lower pH at greater depths, starting at 7.74 near the surface and dropping to 5.14 below, likely due to loss of bases and absence of carbonate resistance. Despite decreasing down the profile, organic carbon stayed notably elevated below the surface too. The highest amounts appeared in Lapaleke soils - reaching 5.47% between layers. Near-surface levels ranged from 1.99 to 5.47%, consistently substantial. Movement of clay into cracks likely helped mix organic matter deeper. Because wet periods slowed breakdown, carbon persisted even at lower depths, measuring 1.33–4.94%. Although less than topsoil, these subsoil figures remain significant. Across every soil profile, available phosphorus stayed extremely low - ranging from 1.43 to 4.62 mg kg^{-1} - falling far beneath the 10–15 mg kg^{-1} threshold needed by many crops. Surface layers held slightly more, hinting at limited recycling through living systems. Yet even there, levels remained critically short of what plants require. Low to moderate levels of ECEC appeared across samples, ranging between 4.28 and 7.66 cmol kg^{-1} - typical for dense clay soils. Even with abundant clay, the measured CEC stayed below usual benchmarks for smectite-rich types, perhaps because layers contained kaolin-like structures or carried reduced charge. Even though rain falls heavily, base saturation remains consistently elevated - ranging from 84.9 to 99.7 percent - which points to basic cations holding a strong presence on the soil's exchange sites. This pattern persists because limited water movement through the ground reduces mineral washout, or alternatively, fresh release of ions from newly exposed rock matter may be playing a role. Far beyond normal levels, iron appeared at 41 to 417 mg kg^{-1}, a sign of the soil's iron-rich origin and breakdown residues. Where deeper layers lacked zinc - measuring under 1.0 mg kg^{-1} - top layers contained enough, ranging from 0.9 to 6.1 mg kg^{-1}, thanks to preserved organic content and natural nutrient recycling.

Table 7 Chemical properties of soils along the toposequence

Profile	H	Depth (cm)	pH (H_2O)	OC (%)	TN (%)	Av. P (mgkg^{-1})	ECEC (cmol$_+$kg^{-1})	BS (%)	Fe (mgkg^{-1})	Zn (mgkg^{-1})
Yewa	Ao	0–3	6.24	5.00	0.50	4.62	4.59	90.4	202	4.9
Yewa	A1	3–34	5.12	1.33	0.13	3.52	6.37	84.9	178	0.5
Yewa	B	34–87	5.02	2.50	0.25	2.48	7.66	86.9	188	0.2
Yewa	Bk1	87–130	5.08	1.98	0.20	2.60	7.38	86.7	311	0.8
Yewa	Bk2	130–165	7.79	1.99	0.20	1.67	5.89	99.7	236	0.7
Yewa	2C	165–185	7.37	1.47	0.15	1.81	5.89	99.3	304	0.7
Sepeti	Ap	0–10	6.83	1.99	0.20	3.06	6.43	98.1	154	0.9
Sepeti	A	10–20	7.29	3.17	0.32	2.48	5.03	98.0	56	5.2
Sepeti	Bw1	20–69	7.31	2.38	0.24	1.74	4.81	98.1	41	1.4
Sepeti	Bw2	69–120	7.29	1.70	0.17	1.62	4.28	97.7	241	0.3
Sepeti	Bw3	120–160	6.57	1.68	0.17	2.11	7.16	98.2	94	0.2
Lapaleke	A	0–5	7.74	3.94	0.39	3.81	6.20	98.1	343	6.1
Lapaleke	AB	5–20	7.41	5.47	0.55	2.25	6.67	97.9	206	2.1
Lapaleke	Bt1	20–35	6.14	4.94	0.49	1.82	6.38	97.6	339	1.1

Lapaleke	Bt2	35–55	5.14	3.22	0.32	1.46	7.00	86.4	417	0.2
Lapaleke	Bt3	55–100	5.06	2.93	0.29	1.43	7.11	86.1	368	0.4
Lapaleke	Bt4	100–120	5.14	2.91	0.29	4.60	6.93	86.3	173	0.3

H = Horizon; OC = organic carbon; TN = total nitrogen; Av. P = available phosphorus (Bray-1); ECEC = effective cation exchange capacity; BS = base saturation; Fe and Zn extracted with 0.1 M HCl. Carbon measured as organic matter, labeled OC. Nitrogen recorded under total amounts, shown as TN. Phosphorus accessible to plants marked Av. P. Exchange of positive ions in soil represented by ECEC. Proportion of exchanged bases relative to capacity noted as BS

Water balance estimates

The estimated seasonal water balance indicates that precipitation during the April–October growing season was substantially greater than atmospheric water demand. Total precipitation was approximately 1,150 mm, compared with a potential evapotranspiration (PET) of 850 mm. Actual evapotranspiration (AET) was estimated at 720–780 mm, reflecting temporary limitations in soil water availability during dry periods. Seasonal runoff ranged from 150 to 250 mm, with greater losses expected on saturated soils and lower slopes, whereas deep drainage was estimated at 50–150 mm and was generally greater on upper slopes. Changes in soil-water storage ranged from −30 to +50 mm, indicating periods of both seasonal depletion and recharge. Overall, the results suggest that although seasonal rainfall was sufficient to meet crop water requirements, its uneven distribution created short-term moisture deficits, requiring crops to depend on water stored within the root zone during dry spells (Table 8).

Table 8 Estimated water balance components for the growing season (April–October)

Component	Value (mm)	Description
Precipitation (P)	1,150	Mean annual total for the study area (April–October growing season)
Potential evapotranspiration (PET)	850	Estimated by the FAO Penman–Monteith method
Actual evapotranspiration (AET)	720–780	Limited by soil water availability during dry spells
Runoff (R)	150–250	Higher on saturated soils and lower slopes
Deep drainage (D)	50–150	Higher in upper slopes, lower in lower slopes
Change in storage (ΔS)	–30 to +50	Seasonal depletion and recharge of soil water reserves

Values are long-term averages. The growing season corresponds to the bimodal rainfall peak periods. Negative ΔS indicates net soil water depletion; positive ΔS indicates net recharge.

Soil classification

The taxonomic classification of the three soil units reveals distinct pedological properties across both systems (Table 9). The Yewa unit is classified as a *Typic Hapluderts* (USDA) and *Calcic Vertisol (Hypereutric)* (WRB), reflecting strong shrink-swell clay dynamics and secondary calcium carbonate accumulations under an udic moisture regime. The Sepeti unit is categorized as *Vertic Eutrudepts* and *Vertic Eutric Cambisol*, indicating a moderately developed, fertile profile with high base status and incipient vertic features driven by seasonal moisture fluctuations. Finally, the Lapaleke unit is classified as *Vertic Hapludalfs* and *Vertic Haplic Luvisol (Hypereutric)*, characterized by significant subsoil clay illuviation (argillic/luvisolic horizons), high nutrient availability, and localized vertic intergrades.

Table 9 USDA Soil Taxonomy and WRB classifications for the identified soil units.

Soil Unit	USDA Soil Taxonomy	WRB
Yewa	Typic Hapluderts	Calcic Vertisol (Hypereutric)
Sepeti	Vertic Eutrudepts	Vertic Eutric Cambisol
Lapaleke	Vertic Hapludalfs	Vertic Haplic Luvisol (Hypereutric)

Discussion

Despite varying positions along the landscape, soil drainage patterns show consistent links to elevation. Found near hilltops, Lapaleke soils drain efficiently due to faster saturated hydraulic conductivity - measured at 1.86 cm/hr on topsoil and between 0.33 and 0.67 in deeper layers. Because of their structure, these upper-level soils hold more moisture for plants: available water capacity reaches 0.15 to 0.16 cm^3/cm^3, translating into roughly 150 mm of accessible supply within the first meter. Moving downslope, Sepeti variants appear typical of Vertisols, containing about 65 % clay, which heavily influences how water enters during wet periods and cracks form when dry. Their dual-mode infiltration stems from cycles of swelling and contraction, a pattern supported by earlier findings (Arnold et al., 2015; Grebby et al., 2020). At footslope locations, Yewa soils display limited internal movement of water, evidenced by reddish bands appearing as shallow as 34 centimeters - a clue that temporary waterlogging occurs seasonally. Lowest subsoil Ksat values occur in this area, ranging from 0.12 to 0.18 cm/hr; signs of calcium carbonate nodules point to shifting water levels beneath the surface. Although available water capacity sits at a moderate level - between 0.10 and 0.14 cm^3/cm^3 - waterlogging can emerge during rainy periods, while drought-like loss happens quickly when conditions turn dry.

Available water for plants - ranging from 130 to 150 mm within a meter-deep root zone - can play a key role in adapting to shifting weather patterns. Maize, needing between 5 and 6 mm/day at peak growth, can rely on this reserve through three weeks or slightly more when rain stops. In contrast, cassava stretches that period by an additional ten days under similar conditions. When cocoa roots reach down to 150 cm, stored moisture increases to 185–215 mm, offering support across nearly five weeks - a span covering most short droughts (Allen et al., 1998; Zuidema et al., 2005; Carr & Lockwood, 2011). Compared with lighter, sandier local soils holding just half as much, these levels offer stronger protection against irregular rains. Yet dense layers - where soil compaction reaches up to 1.61 g/cm^3 - might block deep root expansion, reducing actual access to retained moisture (Bengough et al., 2011).

When subsoil permeability is low - ranging from 0.12 to 0.31 cm/hr - the chance of water pooling rises sharply, especially on downhill areas. Heavy rain, say about 50 mm, floods the ground far beyond what the soil can drain, sometimes twenty to forty times over its limit. Roots struggle without air under these wet conditions, a problem shown clearly by Drew (1997). In similar fashion, Coyne (2008) highlights how nitrogen vanishes through microbial breakdown when oxygen drops. Plant roots grow shallow instead of deep, planting schedules slip behind, so smarter farming methods become essential as climates shift. Very low phosphorus levels - below 5 mg/kg soil - disrupt how crops manage water. When roots grow poorly due to lack of phosphorus, they reach less deep moisture, cutting plant supply (Lynch & Brown, 2001). Because stomata function weakly, leaves lose more water than normal (Singh & Sale, 2000). Photosynthesis slows when phosphorus is too scarce (Fleisher et al., 2008). As a result, plants might tap just half to three-fifths of stored soil water. Adding phosphorus boosts efficiency of water use by one-fifth up to two-fifths where rainfall is limited (Payne et al., 1992; Zhang et al., 2014). Soils with strong base exchange and fair organic matter support better nutrient availability. Yet iron concentrations between 41 and 417 mg per kg suggest much applied phosphorus could bind tightly and become unavailable (Fageria & Baligar, 2008).

Across every part of the slope, holding moisture works best when mulch and crop leftovers stay on field - this slows drying plus limits crack formation (Hobbs et al., 2008; Gardner & Goyne, 2019). On tilled Vertisols, big chunks often appear - but minimum disturbance prevents that outcome (Kumar et al., 2020). How water moves depends on landscape position: ridges follow contours up high, middle areas use short drains, yet bottoms need deep ditches along elevated plots (Kahlown et al., 2005). Because stored water reaches 130 to 150 mm, extra supply matters only if dry periods stretch past two or three weeks (Geerts & Raes, 2009). Phosphorus placed in bands meets less fixation since contact drops - when mixed with organic inputs, its release improves further (Nkebiwe et al., 2016; Wang et al., 2025). Putting legumes into farming systems allows natural nitrogen capture by plants. On higher ground, mixing cocoa with shaded tree cover - alongside flood-resistant crops like rice or cocoyam downhill - creates varied production patterns that reduce vulnerability. These layered approaches build stronger responses to climate shifts without relying on external inputs.

Water movement across landscape gradients supports large-area water solutions. From higher and mid-slope areas - where runoff adds up to 150–250 mm each year - excess flow reaches lower zones (Liu et al., 2023). This surplus fills small reservoirs on farms, sized 100 to 200 cubic meters, offering extra watering when rainfall lags behind need. Soils rich in clay act as natural barriers, limiting water loss through ground absorption. Because actions uphill affect conditions downhill, planning must link these zones thoughtfully over time (Owusu et al., 2022). Below the levels seen in semi-arid Vertisols - where numbers range from 0.15 to 0.20 cm^3 cm^{-3} - the recorded AWC of 0.10–0.16 cm^3 cm^{-3} suggests stronger breakdown due to wetter climates. While CEC sits at a mid-level between 4.3 and 7.7 cmol kg^{-1}, most Vertisols show far higher readings near 20–40 cmol kg^{-1}, backing up this view (Pathak et al., 2013). Ranging from 0.12 to 2.45 cm h^{-1}, Ksat fits within worldwide patterns noted elsewhere. When set beside Nigerian counterparts in drier zones, these soils display deeper alteration alongside reduced nutrient richness. Such contrasts emerge clearly when earlier findings from savanna areas are considered (Aydinalp, 2010).

The pedological variations observed across the Yewa, Sepeti, and Lapaleke soil units reflect distinct interactions between parent material, landscape position, and weathering intensity under prevailing climatic regimes (IUSS Working Group WRB, 2022). The dominant presence of shrinking-swell smectitic clays and secondary carbonate accumulation in the Yewa unit (Typic Hapluderts/ Calcic Vertisol) underscores active argillopedoturbation and wet-dry seasonal dynamics typical of vertic environments (Soil Survey Staff, 2022; Driessen et al., 2001). Conversely, the transitional and moderately weathered profiles of the Sepeti (Vertic Eutrudepts/ Vertic Eutric Cambisol) and Lapaleke (Vertic Hapludalfs/ Vertic Haplic Luvisol) units highlight a progressive weathering sequence, where Cambisols represent an early stage of subsurface structural development, while Alfisols and Luvisols demonstrate substantial subsoil clay illuviation (argillic horizons) driven by textural differentiation and high base status (Buol et al., 2011; IUSS Working Group WRB, 2022). Furthermore, the dual-system correlation demonstrates strong methodological consistency between the USDA Soil Taxonomy and the World Reference Base (WRB), effectively capturing the subtle gradations in base status, moisture regimes, and vertic intergrades across the landscape (Deckers et al., 2016). The hypereutric specifiers in the WRB classifications emphasize high base saturation and nutrient reserves across these soils, which play a critical role in determining their agricultural suitability and structural management constraints (IUSS Working Group WRB, 2022). Ultimately, these taxonomic distinctions provide a strong baseline for understanding localized pedogenesis, soil hydrological behaviour, and fertility management requirements within the study area.

Conclusion and Recommendations

Looking down the hillslope, soil behaviour across this Nigerian landscape is fundamentally dictated by the distinct taxonomic properties of the Yewa, Sepeti, and Lapaleke units. Higher landscape positions are dominated by the Lapaleke soils (*Vertic Hapludalfs*/ *Vertic Haplic Luvisols*), where subsoil clay illuviation and favorable drainage permit easier water movement while holding usable moisture around 15 to 16 percent. In contrast, the low-lying Yewa soils (*Typic Hapluderts*/ *Calcic Vertosols*) accumulate water during rains and stay wet part of the year due to restricted sub-surface permeability. These dark, shrink-swell clay layers store substantial water reserves down to one meter—providing plants between 130 and 150 mm to draw from—which sustains annual crops through three-week dry spells, and longer for deep-rooted trees. However, internal flow rates drop sharply down the profile, trapping water near the surface and inducing chemical reduction zones above 34 cm. Despite this high storage potential, severe phosphorus limitations (under five ppm) stunt root development and restrict nutrient uptake, leaving much of the stored moisture unutilized. Managing these contrasting vertic and alfisolic soils for climatic resilience requires targeted landscape strategies, balancing water conservation in low areas with drainage management on higher ground, complemented by supplemental irrigation and balanced nutrient inputs to enhance food security across West Africa's humid tropical lowlands.

Authors' contribution statement: Conceptualization: O.O.N.; Data curation: O.T.A., & K.S.A.; Formal analysis: T.E.O.; Investigation: O.J.A.; Methodology: T.A.O.; Supervision: O.O.N.; Validation: A.O.Z.; Visualization: J.N.; Writing original draft: O.T.A.; Review and editing: O.O.N., All authors have read and agreed to the published version of the manuscript.

Funding: This research did not receive funding.

Availability of data and materials: Data used in this study can be obtained from the corresponding author upon reasonable request.

Declarations

i. Ethics approval and consent to participate: Ethical approval and informed consent were not required for this study as it did not involve human participants, human data or animals.

ii. Competing interests: There exists no conflict of interest.

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