Riparian soil and hydrological properties across primary, old-growth, and secondary tropical forests in Malaysian Borneo

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Abstract
This study presents a comparative baseline assessment of soil characteristics and hydrological properties across three riparian forest types in Sabah, Malaysia: Primary Forest (PF), Old Regrowth Forest (ORF), and Logged Forest (LF). Conducted in the Imbak Canyon Conservation Area and the Sustainable Forest Education and Research Area, Universiti Malaysia Sabah (SFERA@UMS), measurements focused on soil texture, bulk density, soil moisture, and unsaturated hydraulic conductivity. PF and ORF were characterised by clay-rich soils, higher moisture retention, and moderate unsaturated hydraulic conductivity, whereas LF exhibited sandier textures, lower soil moisture, and markedly reduced conductivity. Bulk density differences were minor and not statistically significant. While bulk density patterns did not strictly follow expected trends, PF and ORF had slightly higher mean values than LF. Results may reflect natural variability and structural recovery stages. Relationships between soil texture and hydrological parameters highlight the influence of disturbance and forest regeneration on riparian ecohydrology. The study provides essential baseline data for future monitoring, reinforces the ecological value of undisturbed and recovering forests, and supports the prioritization of PF and ORF zones in riparian buffer planning and watershed conservation.

Kewords: riparian, tropical, infiltration, forest, Imbak, hydrology

1 Introduction

1.0 Background of study area

Throughout Southeast Asia, forest ecosystems have undergone rapid degradation and fragmentation due to logging, agricultural expansion, infrastructure development, and fires. This has resulted in the loss of biodiversity, disruption of hydrological cycles, and degradation of critical ecosystem services. Riparian zones are particularly vulnerable to such disturbances. The removal of forest cover in these areas can significantly alter infiltration patterns, reduce soil water retention, accelerate streambank erosion, and increase both surface runoff and sediment transport. These hydrological changes compromise water quality, reduce the landscape's resilience to flood and drought events, and impair the ecological functioning of freshwater systems (Dudgeon et al., 2006; S.H. Luke et al., 2017). Fast-growing pioneers like *Acacia mangium* are often dominant in post-logging landscapes and have been shown to significantly alter soil structure, nutrient cycling, and moisture regimes in tropical forests (Hamad-Sheip et al., 2021).

In the face of these threats, it is essential to establish baseline environmental data in pristine and disturbed riparian forest landscapes, especially in regions where scientific documentation remains limited or absent. The hydrology component of the SAFE (Stability of Altered Forest Ecosystems) Project focuses on the effects of varying riparian buffer widths on stream channel suspended sediment, nutrient dynamics, discharge, and morphology following logging and partial conversion to oil palm plantations (Nainar et al., 2018, 2017). Additionally, (Luke et al. 2017b) highlighted the role of riparian buffers in maintaining hydrological functions and water quality in tropical agricultural landscapes.

This report presents the findings of the Imbak Canyon Conservation Area Wildlife & Resource Survey, co-organised by the Sabah Foundation (Yayasan Sabah) and the Sabah Wildlife Department, which took place from 3 to 15 September 2024. It provides a baseline assessment of riparian ecosystem characteristics within a remote and previously unexplored forest reserve in Borneo. Due to the extreme remoteness, such data were previously non-existent. For the same reason, the current expedition and scientific study were logistically challenging and necessarily limited in scope. The study area comprises patches of both Primary Forest (PF) and Old Regrowth Forest (ORF), offering a rare opportunity to compare natural and regenerating forest conditions within riparian zones. All data were collected within these riparian corridors, which are ecologically sensitive areas adjacent to streams that act as buffers, mediating both terrestrial and aquatic processes. The specific objectives of this study were: (i) to document soil characteristics in the riparian zones of both primary and old regrowth forests; (ii) to assess hydrological properties, including soil moisture and unsaturated hydraulic conductivity; and (iii) to visualise and describe stream cross-sectional morphology along selected transects, in order to serve as a baseline for future assessments, support other scientific investigations, and conservation-oriented decision-making.

2 Materials & Methods

2.1 Study area

The state of Sabah, located in Malaysian Borneo, contains extensive tropical forest cover, diverse faunal and floral assemblages, and notable geological features. The state economy is supported primarily by agriculture, forestry, and ecotourism (Sabah State Government, 2025). As of the time of reporting, approximately 4.68 million hectares, equivalent to 65% of the state's total land area remain forested. Of this, 3.85 million hectares (50%) are gazetted as forest reserves, while 1.9 million hectares (26.4%) are classified as Totally Protected Areas (TPAs) (Sabah Forestry Department, 2025).

This study was conducted mainly in two sites within the state of Sabah – the first, in the Imbak Canyon Conservation Area (ICCA) where the primary forest and old growth forest land-uses were; and the second, in the Arboretum of the Sustainable Forest Education and Research Area, Universiti Malaysia Sabah (SFERA@UMS) where the logged forest (LF) land-use was. The Imbak Canyon Conservation Area (ICCA) is part of a larger forest concession area of approximately one million hectares known as the Yayasan Sabah Concession Area (YSCA) – one of the key forest management zones in the state managed by Yayasan Sabah in which the infamous primary forest reserves Danum Valley Conservation Area and Maliau Basin Conservation Area are part of (Sabah Travel Guide, 2025a; The Bornean Hidden Valley, 2024a).

2.1.1 Imbak Canyon Conservation Area

The 27,599 ha ICCA, located in the central interior region of Sabah represents one of the few remaining forest landscapes in the state with minimal prior exploration and serves as a reference site for forest conservation and hydrological research. The area was voluntarily designated as a conservation area by Yayasan Sabah in 2003 and was later gazetted as a Class I (Protection) Forest Reserve in 2009, prohibiting logging activities (The Bornean Hidden Valley, 2024b). The canyon serves as one of the headwaters for the Kinabatangan River, Sabah's longest river, highlighting its ecological significance (The Bornean Hidden Valley, 2024a).

The landscape of ICCA is characterized by a 25-kilometer-long valley flanked by sandstone ridges, which contribute to its unique geological features. The geological formations primarily consist of uplifted and folded sedimentary rocks, including sandstones and shales, which influence soil development and hydrological patterns (The Bornean Hidden Valley, 2025). Notably, the Tanjong Formation, an Early Miocene-aged shallow-marine unit, crops out in the Tongod district, including the Imbak Canyon area. This formation comprises various sedimentary facies, such as mudstone, lenticular, wavy, flaser, hummocky cross-bedded sandstone, swaley cross-bedded sandstone, planar cross-bedded sandstone, and structureless sandstone facies, indicating deposition in a macrotidal open-coast setting with significant tidal influence. These sedimentary structures and compositions play a crucial role in shaping the region's geomorphology and hydrology (Chung et al., 2024).

Soils within ICCA are primarily derived from the underlying sedimentary rocks, resulting in a variety of soil types. The region features soils ranging from sandy loams to clay loams, with varying degrees of fertility and drainage capabilities. These soil characteristics play a crucial role in determining vegetation patterns and hydrological processes within the riparian zones (Kammesheidt et al., 2009).

The region has an equatorial climate, characterized by consistently high temperatures, high rainfall, and elevated humidity throughout the year. In the ICCA, annual rainfall is 3,318 mm (averaged for years 2018-2023, except 2020). Years 2019 and 2023 were the driest (3,037 mm) and wettest (3,771 mm), respectively (Imbak Canyon Archive, 2024). Although such inland mountainous areas are known to have their own localised weather systems, the ICCA is influenced by major regional weather patterns namely the northeast and southwest monsoons, as well as the inter-monsoon phases – evident in the wet months from October to January; and dry months in February, March, and July to September (Imbak Canyon Archive, 2024).

The ICCA itself comprises blocks of primary and old regrowth forest reserves (Figure 1, 2), with the surrounding area consisting of logged forest of varying degradation and oil palm plantations. The vegetation in ICCA is diverse, encompassing several forest types, including lowland dipterocarp forests and lower montane heath forests. The area is home to numerous endemic and rare plant species, such as the pitcher plant *Nepenthes hirsuta* and the recently discovered *Schismatoglottis imbakensis* (Sabah Travel Guide, 2025b). A study conducted in the Batu Timbang area of ICCA documented 413 plant species across 82 families, with 93 taxa endemic to Borneo and 10 endemics to Sabah (Pesiu et al., 2019). These findings underscore the area's significance as a reservoir of plant biodiversity and highlight the importance of ongoing conservation efforts.

Figure 1: View facing downstream, with primary forest visible on the left and logged forest on the right. Differences in canopy cover between the two land uses are apparent.

Figure 2: An old regrowth forest (left) exhibits a denser canopy structure resembling that of primary forest, in contrast to the more open canopy of a recently logged forest (right)

In this study, all measurements were conducted along riparian zones, specifically, at the riverbanks without extending into inland or hillside regions (Figure 3). Sites were stratified into one PF and three ORF sites (ORF1, ORF2, ORF3). Accessibility was limited due to rugged terrain, requiring a week-long field data collection.

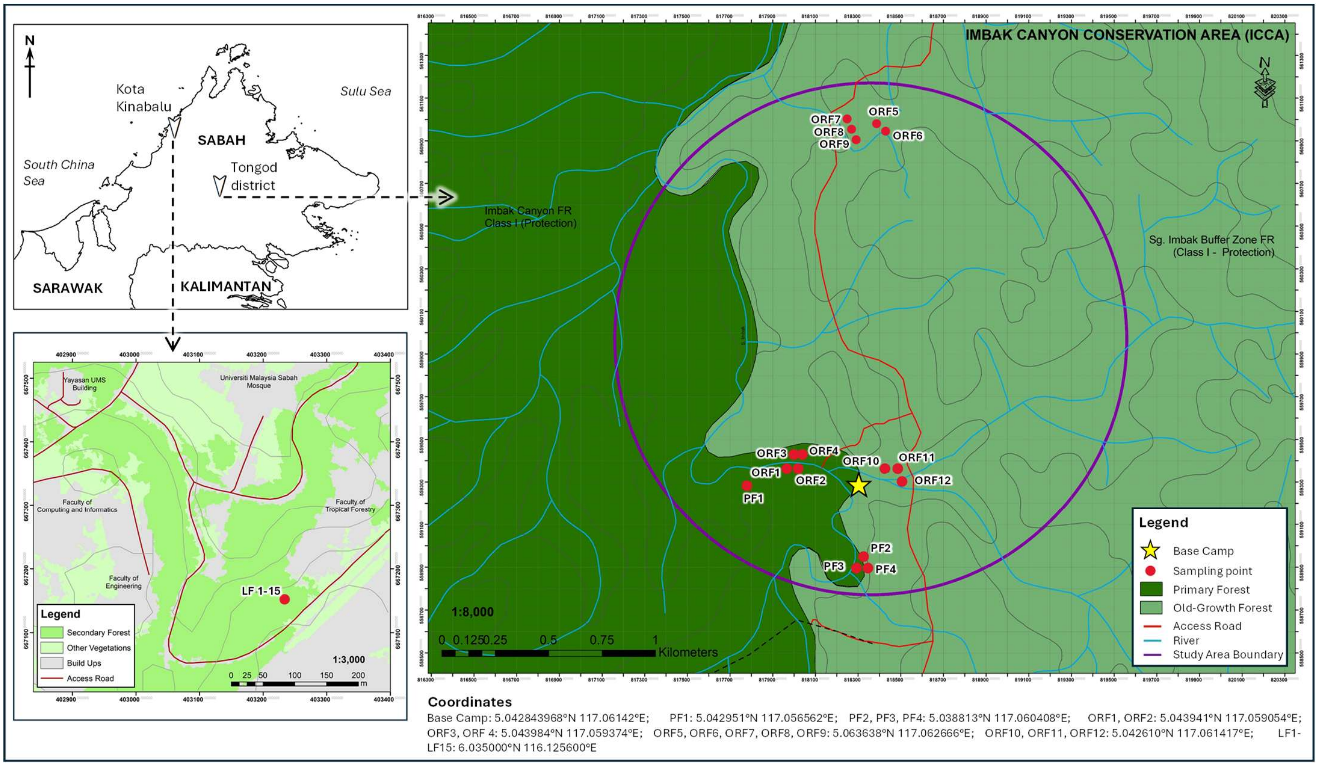

Figure 3: Study area and sampling points

2.2 Soil and Hydrology measurements

At selected riparian points, soil texture, bulk density, soil moisture content, and hydraulic conductivity were measured. A total of 16 points were sampled: 4 from PF, 12 from ORF, and 15 from LF.

At each plot, surface soil samples were collected using steel soil rings and a mallet. Soil texture was analysed in the laboratory using the jar test (wet-settling method). Samples were dispersed in water and allowed to settle, separating the particles into sand, silt, and clay fractions by gravity. Textural classification was performed based on the USDA soil texture triangle, identifying classes such as clay, silty clay, and sandy clay. Soil texture was estimated using the wet-settling jar method. Although less precise than hydrometer or pipette analyses, this approach was appropriate given the remote study setting and baseline objectives. The method provides reliable estimates of relative particle-size distribution for comparative ecological interpretation, with acknowledged limitations in distinguishing fine silt and clay fractions. The second sample was used to determine bulk density and soil moisture content. The intact core was oven-dried at 105°C for 24 hours to obtain the dry mass. Bulk density was calculated as the ratio of oven-dried soil mass to the known ring volume, expressed in g/cm^3. From the same core, gravimetric soil moisture was determined. A subsample was weighed fresh, then oven-dried at 105°C, and reweighed. The moisture content was expressed as a percentage of dry weight.

Infiltration measurements were conducted in the field using a "Decagon Devices" Mini Disk Infiltrometer, a tension infiltrometer designed to measure unsaturated infiltration rates. The device was operated at a suction head of -2 cm, which suppresses macropore flow and ensures that infiltration occurs primarily through the soil matrix. This setup allows for a more accurate estimation of unsaturated hydraulic conductivity, particularly in fine-textured soils where preferential flow can bias results.

3 Results & Discussion

3.1 Soil Texture

Soil texture varied across the three land-use types, reflecting both geological substrate and disturbance history (Figure 4). Primary Forest (PF) plots were predominantly clay-rich, with a mean clay content of 54.57%, accompanied by lower sand (18.25%) and silt (27.18%). Old Regrowth Forest (ORF) also exhibited high clay content (mean 45.30%) but with more

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variable sand and silt proportions, ranging from 0% to nearly 49% sand, and up to 100% silt in one case. The Logged Forest (LF) sites demonstrated a distinct profile, with the highest mean sand content (33.63%) and intermediate levels of silt (40.20%) and clay (39.23%). This may be in part due to natural characteristics and/or alterations in depositional regimes or erosion-recovery dynamics due to logging in the ORF and LF zone (Khairil et al., 2014; Syakilah Suhaili et al., 2023).

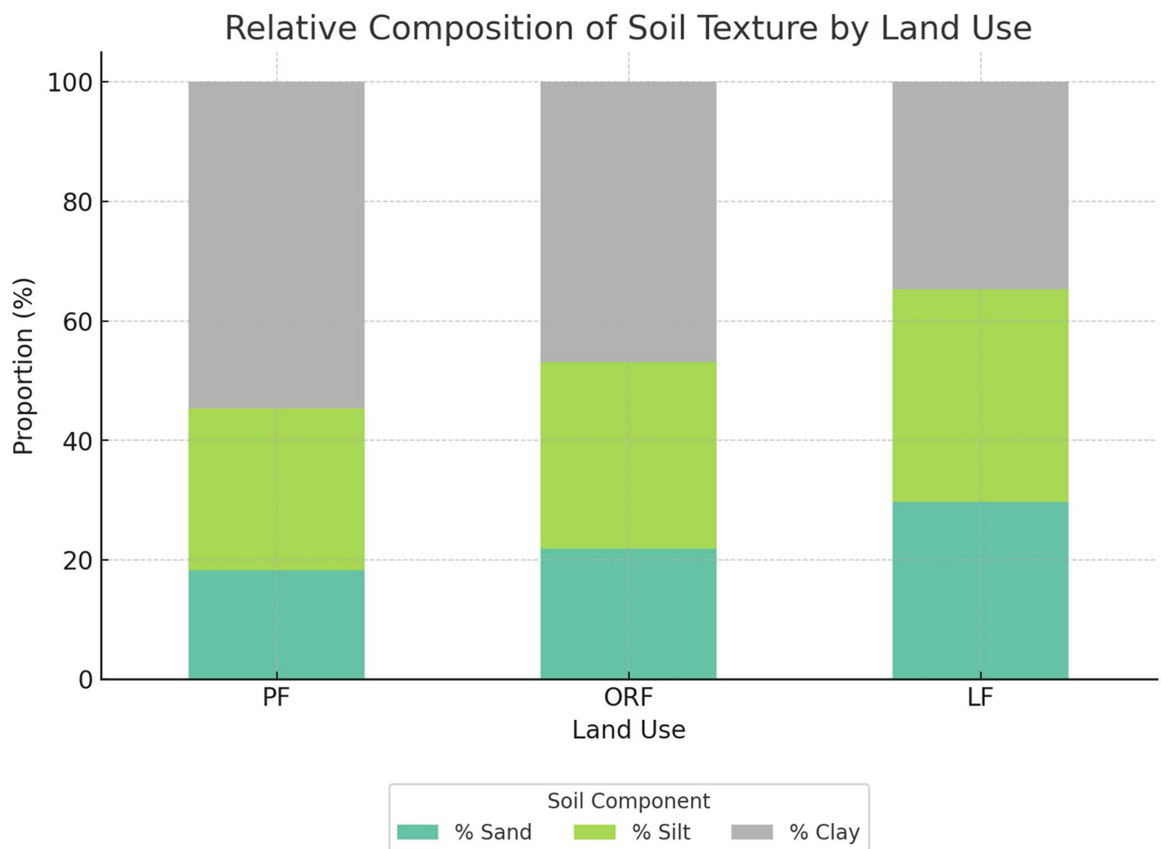

Figure 4: Soil particle-size distribution in PF, ORF, and LF

3.2 Bulk Density

Bulk density ranged from 0.90 to 1.88 g/cm^3 across all sites (Figure 5). Mean values were similar for PF (1.53 g/cm^3) and ORF (1.54 g/cm^3), while LF showed a noticeably lower mean (1.37 g/cm^3). Notably, PF exhibited the widest range (0.92–1.88 g/cm^3), likely reflecting undisturbed soil heterogeneity, such as variation in root networks or organic litter layers. In contrast, LF plots had consistently low bulk density (0.90–1.64 g/cm^3), potentially indicating ongoing soil loosening due to disturbance, vegetation succession, and lack of compaction. These results differed from most studies where forest disturbances, especially logging, resulted in higher bulk densities (Azhar et al., 2025; Nazari et al., 2021; Syakilah Suhaili et al., 2023). One-way ANOVA indicated no significant differences in bulk density between forest types ($p > 0.05$). This suggests that bulk density is not governed solely by broad forest land-use categories but is more strongly influenced by site-specific factors such as recent land-use history, soil type, and disturbance processes.

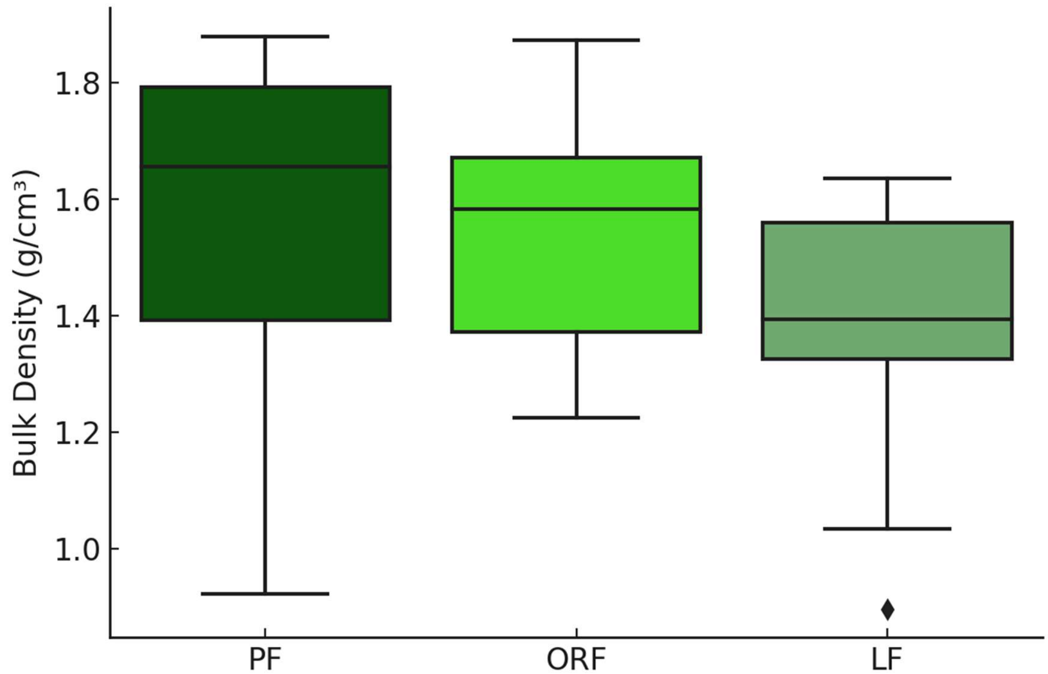

Figure 5: Bulk density of soils in PF, ORF, and LF

3.3 Soil Moisture

Gravimetric soil moisture ranged broadly, from 4.96% to 77.42% (Figure 6). ORF plots had the highest mean moisture content (47.91%), followed by PF (43.77%) and LF (31.30%). The lower average in LF may be linked to its higher sand content and lower water-holding capacity, as well as younger vegetation with less canopy cover for shading and evapotranspiration moderation. PF and ORF both demonstrated wider moisture variability, likely due to localised microtopography and canopy interception. Despite these patterns, ANOVA showed no significant differences in soil moisture among the three-forest land-use types ($p > 0.05$). Wide variability in soil moisture in tropical forest systems under different disturbance regimes has been documented elsewhere; for example (Noguchi et al., 2016) observed marked variation in volumetric soil water content in Pasoh Forest relating to monsoons and canopy cover, while (Azhar et al., 2025) found significantly lower moisture in logged versus natural forests in Selangor, Malaysia.

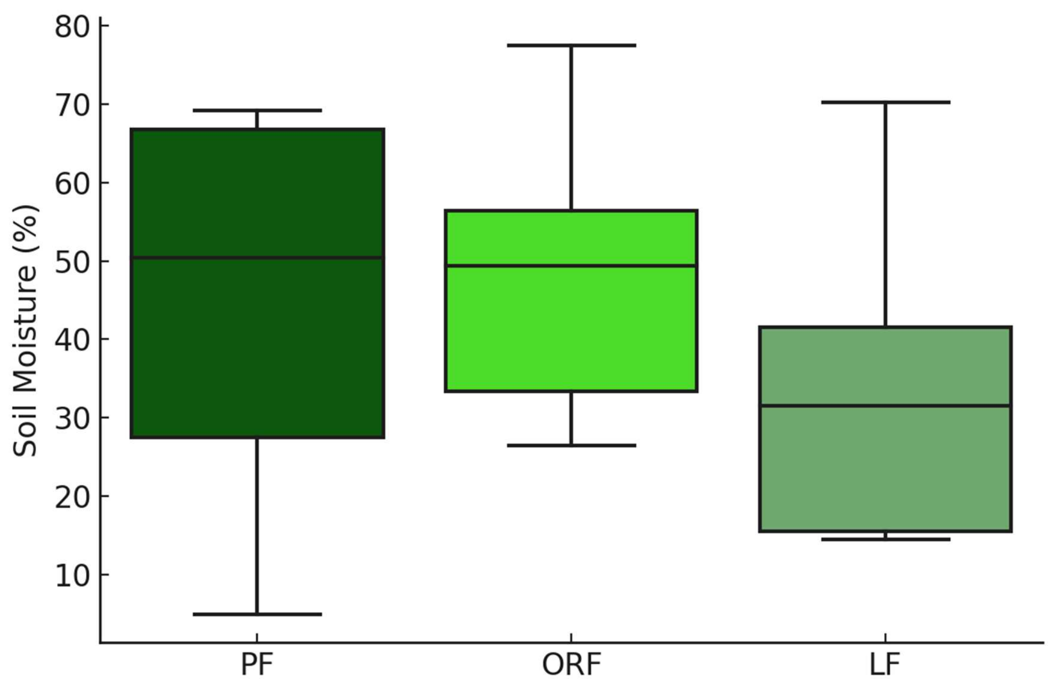

Figure 6: Soil moisture in PF, ORF, and LF

3.4 Hydraulic Conductivity

Hydraulic conductivity values (measured under tension using a Mini Disk Infiltrometer) ranged from 0.000015 cm/s to 0.0347 cm/s (Figure 7). The mean values were nearly identical between PF (0.00381 cm/s) and ORF (0.00413 cm/s), with LF showing a markedly lower mean of 0.00025 cm/s. The extremely low mean for LF could be a consequence of textural heterogeneity in recovering riparian zones with disturbed vegetation. Across all land uses, conductivity values were consistent with matrix-dominated infiltration patterns in fine-textured riparian soils. The Kruskal–Wallis test indicated no statistically significant differences in hydraulic conductivity among PF, ORF, and LF ($p > 0.05$). As shown in Figure 7, variability is mainly driven by differences in outliers, while the medians and interquartile ranges are broadly similar across land-use types.

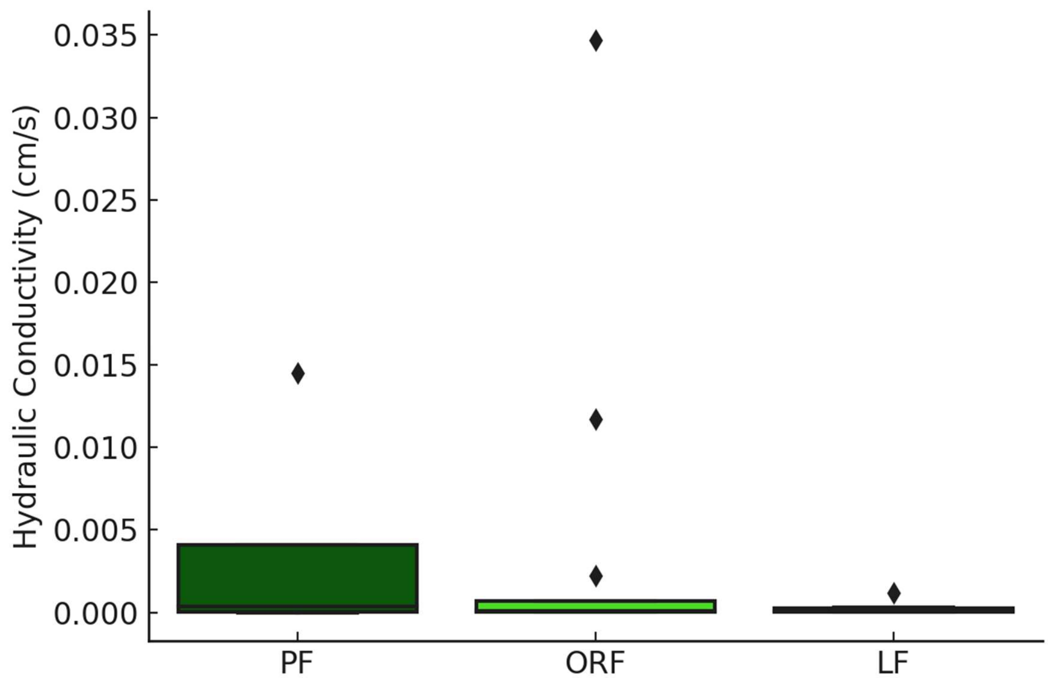

Figure 7: Hydraulic conductivity in PF, ORF, and LF

3.5 Texture-Hydrology Relationships

The scatterplots reveal relationships between soil texture and key hydrological and physical soil properties (Figure 8). In particular, the relationship between percentage sand content and hydraulic conductivity (K) shows a generally positive trend, whereby sites with higher sand content tend to exhibit greater K values. This pattern is especially evident among plots from the Logged Forest (LF) and Old Regrowth Forest (ORF), suggesting that coarser soils in these disturbed landscapes facilitate more rapid unsaturated water movement. Conversely, the percentage clay content is negatively correlated with K. Soils richer in clay consistently exhibit lower conductivity values, aligning with the well-established understanding that fine particles reduce pore size and limit water transmission. These findings echo previous work in tropical and subtropical regions, where soil texture—particularly the balance of sand and clay—emerged as a primary control over infiltration and hydraulic properties (Bargués-Tobella et al., 2024; Tuffour et al., 2019).

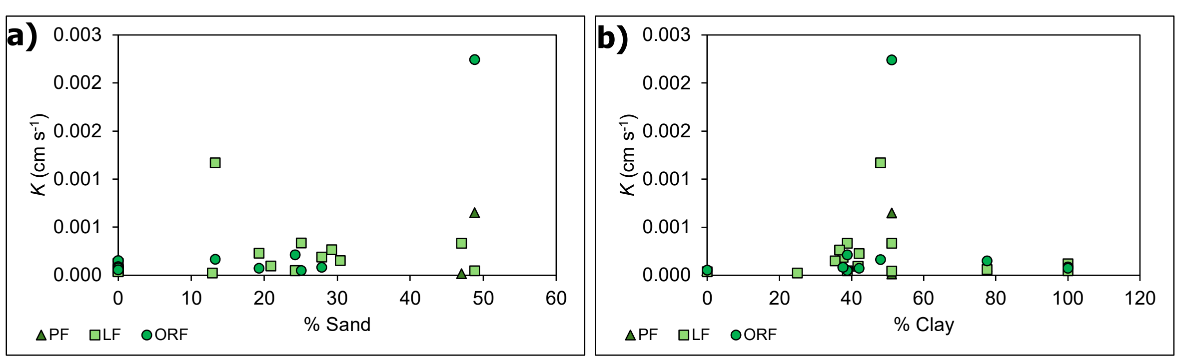

Figure 8: Relationship between soil hydraulic conductivity (K) and (a) percentage sand; (b) percentage clay

Soil moisture content displays an opposite pattern relative to texture (Figure 9). Sites with higher clay content generally show elevated volumetric moisture, while sandier soils tend to retain less water. This is consistent with clay's capacity to retain water within micropores, whereas sandy soils drain rapidly under gravity. The logged forest plots, particularly those with higher clay percentages, demonstrate this relationship clearly, indicating that past disturbance may have promoted fine particle deposition or compaction. The positive association between % clay and soil moisture aligns with empirical observations in tropical forests, where increased clay has been linked to better water holding capacity and more buffered moisture regimes under fluctuating rainfall (Rawls et al., 2003).

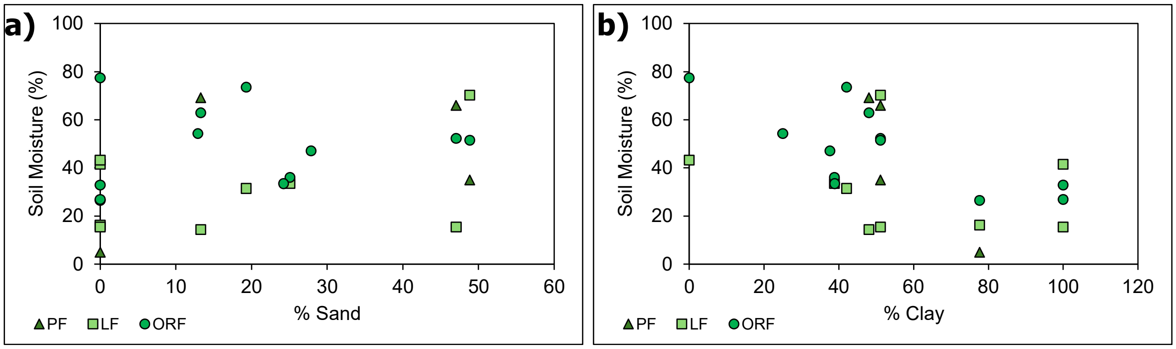

Figure 9: Relationship between percentage soil moisture and (a) percentage sand; (b) percentage clay

In terms of bulk density, sandier soils exhibit marginally higher bulk densities, reflecting a denser packing of particles with fewer micropores (Figure 10). This relationship, while weaker than those observed for conductivity and moisture, suggests that soil structure and compaction may also influence bulk density beyond texture alone. Interestingly, while clay-rich soils typically display lower bulk density due to increased porosity, the logged forest plots exhibit a range of bulk densities, indicating that land-use disturbance and soil structural degradation may play a confounding role. It is therefore likely that soil compaction and loss of organic matter, common in disturbed or regenerating forests, override the influence of texture in some cases (Yu et al., 2019).

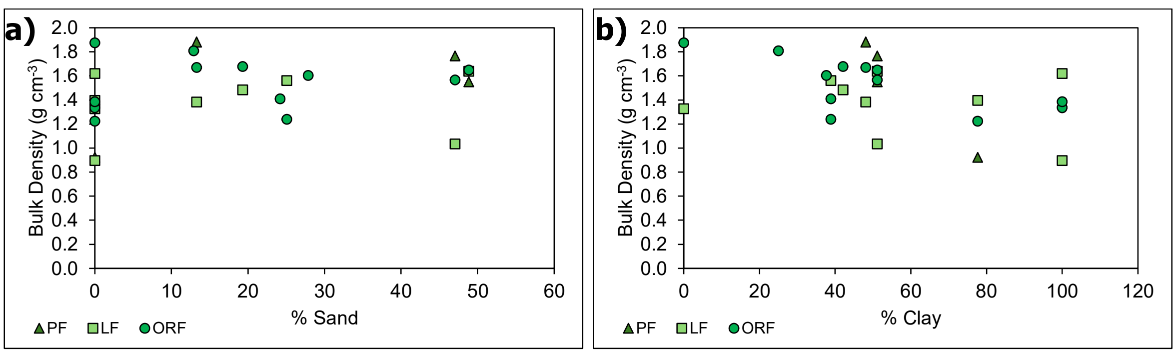

Figure 10: Relationship between bulk density and (a) percentage sand; (b) percentage clay

Together, these relationships underscore the strong interdependency between soil texture, hydrological function, and forest land-use history. Soils richer in sand promote infiltration but lose moisture more rapidly, whereas clay-rich soils retain moisture but impede vertical water movement. The bulk density responses, although subtle, suggest that structural compaction linked to disturbance may influence root penetration and water storage. These insights are particularly relevant for riparian management in mixed-use tropical landscapes, where forest degradation, recovery, and soil heterogeneity intersect to shape hydrological behavior. It is important to note that these analyses were conducted under unsaturated conditions using a Mini Disk Infiltrometer. As such, the findings primarily reflect matrix flow rather than macropore or preferential pathways. In addition, while particle size distribution was estimated using the jar method, some uncertainty in distinguishing clay from silt remains, especially in samples with single-layer settling. Nonetheless, the patterns observed are consistent with theoretical expectations and prior field studies in tropical soils and thus provide a reliable basis for interpreting hydrological function in these forested riparian systems.

4 Conclusion

This study presents a comparative assessment of soil texture, hydrological properties, and stream morphological features across riparian zones under three distinct forest conditions in Sabah: undisturbed primary forest, old regrowth forest, and recently logged forest. Findings revealed that primary and regrowth forests consistently exhibited higher clay content and bulk density, alongside greater soil moisture retention and moderate infiltration rates. In contrast, the logged forest sites were characterised by higher sand content, lower water-holding capacity, and substantially reduced hydraulic conductivity. These patterns reflect both intrinsic differences in vegetation structure and disturbance legacies, particularly the dominance of fast-growing pioneer species such as *Acacia mangium* in regrowth zones and reduced canopy cover in recently logged sites. Furthermore, the observed textural variability and infiltration responses underline the sensitivity of riparian soils to land-use transitions and their role in shaping water regulation functions. Overall, this investigation contributes foundational yet comparative data for understanding riparian ecohydrology in Bornean tropical forests. It underscores the need for continuous monitoring of soil and hydrological parameters as forest recovery progresses. The results not only serve as a baseline for long-term ecological assessment but also provide valuable reference points for informing riparian buffer design, erosion control strategies, and integrated watershed management in regions undergoing rapid land-use change.

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Conflict of interest

The authors declare no conflict of interest.

Authors' contribution

NF: Data curation, Formal analysis, Investigation. **SE:** Data curation, Formal analysis, Investigation. **WS:** Conceptualization, Funding acquisition, Project administration. **JS:** Conceptualization, Funding acquisition, Project administration. **RMM:** Project administration. **MHW:** Project administration. **MM:** Supervision, Writing – review and editing. **RDM:** Supervision, Writing – review and editing. **NAB:** Methodology. **AN:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Validation, Visualization, Writing – original draft, and Writing – review and editing.

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Appendix A

The iconic Imbak Falls, a prominent natural feature within the Imbak Canyon Conservation Area.