Unsaturated Soil Hydraulic Conductivity ($K_h$) and Soil Resistance under Different Land Uses of a Small Upstream Watershed in Mt. Banahaw de Lucban, Philippines

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Soil hydraulic conductivity influences hydrologic processes and the ability of watersheds to provide ecosystem services. Like most soil properties, however, it is highly spatially variable at different scales due to biophysical and anthropogenic factors. To quantify spatial variability, the study assessed the influence of land use/land cover (LULC) on soil hydraulic conductivity and compaction, as reflected by soil resistance in a small upstream watershed. Compaction was measured using a soil compaction tester and the unsaturated soil hydraulic conductivity ($K_h$) was estimated in the field using the inverse auger hole method. Measurements were made across six LULC: agriculture (Agri), coconut with agricultural crops (Coco + Agri), coconut with pasture (Coco + Grass), coconut with forest (Coco + Forest), reforestation area (Refo), and forest (Forest). Measurements were taken at 0–30 cm and 0–50 cm soil depths. Results showed that soil hydraulic conductivity and resistance significantly differed across LULC and soil depths. Soil resistance averages 0.83 MPa for all LULC at 0–30 cm depth, which was significantly lower ($p = 1.184e^{-04}$) than 0–50 cm depth. Coco + forest recorded the highest soil resistance (1.01 MPa at 0–30 cm and 1.82 MPa at 0–50 cm), while Coco + Agri has the lowest resistance. Pairwise comparison of means also revealed that Forest at 0–30 cm depth had significantly higher ($p < 0.01$) $K_h$ at 1.18 cm min$^{-1}$ compared with other LULC across depths. $K_h$ at 0–30 cm depth averages 0.57 cm min$^{-1}$ for all LULC, which is significantly higher ($p = 3.229e^{-02}$) than 0–50 cm depth. This indicated a decreasing hydraulic conductivity with increasing soil depth. This implies that strategies for promoting groundwater recharge and sustaining freshwater supply for lowland communities, in general, should be founded on LULC decisions, especially in upstream watersheds.

Keywords: hydrologic behavior, percolation, soil strength, subwatershed

INTRODUCTION

Conflicts on demands for ecosystem services can lead to land use conversion and prominence of unsustainable land management systems. These pressures push the capacity of many watersheds to support production and maintain ecosystem services. In many watersheds in the Philippines, modification in LULC and soil disturbance brought about by the land management system has been resonating changes to the hydrologic functions of the system. For instance, Mt. Banahaw–San Cristobal Protected Landscape (MBSCPL), a protected area that provides vital ecosystem services to adjoining...
communities, has experienced similar problems as agriculture expanded hillslopes of the landscape for many decades. Mt. Banahaw de Lucban (MBDL) is one of its peaks characterized by distinguishable mountain landform/landscape. It was only in the 1990s that the upland farmers in this area were convinced to vacate their land to give way to rehabilitation and protection for water supply.

Furthermore, many critical watersheds in the country are already degraded reducing their ability to provide surface water suitable for many uses. Over the last decades, accelerated soil erosion occurred in these areas causing deterioration in water quality. In fact, it was estimated that about 90% of the proclaimed watershed are hydrologically critical, degraded, and have become risks to downstream infrastructure (ERDB 2013).

In many LULC studies in a watershed, the role of forest soil and its influence on the ability of watersheds to provide ecosystem services were not discussed in detail. For instance, soil hydraulic conductivity has a key role in environmental and water regime protection (Stibinger 2014) as it can control infiltration rates and the migration of pollutants from contaminated sites to groundwater (Yazdanpanah et al. 2016). Yet very few researchers account for this attribute when they assess LULC. Soil hydraulic conductivity, which pertains to the ability of the soil to conduct water either when all pores are full of water (saturated hydraulic conductivity) or not (unsaturated hydraulic conductivity), has a huge influence on groundwater recharge.

Estimation of soil hydraulic conductivity and other soil properties, however, over a large spatial scale can be challenging and higher accuracy of estimates entails high cost and extensive sampling (Worsham et al. 2012). While saturated hydraulic conductivity can be considered among the most important soil properties that determine water flow behavior in terrestrial ecosystems, it is difficult to predict due to multiple interactions between and among anthropological and geomorphic processes (Hao et al. 2019). Soil hydraulic conductivity can also vary spatially with other soil properties such as soil texture, bulk density, and organic carbon content in given land use (Jarvis et al. 2013). In watersheds, human activities such as fertilizer application (Yazdanpanah et al. 2016) and tillage (Schwen et al. 2014) affect soil hydraulic conductivity. Therefore, assessing hydraulic conductivity at the micro-catchment scale can improve assessment as this scale promotes homogeneity.

This study assessed the influence of land cover and land management system on soil hydraulic conductivity at a micro-catchment scale as an input in the overall evaluation of the change in hydrologic function of the watershed due to LULC change. Specifically, it aimed to 1) measure soil resistance, 2) field estimate unsaturated hydraulic conductivity, and 3) describe their relationship under different LULC. The study hypothesized that soil resistance and unsaturated hydraulic conductivity vary among LULC owing to the differences in land use management practices that can influence soil properties. The study also hypothesized that there is a relationship between soil resistance and unsaturated hydraulic conductivity, given the nature of these two physical properties.

MATERIALS AND METHODS

Study Site
The study was conducted in Pagsipi Catchment, a small watershed in MBDL. MBDL is part of MBSCPL that drains water to Pagsanjan-Lumban Watershed and ultimately to Laguna Lake. The Pagsipi catchment covers an area of 113 ha and is drained by the Pagsipi-Kamatian River that traverses a portion of the protected areas, down to agricultural areas, and the urban and commercial centers in the Municipality of Lucban, Quezon. It is geographically located at 121° 30' 34.92" to 121° 33' 39.66" East longitude and 14° 04' 49.68" to 14° 07' 14.17" North latitude. The town is about 133 km south of Metro Manila through Sta. Cruz, Laguna, and 154 km via Lucena City (Figure 1).

Watershed Characteristics
Pagsipi catchment is classified as a micro-catchment with an area of 113 ha and a small upstream watershed with Type II climate based on the Corona System of Classification. It receives about 3,656.7 mm of rainfall yearly, with rain almost throughout the year and no distinct dry season. The heaviest rain comes from October–December with the driest and hottest months in March and April with a mean temperature of 24.4 and 26.1 °C, respectively. November and December are the coldest with an average temperature of 22.9 and 22.3 °C, respectively.

The slope of the area ranges from flat terrain (0–8% slope) to steep slope at about 30–50% slope. It is generally suitable for planting both perennial and annual crops with soil generally classified as Luisiana sandy clay loam. The Luisiana series was classified by Carating et al. (2014) as fine clayey, acidic, deep, illitic, isohyperthermic, Orthoxic Palehumults. It is a primary soil developed from weathered products of basalt and andesite. The external drainage is rapid to excessive while internal drainage is fair. The soil has a coarse granular structure and is sticky when wet but becomes pliable when dry.
Previous studies in Mt. Banahaw de Dolores and nearby vegetation communities in the area revealed a total of 26 families and 62 species of trees that can be found in the area. The dominant plant families include Euphorbiaceae, Moraceae, Sapindaceae, Meliaceae, Rubiaceae, Lauraceae, Sapotaceae, and Rutaceae. These families are widely distributed over the area.

**LULC**

The soil hydraulic conductivity and soil compaction were evaluated across LULC. The LULC map was formulated by digitizing Google Earth image (dated 2017) using ArcGIS 10.5.1 software (ESRI). The formulated LULC map was validated during reconnaissance and further rectified during actual data collection. LULC included those that are common land use management in the area. The following LULC treatments are described below:

- **Agri** represents areas used mainly for cultivating crops except for rice. These areas have been utilized for agriculture for more than 10 yr with a planting/cropping frequency of at least two times yearly. These areas are subjected to regular cultivation and animal plowing. Agricultural areas with no standing crops during the study were selected for sampling.

- **Coco + Agri** represents areas planted to coconut with agriculture crops as intercropped. These areas, however, did not include coconut area with rice. Areas with no standing crops during the study were selected for sampling.

- **Coco + Grass** represents areas planted to coconut with grasses under its canopy. It is a common practice for large coconut plantations and agricultural areas to allocate areas for pasture purposes. These areas are not cultivated, and grasses are allowed to grow naturally. Carabao grass (*Paspalum conjugatum* P.J. Bergius) commonly dominates with associates including *kaliskis dalag* (*Desmodium triflorum* (Linn.), *makahiya* (*Mimosa pudica* (Linn.), *mutha* (*Cyperus rotundus* L.), and others. Ruminants such as horses, cows, carabaos, and goats are grazed in these areas.

- **Coco + Forest** represents areas where canopy cover is a strong mixture of coconut and forest trees. Other associated vegetation such as banana (*Musa* spp.), palms, and shrubs are also common. Cultivation in these areas may range from minimum tillage, if not lacking.

- **Refo** represents areas planted to forest trees with ages of at least 5 yr. It also includes orchards planted to fruit trees such as *lansones* (*Lansium*...
domesticum Correa), rambutan (Nepheleum lappaceum Linn.), and citrus. These areas are not cultivated.

- Forest includes primary and secondary forests that can be found within the watershed. It included forest strips in riparian buffers and vegetation communities in abandoned areas at a relatively advanced stage of succession.

Field Measurement of Unsaturated Soil Hydraulic Conductivity

Sampling sites for field measurement of soil hydraulic conductivity were selected based on the LULC of the catchment. In each LULC, two 10-cm-diameter holes with 30 and 50 cm depth were dug at least 2 m apart using a 10-cm-diameter auger. The procedure was replicated three times. It was assumed that the upper soil profile, 0–30 cm depth, was relatively exposed to agricultural practices in Pagsipi Catchment. In comparison, 0–50 cm depth was not included as plow depth since animal plowing was the main system of tillage in the area.

Unsaturated soil hydraulic conductivity ($K_h$) was determined using the inverse auger hole method described by Stibinger (2014) (Figure 2). In areas well above the groundwater table, a hole is augured and water is allowed to flow in this dry hole. The rate of lowering of the water is measured. From the changes in the depth/water level and geometry of the borehole, hydraulic conductivity is computed. Based on Darcy’s law, Stibinger (2014) suggested the formula below:

$$K = \left(\frac{L}{2}\right) \cdot \left(t_2 - t_1\right)^{-\frac{1}{2}} \left( \ln \frac{y_1 + \frac{r}{2}}{y_2 + \frac{r}{2}} \right)$$

where $K$ is soil hydraulic conductivity, $r$ is the radius of the auger hole, $y_1$ is the initial water level at time $t_1$, and $y_2$ is the water level after time $t_2$ elapsed.

Field measurement of $K_h$ was done from March 2017–April 2017. During this period, the rainy months are ending and the summer months begin. This presents an ideal condition as the soil profile is moistened during the rainy months and is near field capacity. No measurement was done during rainy days. In case of a rain event, measurement was taken a day after the event.

Field Measurement of Soil Resistance

Soil compaction was measured using the Turf-Tech Soil Compaction Tester/Dial Penetrometer. Compaction was measured in four spots within a 1-m radius of each hole established for soil hydraulic conductivity measurement.

Data Analysis

The analysis of variance for a two-factorial design was conducted using the R software (Version 3.3.2). The variation of soil hydraulic conductivity and soil compaction was assessed under LULC x soil depth.

RESULTS AND DISCUSSION

LULC Distribution

Results show that most of the area was used for planting coconut with crops as intercropped or fruit trees (Table 1). While coconut and agricultural areas were located in the middle and downstream stretch of the catchment, most forest covers are located in the upstream portion (Figure 3).

Table 1. The spatial extent of different LULC in Pagsipi Catchment.

<table>
<thead>
<tr>
<th>LULC</th>
<th>Description</th>
<th>Area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agri</td>
<td>Agricultural areas</td>
<td>47.90</td>
</tr>
<tr>
<td>Agri-Rice</td>
<td>Rice paddy</td>
<td>1.58</td>
</tr>
<tr>
<td>Built-up areas</td>
<td>Built-up areas</td>
<td>4.92</td>
</tr>
<tr>
<td>Coco + Agri</td>
<td>Coconut plantation w/ intercrop</td>
<td>13.34</td>
</tr>
<tr>
<td>Coco + Built-up</td>
<td>Built-up areas w/ patches of coconut</td>
<td>3.12</td>
</tr>
<tr>
<td>Coco + Forest</td>
<td>Coconut strongly forest</td>
<td>37.50</td>
</tr>
<tr>
<td>Forest</td>
<td>Primary and secondary forest</td>
<td>2.01</td>
</tr>
<tr>
<td>Grass</td>
<td>Grasslands</td>
<td>1.76</td>
</tr>
<tr>
<td>Refo</td>
<td>Reforestation/ tree plantation</td>
<td>0.88</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>113.01</strong></td>
</tr>
</tbody>
</table>

Figure 2. The inverse auger hole method [adopted from Stibinger (2014)].
Soil Resistance
The soil resistance to root penetration was measured to estimate soil compaction. Results showed that soil resistance significantly differs ($p = 2.960 \times 10^{-3}$) across LULC and soil depths. The average soil resistance at 0–30 cm soil depth was 0.83 MPa, while the 0–50 cm soil depth averages 1.33 MPa, indicating higher compaction at lower depths. The difference in soil resistance across depth was significant ($p = 1.184 \times 10^{-4}$). The compaction in deeper soil depths is most likely due to LULC and the effects of moisture on the eluviation of clay particles from upper horizons and its illuviation at lower horizons. This movement of colloidal particles fills up pore spaces reducing pore volume, thus increasing soil compaction.

The lowest soil resistance was observed in Coco + Agri with 0.69 and 1.08 MPa for 0–30 and 0–50 cm depths, respectively. The soil resistance in Coco + Agri at 0–30 cm depth was also significantly lower than Agri ($p = 1.112 \times 10^{-2}$) and Coco + Forest ($p = 1.909 \times 10^{-2}$) at 0–50 cm depth, which can be attributed to the cultivation practices and organic matter content of the soil. In terms of intensity, Coco + Agri was less cultivated than Agri, and crops planted under these areas vary. With considerable shading in Coco + Agri, commonly planted crops include bitter gourd (Momordica charantia Linn.), sponge guard (Luffa aegyptiaca Mill.), sayote [Sechium edule (Jacq.) Sw.], and passion fruit (Passiflora edulis Sims.). In Agri, radish (Raphanus sativus Linn.), sweet potato (Ipomoea batatas (L.) Lam.), tomato (Solanum lycopersicum L.), and string beans (Vigna sesquipedalis (L.) Fruwirth) are commonly planted coupled with frequent plowing and crop harvesting with large ruminants. As a result, soil compaction develops at deeper 0–50 cm soil depth. A compacted soil plow pan layer was also detected at 20–25 cm depth in some agricultural areas. Soil plow pan layer may have developed in these areas due to frequent plowing with large ruminants and illuviation of clay particles. The plow pan layer can develop at a depth ranging from 10 cm to greater than 20 cm due to field management practices (Qin et al. 2018; Ebato 2020), including regular soil leveling and conventional tillage operations.

Unlike Coco + Agri, Coco + Forest was not cultivated but it still recorded high soil resistance, although it has more forest litter and presumably more organic matter contributing to better soil aggregation and higher porosity. Rubinić and Husnjak (2016) reported that the deeper portion of the soil can have increased clay content (Bt horizon), higher bulk density, fewer pores, and lower capacity for air due to eluviation of clay and humus. In the case of Coco + Forest, humus from decomposed forest litter and clay may have been eluviated in deeper horizon changing its soil compaction level. The soil compaction of Forest, which was expected to have the highest soil organic matter, was not significantly different from Coco...
+ Forest with depths.

Coco + Forest had the highest soil resistance at 0–30 and 0–50 cm depths at 1.01 and 1.82 MPa, respectively. These high soil resistances, however, were not significantly different than other LULC at the same soil depth. Teferi et al. (2016) reported that LULC and altitude can influence soil bulk density or compactness. The increase in soil compaction in the soil can be attributed to soil moisture content (SMC) (da Silva et al. 2016). However, although Coco + Forest was among LULC with high SMC, the differences were not significant indicating that there may be other factors that affected soil compaction.

The soil resistance at 0–50 cm depth was also higher than its counterpart at 0–30 cm depth regardless of LULC. Coco + Forest exhibited the greatest increase in soil resistance at 80.20% from upper 0–30 cm to 0–50 cm depth (Table 2). The observed high soil resistance in Coco + Forest indicates that soil resistance can increase naturally without human or animal involvement (Batay 2009). Natural soil compaction can occur through the settling of soil (Kozlowski 1999) or due to inherent soil physical, chemical, and mineralogical properties and influenced the physical and morphological properties between horizons (Fabiola et al. 2003).

Results also showed that LULC can influence soil resistance and compaction. In intensive land management systems like agriculture, high mechanical load, less crop diversification, intensive grazing, and irrigation methods can be more crucial in causing soil compaction (Shah et al. 2017). Owuor et al. (2018) also reported significantly lower bulk densities in native forest and forest plantation topsoil (0–5 cm) than from croplands, tea plantations, and pastures. Aside from increased external load from farm machinery and ruminants, a combined increase in load and soil water can amplify soil compaction (Hamza et al. 2011). In areas receiving a high amount of rainfall such as MBDL, the combined increases in soil water attributed to precipitation and external load can increase soil resistance and compaction.

### Unsaturated Soil Hydraulic Conductivity ($K_h$)

Unsaturated hydraulic conductivity significantly differs ($p = 3.83e^{-07}$) across LULC and soil depths. $K_h$ was higher in the upper 0–30 cm depths with 0.57 cm min$^{-1}$ compared to 0.28 cm min$^{-1}$, indicating higher $K_h$ at the upper soil horizon. The difference in $K_h$ at 0–30 and 0–50 cm depths was significantly different ($p = 3.229e^{-02}$). This indicates that soil characteristics could vary with depths in Pagsipi Catchment. In a native forest, for instance, the topmost portion of the soil could have significantly lower bulk densities, higher soil infiltration rates, higher organic carbon contents, and higher plant available water capacity (Owuor et al. 2018) due to high biological activity and lesser soil modification from human activities. These increased human activities in the topmost soil can considerably change its soil hydraulic conductivity. Agricultural practices, including water regime and soil management, naturally influence soil hydraulic properties in an area. Soil cultivation increases aeration and improves infiltration. Because of these, the observed hydraulic conductivity can increase from natural forest to plantation agriculture to croplands (Olorunfemi and Fasimrin 2017).

The highest $K_h$ was recorded under Forest at 0–30 cm depth with an average of 1.18 cm min$^{-1}$ (significant at $\alpha = 0.01$). It was significantly higher than any other LULC regardless of soil depth by at least two folds higher (Table 3). Forest was followed by Coco + Forest with 0.57 cm min$^{-1}$, although this was not significantly different compared to the rest of the other LULC. The occurrence of high $K_h$ in the Forest could be attributed to the active supply of dead organic material incorporated into the organic horizon and the role of roots in the biological process such as increased organic matter, bioturbation, and mycorrhizal fungi network that can increase soil hydraulic conductivity (Archer et al. 2013). Older forest vegetation tends to have higher soil hydraulic conductivity than younger vegetation communities as it has better macroporosity, pore structure, macropore connectivity, and organic matter content (Archer et al. 2016).

### Table 2. Mean soil compaction (MPa) under different LULC.

<table>
<thead>
<tr>
<th>LULC</th>
<th>Soil depth (cm)</th>
<th>Difference</th>
<th>% change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–30</td>
<td>0–50</td>
<td></td>
</tr>
<tr>
<td>Agri</td>
<td>0.96$^{ab}$</td>
<td>1.55$^b$</td>
<td>0.59</td>
</tr>
<tr>
<td>Coco + Agri</td>
<td>0.69$^a$</td>
<td>1.08$^{ab}$</td>
<td>0.39</td>
</tr>
<tr>
<td>Coco + Grass</td>
<td>0.93$^{ab}$</td>
<td>1.22$^b$</td>
<td>0.29</td>
</tr>
<tr>
<td>Coco + Forest</td>
<td>1.01$^a$</td>
<td>1.82$^b$</td>
<td>0.81</td>
</tr>
<tr>
<td>Refo</td>
<td>0.96$^{ab}$</td>
<td>1.49$^{ab}$</td>
<td>0.53</td>
</tr>
<tr>
<td>Forest</td>
<td>0.86$^a$</td>
<td>1.29$^{ab}$</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Mean with different lower-case letters are significantly different at $\alpha = 0.05$ based on Tukey’s HSD test.
Table 3. Mean soil hydraulic conductivity (cm min \(^{-1}\)) under different LULC.

<table>
<thead>
<tr>
<th>LULC</th>
<th>Soil depth (cm)</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–30</td>
<td>0–50</td>
</tr>
<tr>
<td>Agriculture</td>
<td>0.27a</td>
<td>0.58a</td>
</tr>
<tr>
<td>Coco + Agri</td>
<td>0.39a</td>
<td>0.25a</td>
</tr>
<tr>
<td>Coco + Grass</td>
<td>0.34a</td>
<td>0.18a</td>
</tr>
<tr>
<td>Coco + Forest</td>
<td>0.57a</td>
<td>0.32a</td>
</tr>
<tr>
<td>Refo</td>
<td>0.39a</td>
<td>0.20a</td>
</tr>
<tr>
<td>Forest</td>
<td>1.18b</td>
<td>0.27a</td>
</tr>
</tbody>
</table>

Mean with different lower-case letters in each column are significantly different at \(\alpha = 0\) based on Tukey’s HSD test.

The lowest \(K_h\) was observed in Coco + Grass with only 0.18 cm min \(^{-1}\), although it was not significantly different than any other LULC except Forest at 0–30 cm depth. Grazing animals may have trampled the upper soil horizon that can reduce soil hydraulic conductivity (Archer et al. 2013). It was also observed that there was an initially highly compacted layer at depth of 3–5 cm in some Coco + Grass areas, which may have influenced \(K_h\). Except in Agri where \(K_h\) doubled, it generally appeared that \(K_h\) decreases with depth. At depths of 0–50 cm, the \(K_h\) under Forest cover also significantly dropped. Soil hydraulic conductivity decreases with horizon due to clay content and total porosity (Schwen et al. 2014).

Soil Compaction and Hydraulic Conductivity Relation

Results generally show that \(K_h\) decreases with increasing depth, while soil resistance increases with soil depth. This may be attributed to vegetation activity (Song et al. 2017) and soil bulk density as influenced by tillage (Kool et al. 2019). Likewise, both soil hydraulic conductivity and soil compaction differ significantly across LULC and soil depths. Since soil hydraulic conductivity is inversely related to soil compactness, it appears that there exists a correlation between the two soil parameters. However, there was a weak \((r^2 = 0.014, p = 0.956)\) correlation between these two. This is indicative that there may be other soil properties that influence soil hydraulic conductivity.

Soil properties associated with the porosity and bulk density (Eck et al. 2016; Karahan and Erşahin 2016; Jarvis et al. 2013) were among the most common contributor to the patterns of soil hydraulic conductivity. Soil pore spaces influence the movement of the water along the soil profile such that the increase in the volume of pore spaces favors the movement of air and water resulting in increased hydraulic conductivity. Other important factors identified in the literature include soil structure class, stickiness, root size, organic carbon content, and clay soil content.

As forest can increase microporosity, soil water infiltration, carbon storage (Lopes et al. 2020) improve bulk density, total porosity (Ajibola et al. 2018), and macro water-stable aggregates (Hao et al. 2019), it can promote good soil hydraulic conductivity. In our study, \(K_h\) of Forest at 0–30 cm depth was found at least two-fold higher than any other LULC regardless of soil depth. In a similar study, Hao et al. (2019) reported that soil hydraulic conductivity differed with vegetation type and soil depth, highlighting that the impact of vegetation type on saturated soil hydraulic conductivity was dependent on soil depth. Forest and other vegetation enhance soil aggregation with the organic matter provided by forest litters and activities of microorganisms. Higher microbial respiration and mineralization quotient can result in higher levels of water-stable aggregates and more macro-pore fraction, leading to greater hydraulic conductivity (Yazdanpanah et al. 2016). Furthermore, the roots of trees and other vegetation can also enhance hydraulic conductivity by creating channels for soil water movement, physical aggregation of soil, and influencing soil moisture deficits.

Converting native forests and changing LULC can, therefore, affect soil hydraulic properties. Forest restoration benefits soil hydraulic properties, although simply planting may not be sufficient to restore hydrologic functions (Ghimire et al. 2013) and improvement in soil hydraulic properties can be dependent on duration and intensity of land use (Lozano-Baez et al. 2019) and time since land abandonment (Leite et al. 2018) before forest restoration. Changing LULC can also impact water resources (Owuor et al. 2018) as it influences soil hydraulic properties and water balance in the area. This is more crucial for critical watersheds providing water supply for lowland communities. LULC in recharge areas including its small upstream catchments should promote infiltration, hydraulic conductivity, and percolation to replenish groundwater and ensure a sustainable supply of freshwater downstream.

CONCLUSION

The study measured soil resistance and \(K_h\) across LULC and depths of 0–30 and 0–50 cm. As hypothesized, results showed that \(K_h\) and soil resistance significantly differ across LULC and soil depths. Soil resistance also varies with specific LULC, being highest in Coco + Forest and lowest in Coco + Agri, thus reflecting the effects of cultivation. The highest \(K_h\) was recorded in the upper soil horizon of the Forest. While \(K_h\) decreased with soil depth, the soil becomes more compacted with increasing depth. Unlike the third hypothesis that soil resistance is related
to $K_h$, however, the analysis revealed a weak correlation between these two soil properties.

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