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Field evaluation of a simple infiltration test and its relationship with soil physical properties of three different types of land uses

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ABSTRACT

Infiltration capacity is an important variable for understanding and predicting a range of soil processes. A study was conducted to assess infiltration rates across three distinct land types: forested areas, grasslands, and construction zones. The infiltration rate of the soil was assessed utilizing a mini disk infiltrometer, with a subsequent analysis of soil physical properties to establish a correlation with its infiltration capacity. The infiltration rates were observed to be the highest for forestland, followed by grassland, and then construction land. The cumulative infiltration values further support this trend, indicating that forestland exhibits the highest cumulative infiltration, followed by grassland and construction land. Soil physical properties, including particle size distribution, moisture content, and organic matter content, significantly influenced infiltration rates. Soil compaction, characterized by a higher dry bulk density, was associated with reduced infiltration capacity, particularly in construction land. Conversely, higher moisture and organic matter content enhanced infiltration rates. These findings underscore the importance of considering soil properties, land use, and vegetation cover when managing landscapes to mitigate soil erosion and preserve water quality. Understanding the intricate relationship between these factors is crucial for sustainable land use practices and environmental conservation.

Keywords: infiltration rate; soil physical properties; sustainable land use; soil erosion

1. INTRODUCTION

The ability of soil to allow water flow into and through the soil profile is referred to as soil infiltration. The infiltration process is a crucial aspect of soil systems in maintaining the stability of the surrounding environment. Soil infiltration is also important in the runoff generation process. Runoff is generally produced when rainfall exceeds the soil's infiltration capacity. This process plays a definitive role in maintaining soil system functions in the water cycle, namely as a source of groundwater and aquifer water (Saravanan et al., 2019). In addition, soil hydraulic properties control the water retention, rate of water flow, and the fate of nutrients, chemicals, and pollutants in soil, and determine the accessibility of plants for water uptake, crop growth, and environmental quality (Basche and DeLonge, 2019; Fashi et al., 2016). Therefore, it is crucial to understand this complex and very important process.

Soil infiltration is a complex multi-factor process. It consists of a large number of interconnected partial processes localized within the area of study. Soil structure is one of the important factors in determining the infiltration capacity of the soil. Different soil types typically have different infiltration capacities. The texture of the soil creates diverse soil porosity. The presence of macropores can greatly enhance the infiltration capacities of soil. Generally, the more open the macrostructure, the higher the infiltration rate (Cleophas et al., 2017). Soil texture can be altered by external forces such as soil compaction, which can reduce soil volume. Soil compaction increases bulk density and soil strength, and reduces soil porosity and soil hydraulic properties (Anlauf and Rehrmann, 2012). Soil compaction presses soil particles together and drastically reduces soil porosity, hence decreasing saturated hydraulic conductivity, air permeability, and infiltration rate (Gregory et al., 2006; Zemke et al., 2019). The critical values for soil compaction can restrict plant root growth and it varies by soil type. With a higher the density value, there will be an increase in soil compactness and restricted plant root growth, hence, a lower infiltration rate. Furthermore, soil moisture content or the state of antecedent wetness of the soil greatly influences the infiltration rate as the amount of water that is already present in the soil affects the infiltration capacity (Liu et al., 2019).

As infiltration is related to soil structure, any practice that degrades the structure of the soil will have an adverse effect on infiltration. Land use treatment can degrade soil quality by altering soil properties chemically, physiologically, and physically depending on the transformation type and intensity of treatment, and can further influence the soil's hydraulic conductivity (Horel et al., 2015). Land use change causes degradation in the quality of soil properties and catastrophizes infiltration. Several studies have found that changing land cover reduces soil infiltration rates when compared to forest-covered land. It has been reported that land use change from forest to cultivated or grazed land may reduce the infiltration rate from 55% to 91% (Yimer et al., 2008; Neris et al., 2012). Despite numerous studies, estimating the rate of infiltration in different sites is still fraught with uncertainty. The actual infiltration rates achieved onsite may be influenced by a combination of different factors. Therefore, this study was conducted to investigate the infiltration rate on different types of land uses and to examine the influence of soil physical properties on the infiltration capacity.

2. MATERIALS AND METHODS

2.1 Study site background

The study was conducted in the vicinity of the campus area of Universiti Malaysia Sabah on three different land uses. The local climate of the study area is humid, with hot and humid weather all year. The annual rainfall is approximately 2,100 mm, with an average temperature of 27.6 °C. Three sampling stations with different types of land use cover were selected at the study site. Figure 1 shows the location of the study site. Site 1 was forestland with dense with trees (6.041°N, 116.114°E), Site 2 was a grassland area (6.031°N, 116.121°E), and Site 3 was construction land (6.047°N, 116.13°E) that had ongoing construction activity during this study.

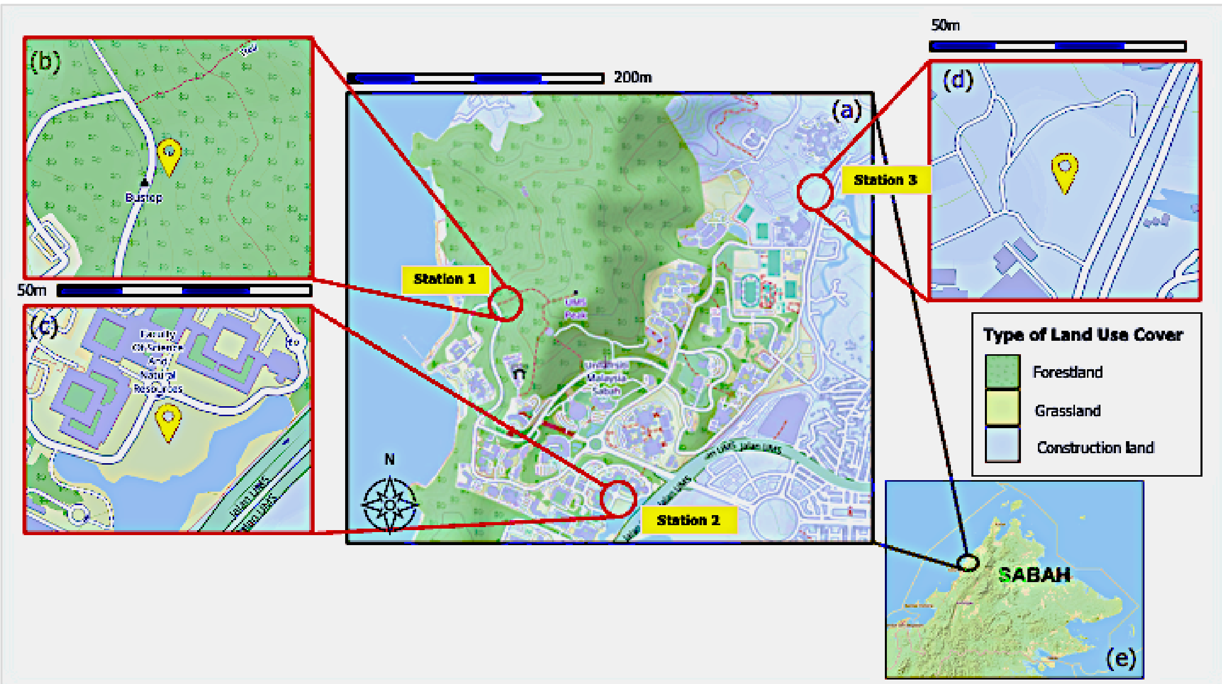

Figure 1. Location of the study area; (a) map of the campus area, (b) forestland, (c) grassland, (d) construction land, and (e) map of Sabah, Malaysia

The soils in the study area are predominantly derived from sandstone, mudstone, and alluvium (European Soil Data Centre, 1974). At each sampling site, nine sub-sample sites were randomly selected representing the land use type for forestland, grassland, and construction land. Forestland represents a section of land covered with trees and understorey vegetation in the vicinity of the study area. The grassland site is an area in which the vegetation is dominated by a nearly continuous cover of grasses, whereas the construction site consisted of bare land with a construction road.

2.2 Soil sampling and analysis

The materials utilized in this study encompassed a systematic collection of soil samples in triplicates from each study site. The physical properties of these collected soil samples were thoroughly analyzed using various techniques. Hydrometer analysis, as outlined by Gavlak et al. (2005), was employed to determine the particle size distribution in the soil samples. The classification of soil texture classes followed the USDA system and was based on a particle size distribution, as specified by Yolcubal et al. (2004). Soil moisture content was determined using an oven drying method in accordance with ASTM standards (2019), while the soil organic matter content was assessed using a loss-on-ignition method following Ball's approach (1964). Estimation of soil bulk density involved dividing the weight of dry soil by a sample volume, following the methodology presented by Rai et al. (2017). The determined soil physical properties, including particle size distribution, soil texture, moisture content, organic matter content, and soil bulk density, were thoroughly examined to establish their relationship with land use types at each study site. Additionally, water infiltration rates were determined at each site, considering the soil physical properties obtained from the analysis. The study measured both steady-state infiltration rates and cumulative infiltration using a mini disk infiltrometer under natural field conditions, employing the method proposed by Zhang (1997).

2.3 Data analysis

Statistical analysis was performed to determine the significant difference between the sampling site and the relationship between infiltration rates and other variables. A one-way analysis of variance (ANOVA) test was used to determine statistical difference between land use types and infiltration. A t-test pairwise analysis was then used to determine the statistical significance of differences between separated land use types of forestland, grassland, and construction land. The paired two-sample means t-test was used to investigate the effect of land use on infiltration and the effect of land use on the physical properties of the soils. The differences between the soils' physical properties and infiltration were also calculated using the paired two samples for means t-test.

3. RESULTS AND DISCUSSION

3.1 Particle size distribution

The percentage of soil particle size distribution of forestland (67.60% sand, 25.20% silt, and 7.2% clay), grassland (79.60% sand, 15.20% silt and 5.20% clay), and construction land (63.60% sand, 27.20% silt and 9.20% clay) are shown in Table 1. The results showed that forestland and construction land had similar proportions of sand, silt, and clay, while grassland had a higher sand content but lower silt and clay contents. Based on the results of this study, there were not many distinctions between the sand, silt, and clay ratio between the three land uses. The ratio of sand was the largest, and clay was the smallest. Grassland has roughly 12% and 16% more sand content to forestland and construction land, but 10% and 12% less silt content and, 2% and 4% less clay content compared to forestland and construction land, respectively. Soil textures for forestland and construction land were also the same, which was sandy loam, whereas grassland was loamy sand. Sandy loam was the soil texture for both forestland and construction land as the distribution was almost the same after measuring using the aid of a soil texture triangle (Groenendyk et al., 2015).

Table 1. Soil texture, soil particle size distribution, dry bulk density, moisture content, organic matter content, and soil textures in relation to land use types

Variables	**Forestland**		**Grassland**		**Construction land**	
soil texture	sandy loam		loamy sand		sandy loam	
sand (%)	67.60		79.60		63.60	
silt (%)	25.20		15.20		27.20	
clay (%)	7.20		5.20		9.20	
	mean ± SE	SD	mean ± SE	SD	mean ± SE	SD
DBD (g/cm^3)	0.89 ± 0.07	0.13	0.83 ± 0.05	0.09	1.04 ± 0.12	0.22
MC	19.02 ± 0.92	1.59	18.27 ± 1.14	1.97	7.58 ± 0.69	1.19
OMC	5.22 ± 0.72	1.25	4.76 ± 0.22	0.38	2.19 ± 0.14	0.25
n	9		9		9	

Note: DBD= dry bulk density; MC = moisture content; OMC = organic matter content.

The mean dry bulk density (DBD) of forestland, grassland, and construction land were 0.89 g/cm^3, 0.83 g/cm^3, and 1.04 g/cm^3, respectively. DBD ranged from 0.75–1.0 g/cm^3 in forestland, 0.176–0.93 g/cm^3 in grassland, and 0.83–1.26 g/cm^3 in construction land. The pairwise t-tests revealed there were no differences between forestland and grassland ($p > 0.05$) or forestland and construction land ($p > 0.05$), but there was a statistical significant difference between grassland and construction land ($p < 0.05$).

The mean moisture contents of forestland, grassland, and construction land were 19.02%, 18.27%, and 7.58%, respectively. The moisture contents in forestland and grassland were 11.06% and 10.33% higher than in the construction land. There was not significant difference between forestland and grassland, according to pairwise t-tests ($p > 0.05$). The spatial variability of soil moisture content is greatly influenced by climate conditions, topographic elements, land use practices, vegetation, and soil properties.

The means of organic matter content of forestland, grassland, and construction land were 5.22%, 4.76%, and 2.19% respectively. Pairwise t-tests indicated that there was no significant difference in organic matter content between forestland and grassland ($p > 0.05$). Conversely, significant disparities were observed between forestland and construction land ($p < 0.05$) as well as between grassland and construction land ($p < 0.05$), highlighting substantial distinctions in these cases.

3.2 Infiltration rate

Results show that forestland had the highest infiltration capacity compared to grassland and construction land. Figure 2 shows the differences in the infiltration between forestland, grassland, and construction land with the forestland having the highest infiltration capacity compared to grassland and construction land. The mean cumulative infiltration values for forestland, grassland, and construction land were 30.62 mm/s, 25.40 mm/s, and 16.13 mm/s.

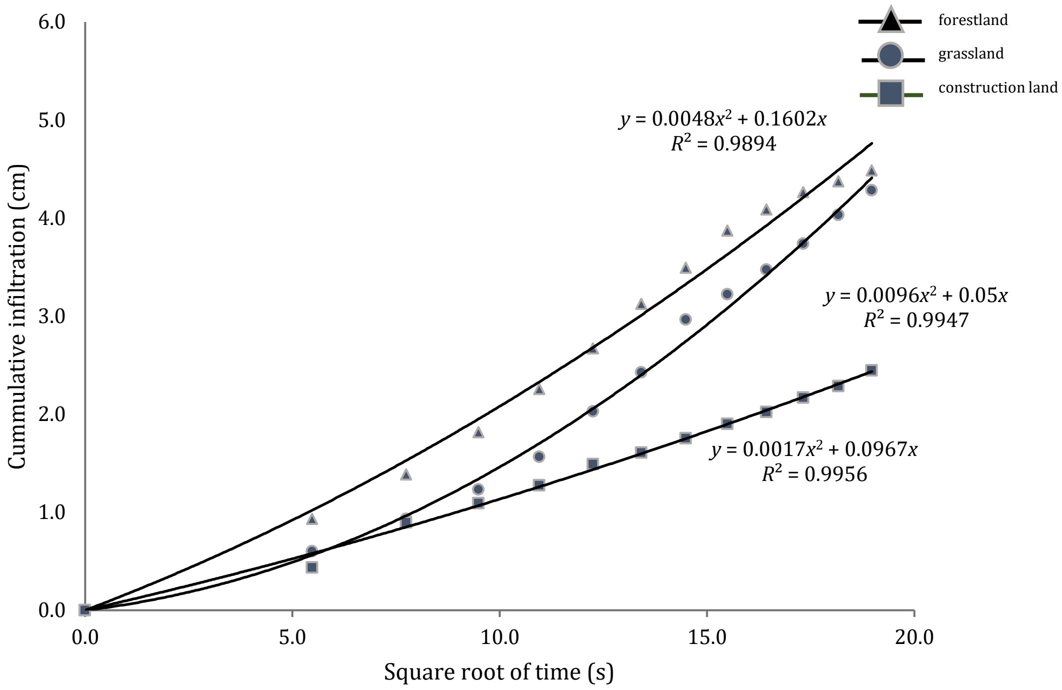

Figure 2. Cumulative infiltration versus the square root of time graph per land use type

The results of ANOVA showed a significant difference in cumulative infiltration rate between the land use type, where the value of F ($df = [2, 36]$, $p < 0.05$) was equal to 3.88. The time of measurement influences the cumulative infiltration as the longer the measurement time, the greater the cumulative infiltration (Panahi et al., 2021). The difference in cumulative infiltration in each land use may be influenced by soil surface covers. Construction land was bare land while the measurements were taken. Construction land had the lowest cumulative infiltration due to the lack of surface covers. This exaggerates the direct impact of rainfall or irrigation onto the ground surface, causing the finer soil particles to be pushed into the surface pores, resulting in the formation of a surface crust (Ibeje et al., 2018).

The mean infiltration rate in construction land was almost half of the forestland rate and the grassland rate at 0.068 mm/s ± 0.039, 0.125 mm/s ± 0.073, and 0.119 mm/s ± 0.119, respectively (Figure 3). This suggests that vegetation cover may have an impact on soil infiltration rates.

According to the one-way ANOVA test, the difference in infiltration rates between the land uses was significant, where F ($df = [2, 33]$, $p < 0.05$) equals 4.14. This result suggests that the lesser the surface vegetation cover, the lower the steady-state infiltration rate. Of all the land types, grassland had a higher infiltration than construction land initially, but its steady-state approaches that of the crusted soil because of a developing crust. Soil crusts can delay the onset of infiltration and reduce the total amount of infiltration (Bu et al., 2014). Also, forestland had a higher rate than construction land partially because of the dense trees and shrubs in forestland areas, which protect the soil from crusting (Danáčová et al., 2017).

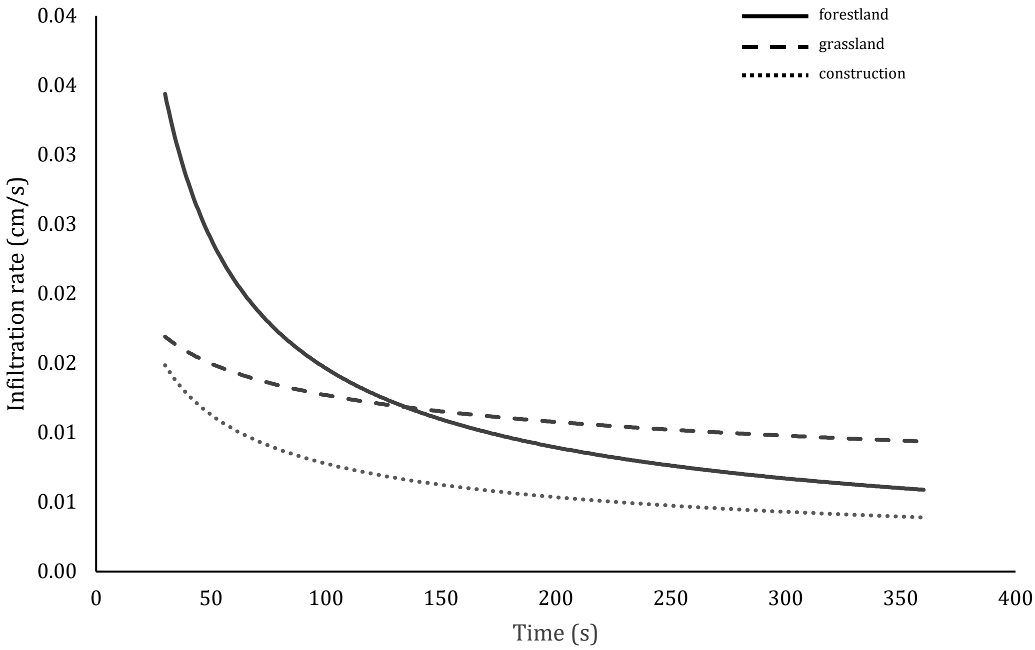

Figure 3. Infiltration rate of the different land uses

According to this study there were slight dissimilarities in cumulative infiltration and infiltration rates between forestland and grassland. The infiltration rate of grassland was about 4.8% lower than forestland. Meanwhile, the infiltration rate in the construction land was 54.4% lower compared to the forestland. Therefore, alternatives should be considered if there will be future land changes in this area to avoid the impact of soil erosion on water quality. The infiltration capacity decreasing would be a major contributor to overland flow and surface runoff generation (Maier and van Meerveld, 2021).

3.3 Effect of soil properties on infiltration

In general, the infiltration process cannot be discussed without considering other related factors. Many studies emphasize the significance of soil physical properties in infiltration (dos Santos et al., 2018; Cleophas et al., 2022). In essence, it directly improves or degrades soil infiltration capacity. In this study, forestland and construction land have the same soil texture, but the infiltration rate results notably flaunted that forestland has higher infiltration capabilities compared to construction land. Although forestland and grassland do not have the same soil texture, both have almost similar infiltration capacities with only 5% difference (Figure 3). Although the relationship between soil texture and infiltration rate has been extensively studied, the relationship in this study did not show significant results because this study was conducted on a small-scale plot in the study area; therefore, the variation of soil type was low. For a wide range of soils, the relationship between soil texture and infiltration rate may be more significant. Therefore, the analysis of soil texture in this study did not allow one to clearly define the relationship between soil type and infiltration rate.

The effects of vegetation on the infiltration rates have already been noted (Kirkham, 2005; Li et al., 2004; Thompson et al., 2010). This study suggests that the variability in soil characteristics associated with the occurrence of vegetation may be important. The infiltration capacities of vegetated land were higher compared to the bare land. This suggests that understanding soil infiltration may require more than just a knowledge of mean soil hydrological characteristics. Rather, the distribution of characteristics within the study area's catchment area could be significant.

The DBD was the highest in construction land and lowest in forestland, indicating difference in soil compactness. Figure 4 shows that construction land has the highest DBD value at the lowest infiltration rate, while forestland has the lowest DBD value at the highest infiltration rate. DBD affects infiltration, rooting depth, available water capacity, soil porosity, plant nutrient availability, and soil microorganism activity (Mukhopadhyay et al., 2019). The difference in DBD values in every land use can be indicated due to the tillage excessiveness that at the same time destroys soil organic matter and weakens the natural stability of soil aggregates. Tillage and construction equipment in construction land traveling on the soil results in compacted soil layers with increased bulk density and reduced porosity from the eroded soil particles that fill the pore space (Al-Shammary et al., 2018). As a result, when this occurs, the soil's available water capacity will also be affected.

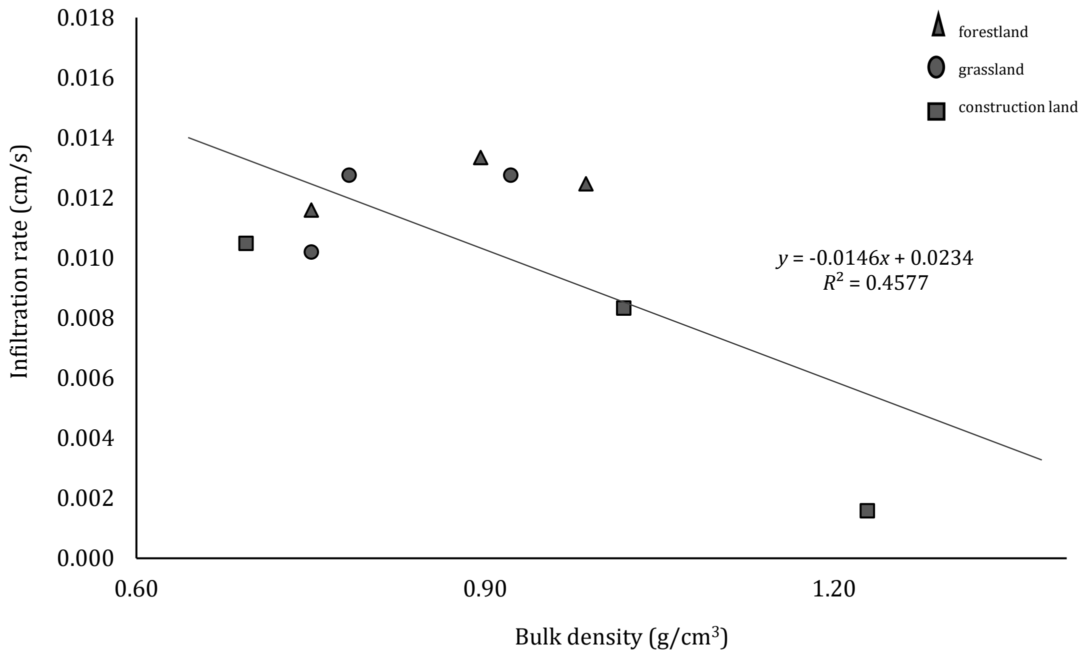

Figure 4. Relationship between dry bulk density and infiltration rate

The soil condition, particularly antecedent or initial soil moisture, is one of the primary factors influencing the initial infiltration rate (Mentges et al., 2016; Wei et al., 2022). It is known to have a substantial impact on infiltration by the moisture distribution in the soil profile (Li et al., 2011). The moisture content of the soil indicates the ability of the soil to infiltrate water. Basically, for initially wetted soil, infiltration reduces remarkably compared to initially dry soil. The infiltration test in this study was carried out in unsaturated layers of soil that already had some moisture content distribution. Moisture content was highest in forestland (19.02%) and grassland (18.27%) compared to construction land (7.94%), suggesting that vegetation cover plays a role in soil moisture retention. The moisture content of the soil showed that at the lowermost infiltration rate in construction land was seen with a low percent moisture, while for the utmost infiltration rate, in forestland, it was seen with a high percentage of moisture. The correlation between soil moisture content and infiltration rate was statistically significant ($p < 0.05$). The positive linear trend line indicates that the infiltration rate will increase with an increase in soil moisture content (Figure 5).

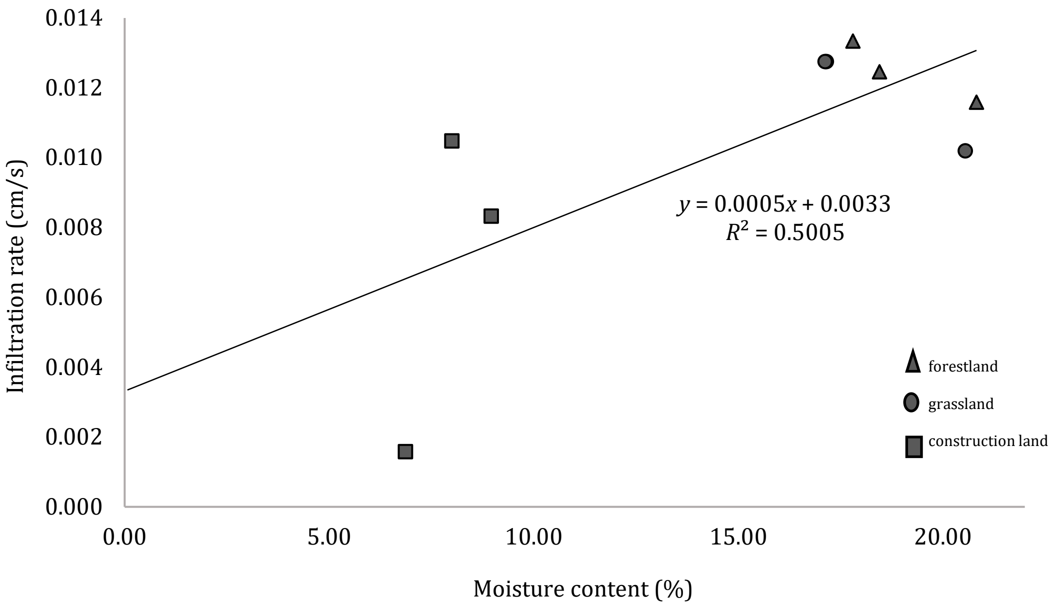

Figure 5. Relationship between soil moisture content and infiltration rate

The organic matter content of the soil samples showed that land use types with the lowest organic matter content, which was construction land, had the slowest infiltration rate, while forestland with the highest organic matter content had the most rapid infiltration rate. The correlation between organic matter content and infiltration rate was statistically significant (p < 0.05). Figure 6 shows the relationship between soil organic matter content and infiltration rate.

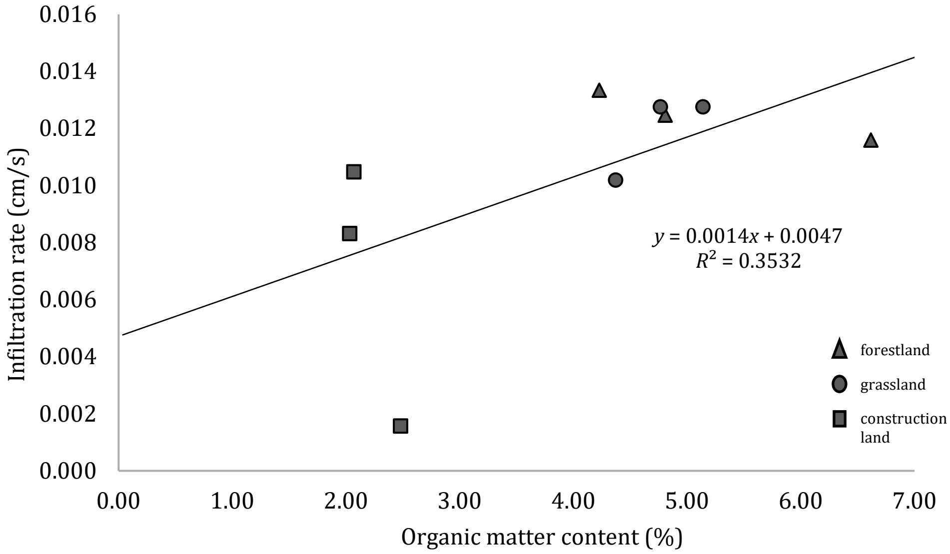

Figure 6. Relationship between soil organic matter content and infiltration rate

Similar to moisture content, an increase of organic matter content also increases the infiltration rate. The decomposition of organic matter in soil is always small, but it plays a huge role in infiltration rate due to its ability to create more macropores and a high-water holding capacity (Sanchez, 2019). It binds soil particles acting as a glue into stable aggregates, increasing porosity and infiltration. It also provides a good habitat for soil biota that enhances pore space and creates continuous pores which lead to long-term solutions for maintaining soil infiltration (dos Santos et al., 2018).

4. CONCLUSION

This study highlights the importance of soil properties and land use in determining infiltration characteristics. The infiltration capacity of soil in forestland was found to be the highest among the three land uses, followed by grassland and construction land. The cumulative infiltration and infiltration rate results demonstrated significant differences between the land uses, with forestland exhibiting the highest values. The presence of vegetation in forestland and grassland likely contributed to their higher infiltration rates compared to construction land, which lacked surface covers. Soil properties such as DBD, moisture content, and organic matter content were found to affect infiltration rates. Construction land, characterized by higher DBD and lower organic matter content, exhibited the lowest infiltration rate. Conversely, forestland, with lower DBD and higher organic matter content, had the highest infiltration rate. Soil moisture content and organic matter content showed positive correlations with infiltration rate, indicating that higher moisture and organic matter content facilitated better infiltration. Forestland, with its sandy loam soil texture, higher moisture content, and organic matter content exhibited the highest infiltration capacity, while grassland and construction land showed lower infiltration rates. These findings emphasize the role of vegetation cover, soil structure, and organic matter in maintaining soil infiltration and suggest the need for considering these factors when managing land use to mitigate soil erosion and preserve water quality.

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