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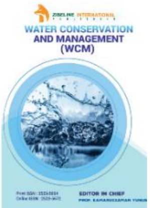

RESEARCH ARTICLE

INFILTRATION DYNAMICS AND RAINFALL CHARACTERISTICS IN HIGHLAND HORTICULTURAL SOILS OF TWIN LAKES, WEST SUMATRA

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ABSTRACT

Water management in tropical highlands always presents challenges, especially in intensive horticultural lands that experience degradation of soil structure and affect groundwater infiltration. This research method was carried out by surveying the soil with 13 location points. Through infiltration measurements at 13 points and nine-year rainfall analysis in the Twin Lakes area. The data were analyzed statistically descriptive, then looked at the relationship between soil properties and infiltration. The results of the study found that the soil infiltration capacity was much lower than expected for volcanic soils. The measured infiltration was only 0.30–4.92 cm h^{-1}, while the annual rainfall routinely exceeded 2,000 mm. From field observations and statistical analysis, soil compaction (high bulk density) and decomposition of organic matter play a major role in suppressing infiltration. A strong negative correlation between infiltration and bulk density (r = –0.78) as well as a positive correlation with porosity (+0.71) and C-organic (+0.65) confirmed this relationship. This condition creates a hydrological imbalance, especially in the peak rainy months (November–December) when the soil is often in a post-harvest open state. These findings point to the need for the immediate adoption of conservation measures such as organic mulching, minimum tillage, and vegetative barriers to restore infiltration capabilities and reduce erosion in steep-sloped horticultural areas.

KEYWORDS

infiltration, rain, dynamics, highland, horticulture, soil properties

1. INTRODUCTION

The activities of communities that are very intensive in cultivating their agricultural land in tropical highland areas, such as the Below lake area in West Sumatra, are subject to a hydrological paradox: high rainfall but limited availability of groundwater due to low infiltration (Abid and Lal, 2020). In the field survey research, low groundwater infiltration was observed. This is as stated by Lee et.al., 2022 that in field observations, runoff occurs quickly even after light rain, indicating that soil infiltration function is not optimal.

Infiltration is an important link between precipitation and other hydrological processes, including runoff, groundwater recharge, and erosion (Gao and Chen, 2021). However, in wet tropical regions, intensive cultivation practices, lack of organic inputs, and soil compaction make infiltration decrease drastically (Aryal et al., 2022 ; Hazarika et al., 2020). These conditions are reported to be similar in Southeast Asia, East Africa, and Latin America on steep slope horticultural lands (Huang et al., 2022 ; Diop et al., 2022 ; Leal et al., 2023).

Volcanic soils in the Andik region actually have high porosity and naturally strong infiltration capabilities, but the soil structure is highly susceptible to degradation when intensively cultivated (Suprayogo et al., 2020 ; González et al., 2024). Decreased infiltration causes runoff to increase, carry sediment and nutrients to rivers and lakes, and worsen water quality (Wang et al., 2023 ; Yustika et al., 2023).

However, empirical data on the relationship between infiltration and soil physical properties and rainfall dynamics in tropical volcanic horticultural land in Indonesia are still minimal (Djauhari et al., 2023). Therefore, this study aims to:

(i) analyze the spatial variation of infiltration,(ii) calculate the gap between infiltration and precipitation,(iii) identify the main controllers of infiltration, and(iv) develop data-driven conservation recommendations.

Soil infiltration is greatly influenced by soil structure and soil physical and biological properties (Aprisal et al., 2019). Furthermore, the physical properties of the soil that greatly affect infiltration are the slope of the land, texture, organic materials, land use, and soil tillage. Intensively cultivated soil will disturb the soil structure. In addition, the pores of the soil really determine how much volume of water can enter. This also includes pores made by roots and other soil fauna. The dominant factor that determines whether or not the soil is easily damaged by rainwater is the texture factor of the clay fraction, meaning that every tiller will change the soil structure and pore space (Aprisal et al., 2019).

2. MATERIALS AND METHODS

2.1 Study Area

The research area is a horticultural production center area located in

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Alahan Panjang, part of the Twin Lake area at an altitude of 1,200–1,500 m above sea level (±1°00'S, 100°45'E). The soils in this region are ordered Andisol and inceptisol, from volcanic parent material laharik, with slopes of 10–40%. Directly, this condition gives the soil a character of large porous but very sensitive to physical disturbances. Intensive tillage patterns on horticultural commodities—such as cabbage, potatoes, and carrots—accelerate the deterioration of soil structure quality, as widely reported in steep-slope horticultural systems in the tropics (Aryal et al., 2022 ; Lee et al., 2022). The local climate includes type Af (Köppen), with no pronounced dry season, with annual rainfall exceeding 2,000 mm (Ding et al., 2021).

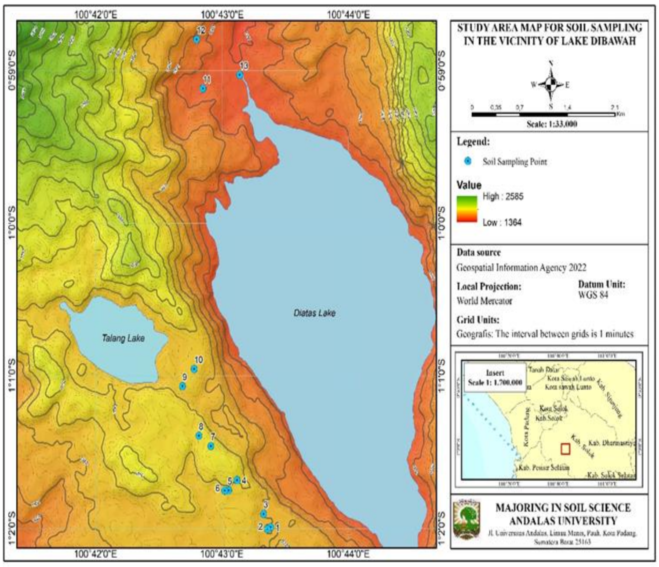

Figure 1 : Map of the research location in the twin lakes area in Alahan Panjang.

2.2 Infiltration Measurement

Infiltration measurements were made using **a double-ring infiltrometer**, following standard procedures commonly applied in tropical infiltration studies (Li et al., 2019 ; Boeno et al., 2021). This method remains the main approach despite its limitations such as *lateral flow bias* and scale influences, especially on heterogeneous volcanic soils (Zhang et al., 2020).

In this study, measurements were carried out at 13 points (K1–K13) which represented the typical variation of horticultural land. Double-rings have a diameter of 25 cm (inner) and 50 cm (outer), with an outer ring installation depth of 5–10 cm to reduce lateral flow. At a number of points, especially points with crusty surfaces, early observations showed a decrease in the rate of infiltration within the first minute—a phenomenon consistent with the report on Brazilian volcanic soils (Lozano-Baez et al., 2020).

Both rings were filled with water as high as ±10 cm, then a drop in the water level in the inner ring was recorded every 5 minutes until the infiltration rate reached a stable condition (CV <10% for three consecutive intervals). Each measurement lasts 60–120 minutes. The infiltration rate (cm h^{-1}) is calculated based on the change in water height per unit time.

To model long-term infiltration capacity, Horton's curve (Horton, 1940) is used:

[f(t)=f_c + (f_0 - f_c). e $^{(-kt)}$]

The initial parameters (f_0), (f_c), and (k) were estimated from the pattern of decreasing infiltration rate in the early minutes. Adjustments were made using non-linear regression (NLIN) in R version 4.3.0. The model evaluation used the determination coefficient (R^2) and RMSE, following the approach used by (Suprayogo et al., 2020 ; Andayono et al., 2024).

2.3 Rainfall Data

Monthly rainfall data (2014–2024) was obtained from the Twin Lakes Meteorological Station, which is located at the research site. Every year it is checked for completeness and no significant data gaps are found, so that the entire period can be analyzed (Ding et al., 2021). Statistical analysis includes averages, minimums, maximums, and inter-year variability (CV), as well as the identification of peak rainfall months that are important for the purposes of interpreting runoff risk (Gao and Chen, 2021 ; Wang et al., 2023). Furthermore, RIMI analysis was also carried out using the Rainfall method – Infiltration Mismatch Index (RIMI) is an analysis indicator developed to measure the level of imbalance between rainfall input (R) and soil infiltration capacity (I). RIMI characterizes whether the landscape segment is dominated by rainfall surplus conditions (R > I) or infiltration surplus conditions (I > R). This index is particularly useful in twin lake areas where high-intensity precipitation often exceeds soil infiltration levels. Calculating the value of the RIMI index is by the formula:

RIMIi,j = Ri,j-Ii

Were:

RIMIi,j = mismatch index for point I in tonth j

Ri,j = rainfall in month j (mm)

Ii = infilteration capacity at point i(mm)

2.4 Soil Physical Analysis

Soil samples were collected by soil survey method. Soil samples are taken at a depth of 0–20 cm. The example of land taken is an example of a representative of each land unit. The number of soil samples taken amounted to 13 sample points. Meanwhile, the infiltration rate is measured directly in the field using a double infiltrometer. Soil samples were analyzed at the Soil Physics Laboratory of Andalas University. The measured parameters include:

- Bulk density uses a 100 cm^3 ring and is dried at 105°C (Hazarika et al., 2020).
- Particle size distribution using the hydrometer method.
- Total porosity was calculated using a particle density of 2.65 g cm^{-3} (Lal, 2022).
- C-organic was analyzed using the Walkley–Black method (Aryal et al., 2022).

This approach follows tropical soil conservation standards and allows for a direct connection between the physical parameters of the soil and the rate of infiltration (Djauhari et al., 2023 ; González et al., 2024).

2.5 Statistical Analysis

Descriptive statistics (mean, SD, range) are used to describe the variations in infiltration and physical properties of the soil. The relationship between infiltration rate and soil properties was tested using Pearson correlation, with a significance level **of $p < 0.05$**, in line with approaches in previous tropical hydrological studies (Lozano-Baez et al., 2020 ; Leal et al., 2023).

The analysis was conducted through R 4.3.0 and Microsoft Excel 2021. The focus of interpretation is directed at parameters that consistently appear as the main controllers of infiltration in tropical ecosystems: bulk density, porosity, and organic matter content (Lal, 2022 ; Entz et al., 2022 ; Yustika et al., 2023).

3. RESULTS

3.1 Spatial Variability of Infiltration Rates

The results of measurements at 13 points (K1–K13) in Table 1 and Figure 2, show that the infiltration rate at all locations is in the Low class (<5 cm h^{-1}). Its value ranges from 0.30 to 4.92 cm h^{-1}, with an average of 3.54 cm h^{-1}. The variation in infiltration is quite pronounced (CV = 42%), indicating that surface conditions and soil management exert different influences between sites, as well as found in other tropical horticultural lands (Suprayogo et al., 2020 ; Lozano-Baez et al., 2020).

Point K1 is the location with the lowest infiltration (0.30 cm h^{-1}), mainly because the surface has undergone crusting and new soil cultivation. In contrast, K12 showed a relatively higher infiltration (4.92 cm h^{-1}), presumably due to the addition of organic mulch a few days before the measurement. This pattern is consistent with experimental studies in tropical horticultural systems that report that organic cover is able to increase infiltration rapidly (Hazarika et al., 2020 ; Entz et al., 2022).

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Table 1 : Nilai rerata, min, max dan SD infiltrasi di lokasi penelitian.

Point	Mean (cm h^{-1})	Min	Max	SD	Class (USDA)
K1	0.3	0.1	0.7	0.24	Low
K2	4.0	1.0	10.0	3.3	Low
K3	2.0	1.0	3.5	0.94	Low
K4	3.92	0.5	8.0	3.3	Low
K5	4.08	0.0	14.0	4.69	Low
K6	3.39	0.0	14.0	4.89	Low
K7	3.85	0.0	10.0	3.29	Low
K8	2.77	0.0	6.0	1.81	Low
K9	4.46	0.0	12.0	3.95	Low
K10	4.46	0.0	13.0	4.08	Low
K11	3.39	0.0	9.0	3.06	Low
K12	4.92	0.0	14.0	4.84	Low
K13	4.46	0.0	15.0	4.93	Low

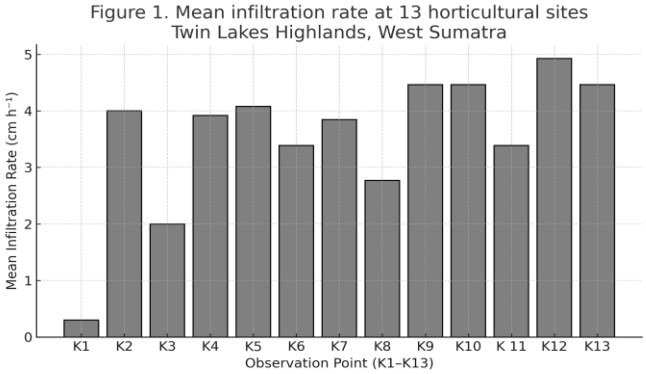

Figure 2 : Average infitration rate in the central area horticulture around the lake in Bahwah.

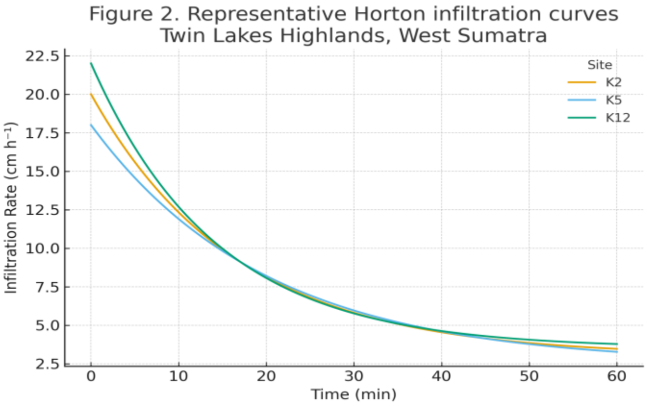

Figure 3 : Average infestation rate curve in the central area horticulture around the lake in Bahwah.

3.2 Infiltration Zonation in the Study Area

Based on the USDA classification, all points are included in the Low infiltration zone (Table 2). This shows that soil structure degradation has occurred widely on the horticultural land of Twin Lakes. Similar conditions have also been reported in intensive land in Vietnam and East Africa, where repeated tillage without recovery breaks causes infiltration to be at the lowest class (Aryal et al., 2022 ; Diop et al., 2022).

Table 2 : Infiltration rate classification zone in the twin lakes area

Zone class	Criteria (cm h^{-1})	n points	Mean (cm h^{-1})	Min	Max
Low	<5	13	3.54	0.30	4.92

A single zone of "Low infiltration" for the entire area shows that the soil's water-absorbing capacity is out of balance with the annual rainfall and the intensity of the daily rainfall that occurs regularly in the region.

3.3 Rainfall Characteristics of the Twin Lakes Highlands

Rainfall analysis in 2016–2024 shows that the Twin Lakes region receives an average rainfall of 2,069 mm per year (figure 4), with variations between years of 1,806–2,401 mm. Almost the entire month has significant rainfall, reflecting a wet tropical climate without a dry season, according to Southeast Asia's wet mountain rainfall reports (Ding et al., 2021). The most critical period is November–December, with an average rainfall of >300 mm per month. In these months, many of the land is in post-harvest conditions so that the land is open. The combination of high rainfall + uncovered soil + low infiltration creates a huge potential for runoff, a phenomenon that is also found in other humid tropical watersheds such as the Andes and the Philippines (Gao and Chen, 2021 ; Leal et al., 2023 ; Yuzanni et al., 2024). The variability between months is quite high (monthly CV 31–67%) table 4 and figure 4. This indicates that the intensity of the rain is not only large but also fluctuating. Rainfall patterns like this are particularly sensitive to infiltration degradation, as any heavy rain has the potential to directly produce runoff.

Table 3: Monthly rainfall distribution (2016–2024)

Month	Mean (mm)	Min (mm)	Max (mm)
Jan	159.4	76	261
Feb	97.6	21	183
Mar	177.6	79	265
Apr	197.4	98	284
May	208.7	72	317
Jun	176.1	91	276
Jul	111.6	46	211
Aug	114.8	28	246
Sep	125.6	1	262
Oct	177.4	49	354
Nov	315.4	83	594
Dec	207.0	14	364

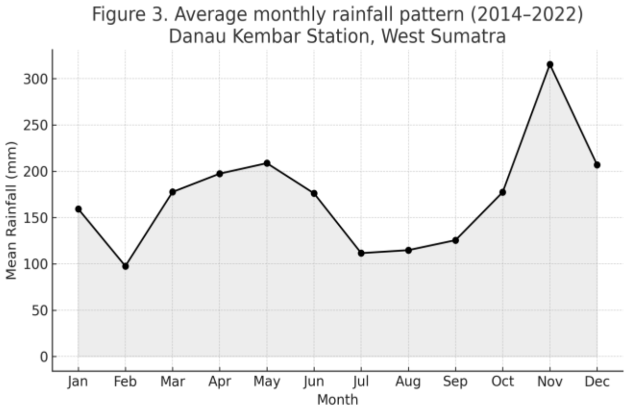

Figure 4 : Average rainfall and rainfall in the twin lake area is Twin Lake.

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3.4 Soil Physical Properties and Their Relationship with Infiltration

Table 4: Characteristics of the physical properties of the soil and its correlation with the rate of soil infiltration.

Parameter	Unit	Min	Max	Mean ± SD	Correlation with infiltration (r)
Bulk density	g cm^{-3}	0.89	1.42	1.12 ± 0.16	–0.78
Total porosity	%	45	68	56.8 ± 5.3	+0.71
Sand	%	37	59	48.3 ± 6.1	+0.18
Silt	%	22	41	27.0 ± 4.7	+0.06
Clay	%	18	31	24.7 ± 3.4	–0.21
Soil organic carbon	%	1.2	3.8	2.5 ± 0.7	+0.65

The results of the analysis of the physical properties of the soil show that:

- Bulk density 0.89–1.42 g cm^{-3} (average 1.12 g cm^{-3})
- Total porosity 45–68% (mean 56.8%)
- C-organic 1.2–3.8% (average 2.5%)
- Textures range from loam to sandy loam, typical of crumb-structured tropical volcanic soils

Pearson's correlation shows a very consistent relationship:

- Bulk infiltration density ↘ ($r = -0.78, p < 0.01$)
- Infiltration porosity ↗ ($r = +0.71, p < 0.01$)
- C-organic ↗ infiltration ($r = +0.65, p < 0.01$)
- Texture (sand, dust, clay) → insignificant ($p > 0.48$)

These findings are in line with numerous tropical studies that confirm that soil structure, not texture, is the main controller of infiltration in volcanic soils (Lal, 2022 ; Djauhari et al., 2023 ; González et al., 2024). Low organic matter worsens compaction and crusting, while high bulk density reduces macropores that serve as the main channels for water inflow.

3.5 *Rainfall–Infiltration Mismatch Index (RIMI)*

The results of the *Rainfall–Infiltration Mismatch Index* (RIMI) analysis Figure 2. show clear spatial and temporal variations between observation points and between months. At the K1 point, the RIMI value tends to be positive, especially in January, November, and December. This pattern indicates an imbalance between high rainfall and relatively low soil infiltration ability. These conditions illustrate the increased potential for surface runoff and erosion risk during the peak periods of the rainy season—a phase that should be a priority in land conservation interventions (Gupta, 2020)

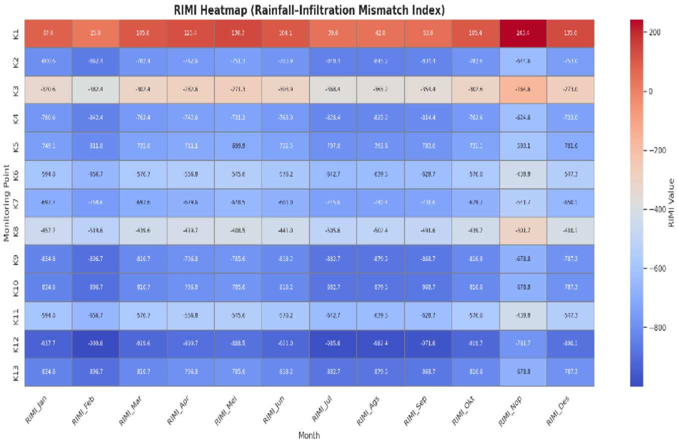

Figure 5: Heat map RIMI (Rainfall -Infiltration Mismact Index) at each infiltration rate point in the horticultural center area around the lake in Bahwah.

4. DISCUSSION

4.1 Causes and Mechanisms of Infiltration Decline

The results of the study (Table 1) showed that all observation points had a low infiltration rate (0.30–4.92 cm h^{-1}). For andik volcanic soils, this value is much lower than the ideal character of similar soils in the tropics (Suprayogo et al., 2020). From field observations, the decrease in infiltration is mainly controlled by soil compaction, lack of organic matter, and surface crust formation, as widely reported in horticultural systems in tropical humid environments (Aryal et al., 2022 ; Lee et al., 2022 ; Lozano-Baez et al., 2020).

Soil compaction was the most dominant factor, as seen from a very strong negative correlation between infiltration and bulk density ($r = -0.78$). Competation generally occurs due to repeated tillage and small mechanical tools commonly used by vegetable growers, as also found in Kenya and Vietnam (Diop et al., 2022 ; Huang et al., 2022). In some locations such as K1 and K7, the bottom solid layer is evident from the difficulty of penetration and increased runoff directly during rain.

The decrease in organic matter also contributes greatly to the decrease in infiltration. The C-organic content (average 2.5%) is below the ideal range for maintaining the stability of tropical volcanic soil aggregates (Lal, 2022). Low organic matter reduces the formation of biological macropores, weakens aggregates, and accelerates scale formation. The positive relationship between infiltration and C-organic ($r = +0.65$) corroborates the key role of organic matter in restoring soil hydrological function (González et al., 2024).

Surface crusting is visible at eight points during the measurement. Smooth sand soils can form impermeable layers when exposed to high-intensity rainfall, as has also been noted in humid tropical landscapes in Brazil and Colombia (Lozano-Baez et al., 2020 ; Leal et al., 2023). Crusting slows infiltration in the early minutes and increases runoff even though soil moisture content is still low. Overall, these three mechanisms work in tandem and explain why infiltration in the Twin Lakes horticultural regions is much lower than in other tropical volcanic areas with better soil management (Suprayogo et al., 2020).

4.2 Hydrological Imbalance: Rainfall vs. Infiltration Capacity

Another important finding is the hydrological imbalance between rainfall and infiltration capacity. With a stable infiltration of about 3.54 cm h^{-1} (≈25–27 mm day^{-1}), >50 mm of daily rainfall—which occurs 15–20 times per year—immediately results in significant runoff. These conditions are similar to reports in other humid mountain ecosystems, for example in the Andean Highlands and East Africa, where similar imbalances lead to increased erosion and downstream sedimentation (Entz et al., 2022 ; Yuzanni et al., 2024).

The most critical conditions occur during the peak of November–December rainfall, when rainfall exceeds 300 mm/month (Ding et al., 2021). At the same time, farmers usually have just finished harvesting and the land is in the open. The combination of bare soil + high rainfall + low infiltration creates runoff up to >10 times more than land covered with vegetation. This is in line with patterns found in tropical soil conservation studies in East Asia and Latin America (Adimassu et al., 2021 ; Leal et al., 2023).

The main implications of this hydrological imbalance include:

- Increased erosion of steep slopes, especially on land with degraded soil structure (Huang et al., 2022).
- Loss of nutrients, both in the form of solution and suspended particles.
- Sedimentation and siltation of water bodies, which have become issues in the Twin Lakes and other tropical volcanic areas (Wang et al., 2023).
- A decrease in groundwater recharge, because most of the rain does not have time to enter the soil profile.

This situation shows that low infiltration capacity is not only an agronomic problem, but also a watershed hydrological problem.

4.3 Soil Physical Controls on Infiltration

The correlation between the physical character of the soil and infiltration suggests that **the soil structure**, not its texture, is the main controller of infiltration in this area. Texture parameters (sand, dust, clay) had a very weak correlation ($|r| < 0.21, p > 0.48$), suggesting that infiltration was not determined by texture, according to the general character of tropical

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Andisol which was influenced by structure, not mineral composition (Lal, 2022 ; Djauhari et al., 2023).

The most influential parameters are:

- Bulk density (–0.78) → denser it gets, the lower the infiltration
- Porosity (+0.71) → higher the total pore, infiltration increases
- C-organic (+0.65) → an important organic matter for macropore formation

This relationship is in line with research conducted on agroforestry and conservation agriculture systems in Southeast Asia, East Africa, and Latin America, where infiltration increased 2–4 times after organic matter enhancement and soil structure improvement (Suprayogo et al., 2020 ; González et al., 2024 ; Entz et al., 2022).

By raising C-organic from 2.5% to >3.5–4.0%, infiltration is projected to increase by 30–50%. In addition, increasing porosity through reduced tillage can improve macropore connectivity, thereby improving infiltration capacity on steep slopes. The association of infiltration with C-organic and strong porosity suggests that improvement of soil structure through the addition of organic matter and minimum tillage has the potential to significantly increase infiltration capacity, as shown in other tropical soil conservation studies (Lozano-Baez et al., 2020 ; Suprayogo et al., 2020 ; Entz et al., 2022).

4.4. Rainfall–Infiltration Mismatch Index (Humanized Version)

Several other points (K2–K13) show a considerable negative RIMI value. This negative value indicates a much higher infiltration capacity than rainfall, so the potential for water absorption into the soil is relatively good. Temporally, RIMI shows an increase in positive mismatch in the rainy season and extreme negative values in the dry season. This pattern reflects the typical hydrological dynamics of the tropics with bimodal rainfall characteristics. These findings confirm the importance of infiltration-based land management strategies, especially in locations with high positive mismatches. These approaches include increasing cover vegetation, micro-drainage arrangements, and soil conservation measures to reduce runoff and maximize groundwater replenishment. Overall, these results are an important basis for formulating recommendations for conservation and flood mitigation in the upstream area of steeply sloped watersheds in West Sumatra.

4.5 Evidence-Based Conservation Strategies

Based on infiltration data, soil properties, and rainfall patterns, the following conservation strategies can be considered the most relevant and effective:

(1) Rapid intervention (0–6 months)

- Organic mulch 5–7 tons ha^{-1} to dampen raindrop energy and retain moisture
- Vegetative barriers (vetiver, napier) at intervals of 5–10 m to break up surface flow
- Cover crop (ground cover legumes) during the break in the growing season

This approach has been shown to be effective in suppressing crusting and increasing early infiltration (Lozano-Baez et al., 2020).

(2) Intermediate intervention (6–24 months)

- Minimum tillage, reducing tillage frequency by 50%
- Retention of plant residues, instead of burning
- Regular addition of compost to improve the structure

Studies by (Suprayogo et al., 2020) and (Entz et al., 2022) show that this practice increases infiltration 1.5–3 times in 1–2 years.

(3) Long-term intervention (2–5 years)

- Conversion of 20–30% of >25° slope to permanent agroforestry
- Establishment of a community infiltration monitoring program
- Integration of infiltration indicators in regional land use policies

Similar structural interventions have been shown to reduce runoff by 30–40% in tropical watersheds in the Philippines and Vietnam (González et al., 2024).

Overall, the results of this study emphasize that improving soil structure through increasing organic matter, reducing tillage, and adding vegetation cover is the most effective strategy in restoring infiltration and reducing hydrological risks in steep horticultural areas.

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