

THE IMPACT OF CONVERTING FORESTS TO INTENSIVE AGRICULTURE ON SOIL HYDROLOGICAL FUNCTIONS IN A TROPICAL WATERSHED IN CENTRAL SULAWESI

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ABSTRACT

Aim of the study

The rapid conversion of tropical secondary forests into intensive agriculture threatens the hydrological functions of the soil. Empirical data on this issue for watersheds in Wallacea remain scarce. This study investigates the impact of changes in land use on soil hydraulic architecture and infiltration capacity in the Wimbi sub-watershed in Central Sulawesi, Indonesia. The results provide a scientific basis for regional watershed preservation.

Material and methods

Soil infiltration was measured in situ by taking stratified purposive samples ($n = 15$ per land use, total of 45 points) using a doublinging infiltrometer across secondary forest, agroforestry, and cultivated land (maize monoculture). Core physical properties, hydrodynamics, and soil organic carbon (SOC) were quantified using standardized laboratory protocols. High-resolution infiltration data were calibrated using the Horton model, which was solved via an iterative non-linear least-squares regression framework.

Results and conclusions

Converting forests to intensive agriculture significantly degrades soil hydraulic properties. Secondary forests exhibited the highest steady-state infiltration capacity ($7.74 \pm 0.45 \text{ cm} \cdot \text{h}^{-1}$), followed closely by agroforestry ($6.94 \pm 0.38 \text{ cm} \cdot \text{h}^{-1}$), with both being categorized as moderately rapid. In contrast, cultivated land showed a 50% decline to $3.87 \pm 0.21 \text{ cm} \cdot \text{h}^{-1}$ (moderate). Non-linear fitting demonstrated that the Horton model effectively captures infiltration dynamics ($R^2 \geq 0.89$). This agricultural restriction was directly associated with mechanical compaction, which increased bulk density ($1.61 \pm 0.07 \text{ g} \cdot \text{cm}^{-3}$) and depleted total porosity ($33.18 \pm 1.45\%$). The critical deficit in SOC ($0.98 \pm 0.08\%$) in cultivated land is highly indicative of accelerated surface sealing, which potentially restricts subsurface internal pore networks. Meanwhile, agroforestry sustained superior soil structural buffering through elevated SOC ($4.20 \pm 0.31\%$), mitigating matrix compaction and enhancing pore connectivity. Transitioning to tree-based farming is essential to reduce runoff and restore tropical watershed resilience.

Keywords: Horton model, land-use conversion, soil infiltration, tropical watershed, watershed management

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HIGHLIGHTS

Forest conversion markedly lowers soil infiltration in tropical watersheds.

Forest and agroforestry sustain higher infiltration rates than cultivated land.

Bulk density and porosity control the extent of infiltration decline after conversion.

The Horton model fits well ($R^2 > 0.89$).

Agroforestry enhances hydrological resilience by acting as a buffer system.

INTRODUCTION

Infiltration is one of the key processes in the hydrological cycle. It plays a crucial role in soil moisture dynamics, surface runoff, erosion, and nutrient transport under different climatic conditions (Zhu et al., 2020). Understanding soil infiltration rates, including subsurface flow, is essential for estimating both natural and artificial groundwater recharge (Thivya et al., 2025; Fariborzi et al., 2024).

Soil water dynamics are an important process as infiltration is a central focus of watershed studies, particularly in context of rainfall models, which are commonly used to simulate water movement (Naharuddin et al., 2021; Wałęga et al., 2017) across different land uses, such as agricultural land, forests, and agroforestry systems (Naharuddin et al., 2022). These dynamics influence the availability of water and nutrients for plant growth (Somaly and Sokra, 2026). Several factors affect infiltration processes, including rainfall characteristics (intensity and volume), soil physical properties (texture, structure, and degree of compaction), and agricultural management practices (conventional tillage, direct planting, or grassland systems) (Peñuela et al., 2026). Certain land preparation practices can increase soil compaction in cultivated areas, thereby reducing infiltration capacity (Geleta et al., 2025; Liang et al., 2025). Low infiltration capacity enhances surface runoff and hinders groundwater recharge (Mengistu et al., 2022). Furthermore, reduced soil cover increases the susceptibility of land surfaces to rainfall events, heightening the risk of water-induced erosion (Bahddou et al., 2023).

Among various methods for measuring infiltration, the double-ring infiltrometer remains the most widely used due to its practicality and reliability (Ban and

Shi, 2024; Vishwakarma et al., 2025). This method utilizes two concentric cylinders of different diameters an inner and an outer ring where the outer ring is designed to minimize lateral water movement from the inner cylinder (Jobbágy et al., 2023). Infiltration readings are taken at predetermined time intervals within the smaller cylinder, allowing vertical infiltration into the soil medium to be accurately assessed.

The Wimbi sub-watershed has undergone significant changes in land use, including the conversion of forests into agricultural land, mining areas, and other types of land use. Such changes have altered key environmental processes, particularly soil infiltration capacity. Infiltration rate, defined as the soil's ability to absorb water, is critical for maintaining hydrological balance and mitigating the risk of flooding and erosion. This study focuses on the impact of change in land use on soil infiltration rates in the Wimbi sub-watershed, where secondary forests, agroforestry, and cultivated land coexist. Different land use types may result in variations in soil structure, bulk density, and organic matter content, all of which influence infiltration rates.

While existing literature has extensively documented infiltration kinetics across diverse pedoclimatic gradients, there is a profound knowledge gap persists regarding the multiscale dynamics of water flux within complex tropical catchments, particularly concerning the heterogeneous transitions between different land-use systems. Prior research has typically adopted a binary approach, separating intensive agricultural plots from undisturbed silvicultural ecosystems. This perspective overlooks the complexity of agroforestry as a strategic socio-ecological interface. Building upon the foundational research of Nungula et al. (2024) and Keprate et al. (2024) concerning climate-resilient landscapes, this study examines agroforestry's role as a critical hydrological regulator that balances multifaceted ecosystem services and socio-economic imperatives at the landscape scale.

A critical lack of empirical evidence in the unique hydro-geological contexts of Indonesian watersheds is central to this paper, most notably in the Palu watershed in Central Sulawesi. Despite the region's heightened vulnerability to landscape shifts and accelerating pressures of land-use conversion, high-resolution infiltration data remains scarce. This geographic and thematic gap poses a significant threat to local soil and

water conservation strategies, as current management frameworks often rely on extrapolated data, which fail to capture the nuances of tropical ‘Wallacean’ soil structures. This research therefore fills a pivotal void by quantifying how agroforestry modifies subsurface hydraulic conductivity, offering a scientific framework for sustainable land use planning.

Furthermore, despite the critical role of soil infiltration in regulating watershed hydrology, there is a lack of empirical evidence in the literature worldwide regarding the tradeoffs between forest conservation and agricultural intensification in the Wallacea region. While most studies focus on monoculture systems, the transitional role of agroforestry in maintaining soil hydraulic functions is often overlooked. This study therefore aims to address this knowledge gap by quantifying soil infiltration dynamics across a land-use gradient ranging from secondary forests and agroforestry to inten-

sively cultivated land within the Wimbi sub-watershed in Central Sulawesi. Employing the Horton infiltration model, we will determine the extent to which soil physical degradation influences water absorption capacity. These findings are expected to provide a scientific basis for the development of integrated watershed management strategies and land use policies that prioritize hydrological resilience in tropical landscapes.

MATERIALS AND METHODS

Study area and research design

The research was conducted in the Wimbi sub-watershed, geographically positioned between 1°02′–1°03′ S and 119°50′–119°51′ E. Administratively, the site is located in the Pamona Utara sub-district in Poso Regency in Central Sulawesi, Indonesia (Figure 1). The study area is characterized by an average annual rainfall

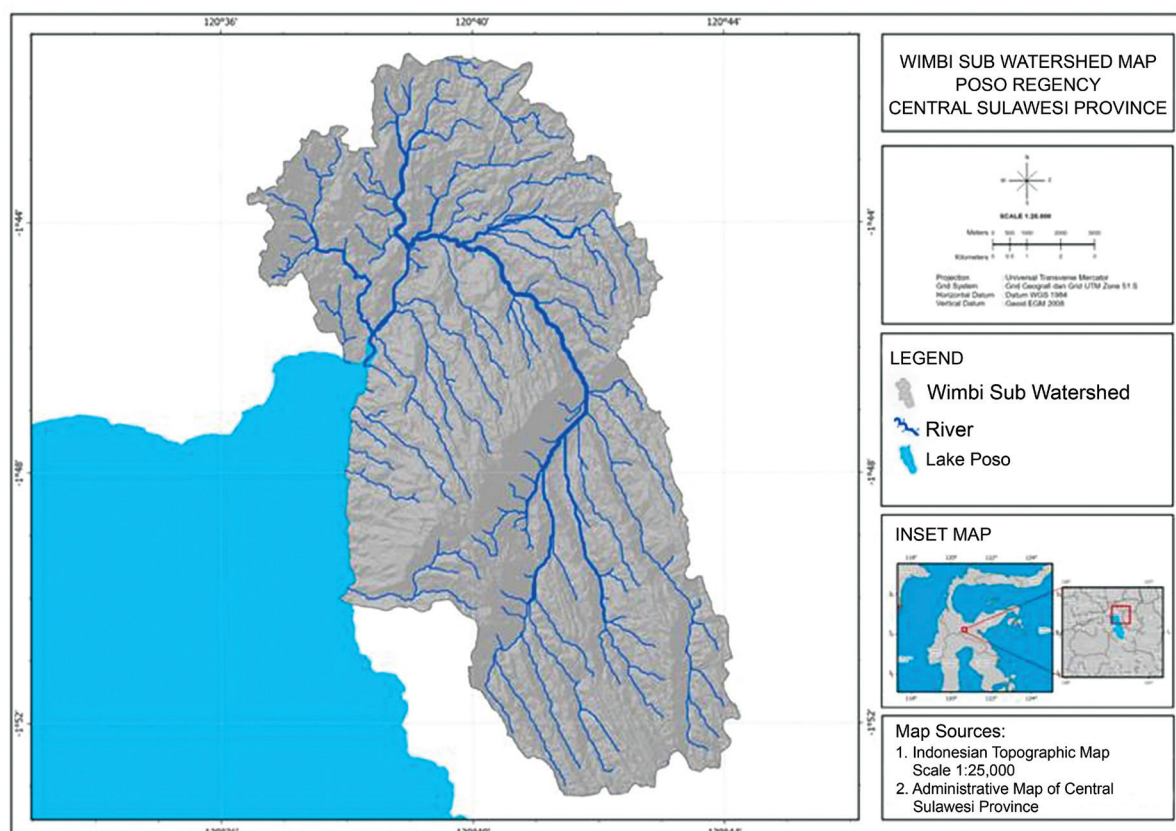


Fig. 1. Study area (Source: Authors’ own elaboration based on the Indonesian Topographic Map (RBI) at a scale of 1:25,000 (BIG / Geospatial Information Agency) and the Digital Elevation Model (DEMNAS), integrated through spatial analysis using ArcGIS/QGIS)

of 1,059 mm and a mean temperature of 18°C. The dominant soils are classified as alluvial and podzolic, originating from mineral-rich parent materials with developing B-horizons.

The study was executed in two systematic stages. The first stage involved field measurements of soil infiltration rates and soil sampling across three distinct land-use types: secondary forests, agroforestry, and cultivated land. In the second stage, laboratory analyses were performed to determine soil physical properties, including texture, organic matter content, bulk density, and porosity. These analyses were carried out at the Soil Science Laboratory (Faculty of Agriculture) and the Forestry Laboratory (Faculty of Forestry), Tadulako University.

Infiltration measurements

Soil infiltration rates were measured in situ using a double-ring infiltrometer to characterize the hydrological behavior of the three land-use types. To ensure statistical validity and capture spatial heterogeneity, a stratified purposive sampling design was employed. A total of 45 sampling points were established, comprising 15 independent replications within each of the three land-use types. The selection of measurement plots was strictly based on the following criteria: (1) representative vegetation cover and management history for each land-use type, (2) an absence of recent anthropogenic disturbances (e.g., footpaths or vehicle tracks), and (3) a uniform slope gradient (<5%) to prevent lateral water runoff on the soil surface. Furthermore, all sampling plots were restricted to the middle-slope position (mesocline) of the watershed, thereby isolating effects of land use from extreme ridge or valley bottom hydrological dynamics.

Additionally, field measurements were conducted under uniform antecedent soil moisture conditions. Sampling was restricted to a period of consecutive dry days following a significant rainfall event to avoid transient saturation, ensuring that soil water content approached field capacity across all plots and isolating the specific impact of land use on infiltration and surface runoff from baseline microclimatic moisture fluctuations.

The apparatus consisted of two concentric stainless steel cylinders with internal diameters of 10 cm (inner ring) and 30 cm (outer ring), both standing 15 cm in

height. The rings were driven vertically into the soil to a depth of 5 cm using a rubber mallet and a wooden buffer to prevent any mechanical disturbance or compaction of the soil surface within the rings.

To ensure strictly vertical water movement and minimize lateral flow, which is a critical factor in the sandy loam and silty clay loam textures of the Wimbi watershed, the outer ring acted as a hydrological buffer. A constant hydraulic head of 5 cm was maintained in both the inner and outer cylinders throughout the experiment using a regulated mini PVC reservoir system.

Infiltration readings were recorded at each sampling point over a total duration of 60 minutes. To capture the initial rapid decay phase of the infiltration curve, measurements were taken at intervals of 1, 2, 5, and 10 minutes, gradually extending the intervals as the process approached a steady-state (equilibrium) infiltration rate (f_c). The temporal data were then fitted to the Horton infiltration model in order to determine the decay constant (k) and the overall infiltration capacity of the site.

Soil sampling

Undisturbed soil samples were collected using cylindrical core rings immediately adjacent (within a 0.5 m radius) to each infiltration measurement point for laboratory analysis of soil physical properties. Prior to both infiltration testing and core sampling, the initial antecedent soil moisture content (θ_i) was measured at a depth of 0–10 cm using a calibrated portable time-domain reflectometry (TDR) probe to ensure that all measurements across the plots were conducted under comparable baseline moisture conditions.

Prior to sampling, surface vegetation was carefully removed with a spade, and the soil surface was leveled. The sampling ring, with its beveled edge facing downward, was driven vertically into the soil using a mallet and wooden block to ensure alignment. Surrounding soil was excavated to facilitate ring retrieval. Excess soil was trimmed flush with the ring edge using a knife. The filled cores were sealed with plastic wrap, secured, labeled, and transported to the laboratory for analysis.

Data analysis

The infiltration data collected from the field were analyzed using the Horton infiltration model, which describes the infiltration capacity curve over time.

The Horton equation is expressed as follows (Horton, 1941; Naharuddin et al., 2022):

$$f_p = f_c + (f_0 - f_c)e^{-kt} \quad (1)$$

where:

- f_p – infiltration capacity at any time t ($\text{cm} \cdot \text{h}^{-1}$),
- f_0 – initial infiltration capacity at $t = 0$ ($\text{cm} \cdot \text{h}^{-1}$),
- f_c – steady-state (final) infiltration capacity ($\text{cm} \cdot \text{h}^{-1}$),
- t – time elapsed from the start of rainfall or ponding (minutes or hours),
- k – the Horton decay constant specific to the soil type and vegetation cover,
- e – base of natural logarithms.

The initial infiltration rate (f_0) was calculated using Equation (2):

$$f_0 = \frac{\Delta h}{\Delta t} \cdot 60 \quad (2)$$

where:

- f_0 – infiltration rate ($\text{cm} \cdot \text{h}^{-1}$),
- Δh – change in water head per time interval (cm),
- Δt – measurement time interval (minutes).

In addition, the Horton decay constant (k) can be expressed using Equation (3):

$$k = -\frac{-1}{(m \log e)} \quad (3)$$

Cumulative infiltration (I) is described by the potential function, expressed in Equation (4):

$$I = k \cdot t^a \quad (4)$$

where:

- I – cumulative infiltration (cm),
- k – soil-dependent constant,
- t – infiltration time (minutes),
- a – soil-dependent constant ranging between 0 and 1.

Statistical analysis and laboratory protocols

Parametric statistical assessments were performed to evaluate the impact of forest conversion on soil hydraulic architecture. Prior to hypothesis testing, the datasets were subjected to Shapiro–Wilk and Levene’s tests to verify normal distribution and homogeneity of variances, respectively.

Statistical variations in the physical properties of the soil matrix, the hydrodynamic boundary conditions, and the Horton calibration parameters (f_0 , f_c , and k) across the three distinctive land-use types (secondary forests, agroforestry, and intensive cultivation) were evaluated using a one-way analysis of variance (ANOVA). Following the detection of statistically significant main effects, mean separations were determined using the Tukey’s honestly significant difference (HSD) post hoc test at a critical alpha level of $\alpha = 0.05$.

Furthermore, a multivariate Pearson correlation coefficient matrix (r) was computed with reference to bulk density (BD), total porosity, soil organic carbon (SOC), initial infiltration rate (f_0), steady-state infiltration capacity (f_c), and the Horton decay constant (k). Concurrently, to evaluate the accuracy of the non-linear Horton model in predicting infiltration kinetics, the coefficient of determination (R^2) and the residual sum of squares (RSS) were calculated with the support of an iterative non-linear least-squares (NLLS) regression framework. A higher R^2 value combined with a minimized RSS indicates a sound fit between the measured hydrographs and the model’s predicted values. All computational and modeling procedures were executed within their respective valid mathematical frameworks, applying linear operations exclusively for the Pearson correlation matrices while retaining strict non-linear optimization for the Horton decay curves to prevent the mathematical artifacts of forced linearization (Tang et al., 2025; Vishwakarma et al., 2025).

In order to identify the underlying physical drivers of watershed hydrological behavior, a range of key soil physical, chemical, and hydraulic properties were rigorously quantified. These parameters included particle size distribution (sand, silt, and clay fractions, as determined by the standardized pipette sedimentation method), soil organic carbon (SOC, using the Walkley–Black wet oxidation method), bulk density (BD, using the core-oven drying protocol), particle density (PD, using liquid pycnometry), and total porosity derived mathematically from BD/PD ratios.

Additionally, hydrodynamic boundary conditions were captured by measuring the saturated water content, field capacity water content (as measured by pressure plate extractors at diagnostic suction pressures),

and initial antecedent moisture content (θ_i) using calibrated field time-domain reflectometry (TDR).

Concurrently, a botanical assessment was conducted to characterize the vegetation composition, canopy density, and litter accumulation across the three land-use gradients (secondary forests, agroforestry, and cultivation). These integrated analytical protocols, explicitly detailed alongside their standardized regulatory methodologies in Table 1, and follow the strict, reproducible scientific frameworks previously established for high-precision tropical watershed assessments (Naharuddin et al., 2022).

RESULTS AND DISCUSSION

Soil physical architecture and baseline characteristics

Characterization of the soil physical matrix across the three distinct land-use types within the Wimbi watershed revealed significant modifications in structural integrity induced by land conversion (Table 2).

The agroforestry system proved to be in the most favorable physical condition, characterized by the lowest bulk density ($1.24 \pm 0.04 \text{ g} \cdot \text{cm}^{-3}$) and the highest total porosity ($48.28 \pm 2.10\%$). This correlated directly with its high soil organic carbon (SOC) accumulation ($4.20 \pm 0.31\%$). Conversely, agricultural land dedica-

ted to intensive maize cultivation showed compaction, indicated by a maximum bulk density of $1.61 \pm 0.07 \text{ g} \cdot \text{cm}^{-3}$ and a minimum total porosity of $33.18 \pm 1.45\%$. The antecedent soil moisture content (θ_i) recorded immediately prior to the infiltration runs showed no statistically significant variations across the plots ($p > 0.05$), ensuring that the measured differences in infiltration kinetics were structurally driven.

In situ onfiltration hydrographs and the Horton model calibration

The in situ double-ring infiltration measurements captured distinct, non-linear decay curves across all systems of land use. To accurately resolve this non-linear hydraulic behavior, the empirical high-resolution time-series data were fitted to the classic Horton infiltration model:

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

The fitting process used a non-linear least-squares (NLLS) regression framework solved with the iterative Levenberg–Marquardt algorithm. This approach preserves the mathematical integrity of the asymptotic curve. The optimized parameter sets (f_0 , f_c , k) along with their respective uncertainty bounds and goodness-of-fit metrics are detailed in Table 3.

Table 1. Observation of soil physical properties, and analysis method / procedure

Soil property parameter	Analysis method / procedure
Soil texture class	USDA soil texture triangle classification
Sand (%)	Pipette method (sedimentation) / hydrometer method (Bouyoucos) after organic matter removal with H_2O_2
Silt (%)	Pipette method (sedimentation) based on Stokes' law
Clay (%)	Pipette method (sedimentation) / hydrometer method (Bouyoucos) based on Stokes' law
Bulk density ($\text{g} \cdot \text{cm}^{-3}$)	Core ring method (oven-drying at 105°C for 24 hours) / ISO 11272
Particle density ($\text{g} \cdot \text{cm}^{-3}$)	Pycnometer method (gas or liquid displacement) / ISO 11508
Total porosity (%)	Mathematical calculation derived from bulk density (BD) and particle density (PD): $\text{porosity} = (1 - \text{PD}/\text{BD}) \times 100\%$
Saturated water content (v/v %)	Gravimetric core method at zero suction / soil moisture retention curve at 0 kPa saturation point
Field capacity water content (v/v %)	Pressure plate extractor apparatus method at pF 2.0 (–10 kPa to –33 kPa)
Soil organic carbon (%)	Walkley–Black chromic acid wet oxidation method
Antecedent moisture (θ_i , % v/v)	Field measurement via calibrated time-domain reflectometry (TDR) probe

Table 2. Soil physical and chemical properties across the evaluated land-use types (mean $\pm$ standard deviation, $n = 15$)

Soil property parameter	Secondary forests	Agroforestry	Agricultural land
Soil texture class	Sandy loam	Clay	Silty clay loam
Sand (%)	72.1 $\pm$ 3.4 ^a	52.1 $\pm$ 2.8 ^b	28.9 $\pm$ 1.9 ^c
Silt (%)	20.3 $\pm$ 1.8 ^b	29.1 $\pm$ 2.1 ^a	58.2 $\pm$ 3.1 ^c
Clay (%)	7.6 $\pm$ 0.9 ^c	18.8 $\pm$ 1.4 ^a	12.9 $\pm$ 1.1 ^b
Bulk density (g $\cdot$ cm ⁻³)	1.44 $\pm$ 0.05 ^b	1.24 $\pm$ 0.04 ^c	1.61 $\pm$ 0.07 ^a
Particle density (g $\cdot$ cm ⁻³)	2.52 $\pm$ 0.03 ^a	2.40 $\pm$ 0.02 ^b	2.41 $\pm$ 0.03 ^b
Total porosity (%)	42.93 $\pm$ 1.85 ^b	48.28 $\pm$ 2.10 ^a	33.18 $\pm$ 1.45 ^c
Saturated water content (v/v %)	48.08 $\pm$ 1.95 ^b	50.06 $\pm$ 2.22 ^a	38.00 $\pm$ 1.60 ^c
Field capacity water content (v/v %)	26.36 $\pm$ 1.12 ^c	36.16 $\pm$ 1.54 ^a	21.95 $\pm$ 0.88 ^b
Soil organic carbon (%)	2.60 $\pm$ 0.15 ^b	4.20 $\pm$ 0.31 ^a	0.98 $\pm$ 0.08 ^c
Antecedent moisture (θ_p , v/v %)	21.40 $\pm$ 1.10 ^a	23.15 $\pm$ 1.25 ^a	20.85 $\pm$ 0.95 ^a

* Note: Means within a row followed by different superscript letters (a, b, c) indicate statistically significant differences based on the Tukey's HSD test ($p < 0.05$).

Table 3. Fitted parameter values and statistical evaluation of the non-linear Horton model

Land-use type	f_0 (cm $\cdot$ h ⁻¹)	f_c (cm $\cdot$ h ⁻¹)	k (h ⁻¹)	Residual sum of squares (RSS)	Coefficient of determination (R^2)
Secondary forests	55.20 $\pm$ 2.41	7.74 $\pm$ 0.45	4.12 $\pm$ 0.18	12.45	0.95
Agroforestry	79.80 $\pm$ 3.85	6.94 $\pm$ 0.38	5.24 $\pm$ 0.22	10.12	0.96
Agricultural land	31.80 $\pm$ 1.92	3.87 $\pm$ 0.21	2.98 $\pm$ 0.14	38.60	0.89

The non-linear fitting confirmed that the Horton model accurately reflects the hydrological processes of these soils, explaining 95%, 96%, and 89% of the variance (R^2) for secondary forests, agroforestry, and agricultural land, respectively.

Multivariate intercorrelation and hydro-structural controls

The multivariate statistical framework revealed robust, highly significant mechanistic couplings between anthropogenic structural degradation and the collapse of subsurface hydraulic conduits. The Pearson correlation matrix (Table 4) established that the steady-state infiltration capacity (f_c) is strongly governed by soil physical architecture, exhibiting a profound positive correlation with total porosity ($r = 0.94$; $p < 0.01$) and SOC accumulation ($r = 0.91$; $p < 0.01$), while maintaining a strong, highly significant inverse correlation with

bulk density ($r = -0.88$; $p < 0.01$). These empirical intercorrelations provide concrete evidence that mechanical compaction under monoculture maize farming drives systemic pore-matrix degradation, whereas the preservation of elevated organic substrates within the agroforestry mosaic successfully maintains structural macro-aggregate stability. Concurrently, the initial infiltration rate (f_0) exhibited significant positive dependencies on both total porosity ($r = 0.71$; $p < 0.05$) and SOC content ($r = 0.82$; $p < 0.01$), corroborating that initial topsoil moisture absorption kinetics are heavily regulated by near-surface organic-structural buffers mediated by multi-layered vegetative covers.

The absolute differences in hydraulic and structural parameters across the land-use gradient were mathematically validated by the one-way ANOVA frameworks (Table 5). The main effect of land use was highly significant for both steady-state infiltration

Table 4. Multivariate Pearson correlation matrix (r) with reference to the soil physical, chemical, and hydraulic properties ($n = 45$)

Variable	Bulk density (BD)	Total porosity	SOC	Initial infiltration (f_0)	Steady-state infiltration (f_c)	Decay constant (k)
BD	1.00					
Total porosity	-0.96**	1.00				
SOC	-0.85**	0.89**	1.00			
f_0	-0.64*	0.71*	0.82**	1.00		
f_c	-0.88**	0.94**	0.91**	0.76*	1.00	
k	-0.52	0.58*	0.74*	0.69*	0.61*	1.00

* Correlation is significant at the $p < 0.05$ level (2-tailed).

** Correlation is highly significant at the $p < 0.01$ level (2-tailed).

Table 5. One-way ANOVA summary table for key soil hydraulic and structural parameters

Parameter	Source of variation	Sum of squares (SS)	Degrees of freedom (d_f)	Mean square (MS)	F -value	p -value	Significance
Steady-state infiltration (f_c)	Between groups	128.42	2	64.210	145.27	<0.001	Highly significant
	Within groups	18.56	42	0.442			
	Total	146.98	44				
Total porosity	Between groups	1714.50	2	857.250	281.43	<0.001	Highly significant
	Within groups	127.92	42	3.046			
	Total	1842.42	44				

capacity (f_c : $F(2,42) = 145.27$; $p < 0.001$) and total porosity ($F(2,42) = 281.43$; $p < 0.001$), proving that the observed variances represent true systemic variations induced by land-use management rather than spatial noise. Post-hoc separations determined by the Tukey's HSD (Table 6) further demonstrated that while the cultivated land experienced a critical hydro-structural collapse ($p < 0.001$), the agroforestry system successfully maintained a hydraulic performance that was statistically equivalent to the secondary forest baseline ($p = 0.125$), validating its role as an effective catchment-level ecological buffer.

Land-use driven infiltration dynamics: mechanisms and controls secondary forest

In the secondary forest plots, water penetration began with a sharp entry rate, showing a drop in water depth of 9.2 ± 0.5 cm within the first 10 minutes. The decay

curve progressed steadily, recording a depth drop of 7.3 ± 0.4 cm at 20 minutes, 6.2 ± 0.3 cm at 30 minutes, and 5.1 ± 0.3 cm at 40 minutes. The system achieved a hydrological steady-state at the 60th minute, stabilizing at a depth drawdown of 2.5 ± 0.1 cm, which translates to a constant infiltration capacity (f_c) of 7.74 ± 0.45 cm $\cdot$ h $^{-1}$ (classified as moderately rapid).

This steady-state infiltration rate is primarily influenced by its sandy loam texture (72.1% sand fraction) and low bulk density (1.44 ± 0.05 g $\cdot$ cm $^{-3}$). The high sand content provides a volume of macropores that facilitate gravity-driven vertical water movement. The decay constant ($k = 4.12 \pm 0.18$ h $^{-1}$) was lower than for agroforestry, showing a gradual decline in water intake. Because the sandy loam matrix does not undergo significant matrix swelling, the matric suction gradient dissipates steadily as the wetting front.

Table 6. Pairwise mean separations using the Tukey’s honestly significant difference (HSD) post-hoc test ($\alpha = 0.05$)

Target parameter	Land-use pairwise comparison	Mean difference	Standard error	<i>p</i> -value	Statistical conclusion
f_c (cm · h ⁻¹)	Secondary forests vs. agroforestry	0.80	0.242	0.125	Not significant ($p > 0.05$)
	Secondary forests vs. agricultural land	3.87	0.242	< 0.001	Highly significant ($p < 0.01$)
	Agroforestry vs. agricultural land	3.07	0.242	< 0.001	Highly significant ($p < 0.01$)

Agroforestry system

The agroforestry system displayed a highest water acceptance capacity during the early stages of the run. At the 10th minute, it recorded a significant water depth reduction of 13.3 ± 0.7 cm, followed by 12.1 ± 0.6 cm at 20 minutes, and 9.7 ± 0.5 cm at 30 minutes. The curve flattened by the 60th minute, stabilizing at 3.2 ± 0.2 cm, yielding a steady-state infiltration capacity (f_c) of 6.94 ± 0.38 cm · h⁻¹.

Despite a high clay fraction (18.8%), the steady-state infiltration remained high. This can be attributed to its high SOC content ($4.20 \pm 0.31\%$), which acts as a binding agent that promotes stable aggregate formation. This structural arrangement counteracts the typical restrictive drainage patterns associated with clay matrices. Interestingly, agroforestry showed the highest initial potential capacity ($f_0 = 79.80 \pm 3.85$ cm · h⁻¹) and the fastest decay constant ($k = 5.24 \pm 0.22$ h⁻¹). The high k value reflects its clay minerals swelling upon wetting, which rapidly closes inter-aggregate cracks and transitions the system toward steady-state flow.

Agricultural land

The intensive agricultural land demonstrated highly restricted water intake from the start of the experiment. The initial depth reduction at the 10th minute was limited to 5.3 ± 0.4 cm, which rapidly dropped to 3.2 ± 0.2 cm at 20 minutes. The infiltration capacity quickly plateaued, showing minor variations between the 50th minute (1.6 ± 0.1 cm) and 60th minute (1.4 ± 0.1 cm), yielding the lowest steady-state capacity of 3.87 ± 0.21 cm · h⁻¹ (moderate classification).

The low SOC content ($0.98 \pm 0.08\%$) further compromises structural stability, rendering the soil aggregates

vulnerable to collapse when exposed to wetting fronts. For the agricultural land, the lower coefficient of determination ($R^2 = 0.89$) and high residual sum of squares (RSS = 38.60) indicate that surface crusting and sealing during the infiltration runs altered the hydraulic conductivity over time, representing a plausible cause for the structural variations that diverge slightly from the standard Horton curve. This structural divergence acts as an indirect mathematical indicator of a surface hydraulic barrier, even in the absence of direct micromorphological pore measurements.

Vegetation cover and potential flow dynamics

The higher hydraulic performance of the secondary forest and the agroforestry system is structurally supported by their vegetation architecture. The multi-layered canopy and permanent litter layer protect the soil surface from the direct kinetic energy of rainfall, which potentially minimizes the detachment of fine particles and prevents surface sealing (Fung et al., 2022; Suprayogo et al., 2020). Furthermore, the root systems of trees and understory vegetation are conceptually hypothesized to induce biogenic macropores. As roots grow, decay, and interact with soil fauna, they may form continuous channels. While these continuous paths could theoretically bypass compacted soil matrices and facilitate preferential flow, thereby maintaining high steady-state infiltration rates (f_c) (Lima et al., 2022), direct visualization or quantification of such biogenic networks was beyond the scope of this study.

On the intensive agricultural land, the lack of consistent canopy and litter cover leaves the soil surface highly vulnerable to the impact of raindrop. This exposure leads to slaking and the subsequent formation

of a depositional surface seal, wherein fine silt particles are presumed to physically clog surface-connected macro- and mesopores (Naharuddin et al., 2023). The shallow root systems of maize monocultures appear insufficient to prevent this structural vulnerability, thereby restricting water movement to the lower hydraulic conductivity of the compacted soil matrix (Nowogóński, 2021).

Hydrological and watershed management implications

The 50% decrease in steady-state infiltration capacity when converting from natural forest or structured agroforestry to intensive agricultural fields has direct implications for watershed hydrology. When the rainfall intensity exceeds the reduced steady-state infiltration capacity ($3.87 \pm 0.21 \text{ cm} \cdot \text{h}^{-1}$), the excess water is converted into surface runoff (Mujiyo et al., 2025). This shift in the water pathway increases peak discharge volumes in the downstream networks of the Wimbi watershed, elevating the risk of local floodings and soil erosion during high-intensity storms (Mongil-Manso et al., 2025).

The findings demonstrate that agroforestry systems can function as effective hydrological buffers. By preserving soil organic carbon and total porosity, agroforestry maintains a vertical drainage capacity ($6.94 \pm 0.38 \text{ cm} \cdot \text{h}^{-1}$) that is statistically comparable to that of natural secondary forests ($7.74 \pm 0.45 \text{ cm} \cdot \text{h}^{-1}$). Integrating sustainable agroforestry systems into agricultural landscapes can help maintain groundwater recharge pathways, reduce surface runoff, and lower the risks of structural land degradation within the watershed ecosystem (Tang et al., 2025).

Comparative analysis with global tropical watersheds

The observed infiltration dynamics in the Wimbi Sub-watershed reflect a broader pattern documented across tropical ecosystems. The superior steady-state infiltration capacity (f_c) of the secondary forests ($7.74 \pm 0.45 \text{ cm} \cdot \text{h}^{-1}$) and agroforestry systems ($6.94 \pm 0.38 \text{ cm} \cdot \text{h}^{-1}$) in Central Sulawesi aligns with hydro-structural dynamics observed in the Amazon Basin and the Brazilian Atlantic Forest (Anderson et al., 2020; Lima et al., 2022). In those landscapes, forest cover consistently maintains high soil macroporosity,

where the accumulation of soil organic carbon serves as the primary driver for aggregate stabilization.

In the African context, research in the East African Highlands and the Nile Basin corroborates our findings regarding the detrimental impact of intensive cultivation on soil hydraulic conduits (Mengistu et al., 2022). The elevated bulk density ($1.61 \pm 0.07 \text{ g} \cdot \text{cm}^{-3}$) and depleted total porosity ($33.18 \pm 1.45\%$) observed in the Wimbi agricultural plots mirror the conditions in heavily tilled tropical soils across Ethiopia and Kenya. In these regions, continuous mechanical disturbance and the absence of permanent soil cover trigger rapid surface sealing, causing a sharp decline in steady-state water intake. Furthermore, the moderate agricultural infiltration capacity recorded in this study ($3.87 \pm 0.21 \text{ cm} \cdot \text{h}^{-1}$) is comparable to rates reported in seasonally dry watersheds of West Africa, where annual monocultures have systematically increased the surface runoff coefficients and accelerated the downstream soil erosion (Bahddou et al., 2023).

In the Southeast Asia, our results reinforce the well documented “sponge effect” of tree-based conservation matrices that are often found in Indonesian and Vietnamese landscape studies. The capacity of the Wimbi agroforestry system to sustain moderately rapid vertical drainage, despite its clay-dominated texture ($18.8 \pm 1.4\%$), strongly resembles observations on the volcanic slopes of East Java (Suprayogo et al., 2020). In both regions, multi-layered vegetative canopies and permanent litter layers successfully mitigate the kinetic energy of tropical rainfall, preserving soil aggregate stability.

Placing the Wimbi Sub-watershed within this pan-tropical framework demonstrates that the observed local hydrological degradation is a critical manifestation of a global trend. These cross-continental comparisons confirm that integrating sustainable agroforestry systems remains one of the most viable, scientifically validated strategies for mitigating the hydraulic conductivity constraints of intensive farming and maintaining watershed health in the tropics.

Policy and watershed management implications

The findings of this study provide critical, data-driven evidence for the strategic management of the Wimbi Sub-watershed and similar fragile tropical landscapes. The significant reduction in infiltration capacity fol-

lowing the conversion of secondary forests to intensive agricultural land underscores the urgent need for strict land-use zoning policies that prioritize the preservation of existing forest fragments. Given that secondary forests exhibited the highest steady-state infiltration capacity ($f_c = 7.74 \pm 0.45 \text{ cm} \cdot \text{h}^{-1}$), regional watershed management authorities should designate these areas as critical protection zones, particularly on vulnerable slopes, to control surface runoff coefficients and mitigate downstream flood risks.

Furthermore, the robust performance of the agroforestry systems in maintaining a moderately rapid infiltration rate ($f_c = 6.94 \pm 0.38 \text{ cm} \cdot \text{h}^{-1}$) establishes a viable, scientifically validated pathway for ecological and hydrological restoration within degraded catchment areas. Policy interventions must actively encourage a structural transition away from intensive maize monocultures which drive soil compaction ($\text{BD} = 1.61 \pm 0.07 \text{ g} \cdot \text{cm}^{-3}$) and total porosity depletion ($33.18 \pm 1.45\%$) toward diversified, tree-based agroforestry matrices.

To bridge the gap between biophysical data and regional enforcement, this transition should be facilitated through target-specific, incentive-based frameworks, such as Payments for Ecosystem Services (PES) schemes. Under these programs, local farmers are economically compensated or supported for adopting multi-story tree systems that measurably enhance soil structural connectivity, promote macrofaunal activity, and maintain vertical water regulation.

Ultimately, embedding these high-infiltration land-use types into the official spatial planning grid of the Palu watershed is a critical requirement for ensuring long-term groundwater security, reducing pluvial disaster vulnerabilities, and fostering climate resilience across Central Sulawesi.

CONCLUSIONS

This study demonstrates that changes in land use in the tropical watersheds of Central Sulawesi alter soil hydraulic architecture. Our findings confirm that the transition from secondary forests to intensive agricultural systems leads to a decline in steady-state infiltration capacity (f_c), dropping by approximately 50% from $7.74 \pm 0.45 \text{ cm} \cdot \text{h}^{-1}$ in secondary forests to

$3.87 \pm 0.21 \text{ cm} \cdot \text{h}^{-1}$ in agricultural land. This degradation is driven by the deterioration of baseline soil physical properties, characterized by an increase in bulk density ($1.61 \pm 0.07 \text{ g} \cdot \text{cm}^{-3}$) and a reduction in total porosity ($33.18 \pm 1.45\%$) under intensive maize monocultures.

While secondary forests maintain superior hydrological functions due to their porous sandy loam matrix, agroforestry systems emerge as a critical hydrological middle-ground. Agroforestry effectively preserves moderately rapid infiltration rates ($6.94 \pm 0.38 \text{ cm} \cdot \text{h}^{-1}$) by maintaining high soil organic carbon ($4.20 \pm 0.31\%$) and superior aggregate structural integrity.

The application of the non-linear Horton infiltration model, calibrated using non-linear least-squares (NLLS) regression, proved effective in capturing the mathematical infiltration decay dynamics across these varying landscapes ($R^2 \geq 0.89$), providing parameters (f_o, f_c, k) for future hydrological modeling. Our findings underscore that the hydrological degradation observed in the Wimbi sub-watershed is a localized manifestation of a regional trend that provides valuable evidence from the Wallacea region. Consequently, this research advocates for a paradigm shift in Indonesian watershed management and land-use policies. Future frameworks should prioritize and incentivize the integration of tree-based systems (agroforestry) into agricultural landscapes as a strategic intervention to restore soil hydrological resilience.

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CONFLICT OF COMPETING INTEREST

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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WPŁYW PRZEKSZTAŁCANIA LASÓW W TERENY INTENSYWNEGO ROLNICTWA NA FUNKCJE HYDROLOGICZNE GLEBY W TROPIKALNEJ ZLEWNI W ŚRODKOWEJ SULAWESI

STRESZCZENIE

Cel badania

Szybka transformacja tropikalnych lasów wtórnych w tereny intensywnego rolnictwa stanowi zagrożenie dla funkcji hydrologicznych gleby. Dane empiryczne związane z tą kwestią dotyczące zlewni w regionie Wallacea są wciąż ograniczone. Niniejsze badanie analizuje wpływ zmian w użytkowaniu gruntów na architekturę hydrauliczną gleby oraz jej zdolność do infiltracji wód w zlewni Wim bi, położonej w środkowej części wyspy Sulawesi w Indonezji. Wyniki badania stanowią podstawę naukową dla regionalnej ochrony zlewni.

Materiały i metody

Infiltrację gleby mierzono in situ poprzez pobranie warstwowej próby celowej ($n = 15$ na każdy typ użytkowania gruntów, łącznie 45 punktów) przy użyciu infiltrometru dwupierscieniowego na obszarach lasu wtórnego, agroleśnictwa oraz gruntów rolnych (monokultura kukurydzy). Podstawowe właściwości fizyczne, parametry hydrodynamiczne oraz zawartość węgla organicznego w glebie (SOC) określono ilościowo przy użyciu standardowych protokołów laboratoryjnych. Dane dotyczące infiltracji o wysokiej rozdzielczości zostały skorygowane przy użyciu modelu Hortona, który został obliczony za pomocą iteracyjnej, nieliniowej regresji metodą najmniejszych kwadratów.

Wyniki i wnioski

Przekształcanie lasów w tereny intensywnego rolnictwa powoduje znaczne pogorszenie właściwości hydraulicznych gleby. Najwyższą zdolność infiltracji w stanie ustalonym wykazały lasy wtórne ($7,74 \pm 0,45 \text{ cm} \cdot \text{h}^{-1}$), a tuż za nimi uplasowały się tereny agroleśne ($6,94 \pm 0,38 \text{ cm} \cdot \text{h}^{-1}$). Oba typy zaklasyfikowano jako umiarkowanie szybkie. Natomiast na gruntach rolnych odnotowano spadek o 50% do wartości $3,87 \pm 0,21 \text{ cm} \cdot \text{h}^{-1}$ (umiarkowana). Dopasowanie nieliniowe wykazało, że model Hortona skutecznie oddaje dynamikę infiltracji ($R^2 \geq 0,89$). To ograniczenie związane z rolnictwem było bezpośrednio powiązane z zagęszczeniem mechanicznym, które zwiększyło gęstość objętościową ($1,61 \pm 0,07 \text{ g} \cdot \text{cm}^{-3}$) i zmniejszyło porowatość całkowitą ($33,18 \pm 1,45\%$). Krytyczny deficyt węgla organicznego w glebie (SOC) ($0,98 \pm 0,08\%$) na gruntach uprawnych wyraźnie wskazuje na przyspieszone uszczelnianie powierzchniowe, co potencjalnie ogranicza

podpowierzchniowe wewnętrzne sieci porów. Tymczasem tereny agroleśne utrzymywały lepszą buforowość strukturalną gleby dzięki podwyższonemu poziomowi SOC ($4,20 \pm 0,31\%$), zmniejszając zagęszczenie macrycy i poprawiając łączność porów. Przejście na rolnictwo oparte na wykorzystaniu drzew ma zasadnicze znaczenie dla ograniczenia spływu powierzchniowego i przywrócenia odporności tropikalnych zlewni.

Słowa kluczowe: model Hortona, przekształcenie użytkowania gruntów, infiltracja gleby, zlewnia tropikalna, zarządzanie zlewnią