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Soil Infiltration Rate at Various Elevations in Padende Sub-Watershed

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ABSTRACT

Infiltration refers to the downward movement of water, including rainwater, from the land surface into the soil profile. This process plays a central role in shaping groundwater recharge, guiding water-resource planning, and mitigating flood risk. When soil infiltration capacity is limited, a greater proportion of rainfall becomes surface runoff. The highest infiltration is generally recorded in upland terrain that is steep, ridge-bounded, and covered by vegetation such as forest stands. Although elevation is frequently linked to steeper slopes, its influence on the movement of surface water operates through slope gradient, surface roughness, and vegetation cover rather than through any change in gravitational acceleration. Based on the 2024 watershed status map published by the NTB Watershed Management Agency, the majority of the Padende sub-watershed remains designated as a protected forest. In contrast, roughly 30% has been converted to other land uses. This study was designed to examine the infiltration rate together with related soil physicochemical characteristics—porosity, texture, organic carbon content, and permeability—across four elevation classes. Field measurements across the four elevation classes (400–1000 m above sea level) yielded infiltration rates of 19–28 cm h⁻¹, all falling within the “fast” category, indicating the absence of a statistically meaningful link between elevation per se and infiltration rate. Principal component analysis further revealed a strong positive association between organic carbon (C-organic) and specific gravity ($r = 0.817$), indicating that soils richer in organic matter tend to exhibit higher specific gravity. C-organic was also moderately and positively correlated with porosity ($r = 0.513$), suggesting that greater organic content coincides with greater pore space. In contrast, C-organic was moderately and negatively correlated with infiltration rate ($r = -0.583$) and weakly to moderately negatively correlated with bulk density ($r = -0.370$), implying that a decline in infiltration rate generally accompanies an increase in organic matter.

1. Introduction

Water from the land surface—rainwater in particular—moves downward into the soil through a mechanism known as infiltration [1]. This mechanism underlies groundwater recharge, informs

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water-resource planning, and helps control flooding. Flood events occur when incoming rainfall exceeds the amount of water the soil can absorb. Not all rainfall that reaches a given area penetrates the ground; under particular conditions, a portion becomes surface runoff. Such conditions include soil that is already saturated [2], low-porosity soils, soils dominated by clay, or a shallow soil solum resulting from erosion accumulated over the rainy season.

A soil with reduced infiltration capacity produces correspondingly greater surface runoff [3]. This runoff can carry soil particles—dislodged by the impact of falling raindrops—downslope into lower terrain. The effect is more pronounced where vegetative cover is sparse or absent; over time, continued runoff strips away the topsoil and gradually thins the soil solum.

Two factors jointly govern the infiltration rate: the soil's infiltration capacity and the intensity of the incoming water supply, i.e., rainfall intensity. When rainfall intensity remains below the soil's infiltration capacity, the actual infiltration rate tracks the rainfall intensity; once rainfall intensity exceeds that capacity, the excess is shed as surface runoff. The infiltration rate, therefore, fluctuates together with changes in rainfall intensity [3, 4]. Because infiltration also varies spatially and temporally, values measured at one site will typically differ from those at another, with slope acting as one of the governing variables—steep slopes being more common at higher elevations [5].

The greatest infiltration is usually observed in upland terrain—sloping, ridge-enclosed, and forested—commonly known as watersheds or rainfall-catchment zones. In its ideal condition, a watershed should capture and store a substantial share of incoming rainwater before releasing it gradually through rivers, reservoirs, lakes, and other water bodies.

Higher elevation tends to coincide with steeper slope gradients, and it is this steepness—rather than any change in gravitational acceleration—that shapes the hydrological behavior of surface water. On steep ground, a larger downslope component of gravitational force accelerates the lateral flow of water across the surface. In contrast, other slope-related conditions—surface roughness, soil structure, and vegetation cover—together determine the fraction of that water that infiltrates before it runs off. Because water travels faster over steep slopes with sparse vegetation, its residence time on the soil surface is shortened, which in turn lowers the effective infiltration rate. Consequently, any relationship detected between elevation and infiltration in this study should be interpreted as being mediated through slope, land cover, and soil properties rather than reflecting a direct gravitational effect.

Every parcel of land ultimately falls within the boundary of some watershed or sub-watershed. In Indonesia, the protection, rehabilitation, and utilization of land and water resources within these units are governed by Law No. 37 of 2014, Law No. 19 of 2004, and Government Regulation No. 37 of 2012. West Nusa Tenggara Province is currently organized into 18 Watershed Management Units (SWP-DAS)—four on Lombok Island and fourteen on Sumbawa Island—encompassing 627 watersheds in total, 145 of which lie on Lombok and 482 on Sumbawa [6]. The Padende sub-watershed falls under the SWP-DAS framework, which covers Sumbawa Island and aims to monitor whether each watershed continues to function as intended.

The 2024 watershed zoning map released by the NTB Watershed Management Agency shows that the bulk of the Padende sub-watershed is classified as protected forest, with the remaining 30% allocated to other uses, including land opened for maize farming. Such conversion places the long-term sustainability of the watershed ecosystem at risk, and, left unmanaged over the coming decades, could lead to substantial degradation of the Padende sub-watershed. Because a watershed's capacity to absorb and hold rainfall—closely tied to its infiltration rate and infiltration capacity, and shaped by land cover, vegetation, and the biophysical character of the land—serves as one indicator of its overall health, it becomes important to quantify the infiltration rate and to examine the factors associated with it.

Prior studies on soil infiltration can be broadly grouped into two complementary strands: those relying on direct field measurements with double-ring infiltrometers under defined land-use or land-cover settings, and those examining the soil physical and chemical properties that control infiltration capacity. Within the first strand, infiltration has been quantified on farmland [7, 8], on forest land previously affected by fire [9], on slopes blanketed by volcanic ash [10], and across a range of land-use categories in Balikpapan City and the Latung sub-watershed [11, 12], with land cover and land-management practice consistently emerging as the dominant explanatory factor. Studies in the second strand instead focus on how soil texture, pore architecture, and other physical attributes regulate infiltration, as demonstrated in research on semi-arid steppe soils [13], clay-rich Mediterranean soils [14], and comparative assessments of infiltration in relation to physical land characteristics across several land-use types [15]. Broader watershed- and land-management literature—for instance, work addressing European agricultural sustainability policy [16, 17]—offers useful background on land-use pressure within agricultural watersheds. However, it does not directly investigate the mechanisms underlying infiltration.

Taken together, this literature consistently points to land cover and soil texture- or pore-related properties as the principal controls on infiltration. At the same time, elevation itself is seldom examined as an explicit variable. This gap is particularly evident for the Padende sub-watershed and for similarly small, forested tropical watersheds, where elevation, slope, and land cover tend to change together rather than independently. The present study, therefore, surveys infiltration and its associated soil physicochemical properties across four elevation classes within the Padende sub-watershed, using elevation as a spatial sampling gradient rather than treating it as an isolated causal driver. More specifically, it seeks to determine which of the measured soil properties—porosity, texture, organic carbon content, bulk density, specific gravity, and permeability—show the strongest association with the variation in infiltration rate observed along this gradient.

2. Methodology

2.1 Data Collection

This research was conducted in the 1080-hectare Padende sub-watershed in Bumi Pajo Village, Donggo District, Bima Regency, West Nusa Tenggara Province, and was carried out in three primary phases. The first phase integrated an examination of pertinent literature with the analysis of spatial (shapefile) data, which included administrative boundary maps and a Digital Elevation Model (DEM). The raster-format DEM was converted to contour lines at 20-meter intervals, and then ArcGIS Map 10.4 was used to create the sampling-point map. Using the DEM, the research region was categorized into four elevation tiers—400, 600, 800, and 1000 meters above sea level—each containing three designated observation sites (see Figure 1).

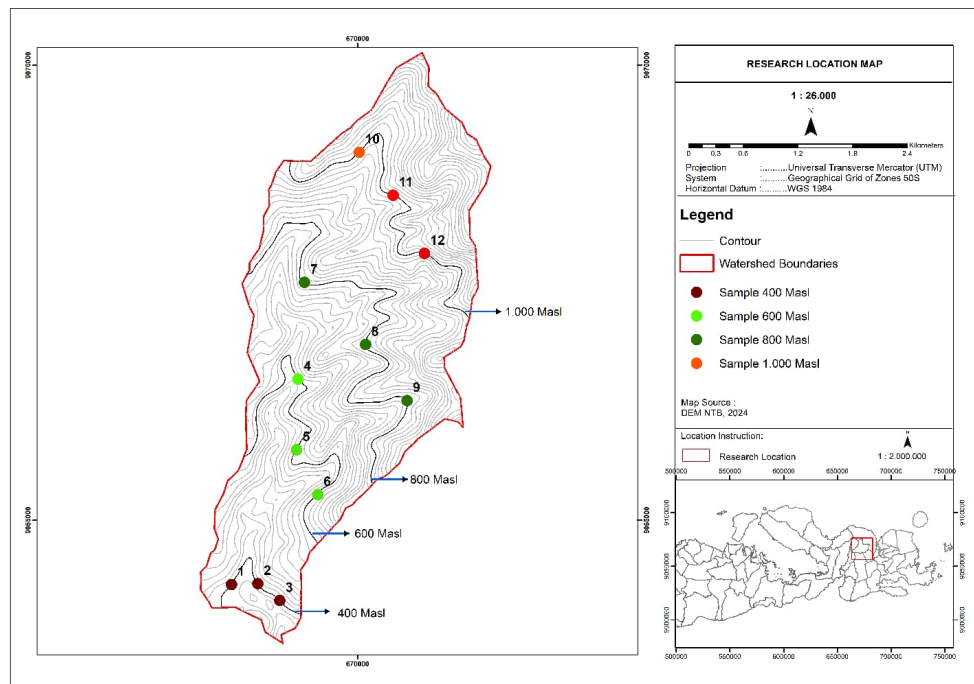


Fig 1. Research location map

2.2 Data Analysis

Infiltration rate was measured in the field following procedures specified in the Indonesian National Standard (SNI) 7752:2012, with the rate calculated using the equation below:

$$F = [\Delta h_c / \Delta t] \times 60$$

Notes:

Δh_c = Change in water level over each time interval (cm)

Δt = Time interval of measurement (minutes)

F = Infiltration rate (cm/hour)

The resulting data were then further processed using the Horton infiltration model, expressed through the following equations:

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

$$V(t) = f_c \cdot t + \frac{f_0 - f_c}{k} (1 - e^{-kt}) \quad (2)$$

Notes

F : Cumulative infiltration rate

f_c : Constant (steady) infiltration rate

f_0 : Initial infiltration rate

e : Euler's number (≈ 2.718)

t : Time (minutes)

k : Constant
V : Infiltration volume (mm³)

Infiltration rates were classified according to the scheme proposed by Kohnke (1968), as cited in [11], summarized in Table 2.

Table 2
Infiltration rate classification

Class	Infiltration (cm.h ⁻¹)
Very slow	0,1
Slow	0,1-0,5
Moderately slow	0,5-2
Moderate	2-6,5
Moderately fast	6,5-12,5
Fast	12,5-25
Very fast	>25

2.3 Statistical Analysis

Data analysis was performed using Principal Component Analysis (PCA) in Excel Stat to identify the dominant factors explaining the variation among the observed parameters.

3. Results

3.1 Measurement Data

Measurement results for each parameter are summarized in Table 3 below:

Table 3
Measurement results of research parameters

Elevation (masl)	Infiltration (cm.h ⁻¹)	C-organic (%)	Bulk density (g.cm ⁻³)	Specific gravity (g.cm ⁻³)	Porosity (%)	Texture	Land cover
400	21	1,85	1,83	91,97	41,52	Sandy clay loam	Mixed garden
600	19	1,44	1,96	119,36	120,57	Loamy sand	Coffee
800	28	1,17	1,96	113,36	93,99	Sandy clay loam	Candlenut
1000	25	1,56	1,74	135,97	148,07	Loamy sand	<i>Duabanga moluccana</i>

3.2 Relationship between infiltration and soil physicochemical properties

Figure 2 illustrates how organic carbon (C-organic), specific gravity, bulk density, and porosity relate to the infiltration rate.

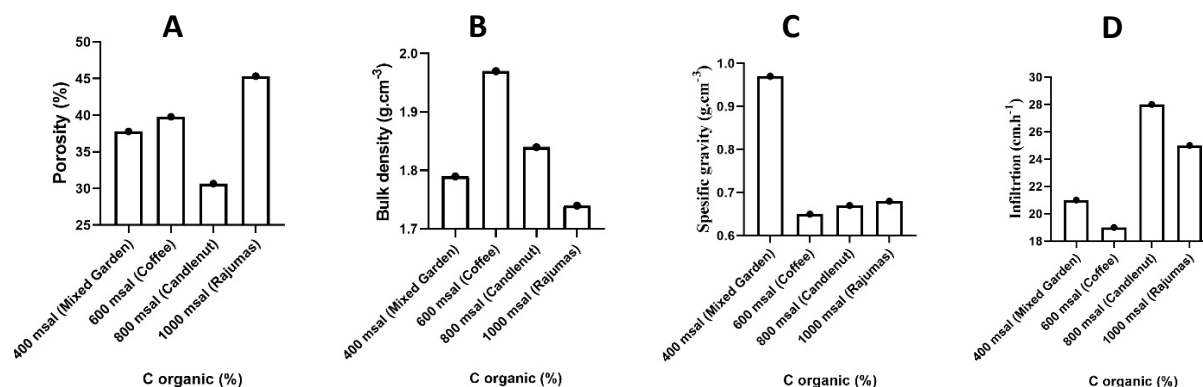


Fig. 2. Relationship between C organic (%), Porosity (A), Bulk density (B), Specific gravity (C), and Infiltration (D)

3.3 Correlation values among measured parameters

A strong positive relationship was found between organic carbon (C-organic) and specific gravity ($r = 0.817$), indicating that soils with greater organic matter tend to have higher specific gravity. A moderate positive relationship was also observed between C-organic and porosity ($r = 0.513$), indicating greater pore space in soils with higher organic matter content. By contrast, C-organic correlated negatively—at a moderate level—with infiltration rate ($r = -0.583$) and, more weakly, with bulk density ($r = -0.370$), implying that as organic matter increases, both infiltration and soil compaction tend to decrease (see Table 4).

Table 4

Inter-parameter correlation values

Variables	C organic (%)	Infiltration (cm.h ⁻¹)	Specific gravity (g.cm ⁻³)	Bulk density (g/cm ⁻³)	Porosity (%)
C organic (%)	1	-0.583	0.817	-0.370	0.513
Infiltration (cm.h ⁻¹)	-0.583	1	-0.317	-0.520	-0.398
Specific gravity (g.cm ⁻³)	0.817	-0.317	1	-0.369	-0.066
Bulk density (g.cm ⁻³)	-0.370	-0.520	-0.369	1	-0.254
Porosity (%)	0.513	-0.398	-0.066	-0.254	1

Values in bold are different from 0 with a significance level $\alpha=0.05$

As described in [20], [21], a PCA biplot shows a positive relationship between variables whose vectors form a narrow angle. In this study, for example, porosity and C-organic form such a narrow angle, pointing to a close association between the two, and the angle between specific gravity and porosity is likewise small, indicating a strong correlation. A wide angle between vectors, on the other hand, signals a negative relationship, as seen among infiltration, C-organic, bulk density, and specific gravity (see Figure 3).

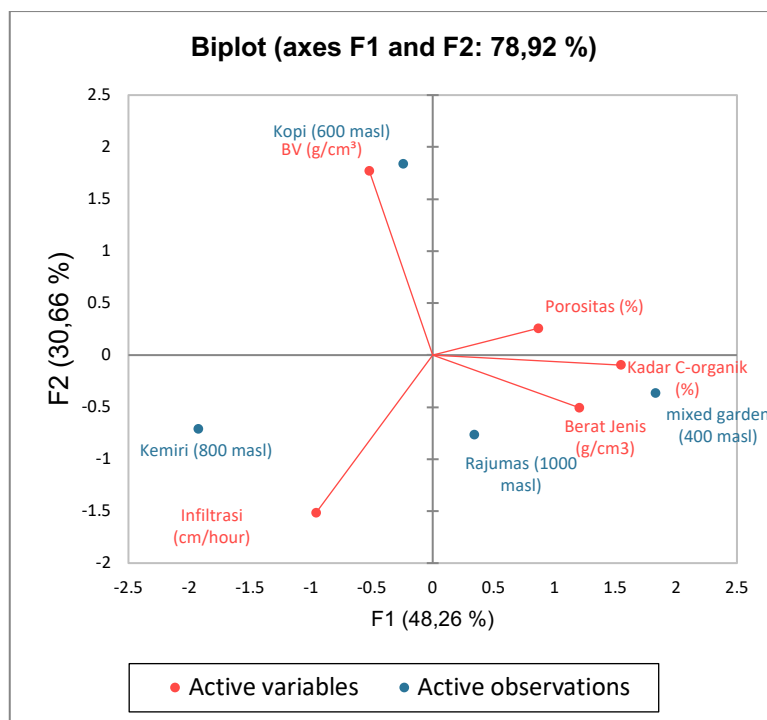


Fig 3. Biplot result of PCA analysis

The first two principal components, F1 (48.26%) and F2 (30.66%), account for 78.92% of the total variation in the soil physical property data set. The chief drivers for Component F1 are porosity, organic carbon, and specific gravity. Infiltration has an inverse relationship with the three factors. The trend is also indicated by the bulk density, which is generally at odds with porosity and organic carbon. However, it also indicates a specific effect on the entire data structure. The observation sites are characterized by altitude: rajumas/Duabanga moluccana stands (1000 masl), and candlenut stands (800 masl). Samples are more related to infiltration, whereas coffee (600 masl) and mixed-garden (400 masl) samples are more related to porosity and C-organic.

The correlation matrix of the relationships among the evaluated soil physical properties, estimated using Pearson correlation coefficients (r) at the 5% significance level ($\alpha = 0.05$), is shown in Table 4. This classification yields several important patterns. The C-organic had a strong positive correlation with specific gravity ($r = 0.817$), i.e., soils with higher organic matter content have higher specific gravity. It also showed a moderate positive correlation with porosity ($r = 0.513$), i.e., as organic matter increases, so does pore space. This trend is consistent with the results obtained at 400 masl, where an infiltration rate of 21 cm/hour is considered fairly rapid (1968). The increased infiltration at this site was probably a consequence of a soil pore architecture dominated by micropores, which occupy most of the pore volume, and was affected by organic matter, clay characteristics, moisture, compaction, and land management [22]; see Chun et al. [23].

At 600 masl, the infiltration rate was 19 cm h⁻¹, slightly lower than at 400 masl but still rapid. This reduction is consistent with an increased bulk density, which reflects a more compact arrangement of particles and thus a reduced pore volume. A negative correlation ($r = -0.520$) was observed, consistent with the lower infiltration rate attributable to the resulting reduction in pore space. This confirms the findings of [15], where weak interrelations among porosity, texture, and tree stands were detected. Likewise, an increase in slope is associated with a decrease in porosity. However, infiltration is on the negative axis of component F1, indicating an inverse relationship between high infiltration and high-porosity soils. This phenomenon could be explained by the fact that, in highly

permeable soils, where macropores are not dominant or the aggregate composition is unstable, large infiltration does not always occur. A decrease in organic content often accompanies a decrease in aggregate stability. For example, sandy soils can have high infiltration rates but low organic matter content.

Environmental factors, such as altitude, somewhat influence the F2 component. This is clearly evidenced by the stratification of the samples at different altitudes: 600 masl (coffee cover), 800 masl (candlenut cover), and 1000 masl (rajumas/Duabanga moluccana) along the F2 axis. Altitude affects temperature, moisture, and vegetation type, which in turn influence the processes of organic matter accumulation. A strong correlation between maximum porosity (148.07%) and infiltration rate (25 cm h⁻¹) was observed in soil under rajumas (Duabanga moluccana) at higher altitudes. This may be explained by a more granular soil composition (sandy loam) or a different moisture pattern. Increased porosity is also related to organic matter. Greater concentrations of organic matter at 1000 masl are probably caused by greater decomposition of foliage and dried twigs in conditions of increased precipitation and humidity. "Precipitation patterns have the biggest impact on the chemical characteristic of the soil called organic matter," Olojugba says. The 1000 masl altitude serves as an important rain-collecting zone, so its vegetation must be preserved. If this area is deforested, the chance of soil degradation will be very high.

These results imply that land cover and the associated physical and chemical properties of the soil (i.e., bulk density, specific gravity, porosity, texture, and organic carbon content) control the infiltration rate more than elevation itself. The infiltration amounts differed numerically among the four elevation classes, but all measurements fell within the "fast" classification, indicating no statistically significant correlation between elevation and infiltration in this dataset. It is important to note that elevation, slope, land cover, and soil characteristics covary within this watershed, with elevated areas mostly characterized by forest or tree-crop cover and lower areas more disturbed. The current sampling methodology cannot completely isolate the independent influence of elevation from these interrelated factors. This association needs to be clarified by further studies with more replicates per elevation class and land-cover type.

4. Conclusions

Infiltration rates in the Padende sub-watershed ranged from 19 to 28 cm h⁻¹ across the four sampled elevation classes (400, 600, 800, and 1000 m above sea level), and all values fell within the "fast" infiltration category regardless of elevation. This indicates that, within the range of conditions sampled, elevation alone was not associated with a systematic increase or decrease in infiltration rate. The variation observed among sites was instead accompanied by differences in land cover, ranging from mixed gardens and coffee at lower elevations to candlenut and rajumas (Duabanga moluccana) stands at higher elevations. These land-cover differences were paralleled by differences in soil physical and chemical properties across the sampled points.

Principal component analysis identified organic carbon content, specific gravity, and porosity as the properties most strongly associated with the observed variation, together explaining 78.92% of the total variance (F1 = 48.26%, F2 = 30.66%). Organic carbon showed a strong positive correlation with specific gravity ($r = 0.817$) and a moderate positive correlation with porosity ($r = 0.513$), while correlating negatively with infiltration rate ($r = -0.583$) and, to a lesser extent, with bulk density ($r = -0.370$). These patterns suggest that soils with higher organic matter content tend to have greater specific gravity and porosity but comparatively lower infiltration capacity, likely reflecting differences in pore-size distribution and aggregate structure rather than elevation itself. Land cover appears to

act as an intermediate factor linking elevation to the soil properties that more directly regulate infiltration.

For watershed management, these findings imply that maintaining forest and perennial tree cover, particularly in the upper part of the Padende sub-watershed, is likely to be more directly effective for sustaining infiltration capacity than managing elevation zones as such. This study is limited by its relatively small sample size (three points per elevation class) and by the confounding of elevation with slope, land cover, and soil properties, which prevents a fully independent statistical test of elevation's effect on infiltration. Future research incorporating a larger number of replicate plots, controlled comparisons of land cover within the same elevation band, and multivariate regression or mixed-effects modeling would help address this limitation. Overall, the results support the conclusion that infiltration in this sub-watershed is primarily controlled by land cover and its associated soil physicochemical properties, with elevation exerting, at most, an indirect influence mediated through these factors.

Conflict of Interest Statement

The authors confirm that no conflict of interest exists in connection with the publication of this article. No external funding, grants, or compensation were received in support of this research, and none of the authors hold commercial or financial ties that would represent a conflict of interest.

Author Contributions Statement

In this study, every author contributed meaningfully to the research process and to the preparation of the final manuscript. Suhairin took the lead in conceptualizing the study design, developing the research methodology, conducting fieldwork, and drafting the initial manuscript. Dyah Roeswitawati helped shape the overall study, assisted with data collection, and provided critical revisions that sharpened the manuscript's clarity. Muhidin contributed to field data collection and assisted with the statistical analysis and interpretation of the results. Joni Safaat Adiansyah was involved in interpreting the data and offered valuable feedback on methodological approaches. Handriany Erlianingsih reviewed and edited the manuscript, ensuring both scientific rigor and clarity of presentation. Ahmad Fathoni supported overall project coordination and participated in discussions on the findings and their implications. Together, the authors collaboratively refined the manuscript into a cohesive and well-rounded presentation of their research findings.

Data Availability Statement

All data relevant to the findings of this study are contained within the manuscript. Supplementary datasets can be obtained from the corresponding author upon reasonable request, and public data sources are properly cited in the references.

Ethics Statement

This research adhered strictly to the ethical guidelines established by the relevant institutional and national research committees. Where mandatory, ethical clearance was secured, and written or verbal informed consent was obtained from all study participants.

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