Journal of Elementology ISSN 1644-2296

Naharuddin, N., Massiri, S., Arianingsih, I., Rachman, I., Afadil, A. and Syahrir, M. (2026) 'Hydro-chemical assessment of soil degradation: linking elemental composition to erosion hotspots for targeted watershed rehabilitation', *Journal of Elementology*, 31(4), 759-778, available: https://doi.org/10.5601/jelem.2026.31.2.3841

RECEIVED: 14 April 2026
ACCEPTED: 11 October 2026

ORIGINAL PAPER

Hydro-chemical assessment of soil degradation: linking elemental composition to erosion hotspots for targeted watershed rehabilitation*

Naharuddin Naharuddin[1], Ida Arianingsih[1], Sudirman Dg Massiri[1], Imran Rachman[1], Afadil Afadil[2], Muhammad Syahrir[3]

[1] Department of Forestry, Faculty of Forestry, Tadulako University, Central Sulawesi 94119, Indonesia
[2] Department of Chemistry Education, Faculty of Education, Tadulako University, Central Sulawesi 94119, Indonesia
[3] Department of Chemistry, Makassar State University, Jl. Dg Tata 2 Kampus FMIPA Parangtambung, Makassar 90222, Indonesia

Abstract

Soil degradation in tropical watersheds is a synergistic process where physical mass loss is intrinsically linked to chemical instability and elemental depletion. This study quantifies soil loss and evaluates the hydro-chemical drivers of erosion in the Wimbi Sub-watershed, Poso Watershed, Indonesia, using an integrated Revised Universal Soil Loss Equation (RUSLE) and Geographic Information System (GIS) framework. The analytical focus was directed toward the interaction between rainfall erosivity (R=1,378.61), topographic factors, and the chemical properties of dominant soil types, specifically Dystropepts (59% coverage) and Hapludults (15%). Laboratory analysis reveals that high erodibility (K-factor up to 0.17) is primarily driven by the depletion of Soil Organic Carbon (SOC < 2.0%) and advanced mineral weathering under acidic conditions (pH 4.0-4.8). These chemical environments facilitate soil dispersion and reduce aggregate stability, leading to significant nutrient leaching, characterized by low Base Saturation (<20%) in Hapludult groups. Spatial modeling identified 1,417 ha (7.5%) as Critical Source Areas (CSAs), where steep topography (LS up to 9.5) and high erosivity converge with poor chemical buffering capacity. The findings indicate that these hotspots are not merely zones of physical detachment but represent primary sites for the export of essential elements into Lake Poso, threatening the lacustrine chemical balance and endemic biodiversity. The results underscore that effective watershed rehabilitation must move beyond physical stabilization to include chemical soil amendments that restore structural integrity and nutrient cycles. This study provides a vital empirical foundation for site-specific forest and land rehabilitation (FLR) strategies aimed at ensuring long-term hydrological and elemental stability in tropical basins.

Keywords: soil erosion, RUSLE model, elemental composition, nutrient leaching, watershed management.

Prof. Dr. Ir. Naharuddin, S.Pd., M.Si. Forestry Study Program, Faculty of Forestry, Tadulako University, Central Sulawesi 94119, Indonesia, e-mail: nahar.pailing@gmail.com or naharuddin.sumani@untad.ac.id

* This research was funded by the Public Service Agency of Tadulako University under the Budget Implementation List, according to the Rector's Decree No. 2653/UN28/KU/2024 dated May 22, 2024.

INTRODUCTION

Land resource degradation, particularly soil degradation, has emerged as one of the most persistent environmental challenges threatening food security, ecosystem integrity, and biodiversity in many developing countries. Soil, as a complex and dynamic natural medium, is inherently fragile and vulnerable to degradation processes such as erosion, organic matter depletion, and landslides (Putra et al. 2025).

Among these, soil erosion represents the second largest global environmental problem after population growth (Borrelli et al. 2020, Naharuddin et al. 2022). It poses a serious threat to the ecological stability of watersheds (De Mello et al. 2018), undermines agricultural productivity (Gomiero 2016) and contributes to the loss of fertile topsoil, biodiversity decline, and increased poverty among local communities (Sun et al. 2013, Sokouti, Nikkami 2017).

Anthropogenic pressures such as settlement expansion, unsustainable agricultural practices, and mining have accelerated soil erosion rates far beyond natural regeneration capacity (Wynants et al. 2019). Furthermore, unplanned and inappropriate land use cases are very important factors that put significant pressure on water and soil resources (Atmaca, Boyraz Erdem 2025). Consequently, many nations now prioritize soil and water conservation as a key strategy to achieve sustainable development goals and food security (Naharuddin et al. 2023). The effectiveness of conservation planning, however, largely depends on the ability to quantify soil loss and map erosion-prone areas in order to design targeted interventions (Gomiero 2016). Accurately determining the magnitude and spatial distribution of erosion helps policymakers and land managers minimize further degradation and develop site-specific rehabilitation programs (Bhat et al. 2017).

At the watershed scale, erosion assessment remains challenging due to the high degree of biophysical heterogeneity, including variations in topography, rainfall intensity, vegetation cover, and land-use patterns (Ballabio et al. 2017). These spatial temporal dynamics complicate the estimation of soil erosion and sediment yield. To address this complexity, empirical erosion models have been widely applied to simulate soil loss processes and support conservation planning (Hategekimana et al. 2020). Among these, the Revised Universal Soil Loss Equation (RUSLE) model has gained global recognition for its flexibility, simplicity, and proven accuracy across diverse landscapes (Gelagay, Minale 2016, Zou et al. 2020). RUSLE, an advanced version of the original USLE model, integrates rainfall erosivity, soil erodibility, topography, land cover, and conservation practices, making it an indispensable tool in land management and watershed restoration programs (Kalambukattu, Kumar 2017, Tessema et al. 2020). According to Phinzi et al. (2021), RUSLE serves as an essential framework for identifying erosion--prone zones and guiding forest and land rehabilitation efforts.

Beyond physical displacement, soil erosion in tropical basins acts as a primary mechanism for nutrient depletion. The loss of fertile topsoil involves the removal of essential elements and organic carbon, which are critical for maintaining the soil's buffering capacity and structural integrity. In the Wimbi Sub-watershed, understanding the chemical composition of dominant soil types, such as Dystropepts, is vital for assessing how elemental imbalances contribute to inherent soil vulnerability (K-factor) – Naharuddin et al. (2026).

Land degradation in tropical watersheds, particularly within the Wimbi Sub-watershed of the upper Poso Basin, has reached a critical threshold due to intensive anthropogenic pressures, including shifting cultivation and unsustainable land-use practices. While the physical manifestations such as increased flooding, downstream sedimentation, and the shallowing of the Poso River are well-documented, the underlying hydro-chemical mechanisms remain poorly understood. Current data indicates that approximately 1,354.6 ha of the 17,978.87 ha of total area are severely degraded, serving as primary sediment sources that jeopardize the ecological integrity of Lake Poso (Naharuddin et al. 2025, Palipadang et al. 2025). However, this degradation is not merely a physical displacement of soil mass but a profound disruption of elemental cycles, where the removal of fertile topsoil leads to the systemic depletion of essential nutrients and organic carbon.

The urgency of this research is underscored by the high rainfall erosivity (R=1,378.61 mm) and the predominance of inherently vulnerable soil types like Dystropepts, which are characterized by advanced weathering and poor chemical buffering capacity (Damanik et al. 2024). In these tropical environments, soil erodibility (K-factor) is dictated by a synergistic interaction between physical structure and chemical stability. The depletion of soil organic matter and acidic conditions (pH 4.0-4.8) facilitate soil dispersion and nutrient leaching, thereby accelerating both physical erosion and chemical degradation (Naharuddin et al. 2025). Without a spatially explicit understanding of these "elemental hotspots," rehabilitation efforts often fail to address the root causes of watershed instability.

Scientific assessments that integrate physical soil loss with chemical vulnerability in this specific catchment remain significantly limited. There is a critical knowledge gap regarding how the elemental composition of dominant soil types influences the watershed's overall response to erosive forces. This lack of empirical data hinders the development of targeted forest and land rehabilitation (FLR) strategies that could effectively mitigate the sediment and nutrient flux into Lake Poso, a tectonic system hosting irreplaceable endemic biodiversity.

Consequently, the novelty of this study lies in its integrated approach, utilizing high resolution RUSLE modeling and GIS-based spatial analysis to link soil chemical properties, specifically organic carbon and pH, to erosion hotspots. By identifying Critical Source Areas (CSAs), this research provides

a robust empirical foundation for policy formulation and site-specific land management. Therefore, this study aims to assess the erosion hazard levels and their spatial distribution in the Wimbi Sub-watershed, providing a scientific basis for developing sustainable rehabilitation strategies that restore both the hydrological stability and the elemental balance of the Poso Watershed ecosystem.

MATERIALS AND METHODS

Study area

The study was conducted from April to November 2024 in the Wimbi Sub-watershed, which forms part of the Poso Watershed in Central Sulawesi, Indonesia. This specific 8-month timeframe was strategically selected to capture the critical hydrological dynamics spanning the transition between the peak rainy season and the early dry season in Central Sulawesi. This operational window ensures optimal field conditions for conducting in-situ soil infiltration measurements using the Horton infiltrometer, collecting undisturbed soil samples without severe accessibility hazards caused by extreme hydro-meteorological events, and allowing sufficient temporal duration for comprehensive laboratory chemical analyses and GIS-based spatial modeling across the watershed. The research site is geographically located between 1°42′48.28″-1°54′13.87″ South Latitude and 120°38′56.19″-120°43′24.94″ East Longitude (Figure 1).

The Wimbi Sub-watershed covers approximately 17,978.87 ha and is characterized by diverse topography ranging from flat areas to very steep slopes. The region experiences a tropical climate with high rainfall intensity, and land use is dominated by mixed dryland agriculture, secondary forest, and shrubland.

Analysis of soil physical and chemical properties was carried out in the Soil Science Laboratory of the Faculty of Agriculture and the Laboratory of the Faculty of Forestry, Untad.

Data collection and analysis

This research employed a spatial quantitative approach integrating field observations, laboratory analyses, and Geographic Information System (GIS)-based modeling (Dilekoglu et al. 2025, Sari, Topal 2025). Primary data were collected through ground checks and field surveys to validate land use types, soil conditions, and slope gradients. Secondary data were obtained from multiple sources:

1. Rainfall data from the Meteorology, Climatology, and Geophysics Agency for the past ten years.
2. Soil maps and land system data from the Palu-Poso Watershed Management Center, Central Sulawesi.

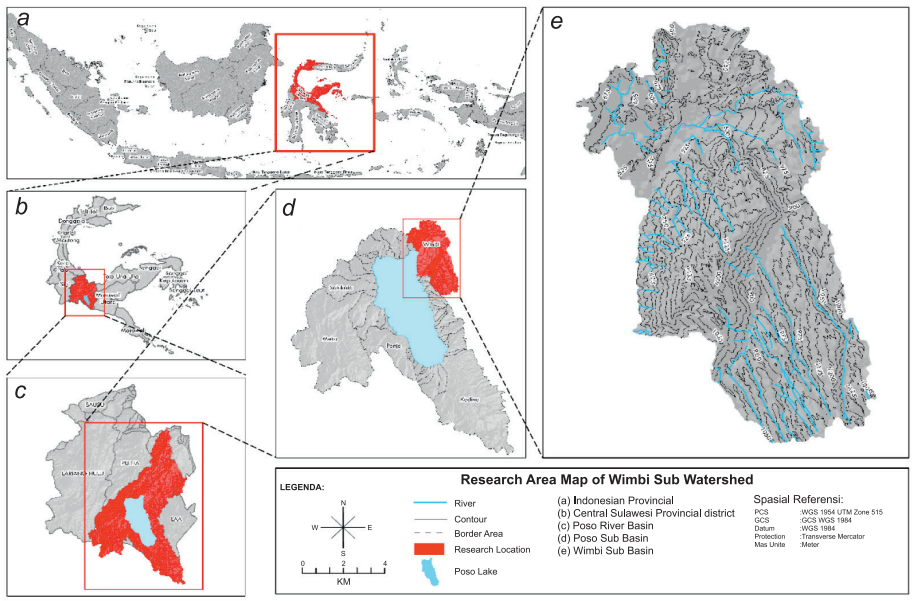


Fig. 1. Research area map of the Wimbi Sub-Watershed: *a* – Indonesian national map highlighting Central Sulawesi Province, *b* – Central Sulawesi Province showing Poso Regency, *c* – Poso Watershed and Poso Lake system, *d* – Poso Sub- Watershed highlighting the Wimbi Sub-Watershed location, *e* – Detailed topographic and river network map of the Wimbi Sub-Watershed

3. Digital Elevation Model (DEM) data with 30-meter resolution from the field survey.
4. Land-use/land-cover (LU/LC) data derived from Sentinel-2 imagery (2024).

All spatial datasets were processed and standardized in the same coordinate system (UTM Zone 51S, WGS 84). Data analysis was conducted using ArcGIS 10.8 and QGIS 3.28 software to perform raster processing, overlay analysis, and erosion risk mapping. Descriptive statistics were applied to quantify the extent of each erosion hazard class.

To establish the granulometric composition and inherent soil erodibility parameters, disturbed and undisturbed soil samples collected across representative land units underwent rigorous laboratory analyses. Soil texture comprising the quantitative distribution of sand, silt, and clay fractions was determined using the hydrometer method to evaluate particle-size distribution and its mechanical influence on aggregate stability. Furthermore, soil organic carbon was quantified via the Walkley-Black method, soil pH was measured in a H_2O suspension, and Cation Exchange Capacity (CEC) was assessed to comprehensively integrate physical and chemical attributes into the Revised Universal Soil Loss Equation (RUSLE) framework.

RUSLE modeling procedure

The Revised Universal Soil Loss Equation (RUSLE) model (Renard et al. 1997, Naharuddin et al. 2019) was used to estimate the average annual soil loss (A) in tons per hectare per year (t ha^{-1} yr^{-1}) using the following equation:

$$A=R \cdot K \cdot LS \cdot C \cdot P,$$

where: A = average annual soil loss (t ha^{-1} yr^{-1}),
R = rainfall erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}),
K = soil erodibility factor (t h MJ^{-1} mm^{-1}),
LS = slope length and steepness factor (dimensionless),
C = cover-management factor (dimensionless),
P = conservation practice factor (dimensionless).

Each factor was derived as follows:

R factor (rainfall erosivity) was calculated using long-term rainfall data following the empirical equation proposed by *Wischmeier and Smith (1978)* and adjusted for tropical conditions.

K factor (soil erodibility) was determined based on soil texture, organic matter content, structure, and permeability using the *Nomograph* method (Akpa et al. 2025).

LS factor (slope length and steepness) was extracted from the DEM using a spatial analysis algorithm to represent topographic influence on run-off and erosion potential.

C factor (cover-management) was assigned according to land-use types derived from Sentinel-2 imagery, referencing literature values for tropical ecosystems.

P factor (conservation practice) was based on existing land management practices such as contour farming, terracing, and agroforestry.

Each parameter was converted into a raster layer and processed using map algebra within ArcGIS to compute the spatial distribution of potential soil loss (Alemayehu et al. 2025, Thakur et al. 2025, Oualid et al. 2026). The final erosion hazard map was classified into five categories of areas: very low, low, moderate, high, and very high erosion risk (Bhat et al. 2017).

Field validation was performed through random sampling at 20 representative locations across different slope classes and land uses to ensure model reliability. The resulting data were compared with the observed soil erosion indicators (e.g., rill formation, sediment depth, and vegetation cover).

Chemical analysis

The chemical characteristics of the soil were determined at the Soil Science Laboratory, Faculty of Agriculture, Tadulako University, to provide a deeper understanding of the inherent vulnerability of the Wimbi Sub-watershed. This analysis focused on three pivotal parameters: soil organic carbon

(SOC), determined via the Walkley-Black method (Ratefinjanahary et al. 2025), soil pH (H_2O), and cation exchange capacity (CEC) according to instructions of Qing et al. (2025) and Peng et al. (2022). By quantifying SOC, the study assessed the soil's structural integrity and its role in maintaining aggregate stability against raindrop impact, while the measurement of pH provided critical insights into the degree of mineral weathering and solubility within this tropical ecosystem.

These chemical attributes are fundamentally linked to the soil erodibility factor (K) and the watershed's overall response to erosive forces. The integration of CEC data is particularly vital for evaluating the soil's capacity to retain essential nutrients against the intense leaching processes common in humid tropical environments, where the rainfall erosivity index reaches a high of R = 1,378.61. This shows that the integration of cation exchange capacity (CEC) data is critically important for evaluating the soil's capacity to retain essential nutrients against intense leaching processes typical of humid tropical environments, particularly in regions characterized by an exceptionally high rainfall erosivity index reaching R = 1,378.61. This hydro--chemical approach ensures that the resulting erosion hazard map not only identifies physical soil loss but also reflects the potential for chemical degradation and nutrient depletion in Critical Source Areas (CSAs), providing a more robust empirical foundation for targeted forest and land rehabilitation.

Analytical framework

The analytical framework integrates biophysical, spatial, and management factors to evaluate the erosion hazard level and identify priority areas for rehabilitation. This approach provides a scientific foundation for developing sustainable forest and land management strategies in the Poso Watershed and supports decision making processes in watershed policy and conservation planning.

RESULTS AND DISCUSSION

Rainfall erosivity (R)

The spatial and temporal distribution of rainfall plays a fundamental role in determining the magnitude of erosive forces acting on the landscape. In the Wimbi Sub-watershed, annual precipitation ranges from 2,000 to 3,000 mm, with a mean rainfall erosivity index (R) of 1,378.61 mm. This value is characteristic of humid tropical environments where the intensity and frequency of convective rainfall events are typically high. The notable variation of rainfall across the watershed indicates that erosive energy is not uniformly distributed. Instead, certain zones experience concentrated

high-energy rainfall events, which intensify soil detachment and enhance the mobilization of sediments.

To provide a clearer hydrological context for the 2024 study period, precipitation data recorded from local climate stations demonstrate distinct seasonal distribution characteristics between April and November. The cumulative rainfall during this 8-month operational window reached approximately 1,850 mm, accounting for nearly 65% of the annual total precipitation. A notable peak in monthly rainfall was observed between April and June, with average rainfall depths ranging from 250 to 320 mm per month and high daily intensities. These conditions drive intense convective events that contribute significantly to the rainfall erosivity index (R = 1,378.61). Conversely, a progressive decrease in rainfall volume occurred from August to October (dropping below 120 mm per month) corresponding to the transition into the early dry season. This temporal distribution highlights that the heightened risk of soil detachment and sediment mobilization is much more common during the high-intensity rainfall months within the monitored timeframe.

To establish a robust climatological baseline, historical precipitation records spanning the last ten years (2014-2024) and obtained from local meteorological stations were analyzed. Over this decadal timeframe, the annual precipitation has exhibited an average baseline of 2,400 to 2,800 mm, while the specific April–November period consistently accounts for roughly 65% to 70% of the total yearly volume (averaging 1,700 to 1,950 mm). Long-term trend analysis indicates an increasing inter-annual variability, marked by higher frequency of extreme convective storms during the transitional months (April–June) and more pronounced dry spells between August and October. This decadal persistence of high-intensity rainfall events underpins the high cumulative rainfall erosivity index (R = 1,378.61) utilized in this study, confirming that the erosion dynamics observed during the 2024 monitoring window reflect systemic long-term climatic patterns rather than isolated seasonal anomalies.

The heterogeneity observed in the distribution of R values suggests the influence of localized climatic factors, including elevation gradient, cloud formation patterns driven by orographic lifting, and seasonal shifts in monsoon dynamics. Areas at higher altitudes or those directly exposed to windward slopes tend to exhibit higher erosive forces compared to valley floors or leeward zones. This uneven distribution is consistent with erosion studies in tropical regions that highlight spatial variability in rainfall as a critical determinant of soil loss (Ganasri, Ramesh 2016, Tessema et al. 2020).

Furthermore, the significant rainfall erosivity implies that even minor disturbances in land cover, such as the clearing of vegetation, improper tillage, or exposure of bare soil, can rapidly escalate erosion rates. The combination of high-intensity rainfall and steep topography in the study area exacerbates the susceptibility of soil to detachment, emphasizing the necessity for adaptive and site-specific soil conservation strategies.

Soil erodibility (K)

Soil erodibility (K) describes the inherent vulnerability of soil to erosion under standardized conditions. The Wimbi Sub-watershed comprises six dominant soil types, with Dystropepts covering approximately 59% of the land area. This prevalence contributes significantly to the watershed's overall erosion dynamics. The mean erodibility value (K = 0.95) indicates a high susceptibility to erosion, reinforcing the importance of understanding soil characteristics when designing management interventions.

Among the soil groups, Hasplustult soils exhibit the highest erodibility (K = 0.17), whereas Rendolls exhibit the lowest one (K = 0.13). Several physical and chemical attributes contribute to the high erodibility of these soils. First, silt-loam texture, commonly found in the area, is well-documented as being highly prone to detachment due to weak aggregation. Second, the soil generally contains low organic matter, reducing their structural stability and limiting biological binding agents such as roots and microbial exudates. Third, moderate to high permeability increases the likelihood of rapid saturation during heavy rainfall events, promoting surface runoff and sediment transport.

Furthermore, laboratory analysis of the soil's granulometric composition confirmed that the high erodibility observed across the dominant soil units is heavily influenced by particle-size distribution. The analytical results indicate that the soils are predominantly composed of silt-loam and fine sandy--loam fractions, where silt and very fine sand contents frequently exceed 55% to 65%. This specific granulometric composition imparts weak structural aggregation and low cohesion, rendering the soil particles exceptionally vulnerable to detachment under high-intensity rainfall events and facilitating rapid sediment transport across steep slopes.

These findings align with broader literature on tropical soils, where weathered mineral compositions, acidic conditions, and reduced organic carbon contribute to high erodibility (De Mello et al. 2018, Phinzi et al. 2021). The predominance of such soils accentuates the need for vegetative cover and conservation practices to enhance aggregate stability and reduce the likelihood of soil detachment. In areas where erodible soils intersect with high LS values and elevated CP factors, erosion risks are compounded, reinforcing the complexity of watershed management in this landscape.

The spatial distribution and chemical characterization of dominant soil types in the Wimbi Sub-watershed reveal a complex interplay between pedological development and landscape stability (Table 1). The region is predominantly characterized by Dystropepts (59%) and Hapludults (15%), which exhibit advanced stages of weathering and acidification, with soil pH values ranging from 4.0 to 4.8. This acidic environment is intrinsically linked to intensive leaching processes, as evidenced by significantly low base saturation (BS) levels in Hapludults (< 20%) and Dystropepts (< 35%). Such low BS levels indicate a depletion of essential basic cations (Ca, Mg) and a heigh-

Table 1

Chemical properties and nutritional status of dominant soil types in the Wimbi Sub-watershed

Soil type (land System)	Area coverage (%)	Erodibility factor (K)	pH (H_2O)	Organic carbon (%)	Base saturation (%)
Dystropepts	59	0.15	4.2-4.8	low (< 2.0)	< 35
Hapludult	15	0.17	4.0-4.5	very low (1.5)	< 20
Rendolls	26	0.13	6.5-7.5	high (> 3.0)	> 50

tened risk of aluminum fixation, creating a nutrient-impoverished substrate that contrasts sharply with the Rendolls (26%). The Rendolls maintain a more neutral to slightly alkaline reaction (pH 6.5-7.5) and superior nutritional status (BS > 50%), reflecting the strong influence of basic parent materials.

The physical stability of these soils is heavily dictated by their elemental composition and organic matter status. In the dominant Dystropepts, the low organic carbon content (< 2.0%) acts as a primary driver for weak aggregate stability. This deficiency in organic "binding agents" renders the soil highly susceptible to detachment, particularly when exposed to high rainfall erosivity (R = 1,378.61). These chemical environments further facilitate soil dispersion during high-intensity convective rainfall events. Consequently, the soil erodibility factor (K) reaches its peak in Hapludults (0.17), representing the most vulnerable soil group despite its limited spatial coverage. Conversely, Rendolls exhibit the highest relative stability (K = 0.13), attributed to their thicker surface horizons and higher organic carbon accumulation (> 3.0%).

Furthermore, the quantitative estimation of nutrient depletion reveals alarming levels of nitrogen (N) and phosphorus (P) losses across the vulnerable soil units. In the Hapludults and Dystropepts, which cover 15% and 59% of the watershed, respectively, the total nitrogen loss due to accelerated surface runoff and organic matter stripping is estimated to range between 1.2 to 2.5 t ha^{-1} yr^{-1}, while available phosphorus loss reaches 45 to 85 kg ha^{-1} yr^{-1} in the designated Critical Source Areas (CSAs). This severe depletion is primarily driven by intense leaching under high rainfall erosivity (R=1,378.61) and low base saturation (<20%), where acidic soil conditions (pH 4.0-4.8) induce the fixation of phosphorus and rapid mineralization or volatilization of nitrogen. The substantial export of these essential macronutrients not only impoverishes the upland agricultural soils but also triggers severe downstream aquatic enrichment, threatening the oligotrophic balance and endemic biodiversity of Lake Poso.

Beyond mere physical degradation, the 1,417 ha identified as critical source areas (CSAs) represent significant zones of nutrient export. The transport of these leached elements and sediment-bound nutrients into Lake Poso poses a long-term threat to the lacustrine chemical balance and endemic

biodiversity. Therefore, the land dominated by Hapludults and Dystropepts necessitates intensive organic matter management and robust conservation strategies to mitigate both mass loss and nutrient flux. Collectively, these pedological insights provide a critical foundation for sustainable land-use planning and the preservation of the Wimbi Sub-watershed's ecological integrity.

Slope length and steepness (LS)

The LS factor reflects the combined influence of slope gradient and slope length on the accumulation and velocity of runoff. LS values in the Wimbi Sub-watershed range from 0.4 on flat or gently sloping terrain to 9.5 in very steep upland regions. The dominance of moderately steep slopes (representing 38% of the watershed) is a significant driver of erosion potential, especially when coupled with high rainfall erosivity and erodible soil types.

Steeper slopes are particularly vulnerable because increased gravitational force accelerates runoff velocity, enhancing the transport capacity of overland flow. Longer slope lengths further allow runoff to accumulate, intensifying its erosive power. These interactions indicate that the physical configuration of the watershed inherently predisposes it to elevated erosion risks.

Slope-driven erosion is well established in global erosion models, where even minor changes in slope gradient can lead to disproportionate increases in soil loss (Sun et al. 2013). In the Wimbi Sub-watershed, areas with the highest LS values coincide with land-cover types such as shrublands and mixed dryland farming, which typically have limited protective vegetation structures. This convergence of biophysical risk factors significantly contributes to the formation of gullies and rill erosion in disturbed landscapes.

The spatial pattern of LS values thus not only identifies erosion hotspots but also underscores the importance of implementing mechanical conservation techniques such as terracing, contour bunds, and check dams in steep upland zones.

Vegetation management and conservation factors (C and P)

Vegetation cover (C factor) and conservation practices (P factor) jointly determine the extent to which human and ecological systems mitigate the erosive pressures exerted on the landscape. In the study area, C and P values exhibit substantial variability, reflecting the diversity of land uses, management regimes, and vegetation structures.

Areas with the highest CP values such as settlements (0.40) and open land (0.30) exhibit minimal protective cover, leaving the soil surface highly exposed to rainfall impact and surface runoff. Such land uses typically lack root networks and surface litter that enhance soil cohesion. Conversely, primary dry forest demonstrates the lowest CP value (0.05), emphasizing the significant protective role of dense and multi-layered vegetation in reducing rainfall energy and improving infiltration.

The moderate CP values observed in agricultural areas (0.15-0.20) suggest partial soil protection depending on crop type, management intensity, and the presence of conservation structures. However, the absence of consistent contour farming or other soil conservation measures in many cultivated areas reduces their effectiveness in slowing runoff and preventing sediment transport.

This pattern aligns with established findings that vegetation structure, especially canopy cover, understory vegetation, and root density, is a key determinant of erosion control in tropical landscapes (Sokouti, Nikkami 2017). High CP zones identified in the Wimbi Sub-watershed signify areas where conservation agriculture, agroforestry, and mechanical soil protection practices should be prioritized.

Spatial heterogeneity and drivers of soil loss

The spatial assessment of erosion hazard in the Wimbi sub-watershed reveals a landscape defined by a sharp gradient of vulnerability, encompassing a total area of 18,025 ha. The results indicate a predominant distribution of lower-intensity erosion regimes, yet the presence of localized high-magnitude hotspots poses a significant threat to the long-term hydrological stability and sediment budget of the Poso River system.

General distribution of erosion hazard classes

Table 2 summarizes the extent of erosion hazard across five classification levels. The data shows that 57% of the sub-watershed is characterized by relatively stable conditions (very low to low), while 35% sits at a critical transitional state (Moderate), and approximately 7.5% represents high-risk zones that require immediate conservation intervention.

Table 2

Spatial Distribution of Erosion Hazard in Wimbi Sub-watershed

Class	Area (ha)	Percentage (%)
Very low	3,054	17
Low	7,256	40
Moderate	6,298	35
High	1,334	7
Very high	83	0.5
Total	18, 025	100

Very low and low-intensity regimes: The forest buffer effect

The “very low” (3,054 ha) and “low” (7,256 ha) classes are primarily situated within primary and secondary dryland forests that maintain dense,

multilayered vegetation structures. In these zones, the high canopy cover and well-developed root systems function as a biological shield against rainfall erosivity (R). Mechanistically, the multilayered canopy intercepts raindrops, reducing their terminal velocity and kinetic energy before they reach the soil surface.

Furthermore, these zones exhibit relatively low LS (slope length and steepness) values, reflecting gentler foot-slopes and alluvial plains. The combination of high organic matter content, which enhances soil aggregate stability, and minimal land disturbance (C and P factors) reinforces the erosional stability of these areas. These forested landscapes act as natural sediment buffers, preventing the transport of particles into the main drainage network (Archer et al.2021, Abebe et al. 2023).

Moderate hazard zones: The transitional threshold

The "moderate" hazard class, covering 6,298 ha (35%), represents the most extensive transitional zone. These areas are widely distributed across mixed agricultural landscapes, including agroforestry systems and partially cultivated uplands. The variability in vegetative cover throughout the year, particularly during the transition between planting seasons, increases the susceptibility of these areas to episodic soil loss.

From a pedological perspective, these moderate zones often occur on undulating terrain, where the balance between soil protection and erosive forces is precariously unstable. These areas are priority targets for land rehabilitation. Without the implementation of sustainable practices such as contour planting, mulching, or vegetative buffer strips, these 6,298 hectares are at high risk of shifting into the "high" hazard category due to the synergistic effect of slope length and seasonal tillage (Nugroho et al. 2020, Mekonnen, Melesse 2021).

High and very high hazard hotspots: Critical source areas (CSAs)

The "high" (1,334 ha) and "very high" (83 ha) classes constitute the "hotspots" of the Wimbi sub-watershed. Although they represent only 7.5% of the total landmass, their contribution to the total sediment yield is disproportionately high. These hotspots are concentrated in shrublands and open lands located on steep to very steep slopes (>40%).

These zones are characterized by elevated LS values and high soil erodibility, conditions that collectively amplify surface runoff and soil detachment. The absence of adequate ground cover exposes the soil to direct raindrop impact, facilitating the transition from sheet erosion to more aggressive rill and gully erosion. In mountainous catchments, such slope instability and land degradation intensify sediment fluxes, posing substantial risks to river morphology and the water quality of Lake Poso (Phinzi, Ngetar 2021, Rahman et al. 2022). For clarity, the spatial distribution of erosion hazard in Wimbi Sub-watershed can be seen in Figure 2.

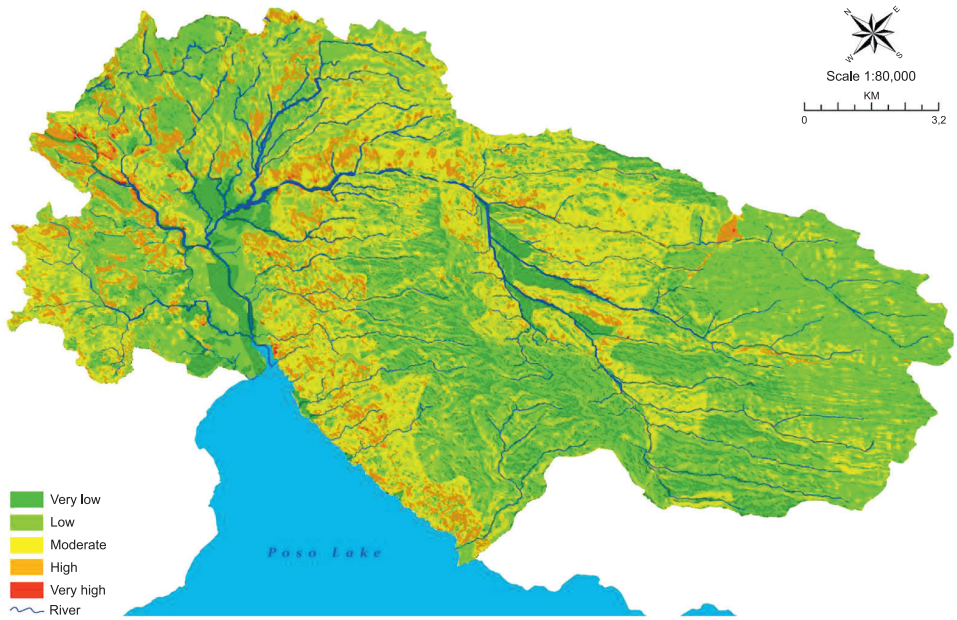


Fig.2. Spatial distribution of erosion hazard in Wimbi Sub-watershed

Elemental composition and soil erodibility (K)

The high mean erodibility (K=0.95) observed in the Wimbi Sub-watershed is a direct reflection of the synergistic interaction between its inherent physical limitations and chemical instability. A primary driver of this vulnerability is the widespread depletion of soil organic matter, with most sampled areas exhibiting low organic carbon levels. In these tropical soils, organic carbon serves as a vital biological binding agent the "chemical glues" necessary for maintaining structural integrity. The deficiency of these agents, particularly in soils with silt-loam textures, results in weak soil aggregation, rendering the surface particles highly prone to detachment under the kinetic energy of intense rainfall.

Furthermore, the prevalence of Dystropepts, which cover approximately 59% of the study area, indicates highly acidic conditions and advanced mineral weathering typical of humid tropical environments. These chemical environments are characterized by reduced structural stability and moderate to high permeability, which often lead to rapid saturation during heavy precipitation events. Such conditions facilitate the transition from infiltration to surface runoff, accelerating the mobilization of sediments across the watershed's steep topography where LS values reach up to 9.5.

The ecological implications of this erosion extend beyond physical land degradation to a significant phenomenon of nutrient export, particularly within the 1,417 hectares identified as Critical Source Areas (CSAs). These hotspots are not merely losing soil mass; they function as primary zones for

the intense flux of essential elements into the Poso River and Lake Poso. This chemical discharge, characterized by increased loading of phosphorus and nitrogen, poses a severe threat to the lacustrine biodiversity of the ancient tectonic lake system. The resulting sedimentation and nutrient enrichment jeopardize the water quality and the delicate ecological balance of the entire basin.

Furthermore, the intensity of soil degradation, particularly chemical erosion, is significantly influenced by the chemical properties and acidic reaction of incident rainfall. In humid tropical environments, rainwater interacting with atmospheric carbon dioxide and localized emissions exhibits a mildly acidic reaction, which, upon infiltrating the soil matrix, accelerates mineral weathering and the displacement of essential basic cations. This hydro-chemical interaction between rainfall acidity and vulnerable soil minerals (such as Dystropepts and Hapludults) exacerbates elemental leaching and structural dispersion, reinforcing the necessity to account for rainfall-soil chemical reactions when evaluating comprehensive watershed degradation dynamics.

Synthesis of biophysical drivers

The spatial distribution of erosion hazard in the Wimbi Sub-watershed is fundamentally shaped by the synergistic interaction between topography, soil vulnerability, and vegetation disturbance. The results align with global evidence demonstrating that erosion risk escalates when biophysical drivers, specifically high R and LS factors, operate simultaneously without adequate conservation measures (Borrelli et al. 2020, Zema et al. 2023).

The findings underscore an urgent need for integrated watershed-scale management. While the low-hazard zones provide essential ecosystem services, the moderate to high-risk areas require a shift toward climate-smart land-use planning and biotechnical slope stabilization to mitigate the downstream impacts on the Poso River's hydrological regime.

To better expose the most important factors influencing the intensity of soil erosion across the watershed, a comparative synthesis of the Revised Universal Soil Loss Equation (RUSLE) parameters was evaluated. The analytical breakdown indicates that topographic steepness (LS factor up to 9.5) coupled with high rainfall erosivity (R=1,378.61) serves as the primary hydrodynamic driver governing soil detachment intensity, overshadowing the moderating effects of vegetative cover in steep upland sectors. While soil erodibility (K-factor) dictates the inherent vulnerability of dominant soil units such as Dystropepts and Hapludults, spatial variance in soil loss is overwhelmingly dictated by the convergence of steep slopes and high--intensity convective rainfall. Consequently, targeted intervention strategies must prioritize slope-length reduction and mechanical-biological stabilization in zones where LS and R factors synergistically amplify erosion hazards.

The magnitude of soil loss observed in the Wimbi sub-watershed reflects

broader erosional trends documented in other critical tropical basins (Borrelli et al. 2020). When compared to high energy environments such as the Amazon Basin and the humid catchments of Central Africa, the Wimbi sub-watershed exhibits a similar 'hotspot' dynamic, where a small fraction of the landmass, primarily steep, disturbed slopes, dominates the total sediment budget (Rahman et al. 2022). For instance, the high rainfall erosivity (R=1,378.61) and steep topography (LS up to 9.5) found in this study align with findings from the tropical Andes and the Congo Basin, where synergistic biophysical drivers trigger rapid land degradation once the protective forest canopy is removed (Abebe et al. 2023, Useni Sikuzani, Bogaert 2025). However, the Wimbi sub-watershed presents a unique challenge due to its direct hydrological link to Lake Poso, an ancient tectonic lake system. While erosion in the Amazon primarily affects large-scale river morphology (Zema et al. 2023, Cruz et al. 2025, Ribas et al. 2025), the localized sediment delivery in Wimbi poses an immediate threat to endemic lacustrine biodiversity and regional water security, highlighting the global significance of site-specific rehabilitation in island-based tropical watersheds (Phinzi, Ngetar 2021).

CONCLUSIONS

This study provides robust empirical evidence that soil vulnerability within the Wimbi Sub-watershed is a synergistic consequence of aggressive hydro-climatic drivers and inherent chemical instability. Integration of RUSLE modeling and GIS-based spatial analysis across the 18,025-hectare landscape reveals a distinct vulnerability gradient. While 57% of the area remains relatively stable due to the protective buffering capacity of intact forest cover, 43% of the watershed is under significant degradation risk. These dynamics are fundamentally driven by high rainfall erosivity (R=1,378.61) and steep topographic factors (LS values up to 9.5), which overwhelm the natural resilience of the landscape when vegetation is disturbed.

A critical pedological finding of this research is that high erodibility is intrinsically linked to the depletion of soil organic carbon and poor chemical buffering capacity. In the identified 1,417 hectares (7.5%) of Critical Source Areas (CSAs), the "very high" erosion hazard is exacerbated by low organic matter status, which compromises soil structural integrity and facilitates rapid particle detachment. These hotspots are not merely physical sediment sources but are primary zones of elemental export that threaten the nutrient balance and endemic biodiversity of Lake Poso.

The practical implications of this study necessitate a paradigm shift from generalized conservation to spatially targeted, hydro-chemical rehabilitation. Priority interventions must be directed toward the CSAs, where bio-

technical slope stabilization should be integrated with chemical soil amendments. Restoring soil organic carbon and balancing the elemental composition is essential to improve the physical resilience of the soil against erosive forces. Ultimately, this integrated approach provides a vital foundation for adaptive land management and the long-term preservation of the hydrological and geochemical stability of the Poso Watershed ecosystem.

Author contributions

N.N: Conceptualization (research idea), Methodology (RUSLE model development), Software (GIS processing), Formal analysis (erosion rate analysis), Investigation (field surveys), Resources (provision of facilities), Data Curation (spatial data management), Writing – Original Draft (initial draft preparation), Writing – Review & Editing (manuscript revision), Visualization (map and chart creation), Supervision (primary supervision), Project administration (research administration), Funding acquisition (securing financial support). **I.A:** Methodology (design assistance), Investigation (field activities), Data Curation (nutrient data verification), Writing – Review & Editing (manuscript editing), Supervision (technical supervision). **S.D.M:** Formal analysis (landscape and ecosystem analysis), Investigation (land cover condition verification), Resources (forestry technical support), Writing – Review & Editing (conservation policy review). **I.R:** Methodology (soil and water conservation strategies), Investigation (soil sampling), Writing – Review & Editing (forestry technical validation). **A.A:** Formal analysis (laboratory soil chemical analysis), Investigation (cation and pH analysis), Validation (chemical data validation), Writing – Review & Editing (editing of environmental chemistry aspects). **M.S:** Formal analysis (micro and macro element analysis), Validation (laboratory result verification), Data Curation (statistical analysis of chemical data), Writing - Review & Editing (critical review of soil physicochemical aspects).

ACKNOWLEDGMENTS

This research was supported by the Public Service Agency of Tadulako University under the Budget Implementation List, pursuant to the Rector's Decree No. 2653/UN28/KU/2024 dated May 22, 2024. The authors extend their sincere gratitude to the Rector of Tadulako University and the Institute for Research and Community Service for their institutional support. Special thanks are also due to the Director of Postgraduate Studies and the MBKM students for their invaluable field assistance and cooperation throughout this study.

Conflicts of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as

a potential conflict of interest. No funding body or third party had any role in the design of the study, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

REFERENCES

Abebe, A., Tilahun, S., Dagnew, D. and Moges, M. (2023) 'Effects of land cover change on soil erosion in tropical highland watersheds', *Catena*, 221(1), 106779, available: https://doi.org/10.1016/j.catena.2022.106779

Akpa, E.A., Okon, P.B., and Abam, P.O. (2025) 'Application of erodibility nomograph from universal soil loss equation in the assessment of soil erosion in two agroecological zones', *Discover Soil*, 2(1), 14, available: https://doi.org/10.1007/s44378-025-00038-3

Alemayehu, S., Getahun, E. and Jothimani, M. (2025) 'Spatial and temporal analysis of soil erosion and sediment yield in the Shafe watershed, main Ethiopian rift region: integrating RUSLE model, GIS, and remote sensing techniques', *Discover Sustainability*, 6(1), 584-614, available: https://doi.org/10.1007/s43621-025-01427-y

Archer, M.S., Ali, A. and Mijatović, D. (2021) 'Forest ecosystem integrity and erosion mitigation in tropical landscapes', *Environmental Research*, 200(1), 111350, available: https://doi.org/10.1016/j.envres.2021.111350

Ballabio, C., Borrelli, P., Spinoni, J., Meusburger, K., Michaelides, S., Beguería, S. and Panagos, P. (2017) 'Mapping monthly rainfall erosivity in Europe', *Science of the Total Environment*, 579(1), 1298-1315, available: https://doi.org/10.1016/j.scitotenv.2016.11.123

Bhat, S.A., Hamid, I., Dar, M.U.D., Rasool, D., Pandit, B.A. and Khan, S. (2017) 'Soil erosion modeling using RUSLE & GIS on micro watershed of J&K', *Journal of Pharmacognosy and Phytochemistry*, 6(5), 838-842, available: https://www.phytojournal.com/archives/2017/vol6issue5/PartL/6-5-38-651.pdf

Borrelli, P., Robinson, D.A., Panagos, P., Lugato, E., Yang, J.E., Alewell, C. and Ballabio, C. (2020) 'Land use and climate change impacts on global soil erosion by water (2015-2070)', *Proceedings of the National Academy of Sciences*, 117(36), 21994-22001, available: https://doi.org/10.1073/pnas.2001403117

Cruz, G.M., Faria, A.P.J., Monteles, J.S., Dias-Silva, K., Casatti, L., Rivera-Perez, J.M. and Juen, L. (2025) 'Stream degradation: direct and indirect impacts of Amazonian deforestation', *Ecosystems*, 28(6), 1-16, available: https://doi.org/10.1007/s10021-024-00936-0

Damanik, A., Janssen, D.J., Tournier, N., Stelbrink, B., von Rintelen, T., Haffner, G.D., and Vogel, H. (2024) 'Perspectives from modern hydrology and hydrochemistry on a lacustrine biodiversity hotspot: Ancient Lake Poso, Central Sulawesi, Indonesia', *Journal of Great Lakes Research*, 50(3), 102254, available: https://doi.org/10.1016/j.jglr.2023.102254

De Mello, K., Valente, R.A., Randhir, T.O. and Vettorazzi, C.A. (2018) 'Impacts of tropical forest cover on water quality in agricultural watersheds in southeastern Brazil', *Ecological Indicators*, 93(1), 1293-1301, available: https://doi.org/10.1016/j.ecolind.2018.06.030

Gelagay, H.S. and Minale, A.S. (2016) 'Soil loss estimation using GIS and Remote sensing techniques: A case of Koga watershed, Northwestern Ethiopia', *International Soil and Water Conservation Research*, 4(2), 126-136, available: https://doi.org/10.1016/j.iswcr.2016.05.002

Gomiero, T. (2016) 'Soil degradation, land scarcity and food security: Reviewing a complex challenge', *Sustainability*, 8(3), 281, available: https://doi.org/10.3390/su8030281

Hategekimana, Y., Allam, M., Meng, Q., Nie, Y. and Mohamed, E. (2020) 'Quantification of soil losses along the coastal protected areas in Kenya', *Land*, 9(5), 137, available: https://doi.org/10.3390/land9050137

Kalambukattu, J. and Kumar, S. (2017) 'Modelling soil erosion risk in a mountainous watershed of Mid-Himalaya by integrating RUSLE model with GIS', *Eurasian Journal of Soil Science*, 6(2), 92-105, available: https://doi.org/10.18393/ejss.286444

Mekonnen, M. and Melesse, A.M. (2021) 'Soil erosion vulnerability under agricultural intensification in East African watersheds', *Sustainability*, 13(4), 2144, available: https://doi.org/10.3390/su13042144

Naharuddin, N., Massiri, S.D., Arianingsih, I., Malik, A., Rachman, I., Hamzari, H., and Malik, M (2026) 'Impact of forest conversion to intensive agriculture on soil hydrological functions in a tropical watershed, Central Sulawesi', *Acta Scientiarum Polonorum. Formatio Circumiectus*, 25(3), 89-99, available: https://doi.org/10.15576/ASP.FC/224817

Naharuddin, N., Rukmi, R., Massiri, S.D., Rachman, I., Malik, A., Golar, G., and Yahya, Y. (2025) 'Land Critical Level Degradation: Towards a Watershed Conservation Approach on A Continuous Basis', *Journal of Chinese Soil and Water Conservation*, 56(2), 66-74, available: https://doi.org/10.29417/JCSWC.202506_56(2).0003

Naharuddin, N., Wahid, A., Golar, G., Rachman, I., Akhbar, A., & Massiri, S.D. (2022) 'Soil infiltration in various areas as a basis for hydrological alterations in the Toboli Watershed, Central Sulawesi, Indonesia', *Water Conservation & Management*, 6(2), 76-80, available: http://doi.org/10.26480/wcm.02.2022.76.80

Naharuddin, N., Wahid, A., Rachman, I., Akhbar, A. and Golar, G. (2023) 'Assessment of Land and Water Conservation Practices Against Runoff and Erosion', *Polish Journal of Environmental Studies*, 32(1), 469-475, available: https://doi.org/10.15244/pjoes/154770

Nugroho, A.P., Arsyad, D.M. and Pramudita, H. (2020) 'Effectiveness of soil conservation practices in reducing erosion on sloping agricultural land', *Geoderma Regional*, 21(1), e00299, available: https://doi.org/10.1016/j.geodrs.2020.e00299

Oualid, A. T., Hamimed, A., Benamina, B., Miloudi, K. and Benslimane, M. (2026) 'Assessment of water erosion risk in the Fergoug watershed in Algeria using a GIS-based RUSLE approach', *Journal of Degraded and Mining Lands Management*, 13(1), 9531-9544, available: https://doi.org/10.15243/jdmlm.2026.131.9531

Palipadang, L., Sulbadana, S., Purnamasari, A.I., and Supriyadi, S. (2025) 'Preserving Lake Poso Through the Integrated and Comprehensive Legal Policies', *Cepalo*, 9(1), 25-36, available: https://doi.org/10.25041/cepalo.v9no1.3704

Phinzi, K. and Ngetar, N.S. (2021) 'Delineation of soil erosion hotspots in mountainous catchments using RUSLE and geospatial tools', *International Soil and Water Conservation Research*, 9(4), 526-537, available: https://doi.org/10.1016/j.iswcr.2021.03.003

Rahman, M., Tsujimoto, T. and Hagihara, Y. (2022) 'Sediment dynamics and erosion processes in steep-slope tropical watersheds', *Journal of Hydrology*, 610(1), 127963, available: https://doi.org/10.1016/j.jhydrol.2022.127963

Ratefinjanahary, I., MacKenzie, R., Sharma, S., Razakamanarivo, H., Razafintsalama, V., Ravelosamiariniriana, K., and Ramifehiarivo, N. (2025) 'Development of soil organic carbon quantification model and comparison based on CHN analyser, Loss on Ignition, and Walkley-Black methods for mangrove soils in Madagascar', *Estuarine, Coastal and Shelf Science*, 317, 109182, available: https://doi.org/ 10.1016/j.ecss.2025.109182

Ribas, C.C., Sawakuchi, A.O., de Almeida, R.P., Pupim, F.N., Rego, M.A., Batista, R. and Knowles, L.L. (2025) 'The role of rivers in the origin and future of Amazonian biodiversity', *Nature Reviews Biodiversity*, 1(1), 14-31, available: https://doi.org/10.1038/s44301-024-00005-w

Sokouti, R. and Nikkami, D. (2017) 'Optimizing land use pattern to reduce soil erosion', *Eurasian Journal of Soil Science*, 6(1), 75-83, available: https://doi.org/10.18393/ejss.284272

Sun, W., Shao, Q. and Liu, J. (2013) 'Soil erosion and its response to the changes of precipita-

tion and vegetation cover on the Loess Plateau', *Journal of Geographical Sciences*, 23(6), 1091-1106, available: https://doi.org/10.1007/s11442-013-1065-z

Tessema, Y.M., Jasińska, J., Yadeta, L.T., Świtoniak, M., Puchałka, R. and Gebregeorgis, E.G. (2020) 'Soil loss estimation for conservation planning in the Welmel watershed of the Genale Dawa Basin, Ethiopia', *Agronomy*, 10(6), 777, available: https://doi.org/10.3390/agronomy 10060777

Thakur, T.K., Patel, D.K., Thakur, A. and Arora, N.K. (2025) 'Evaluation of land degradation vulnerability in coal mined areas of Madhya Pradesh, India using geospatial and AHP modeling: a 40-year assessment and eco-restoration of degraded landscape', *Environmental Sustainability*, 8(1), 85-101, available: https://doi.org/10.1007/s42398-024-00320-7

Useni Sikuzani, Y. and Bogaert, J. (2025) 'The evolution of landscape ecology in the Democratic Republic of the Congo (2005-2025): Scientific advances, methodological challenges, and Future Directions', *Earth*, 6(3), 97, available: https://doi.org/10.3390/earth6030097

Zema, D.A., Tamburino, V. and Zimbone, S.M. (2023) 'Soil erosion modeling and sediment management in Mediterranean catchments: Advances and challenges', *Catena*, 225(1), 107052, available: https://doi.org/10.1016/j.catena.2023.107052

Zou, L., Liu, Y., Wang, Y. and Hu, X. (2020) 'Assessment and analysis of agricultural non-point source pollution loads in China: 1978-2017', *Journal of Environmental Management*, 263(1), 110400, available: https://doi.org/10.1016/j.jenvman.2020.110400