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Integrated GIS-based soil erosion assessment and conservation planning for sustainable watershed management in the Comoro Basin, Timor-Leste

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ABSTRACT

Soil erosion and land degradation have become critical environmental challenges in Timor-Leste due to rapid land-use change, deforestation, and unsustainable watershed management practices. The Comoro Watershed, one of the priority river basins in Timor-Leste, has experienced increasing surface runoff, erosion, and sedimentation that threaten water resources sustainability and ecosystem stability. This study aimed to assess spatial soil erosion rates and develop integrated land conservation strategies based on water resource management using Geographic Information Systems (GIS), the Revised Universal Soil Loss Equation (RUSLE), and the Modified Universal Soil Loss Equation (MUSLE). Spatial analyses were conducted using rainfall, topography, soil type, and land-use data for the 2021 land-use condition in the Comoro Watershed. The estimated annual soil erosion rate reached 27.1 t ha^{-1} yr^{-1}, with the RUSLE model providing the most representative erosion estimation. Areas with steep slopes, sparse vegetation cover, and intensive land conversion exhibited the highest erosion susceptibility. To reduce erosion risk, integrated watershed conservation measures were developed through vegetative and mechanical approaches within an Integrated Water Resources Management (IWRM) framework. Vegetative conservation strategies included the designation of protected areas, buffer zones, perennial crop cultivation, and agroforestry-based land management. Mechanical conservation was proposed through the construction of a check dam in the Comoro River. The conservation scenario significantly reduced the estimated erosion rate to 0.73 t ha^{-1} yr^{-1}, indicating the effectiveness of integrated land conservation planning for erosion mitigation. The study demonstrates that GIS-based erosion modeling combined with integrated watershed conservation planning provides an effective approach for sustainable land and water resource management in tropical watershed systems, particularly in developing countries such as Timor-Leste.

1. Introduction

Watershed degradation and soil erosion have become major environmental challenges in many developing countries, particularly in tropical regions experiencing rapid land-use change and deforestation. Soil erosion not only reduces land productivity but also increases sediment transport, river siltation, flooding, and deterioration of water resource sustainability. In watershed systems, uncontrolled land conversion and inadequate conservation practices significantly disturb hydrological processes, resulting in increased surface runoff and land degradation [1, 2]. Consequently, sustainable watershed management has become an essential strategy for maintaining environmental stability and supporting long-term socio-economic development.

Timor-Leste is a mountainous tropical country characterized by steep topography, fragile land resources, and highly seasonal rainfall patterns. Approximately 59% of the country's territory was historically covered by forest ecosystems; however, substantial land-cover changes have occurred over recent decades due to agricultural expansion, forest exploitation, settlement development, and unsustainable land management practices. Previous studies reported that Timor-Leste lost approximately 24% of its vegetation cover over a 27-year period, resulting in increased watershed vulnerability to erosion and hydrological disturbances. These environmental changes have accelerated land degradation processes and reduced the capacity of watersheds to regulate water flow and maintain ecological balance [3–5].

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The Comoro Watershed, located in Dili, is one of the most important river basins in Timor-Leste because it supports urban activities, agricultural production, and water resource availability for surrounding communities. However, rapid land-use transformation within the watershed has intensified erosion hazards, increased sedimentation, and reduced watershed functionality [6, 7]. The upstream areas of the watershed are particularly vulnerable due to steep slopes, sparse vegetation cover, and inappropriate land utilization. If these conditions continue without proper conservation measures, the watershed may experience severe environmental degradation, including floods, sediment accumulation, and declining water quality.

Soil erosion is strongly influenced by rainfall intensity, slope characteristics, soil properties, vegetation cover, and land management practices. Therefore, effective watershed conservation requires integrated approaches that combine hydrological assessment, land-use planning, and environmental management. Geographic Information Systems (GIS) have become an effective tool for spatial analysis and watershed evaluation because they allow the integration of topographic, hydrological, climatic, and land-use data into comprehensive spatial models. In erosion studies, GIS is commonly integrated with empirical erosion models such as the Revised Universal Soil Loss Equation (RUSLE) and the Modified Universal Soil Loss Equation (MUSLE) to estimate erosion rates and identify priority conservation areas [8–10].

Several previous studies have applied RUSLE and GIS approaches for erosion assessment and watershed management in different regions. In the previous research some researcher demonstrated that steep slopes combined with intensive land-use activities significantly increased erosion risk in the Langat Watershed, Malaysia [3]. Another researchers emphasized that spatial erosion assessment is essential for identifying conservation priority areas and supporting sustainable watershed planning in Rwanda [4]. Similarly, some researcher also highlighted the importance of watershed-based soil erosion modeling for developing effective soil and water conservation strategies in Ethiopia [5]. Although numerous studies have investigated erosion modeling using GIS and RUSLE, studies integrating erosion assessment with Integrated Water Resources Management (IWRM)-based conservation planning in Timor-Leste remain very limited [3, 11].

Previous research in the Comoro Watershed primarily focused on general land-use analysis and erosion estimation without comprehensive integration between spatial erosion assessment and conservation planning strategies [12, 13]. Moreover, limited studies have evaluated the effectiveness of combined vegetative and mechanical conservation approaches in reducing erosion rates within tropical watershed systems in Timor-Leste. Therefore, there is still a significant research gap regarding integrated GIS-based watershed conservation planning for sustainable erosion mitigation in the Comoro Basin [6, 14, 15].

This study aims to assess the spatial distribution of soil erosion in the Comoro Watershed using RUSLE and MUSLE models integrated with GIS analysis and to develop conservation planning strategies based on Integrated Water Resources Management (IWRM) principles. Specifically, this study aims to: (1) estimate soil erosion rates under existing land-use conditions, (2) identify appropriate land conservation strategies for erosion reduction, and (3) evaluate the effectiveness of conservation scenarios in reducing soil erosion rates within the watershed. The findings of this study are expected to support sustainable watershed management and provide scientific references for land conservation planning in Timor-Leste and other tropical developing regions.

2. Materials and Methods

2.1. Study area

The study was conducted in the Comoro Watershed located in Dili, Timor-Leste (Fig. 1). The Comoro Watershed is one of the priority watersheds in Timor-Leste due to its strategic role in supporting urban water supply, agricultural activities, and ecosystem sustainability. Geographically, Timor-Leste is situated between 123°–127° E and 8°–10° S, while the Comoro Watershed is characterized by mountainous upstream areas and relatively flat downstream regions. The watershed experiences tropical climatic conditions with distinct wet and dry seasons, resulting in high rainfall variability and increased susceptibility to erosion processes [4, 16].

Topographically, the watershed consists of steep slopes in the upstream areas that gradually transition into lowland plains near the downstream section. Land-use types within the watershed include forest areas, agricultural land, settlements, shrubland, and open land. Rapid land-use changes and vegetation loss in recent decades have increased surface runoff, soil erosion, and sedimentation within the watershed system [17, 18].

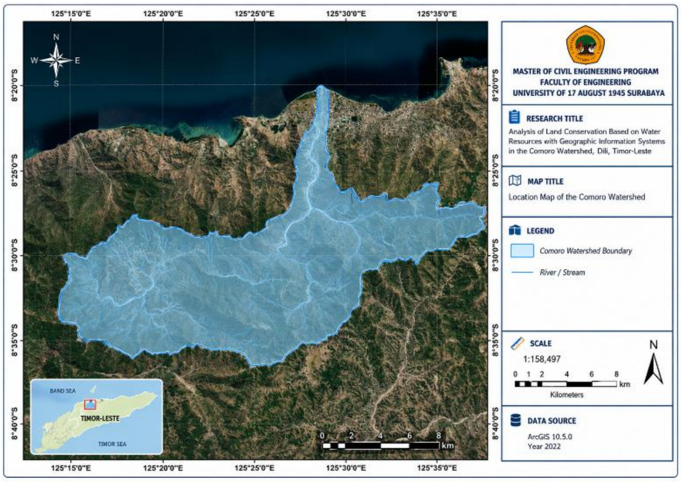


Fig. 1. Geographic location of the Comoro Watershed in Dili, Timor-Leste, including watershed boundary delineation and river network derived from GIS spatial analysis. The watershed area is characterized by mountainous upstream terrain and coastal downstream regions that influence hydrological response and soil erosion dynamics.

2.2. Data collection

This study utilized both primary and secondary data. Secondary data included rainfall records, land-use maps, soil type maps, topographic maps, and Digital Elevation Model (DEM) data. Rainfall data were obtained from available hydrological stations surrounding the watershed area [3, 6, 16]. Land-use and spatial datasets were processed using Geographic Information Systems (GIS) software. The required datasets consisted of :

- Annual and monthly rainfall data
- Digital Elevation Model (DEM)
- Soil type and soil characteristics data
- Land-use and land-cover maps for 2021
- River network and watershed boundary maps
- Hydrological and topographical information

Primary observations were conducted to verify land-use conditions and identify erosion-prone areas within the watershed [19–21].

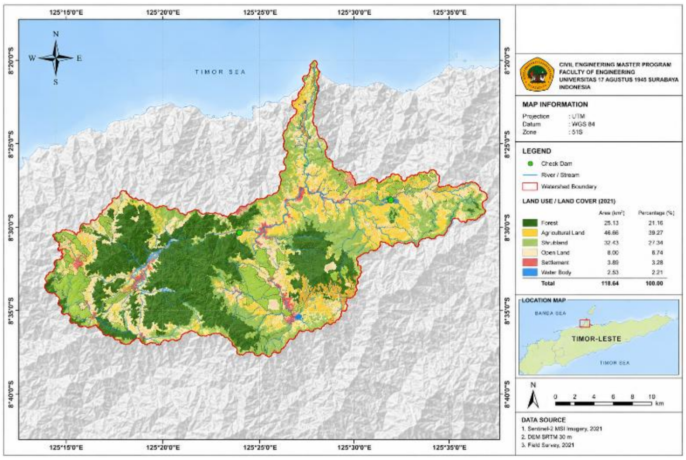


Fig. 2. Land-use or lland-cover distribution in the Comoro Watershed, Dili, Timor-Leste (2021), derived from GIS spatial analysis.

2.3. *Research framework*

The research framework consisted of several sequential stages, including:

- Collection and preparation of spatial and hydrological data
- Hydrological analysis and rainfall assessment
- GIS-based spatial analysis
- Estimation of soil erosion using RUSLE and MUSLE methods
- Identification of erosion hazard levels
- Development of integrated land conservation strategies
- Evaluation of erosion reduction under conservation scenarios

The overall workflow integrated hydrological analysis and GIS-based spatial modeling to support watershed conservation planning [3, 6, 16].

2.4. *Hydrological and runoff discharge analysis*

Rainfall data consistency was evaluated using the Double Mass Curve method to ensure the reliability of rainfall records. This method compares cumulative rainfall data from the target station with cumulative rainfall from surrounding stations. Consistent rainfall data produce a linear relationship, whereas inconsistencies indicate possible observational errors or environmental changes. Average watershed rainfall was calculated using the Thiessen Polygon method because rainfall stations within the study area were not uniformly distributed. This method assigns weighting factors based on the representative area of each rainfall station [6, 14, 15].

Design rainfall was estimated using the Log Pearson Type III distribution, which is widely applied in hydrological frequency analysis due to its flexibility in handling skewed hydrological datasets. Statistical parameters including mean, standard deviation, skewness coefficient, and kurtosis coefficient were calculated to evaluate rainfall distribution characteristics. The suitability of the selected probability distribution was tested using chi-square test and smirnov–kolmogorov test.

Peak runoff discharge was estimated using the Modified Rational Method. The method considers rainfall intensity, runoff coefficient, watershed area, and storage coefficient. The runoff discharge equation is expressed as:

$$Q = 0.278 \times C_s \times C \times I \times A \qquad \ldots (1)$$

where: Q = peak discharge (m³/s)*;* Cs = storage coefficient*;* C = runoff coefficient*;* I = rainfall intensity (mm/h)*;* A = watershed area (km²).

Rainfall intensity was calculated using the Mononobe equation based on rainfall duration and concentration time [19–21].

2.5. *Soil erosion analysis.*

Soil erosion rates were estimated using the Revised Universal Soil Loss Equation (RUSLE) integrated with GIS spatial analysis. The RUSLE equation is expressed as:

$$\boldsymbol{A = R \times K \times LS \times C \times P} \qquad (2)$$

where: A = annual soil erosion rate (t ha⁻¹ yr⁻¹); R = rainfall erosivity factor; K = soil erodibility factor; LS = slope length and steepness factor; C = cover management factor; P = conservation practice factor.

Each factor was generated spatially using GIS raster analysis. The rainfall erosivity factor was derived from rainfall intensity data, while the LS factor was generated from DEM-based slope analysis.

The Modified Universal Soil Loss Equation (MUSLE) was applied to estimate sediment yield based on runoff characteristics. The MUSLE equation is expressed as:

$$\boldsymbol{SY = a\left(V_q \times Q_p\right)^b \times K \times LS \times C \times P} \qquad (3)$$

where: SY = sediment yield (ton/year); Vq = runoff volume (m³); Qp = peak discharge (m³/s); K = soil erodibility factor; C = cover management factor; P = conservation practice factor; LS = slope length and steepness factor; a *and* b = empirical coefficients. The MUSLE model was used to compare erosion estimates obtained from the RUSLE method.

Spatial analyses were conducted using Geographic Information Systems (GIS) to integrate thematic layers including:

- Rainfall distribution,
- Slope classes,
- Soil types,
- Land-use maps,
- Erosion hazard levels.

Overlay analysis was applied to identify erosion-prone zones and determine conservation priority areas within the watershed.

Land conservation planning was developed based on Integrated Water Resources Management (IWRM) principles through vegetative and mechanical conservation approaches. Vegetative conservation strategies included:

- Protected forest zones,
- Agroforestry systems,
- Perennial crop cultivation,
- Buffer zone management.

Mechanical conservation focused on the construction of check dams in erosion-prone river sections to reduce sediment transport and stabilize runoff flow. The effectiveness of conservation planning was evaluated by comparing erosion rates before and after conservation implementation scenarios. Changes in RUSLE and MUSLE parameters, particularly cover management and conservation practice factors, were simulated spatially using GIS to estimate erosion reduction within the watershed.

3. Results and discussion

The Comoro Watershed is one of the most important watershed systems in Dili, Timor-Leste, due to its strategic role in supporting water resources, agricultural activities, and urban development. The watershed covers approximately 118.64 km² and is characterized by mountainous upstream terrain and relatively flat downstream coastal areas. These topographical conditions strongly influence hydrological processes, runoff generation, and soil erosion intensity within the watershed. The geographic location and spatial extent of the watershed are presented in Fig. 1.

Land-use analysis derived from GIS spatial interpretation indicated that agricultural land and shrubland dominate the watershed area, reflecting extensive land-cover conversion and vegetation degradation. The spatial distribution of land use within the Comoro watershed is presented in Fig. 2. Agricultural land occupied approximately 39.27% of the watershed area, followed by shrubland (27.34%) and forest areas (21.16%). Smaller proportions consisted of open land, settlements, and water bodies. The dominance of agricultural and degraded shrubland areas indicates increasing anthropogenic pressure on the watershed ecosystem [14, 22, 23].

Table 1
Land-use distribution in the Comoro watershed (2021)

Land Use Type	Area (km²)	Percentage (%)
Forest	25.13	21.16
Agricultural Land	46.66	39.27
Shrubland	32.43	27.34
Open Land	8.00	6.74
Settlement	3.89	3.28
Water Body	2.53	2.21
Total	118.64	100.00

The conversion of forested areas into agricultural land and shrubland has significantly reduced vegetation density and watershed protection capacity. Reduced vegetation cover decreases infiltration and accelerates surface runoff, which subsequently increases erosion susceptibility. Similar observations were reported in tropical watershed studies where land-use change was identified as one of the dominant factors controlling watershed degradation and sediment production.

Slope analysis derived from the Digital Elevation Model (DEM) revealed that steep slopes dominate the upstream portions of the watershed. The spatial distribution of slope classes is shown in Fig. 3. Areas with slopes greater than 25% were primarily concentrated in mountainous regions and exhibited high susceptibility to runoff generation and erosion processes. Steeper slopes increase runoff velocity and sediment transport capacity, thereby intensifying soil loss during high rainfall events.

Table 2
Slope classification in the Comoro watershed

Slope Class (%)	Area (km²)	Percentage (%)	Topographic Description
0–8	19.42	16.37	Flat
8–15	24.86	20.95	Gentle
15–25	31.77	26.78	Moderately Steep
25–40	28.64	24.14	Steep
>40	13.95	11.76	Very Steep
Total	118.64	100.00	

The combination of steep topography and degraded land cover substantially increases erosion vulnerability in the upstream watershed areas. According to previous studies, slope steepness is one of the most influential parameters in erosion prediction models because it directly affects runoff energy and sediment transport dynamics.

Rainfall analysis was conducted using rainfall records from 2000–2021. Spatial rainfall distribution generated through GIS interpolation is presented in Fig. 4. The watershed experiences highly seasonal tropical rainfall characterized by intense precipitation during the wet season. Rainfall intensity increases significantly during extreme rainfall events, resulting in high runoff generation and enhanced erosion potential. The design rainfall estimation using the Log Pearson Type III distribution is summarized in Table 3.

Table 3
Design rainfall estimation using Log Pearson Type III distribution

Return Period (years)	Rainfall (mm)	Chi-Square (χ^2calc)	Smirnov–Kolmogorov (Dcalc)	Conclusion
2	89.40	2.74	0.073	Accepted
5	120.45	3.21	0.081	Accepted
10	142.98	4.05	0.096	Accepted
25	168.76	5.12	0.102	Accepted
50	189.50	6.10	0.115	Accepted
100	211.64	7.21	0.128	Accepted

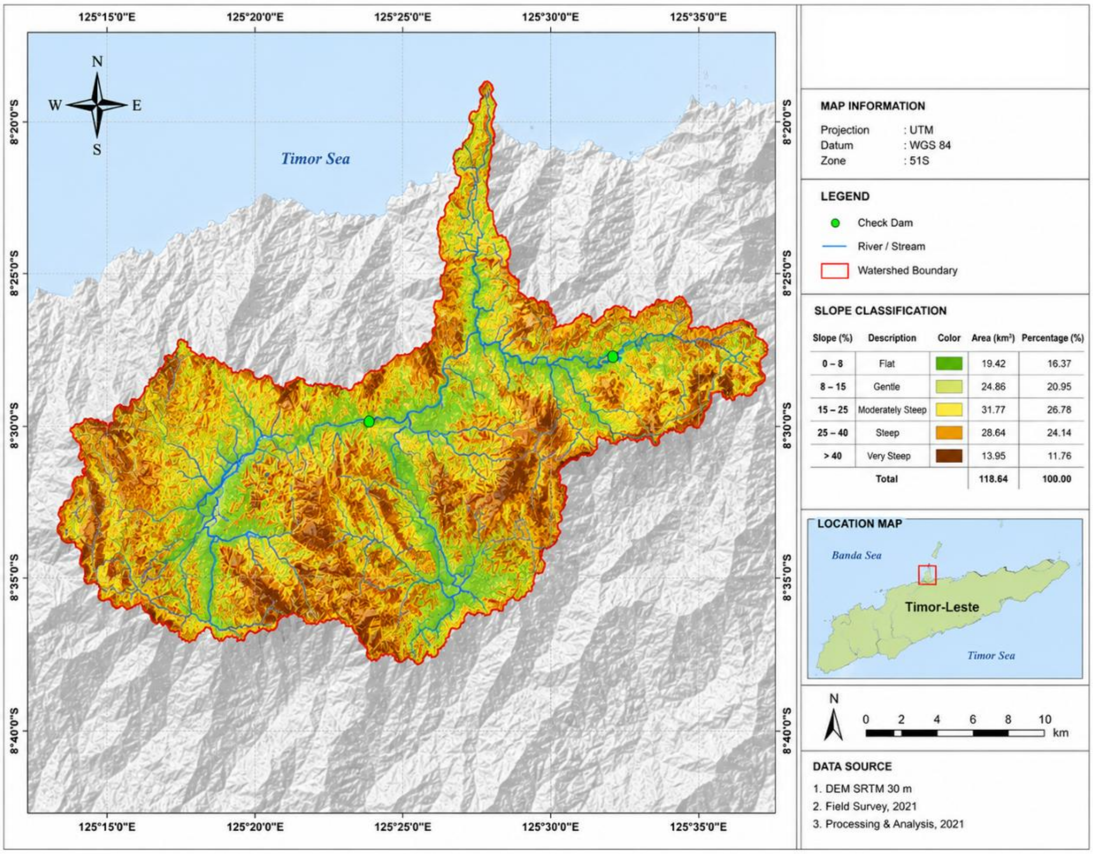


Fig. 3. DEM-derived slope classification map of the Comoro Watershed, Dili, Timor-Leste, showing terrain steepness variability and topographic characteristics generated through GIS spatial analysis.

The increasing rainfall magnitude associated with longer return periods indicates the potential occurrence of extreme hydrological conditions within the watershed. Rainfall erosivity is a major controlling factor for soil detachment and sediment transport in tropical watersheds, particularly in areas with insufficient vegetation cover. Peak runoff discharge was estimated using the Modified Rational Method. The results demonstrated that runoff discharge increases proportionally with rainfall intensity and return period. Watershed areas with degraded vegetation cover exhibited higher runoff coefficients due to reduced infiltration capacity and increased surface flow generation [24].

Table 4

Peak discharge estimation in the Comoro watershed

Return Period (years)	Rainfall Intensity (mm/hr)	Runoff Coefficient (C)	Peak Discharge Q (m^3/s)
2	38.20	0.48	94.36
5	51.62	0.48	127.54
10	61.28	0.48	151.42
25	72.33	0.48	178.66
50	81.22	0.48	200.60
100	90.76	0.48	246.21

The increasing runoff discharge values indicate that hydrological instability within the watershed has intensified due to vegetation loss and land degradation. High runoff discharge contributes directly to sediment transport, downstream sedimentation, and flood risk. Soil erosion analysis was performed using the Revised Universal Soil Loss Equation (RUSLE) and the Modified Universal Soil Loss Equation (MUSLE) integrated with GIS spatial analysis. One of the major novelties of this study lies in the integration of RUSLE, MUSLE, hydrological runoff analysis, and GIS-based conservation planning into a unified watershed management framework. Previous erosion studies in Timor-Leste generally focused only on erosion estimation without evaluating conservation effectiveness spatially.

The spatial distribution of erosion hazard classes generated using the RUSLE model is presented in Fig. 5. The RUSLE model estimated an average annual soil erosion rate of:

$$A = 27.1\ t\ ha^{-1} yr^{-1}$$

Meanwhile, the MUSLE model estimated an average sediment yield of 24.6 tons/ha/year.

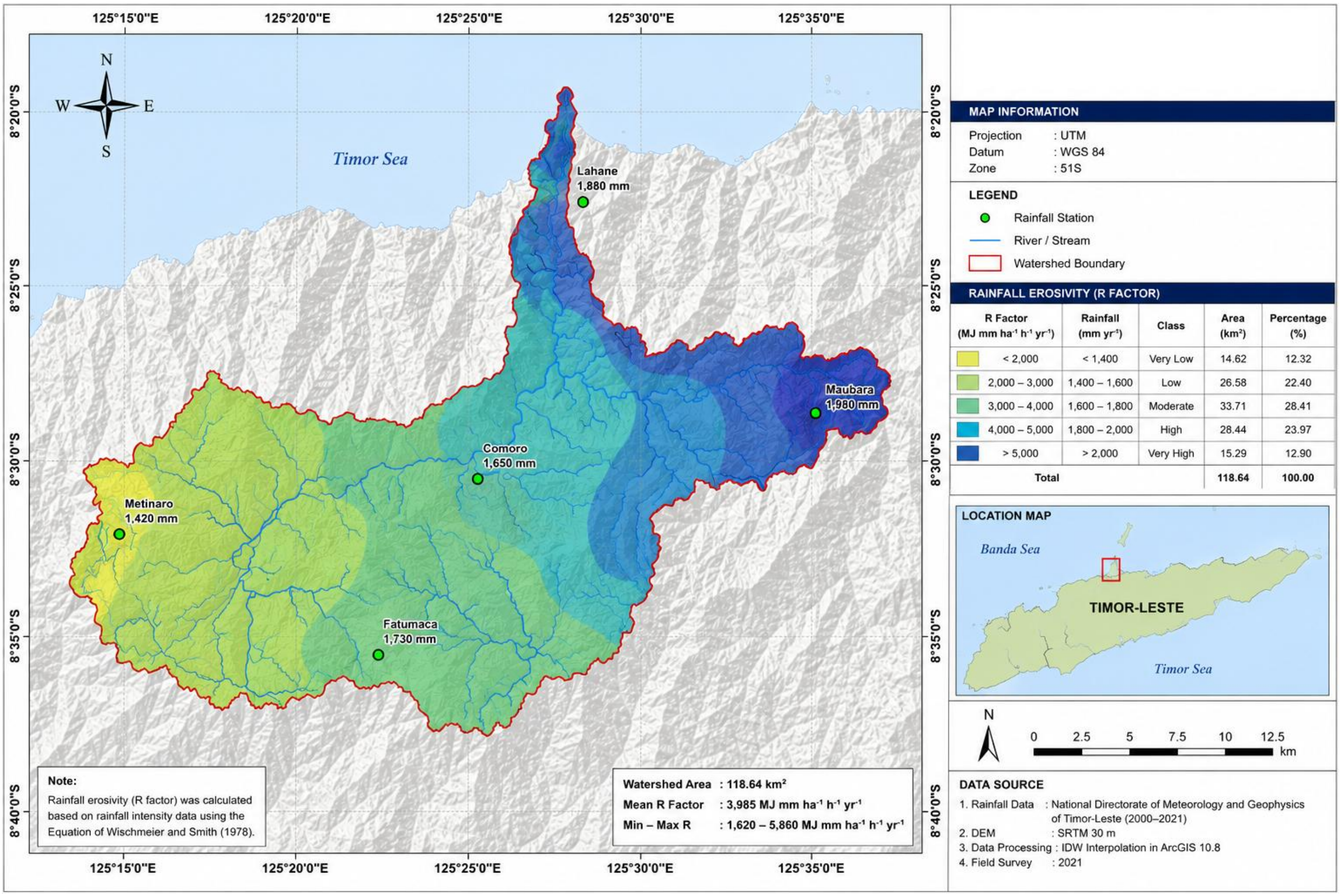
Table 5

Soil erosion and sediment yield estimation

Model	Average (tons/ha/year)	Minimum (tons/ha/year)	Maximum (tons/ha/year)	Standard Deviation
RUSLE (A)	27.10	0.15	186.32	19.84
MUSLE (SY)	24.60	0.12	158.47	17.25

The highest erosion rates were concentrated primarily in mountainous upstream regions characterized by steep slopes, sparse vegetation cover, and intensive agricultural activities. The LS factor was identified as one of the dominant parameters controlling erosion intensity because slope steepness significantly increases runoff velocity and sediment transport capacity. The erosion hazard classification is summarized in Table 6.

Approximately 22.01% of the watershed falls into high and very high erosion hazard categories. These critical erosion zones are concentrated mainly in upstream mountainous regions where vegetation degradation and inappropriate land-use practices are intensive. The integration of GIS spatial prioritization allowed critical erosion areas to be identified more effectively, thereby improving conservation planning accuracy.



R Factor ($MJ\ mm\ ha^{-1}\ h^{-1}\ yr^{-1}$)	Rainfall ($mm\ yr^{-1}$)	Class	Area (km^2)	Percentage (%)
< 2,000	< 1,400	Very Low	14.62	12.32
2,000 – 3,000	1,400 – 1,600	Low	26.58	22.40
3,000 – 4,000	1,600 – 1,800	Moderate	33.71	28.41
4,000 – 5,000	1,800 – 2,000	High	28.44	23.97
> 5,000	> 2,000	Very High	15.29	12.90
Total			**118.64**	**100.00**

Note:
Rainfall erosivity (R factor) was calculated based on rainfall intensity data using the Equation of Wischmeier and Smith (1978).

Watershed Area : 118.64 km^2
Mean R Factor : 3,985 $MJ\ mm\ ha^{-1}\ h^{-1}\ yr^{-1}$
Min – Max R : 1,620 – 5,860 $MJ\ mm\ ha^{-1}\ h^{-1}\ yr^{-1}$

DATA SOURCE
1. Rainfall Data : National Directorate of Meteorology and Geophysics of Timor-Leste (2000–2021)
2. DEM : SRTM 30 m
3. Data Processing : IDW Interpolation in ArcGIS 10.8
4. Field Survey : 2021

Fig. 4. Spatial distribution of rainfall erosivity (R factor) within the Comoro Watershed, Dili, Timor-Leste, derived from GIS-based rainfall intensity interpolation and hydrological analysis.

Table 6
Erosion hazard classification in the Comoro watershed

Erosion Hazard Class	Erosion Rate (tons/ha/year)	Area (km²)	Percentage (%)	Description
Very Low	< 5	28.87	24.32	Low erosion potential
Low	5–15	27.41	23.09	Relatively low erosion
Moderate	15–50	36.27	30.58	Moderate erosion
High	50–100	16.02	13.50	High erosion risk
Very High	> 100	10.07	8.51	Very high erosion risk
Total		118.64	100.00	

The spatial distribution of proposed conservation planning is presented in Fig. 6. Integrated conservation strategies were developed using both vegetative and mechanical conservation approaches within an Integrated Water Resources Management (IWRM) framework. Vegetative conservation included:

- Reforestation,
- Agroforestry systems,
- Perennial crop cultivation,
- Protected forest zones,
- Riparian buffer zones.

These measures were designed to improve vegetation density, increase infiltration capacity, reduce runoff velocity, and stabilize soil structure. Agroforestry systems were identified as particularly effective because they provide both ecological protection and socio-economic benefits for local communities.

Mechanical conservation focused on the construction of a check dam within the Comoro River system. The proposed check dam functions as sediment retention infrastructure capable of reducing sediment transport and stabilizing river discharge during high-flow conditions. Unlike many previous watershed studies that focused only on erosion mapping, this study quantitatively evaluated the effectiveness of integrated conservation scenarios using spatial erosion simulation. The comparison of erosion conditions before and after conservation implementation is illustrated in Fig. 7. The conservation scenario significantly reduced the estimated erosion rate to:

$$A = 0.73\ t\ ha^{-1} yr^{-1}$$

Table 7
Comparison of soil erosion before and after conservation

Condition	Average Erosion Rate (tons/ha/year)	Reduction (tons/ha/year)	Reduction (%)
Existing Condition (2021)	27.10	–	–
After Conservation	0.73	26.37	97.30

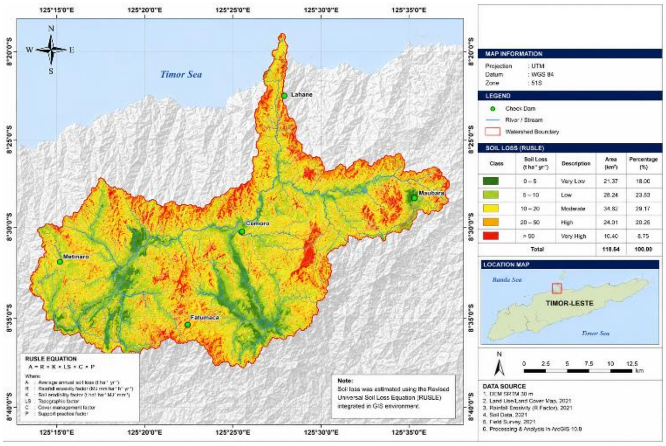


Fig. 5. Spatial distribution of soil erosion hazard classes in the Comoro Watershed, Dili, Timor-Leste, estimated using the Revised Universal Soil Loss Equation (RUSLE) integrated with GIS spatial analysis.

The conservation scenario reduced soil erosion by approximately 97.3%, demonstrating the effectiveness of integrated watershed conservation strategies for erosion mitigation in tropical environments. The substantial reduction was primarily influenced by improved vegetation cover, enhanced infiltration capacity, reduced runoff velocity, and sediment retention by structural conservation measures.

The quantitative evaluation of conservation effectiveness represents another important novelty of this study because previous studies in Timor-Leste rarely integrated erosion modeling with conservation scenario assessment. Furthermore, the integration of vegetative restoration and mechanical sediment-control structures into a unified conservation framework provides a more comprehensive watershed management strategy compared with single-method approaches.

Overall, the results demonstrate that integrating RUSLE, MUSLE, GIS spatial analysis, hydrological modeling, and IWRM-based conservation planning provides an effective framework for sustainable watershed management in Timor-Leste. The study also highlights the importance of combining spatial erosion assessment with conservation scenario evaluation to support evidence-based environmental management and watershed conservation policy in tropical developing regions [20, 21, 25].

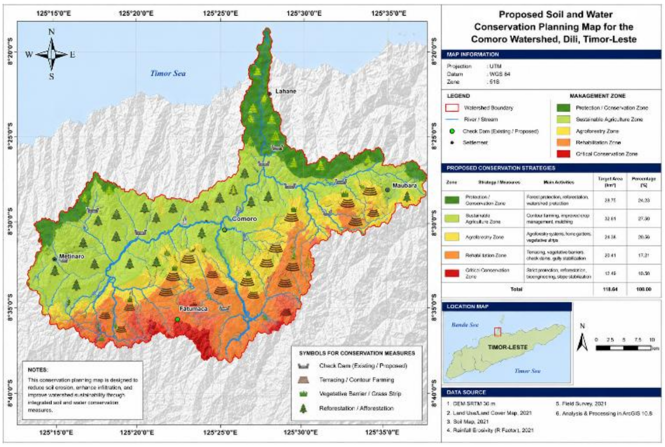


Fig. 6. Proposed integrated soil and water conservation planning map for the Comoro Watershed, Dili, Timor-Leste, showing spatial prioritization of conservation zones and recommended vegetative and mechanical conservation measures derived from GIS-based watershed analysis.

This study provides several important scientific and practical contributions to watershed conservation and soil erosion research, particularly in tropical developing regions such as Timor-Leste. The study integrates the Revised Universal Soil Loss Equation (RUSLE), the Modified Universal Soil Loss Equation (MUSLE), hydrological runoff analysis, and Geographic Information Systems (GIS) into a comprehensive watershed-scale assessment framework. Previous studies in Timor-Leste generally focused only on basic erosion estimation or land-use analysis without integrating spatial hydrological modeling and conservation scenario evaluation. The integration of multiple analytical approaches in this study improves the accuracy and applicability of watershed conservation planning [16, 26, 27].

The first comprehensive GIS-based watershed conservation assessments conducted in the Comoro Watershed, Timor-Leste. Scientific studies related to spatial erosion modeling and integrated watershed management in Timor-Leste remain limited compared with other tropical regions. Therefore, this study contributes important baseline information for future watershed management and environmental policy development in the country. Unlike many previous erosion studies that primarily focused on erosion mapping, this research quantitatively evaluates the effectiveness of integrated conservation scenarios through both vegetative and mechanical conservation approaches. The study demonstrates that integrated conservation strategies can reduce soil erosion rates by approximately 97.3%, highlighting the effectiveness of combining watershed rehabilitation with structural erosion-control measures. Introduces GIS-based spatial prioritization for identifying critical erosion zones and determining appropriate conservation strategies based on topographic conditions, land-use characteristics, rainfall erosivity, and watershed hydrological response. This spatial prioritization approach improves the effectiveness of watershed management planning and supports evidence-based environmental decision-making.

The integration of vegetative conservation measures, including agroforestry systems, reforestation, riparian buffer zones, and perennial crop cultivation, with mechanical conservation structures such as check dams, provides a more comprehensive conservation framework compared with single-method approaches commonly used in previous studies. This integrated strategy not only reduces erosion intensity but also improves watershed sustainability and ecological resilience.

Finally, the study demonstrates the applicability of GIS-based erosion modeling and integrated watershed management approaches for tropical developing countries characterized by limited environmental monitoring systems and rapid land-use changes. The methodological framework developed in this study can therefore be adapted and applied to other erosion-prone watersheds with similar environmental characteristics [28, 29].

4. Limitations

Despite providing important contributions to watershed conservation research, this study has several limitations that should be considered in interpreting the results. The erosion assessment relied primarily on available rainfall, land-use, soil, and topographic datasets. Spatial resolution limitations of the available datasets may influence the accuracy of erosion estimation and spatial interpolation results. Higher-resolution spatial datasets could improve the precision of future watershed analyses. The study utilized rainfall records from a limited number of rainfall stations within and around the watershed area. Consequently, spatial rainfall variability may not be fully represented, particularly in mountainous regions where precipitation patterns are highly heterogeneous.

The RUSLE and MUSLE models used in this study are empirical models that simplify complex hydrological and geomorphological processes. Although these models are widely applied in watershed studies, they may not fully capture temporal variations in sediment transport, gully erosion, channel erosion, and extreme rainfall events. The conservation scenario analysis was conducted through spatial simulation rather than long-term field implementation and monitoring. Therefore, the estimated erosion reduction values represent projected conservation effectiveness under modeled conditions. Field-based monitoring and validation are necessary to evaluate the long-term performance of the proposed conservation measures.

This study focused primarily on soil erosion and watershed conservation without incorporating climate change projections or socio-economic factors influencing land-use dynamics. Future studies should integrate climate variability scenarios, community-based watershed management approaches, and socio-economic analyses to improve conservation planning sustainability. Finally, sediment yield and runoff analyses were evaluated at the watershed scale and may not fully represent micro-scale hydrological variability within individual sub-watersheds. Future studies incorporating higher temporal and spatial resolution hydrological monitoring are recommended to improve watershed-scale environmental assessment accuracy.

5. Conclusion

This study assessed soil erosion and developed integrated conservation planning in the Comoro Watershed, Dili, Timor-Leste, using Geographic Information Systems (GIS), the Revised Universal Soil Loss Equation (RUSLE), and the Modified Universal Soil Loss Equation (MUSLE). The results demonstrated that land-use change, steep topography, high rainfall erosivity, and inadequate vegetation cover are the primary factors controlling erosion intensity within the watershed.

The RUSLE model estimated an average annual soil erosion rate of 27.1 t ha^{-1} yr^{-1}, indicating moderate to high erosion vulnerability in several parts of the watershed, particularly in mountainous upstream regions. Spatial analysis revealed that high and very high erosion hazard classes were concentrated in areas characterized by steep slopes, intensive agricultural activities, and degraded vegetation cover. Meanwhile, the MUSLE model confirmed that runoff-driven sediment transport significantly contributes to watershed degradation and downstream sedimentation.

Integrated conservation planning based on Integrated Water Resources Management (IWRM) principles was developed through both vegetative and mechanical conservation approaches. Vegetative conservation strategies included reforestation, agroforestry systems, riparian buffer zones, perennial crop cultivation, and protected forest areas, while mechanical conservation focused on check dam construction and slope stabilization measures. GIS-based spatial prioritization enabled the identification of critical conservation zones and improved the effectiveness of conservation planning.

The conservation scenario simulation demonstrated that integrated conservation measures substantially reduced the estimated soil erosion rate from 27.1 to 0.73 t ha^{-1} yr^{-1}, representing an erosion reduction of approximately 97.3%. These findings indicate that integrated watershed management strategies are highly effective for mitigating erosion and improving watershed sustainability in tropical environments.

This study contributes important scientific and practical insights by integrating RUSLE, MUSLE, hydrological analysis, GIS spatial modeling, and conservation scenario evaluation into a comprehensive watershed management framework. The methodological approach developed in this study can be applied to other tropical developing regions experiencing rapid land degradation and watershed deterioration. Future studies are recommended to incorporate higher-resolution spatial datasets, climate change projections, and long-term field monitoring to further improve watershed conservation planning and environmental management effectiveness.

CRediT authorship contribution statement

Hironimus Gomes Settu: Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hanie Teki Tjendani:** Writing – review & editing, Investigation. **Esti Wulandari:** Methodology, Investigation, Formal analysis, Writing – review & editing, Investigation.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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