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Effects of Land Use Change on Soil Erosion and Land Critical Level Using GIS in the Mayang Watershed

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ABSTRACT

The increasing population in an area often triggers heightened development, leading to diminished land availability and subsequent land conversion. This transformation, predominantly observed in agricultural and plantation lands, is driven by the need for residential areas. However, continuous land use changes contribute to erosion, a natural process wherein soil is transported, leading to sedimentation and eventual flooding. This study aims to identify critical areas prone to erosion and land degradation. To address this, we used the Universal Soil Loss Equation (USLE) method for erosion prediction, leveraging its simplicity and accuracy. This study focuses on the Mayang watershed in East Java, utilizing a combination of USLE, spectral index modeling, and Geographic Information System (GIS) techniques to estimate soil erosion and land criticality. By integrating methodologies and analyzing data spanning from 2011 to 2021, the study reveals shifts in erosion danger levels and land use patterns. While regions with low erosion remained stable, areas with medium to high erosion declined, yet those with very high erosion exhibited a worrisome increase. Changes in land use, including forest loss and urban expansion, underscore the ecological shifts exacerbating erosion hazards. The study emphasizing the necessity for targeted conservation strategies and comprehensive land management plans to mitigate erosion risks and preserve environmental sustainability.

Keywords: Land use change; USLE; erosion; critical land

INTRODUCTION

An increasing population in an area had an impact on increased development which led to reduced land availability (Akhirul et al., 2020; Purwaningsih et al., 2015). Land use change was a conversion of land usage and the surrounding environment. Land conversion usually occurred on agricultural land and plantations because it had sufficient area to be used as residential land (Alinda et al., 2021; Nurmi et al., 2020). Changes in land use that continued caused erosion, which erosion is a natural process of moving or transporting soil from one location to another so that the soil carried from one location is deposited in another location and causes flooding (Hisyam & Shodiq, 2019; Lucyana & Azwar, 2022).

Decreasing forest land due to land use changes that hapened in the Mayang watershed has an impact on increasing the peak flood discharge by 67.48% which occurred regularly in 2011 and 2021 that caused inundation of the village which hit three villages, namely Wonoasri Village, Curah Nongko, Andungrejo, and Tempurejo District (Putri et al., 2021). Apart from flooding, the region is also more vulnerable to erosion due to the reduction in forest cover (Sujarwo et al., 2023). Rainfall-induced erosion is a serious danger to soil stability due to the loss of protecting vegetation, which causes land surfaces to erode and deteriorate (Bao et al., 2023; Negese et al., 2021). Thus, the level of land criticality and erosion hazard is important for enforcing land conservation management.

The method for predicting the erosion of a watershed often uses the USLE method (Taslim et al., 2019). The USLE method has advantages, consisting simple data processing, and it is also considered quite accurate and has been used on a large scale at the national or regional level (Alewell et al., 2019; Liang et al., 2020). By considering additional parameters such as land use, slope, vegetation cover, and rainfall patterns, the USLE was able to identify locations with a significant possibility of land degradation as well as critical land formation (Ambarwulan et al., 2021; Wondrade, 2023). The integration of the USLE with Inverse Distance Weighting (IDW) interpolation enables the extrapolation of erosion-related parameters across landscapes, which improved the spatial resolution and accuracy of erosion estimates, particularly in areas with limited data (Jemai et al., 2021; Kardhana et al., 2024).

On the other hand, the spatial dataset from diverse sources, including satellite imagery, topographic maps, soil data, and climate information were used to generate the potential erosion and critical land. Thus, GIS plays a crucial role in combining various spatial datasets needed for USLE modeling, allowing for the development of precise analysis and mapping. Furthermore, in the beginning of mapping, GIS enables researcher to do spatial analysis, including the identification of watersheds and determination of boundaries which further can modeling of land use changes over time (Mihi et al., 2020; Nag et al., 2020; Selmy et al., 2021). However, integration of the USLE with additional parameters remains limited across several tropical regions such as Indonesia. This study incorporated the USLE, IDW and GIS to obtain soil erodibility parameters based on soil types and topographic factors, providing a new insight of erosion hazard and land critical level studies, particularly in tropical region. Therefore, this study aims to analyze effects of land use change on soil erosion and land critical level using GIS in the Mayang Watershed.

STUDY AREA

The study area is located in the Mayang Watershed, Jember Regency, East Java, which has an area of 120,300.39 ha as shown in Figure 1. Administratively, the Mayang Watershed includes several districts including Silo District, Mayang District, Mumbulsari District, Tempurejo District, and Jenggawah District. The geographical location of the Mayang Watershed is at latitude 113°30'0" - 114°0'0" East Longitude and 8°30'0" - 8°10'0" North Latitude.

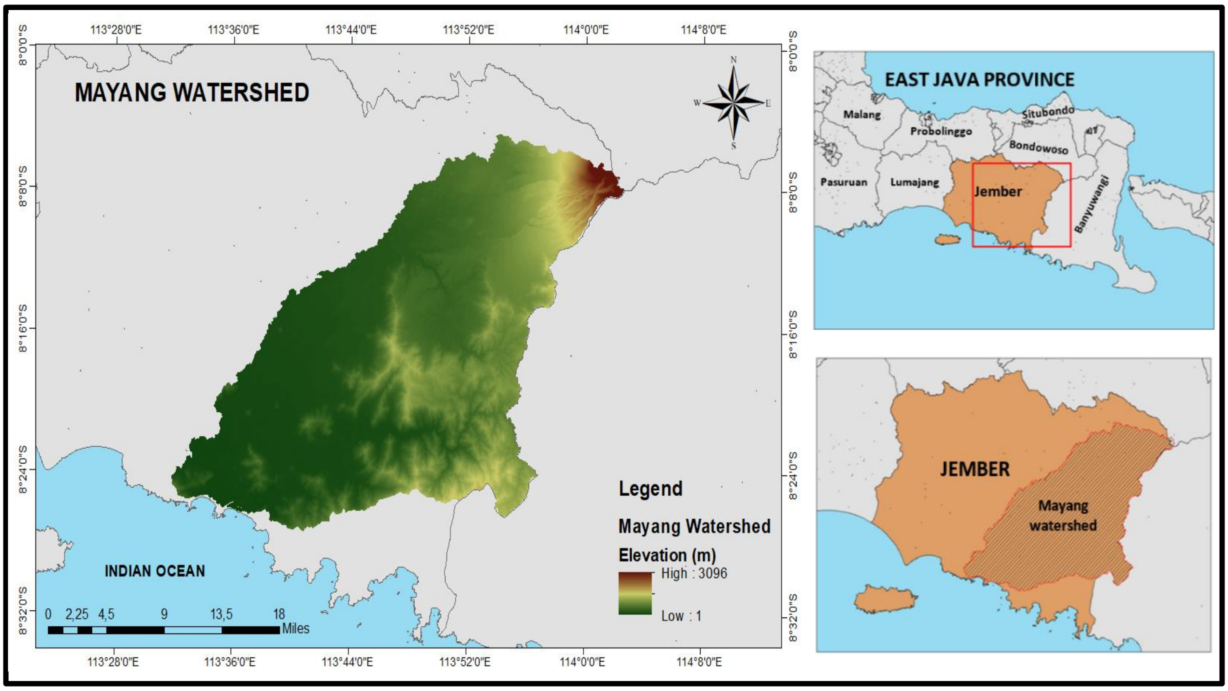


Figure 1. Study Area

METHODS

We carried out the research through four stages. The first stage was the processing of spatial data, which was used to make maps for input into ArcGIS. The second stage was making a map of the level of erosion hazard and a land use map to determine the parameters that determine critical land. The third stage is to carry out the scoring method with the technique (overlay). The fourth stage is data analysis using the ArcGIS program. The research framework is shown in Figure 2.

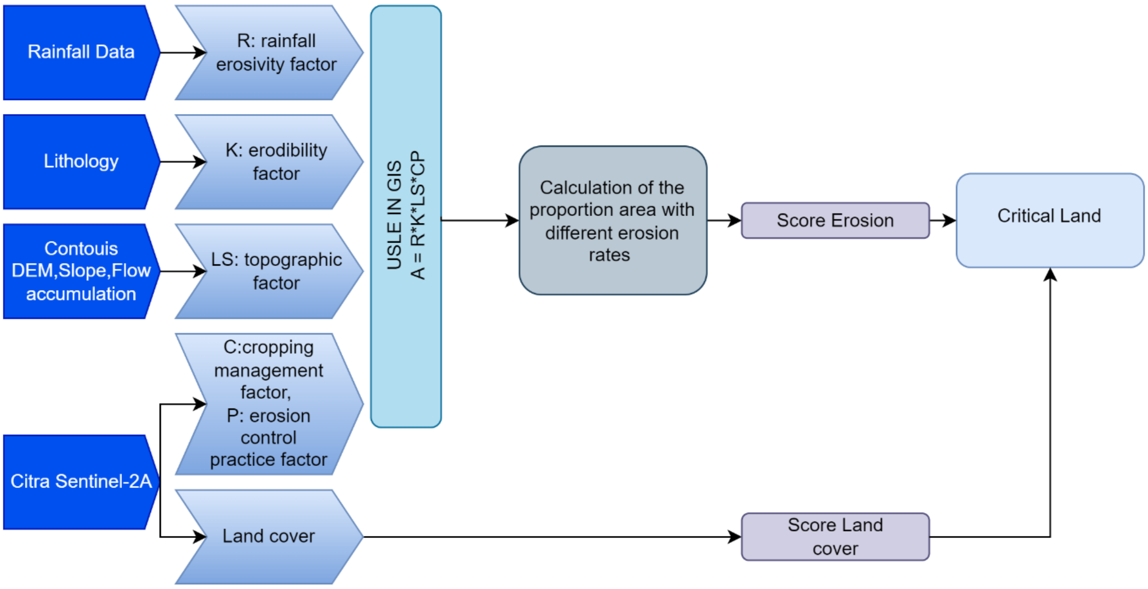


Figure 2. Research Framework

Data Sources

The data requirements in this study are summarized in Table 1. The land use and land cover dataset were obtained by a human-computer interactive interpretation method from remote sensing land cover information to interpret Sentinel 2 digital imagery (2011, 2021). Sentinel-2 offers high spatial resolution images (10-60 m) with optical imagery for detailed land cover/use mapping, systematically acquires data for global monitoring capabilities, and provides free and open-access data, making it a cost-effective option for obtaining land cover/use data (Sellami et al., 2022). Land cover in the Mayang watershed includes six classes, including cropland, rice fields, forests, water bodies, built-up areas, and bare land.

Table 1. Data Description

Data	Year	Data Sources	Resolution
Rainfall data	2021	Department of Public Works (PU) Highways and Water Resources Kab. Jember	Daily
Soil type map	2021		1000m x 1000m
Land use map (*Sentinel-2A*)	2011 2021	https://earthexplorer.usgs.gov/	10m x 10m
DEM map	2018	https://tanahair.indonesia.go.id/demnas/	10m x 10m

Erosion Hazard Level Analysis

The level of erosion hazard is a parameter to determine an area's erosion process, which can be calculated by estimating the average loss of soil developed. Calculation of the level of erosion hazard using the formulas with erosion predictions reviewed based on the erosivity of rainfall, soil erodibility, length, and slope of the slope as well as crop management and soil conservation factors which can be seen in Equation 1 (Negassa et al., 2021).

$$A = R \times K \times LS \times C \times P \tag{1}$$

Where:
A = annual soil loss rate average (ton/ha/year)
R = Rainfall erosivity factor
K = Soil erodibility factor
LS = Topographic factor
C = Cropping management factor
P = Erosion control practice factor

Raster data is used to equalize the resolution of the data scale and continue with the process raster calculator to classify into five erosional classes (PDASHL, 2018). The score is given based on the five erosion classes (the erosion weight is 40) multiplied by the serial number of the erosion class, then divided by the total erosion class. Classification of land use and scores for each class can be seen in Table 2.

Table 2. Erosion Class Classification and Scoring (PDASHL, 2018)

Classification	Erosion	Score
Very Low	<15	8
Low	15-60	16
Medium	60-180	24
High	180-480	32
Very High	>480	40

Parameter of Rainfall Erosivity (R)

Erosivity is one of the determining parameters of the magnitude of soil erosion with the rainfall component. The daily rainfall data is processed first to obtain the monthly rainfall erosivity value using the bols formula in Equation 2. Then calculate the annual erosivity value in Equation 3 and input it into the layer rain station to determine the erosivity value based on the area using the inverse *distance weighted* (IDW) *method* (Rampu, 2021).

$$R_m = 6.119x(Rain)_m{}^{1.21}x\ (Days)_m{}^{-0.47}\ x\ (MaxP)_m{}^{0.53} \tag{2}$$

Where:
R_m = Monthly rainfall erosivity
$(Rain)_m$ = The amount of monthly precipitation in cm
$(Days)_m$ = Number of rainy days monthly
$(MaxP)_m$ = Maximum daily rainfall in cm

$$R = \sum_{m=1}^{12}(R_m) \tag{3}$$

Where:
R = average annual rainfall erosivity = amount of Rm over 12 months

Soil Erodibility Parameters (K)

Soil erodibility is the resistance of soil particles to the transport of soil particles from the force of rainwater (Andriyani et al., 2020). Soil erodibility is used to assess the sensitivity of soil types to erosion. The higher the value of k, the more vulnerable it is to erosion (Suntoro et al., 2019). Soil erodibility values can be seen in Table 3 based on BAPPENAS (2012), then input into layer soil type.

Table 3. K value by soil type (BAPPENAS, 2012)

Soil Type	K Value
Alluvial	0.29
Andosol	0.28
Gleisol	0.29
Mediteran	0.16
Regosol	0.31

Parameter of Slope Length and Slope (LS)

The slope and slope length (LS) parameters are two topographic components that significantly affect the amount of erosion (Andriyani et al., 2020). Calculating the LS factor requires slope to slope and flow direction (*flow* accumulation) derived from DEMNAS data. The slope parameters and length are calculated in Equation 4.

$$LS = (X * \frac{CZ}{22.13})^{0.4} * (sin\theta/0.0896)^{1.3} \quad (4)$$

Where:
LS = Slope Length
X = Accumulated Flow (FlowAcc)
CZ = Pixel DEM
θ = Slope

Parameters of Plant Management and Soil Conservation (CP)

Parameters of crop management and soil conservation (CP) are one of the vegetation cover factor that affects erosion to protect the soil surface against degradation (Putra et al., 2018). Vegetation ground cover was obtained based on the type of land use map used to determine the condition of land use in the study area. The CP parameter can be determined based on BAPPENAS (2012) in Table 4, and then the CP value is input into layer land use.

Table 4. Parameters (CP) for various types of land use (BAPPENAS, 2012)

Land Use	CP Factor
Built-up Area	1
Water Bodies	0.001
Ricefield	0.2
Forest	0.001
Cropland	0.3

Land Use Analysis

Land use is arranged or grouped into several classes based on object categories. Object categories include settlements, rice fields, forests, plantations, and water bodies derived from imagery Sentinel-2A. The land use classification process uses the method of supervised or guided classification and is classified into five classes. In determining critical land, the land use parameter weights 60, multiplied by the land use class, then divided by the whole class made (Regulation of the Director General of Watershed Control and Protection Forest Number P.3/PDASHL/SET/KUM.1/7 /2018). Land use classification and scores for each class can be seen in Table 5.

Table 5. Land Use Classification and Scoring (BAPPENAS, 2012)

Classification	Class	Score
Water Bodies Built-up Area Primary Dryland Forest Ricefield	1	12
Secondary Dryland Forest	2	24
Cropland	3	36
Shrubs/Bushes Scrub/Swamp Dryland Agriculture Mixed Dryland Farming	4	48
Bare Land Mining	5	60

Determination of Critical Land

Critical land is a process of physical, chemical, and biological damage beyond the user's control and endangers the environment, agricultural productivity, settlements, and social life (Auliana et al., 2018). The process of analysis, in a way, overlays or the sum of the scores on the parameters that have been obtained. Furthermore, it is classified into five classes to determine critical land. The total score of land criticality can be seen in table 6.

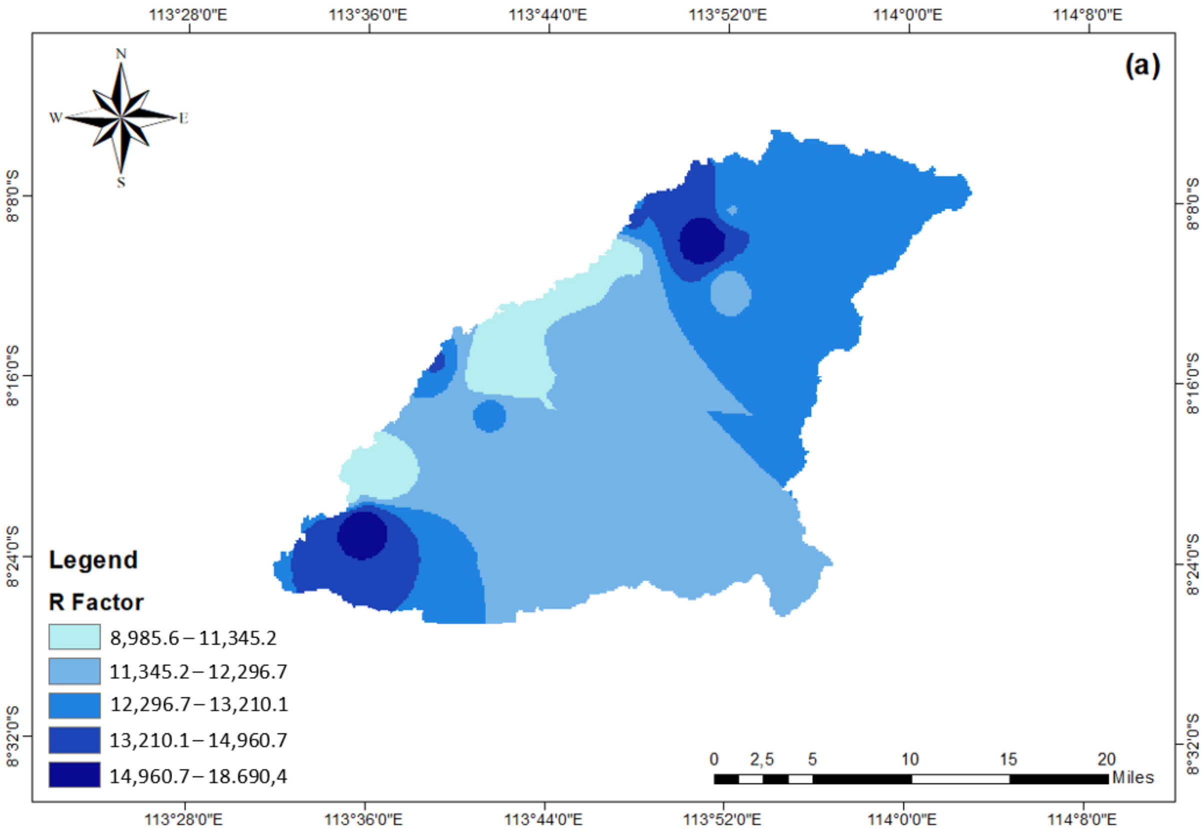
Table 6. Land Criticality Score (PDASHL, 2018)

Classification	Critical Land Score
Not Critical	20-36
Potentially Critical	36-52
Rather Critical	52-68
Critical	68-84
Very Critical	84-100

RESULTS AND DISCUSSION

Erosion Hazard Identification

In this study, the annual soil loss is estimated using *USLE*, which multiplies the five determinants. Map of the spatial distribution of factor values *USLE* illustrated in Figure 3a–d. The erosivity factor (R) of the rain erosivity value was obtained from 17 stations in the Mayang watershed, which the R value is dominated by 11.4 – 12.3 (Figure 3a). The erodibility factor (K) was obtained from the study site's soil type. The five soil types are alluvial, mediterranean, regosol, glei, and andosol. Based on the analysis results, two types of soil dominate: Mediterranean soil, which has an area of 35.36%, and andosol soil, with 55.18% (Figure 3b). The length and slope factor (LS) from the calculation results shows that the light blue color has a value of 0 while the dark blue color has a value of 5,275.31 (Figure 3c). Factors of Plant Management and Soil Conservation (CP) from the analysis of vegetation cover soil obtained six types of land use. Land use in 2011 was dominated by forests of 54,579.35 ha and ricefields of 32,638.71 ha, while in 2021, there was an increase of 3,415.29 ha by forest, and a decrease in ricefields by 11,624.29 ha (Figure 3d – 3e).


113°28'0"E
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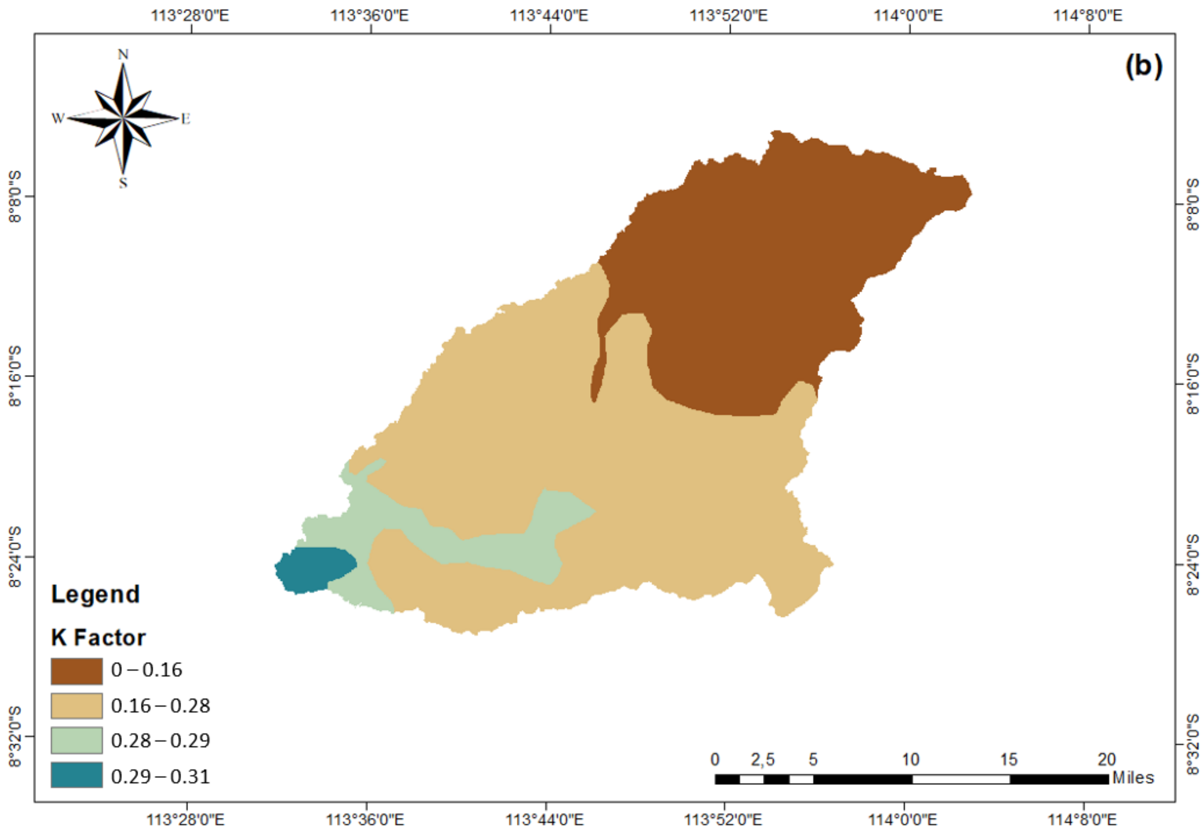
(a)
N
W
E
S
8°8'0"S
8°16'0"S
8°24'0"S
8°32'0"S
Legend
R Factor
8,985.6 – 11,345.2
11,345.2 – 12,296.7
12,296.7 – 13,210.1
13,210.1 – 14,960.7
14,960.7 – 18.690,4
0
2,5
5
10
15
20
Miles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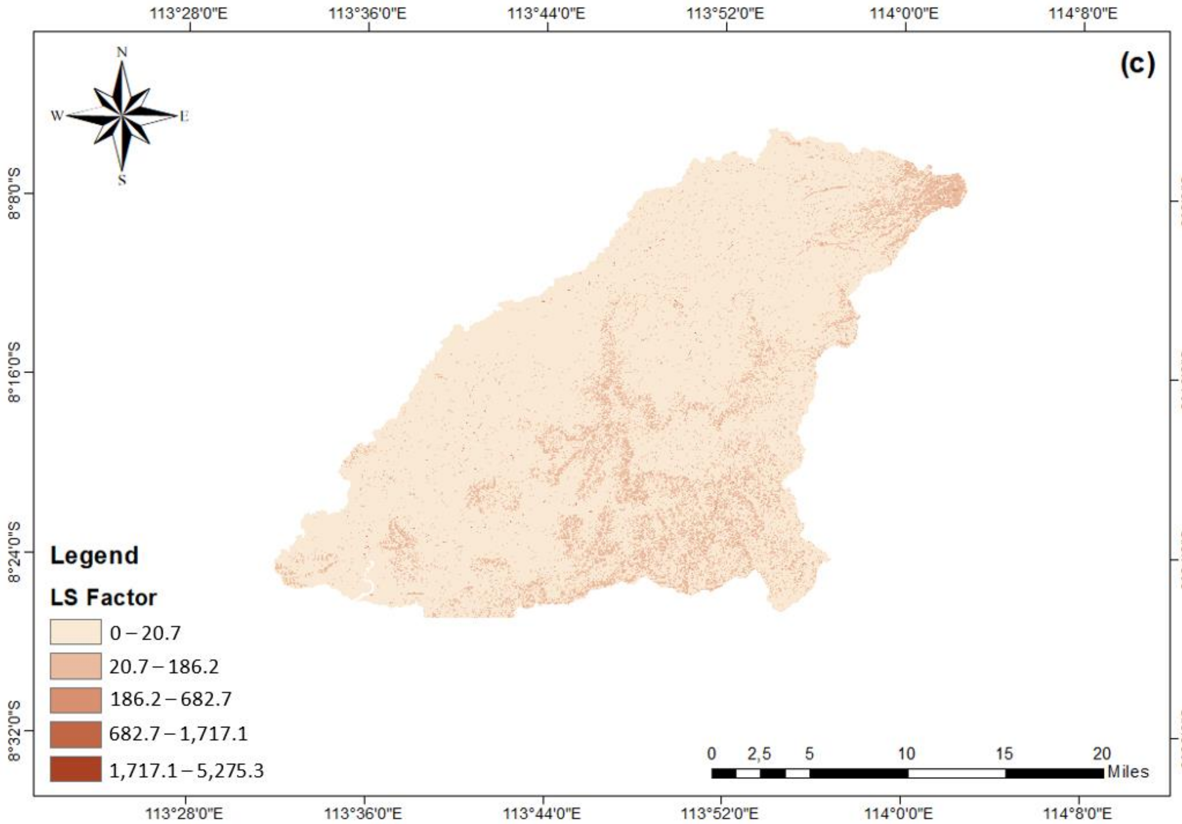
(b)
N
W
E
S
8°8'0"S
8°16'0"S
8°24'0"S
8°32'0"S
Legend
K Factor
0 – 0.16
0.16 – 0.28
0.28 – 0.29
0.29 – 0.31
0
2,5
5
10
15
20
Miles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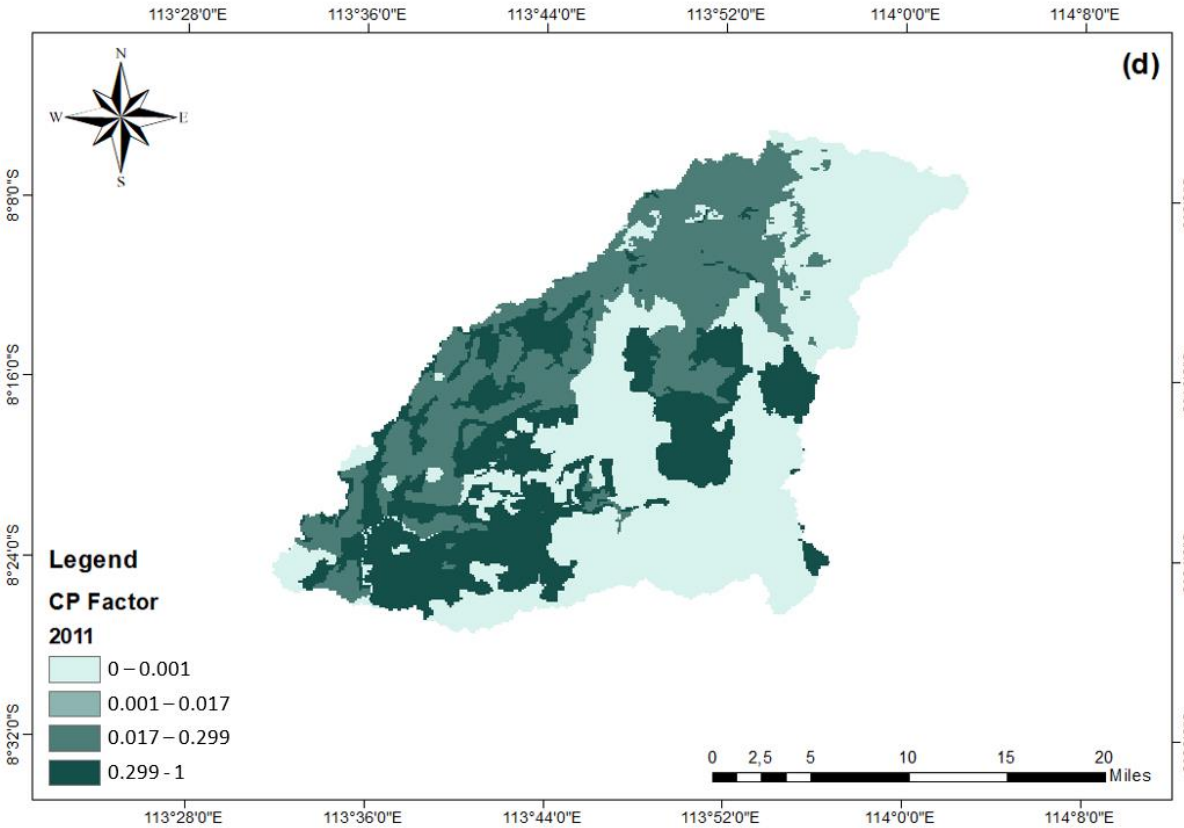
113°44'0"E
113°52'0"E
114°0'0"E
114°8'0"E
8°8'0"S
8°16'0"S
8°24'0"S
8°32'0"S
N
S
W
E
(c)
Legend
LS Factor
0 – 20.7
20.7 – 186.2
186.2 – 682.7
682.7 – 1,717.1
1,717.1 – 5,275.3
0 2,5 5 10 15 20
Miles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114°0'0"E
114°8'0"E
8°8'0"S
8°16'0"S
8°24'0"S
8°32'0"S
N
S
W
E
(d)
Legend
CP Factor
2011
0 – 0.001
0.001 – 0.017
0.017 – 0.299
0.299 - 1
0 2,5 5 10 15 20
Miles

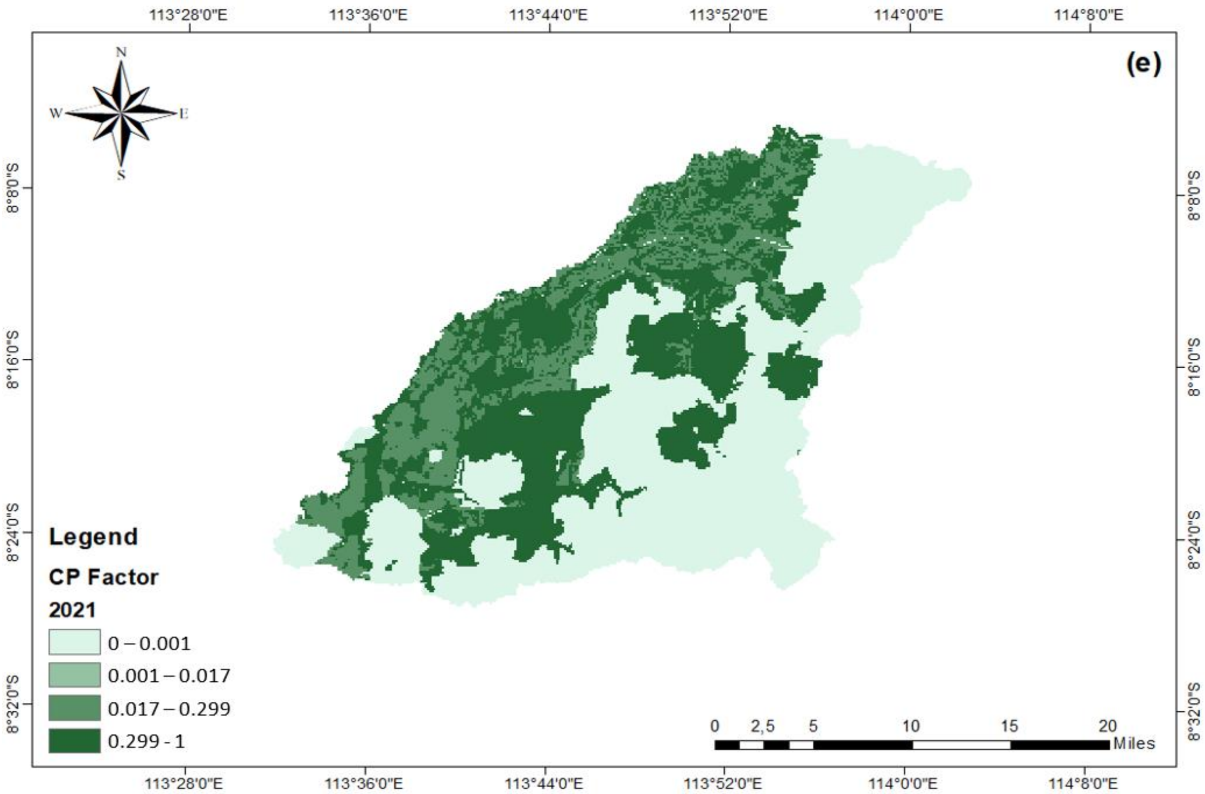


Figure 3. Distribution map of the USLE factor for the study area: (a) Rain Erosivity (R), (b) Soil Erodibility (K), (c) Slope Length and Slope (LS), (d) 2011 CP Factor, and (e) 2021 CP Factor

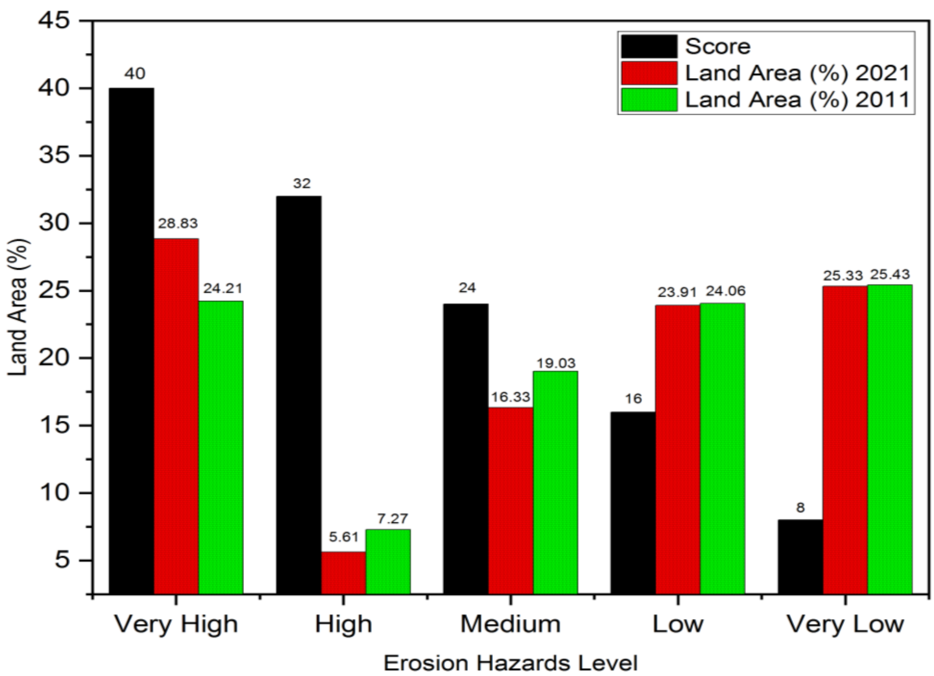
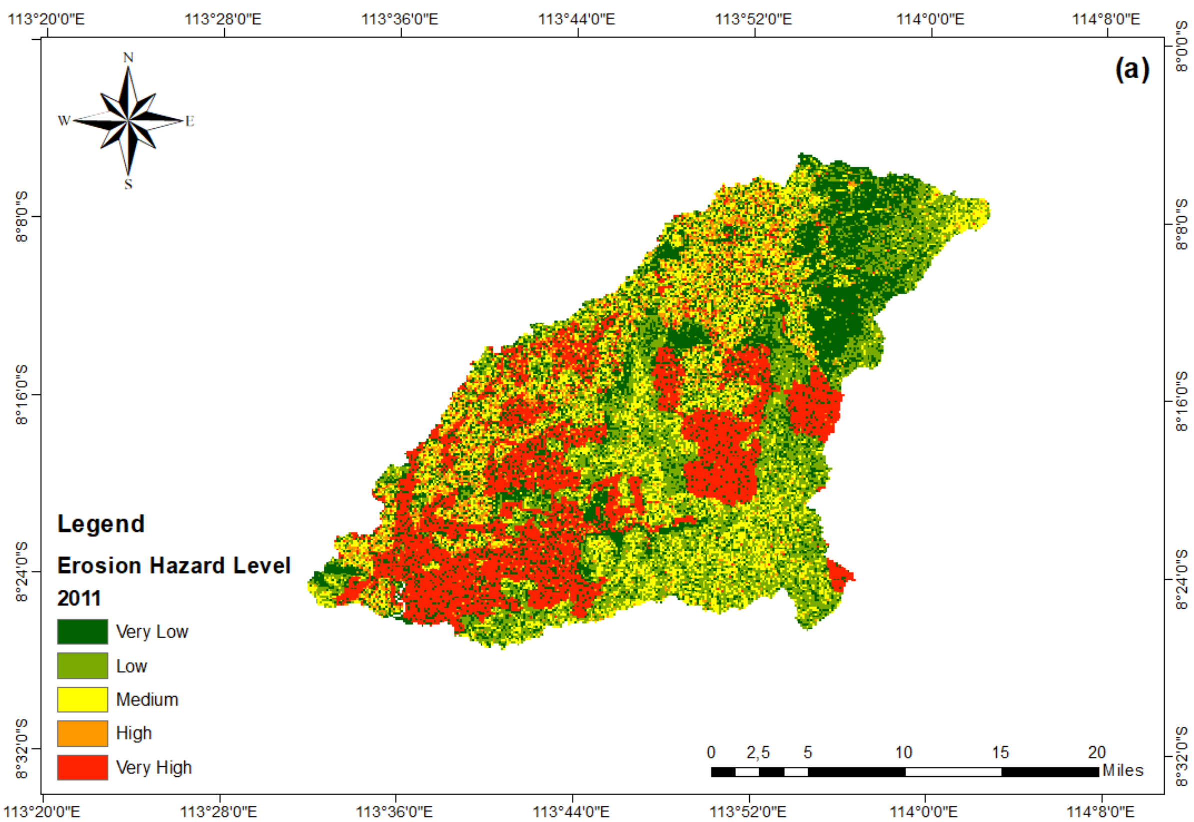


Figure 4. Classification of Erosion Hazard Levels in 2011 and 2021

Spatially distributed raster data, according to the above factors, are integrated. Diverse patterns can be seen in the erosion danger levels from 2011 to 2021 as shown in Figure 4. Between 2011 and 2021, the area impacted by very low erosion decreased somewhat, from 30,243 ha (25.43%) to 30,055 ha (25.33%). Comparably, the region with low erosion changed very little, shrinking slightly from 28,558 ha (24.06%) to 28,372 ha (23.91%). On the other hand, a more pronounced decline was observed in the region categorized as medium erosion, which decreased from 22,579 hectares (19.03%) to 19,380 hectares (16.33%). Significant reductions were also observed in the area with high erosion, which went from 8,623 ha (7.27%) to 6,655 ha (5.61%). The area affected by very high erosion, on the other hand, showed the most concerning rise, rising significantly from 28.735 ha (24.21%) in 2011 to 34,212 ha (28.83%) in 2021.

The stability observed in areas with very low and low erosion levels suggests that the majority of land remains relatively unaffected by erosion issues, indicating effective and consistent land management practices in these regions. Conversely, the decrease in areas affected by medium and high erosion signifies progress in erosion control measures or alterations in land use practices aimed at reducing erosion rates. However, the significant rise in very high erosion is cause for concern as shown in Figure 5. This notable increase suggests that regions experiencing the highest erosion levels are expanding, potentially due to factors such as deforestation, intensified agricultural activities, or urbanization, all of which contribute to exacerbated soil degradation.

According to Salim et al. (2019), forest land is land that is most vulnerable to major erosion events, because a reduction in forest area resulted in a decrease in water storage capacity which could increase erosion. This is proven by a decrease in the level of erosion in 2021 in the Mayang watershed due to the increase in forest area. The finding is in line with previous study by Cornelio & Bk (2011), which stated that forest land can be an effective barrier in controlling soil loss due to less sediment produced, and also strengthens by Negassa et al. (2020), which stated that erosion would increase if rice fields and open land were turned into plantations and settlements.



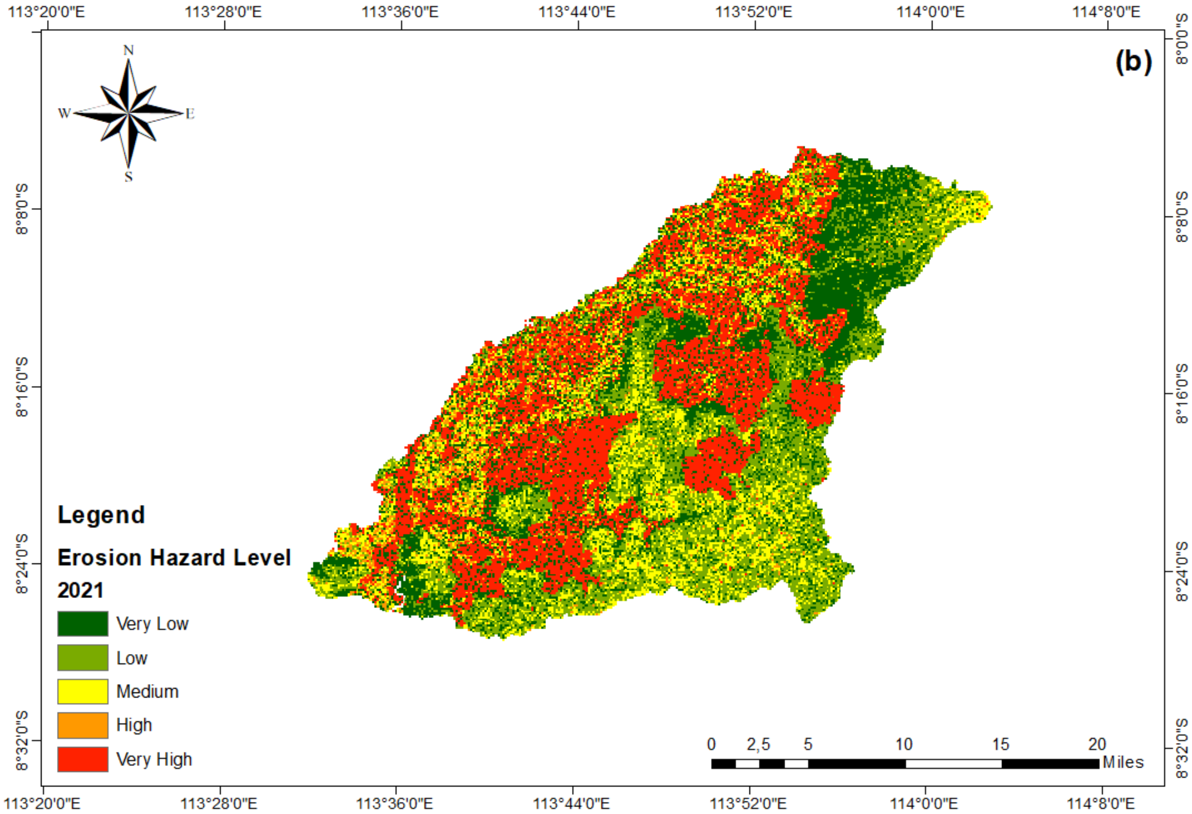


Figure 5. (a) Erosion Hazard Level Map for 2011 and (b) Erosion Hazard Level Map for 2021

Land Use Map

The land use maps in 2011 and 2021 show differences in predetermined classes as shown in Figure 6. In 2011, class 1 represents primary dryland forests that remain untouched by human activity or logging. Class 2 includes secondary dryland forests that have been logged and damaged, as well as settlements, rice fields, and water bodies. Class 3 consists of plantations, and class 5 represents open land. In contrast, the land use in 2021 shows that class 1 now includes settlements, water bodies, and rice fields. Class 2 still represents secondary dryland forests, and class 3 continues to consist of plantations.

An examination of the changes in land use classification between 2011 and 2021 uncovers several remarkable patterns. By 2011, the primary dry land forest spanned an area of 6309.91 hectares, accounting for 5.25% of the total land. However, by 2021, it had vanished entirely, suggesting possible deforestation or conversion to alternative land purposes. In contrast, the area of secondary dry land forest expanded from 48,269.44 ha (40.12%) to 57,994.64 ha (48.21%), indicating either reforestation initiatives or spontaneous regrowth. The rice field area had a significant decline from 32,638.71 ha (27.13%) to 21,014.41 ha (17.47%), possibly as a result of urbanization or the conversion of land for other purposes. The area of water bodies had a significant rise from 84.77 ha (0.07%) to 292.35 ha (0.24%), potentially as a result of reservoir construction or the enlargement of existing water bodies. The settlement areas increased from 6,124.64 ha (5.09%) to 9,997.95 ha (8.31%), indicating the expansion of urban development. The plantation areas expanded from 26,009.78 ha (21.62%) to 30,989.67 ha (25.76%), suggesting a transition towards commercial agriculture. By 2021, the open land that occupied 941.21 hectares (0.78%) in 2011 had completely vanished, indicating its transformation into different land uses such as towns, plantations, or secondary forests. Similar results had previously been reported Bwalya et al. (2023) which stated that these modifications have substantial consequences for the preservation of the environment, farming methods, and city development, underscoring the necessity for well-rounded land management plans.

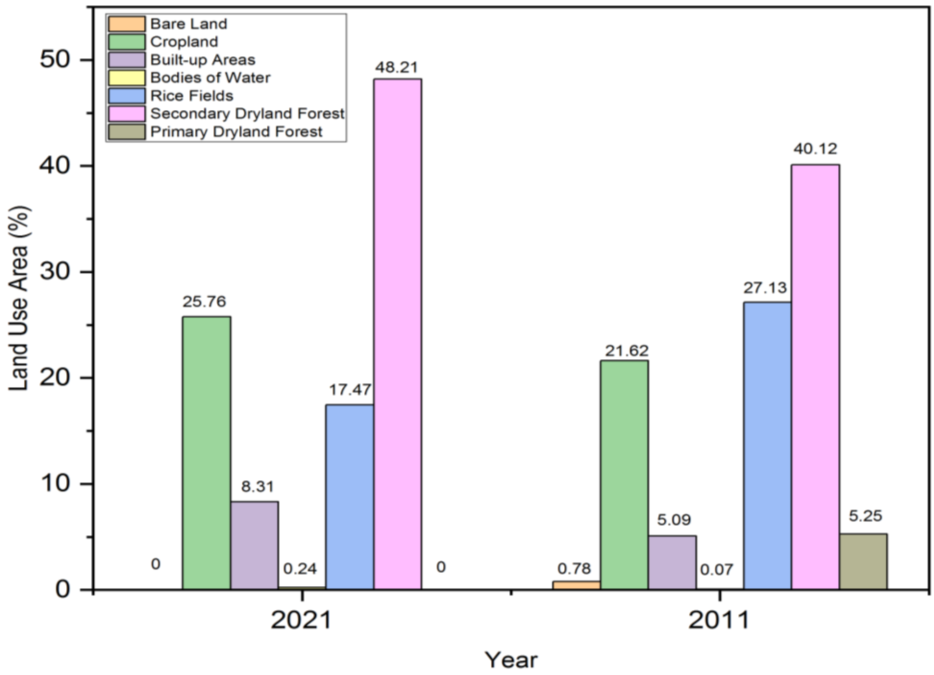
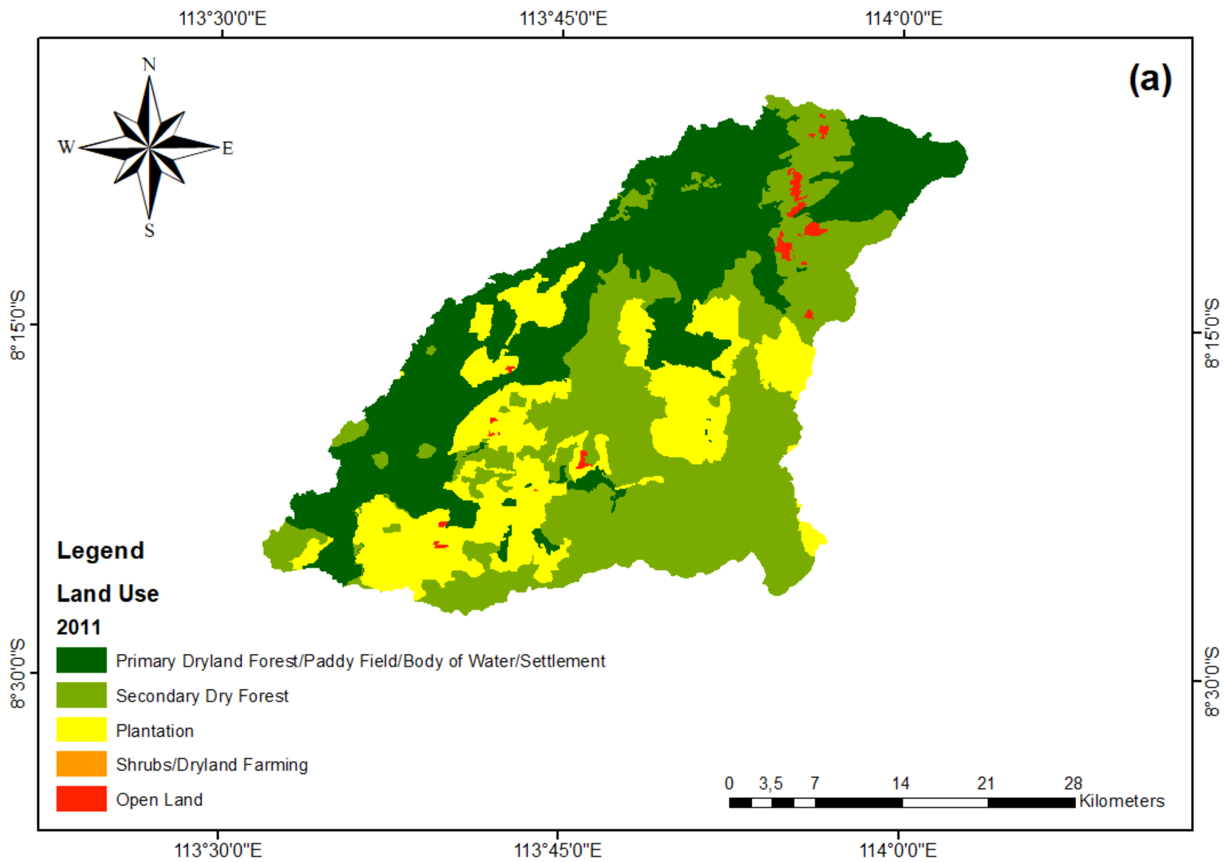


Figure 6. Classification of Land Use



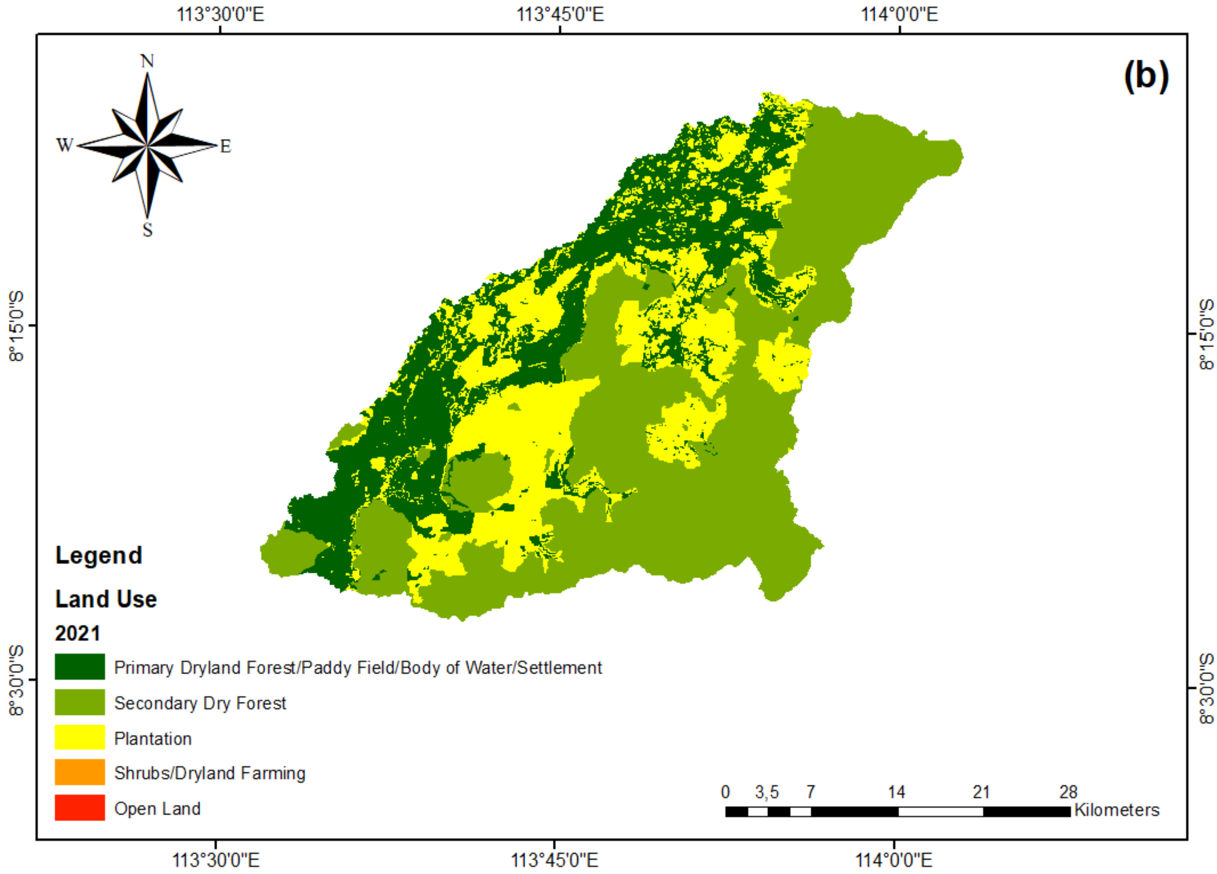


Figure 7. (a) Landuse Map for 2011 and (b) Landuse Map for 2021

There were substantial repercussions for environmental sustainability, agricultural practices, and urban planning as a result of the significant changes in land use classification that took place between 2011 and 2021. The increase of secondary forests have a beneficial trend for Mayang watershed community, however, based on Mayer et al. (2020), it is important to note that these younger woods are typically less successful in preventing erosion when compared to primary forests that have reached maturity. Thus, it is possible that the loss of these areas, in conjunction with the growth of settlements, which increased from 5.09% to 8.31%, could make soil erosion worse and lower the quality of the land. This is in accordance with study by Indrajaya et al. (2022) which stated that the removal of primary dry land forests and open land is indicative of significant ecological alterations, which may result in an increase in the danger of erosion. Through the use of their root systems, primary forests are able to significantly contribute to the stabilization of soil and the prevention of erosion.

Critical Land Map

The factors that determine critical land are categorized into five groups: not critical, which has a score of 36; potentially critical, which has a score between 36 and 52; moderately critical, which has a score between 52 and 68; critical, which has a score between 68 and 84; and very critical, which has a score between 84 and 100 as shown in Figure 8.

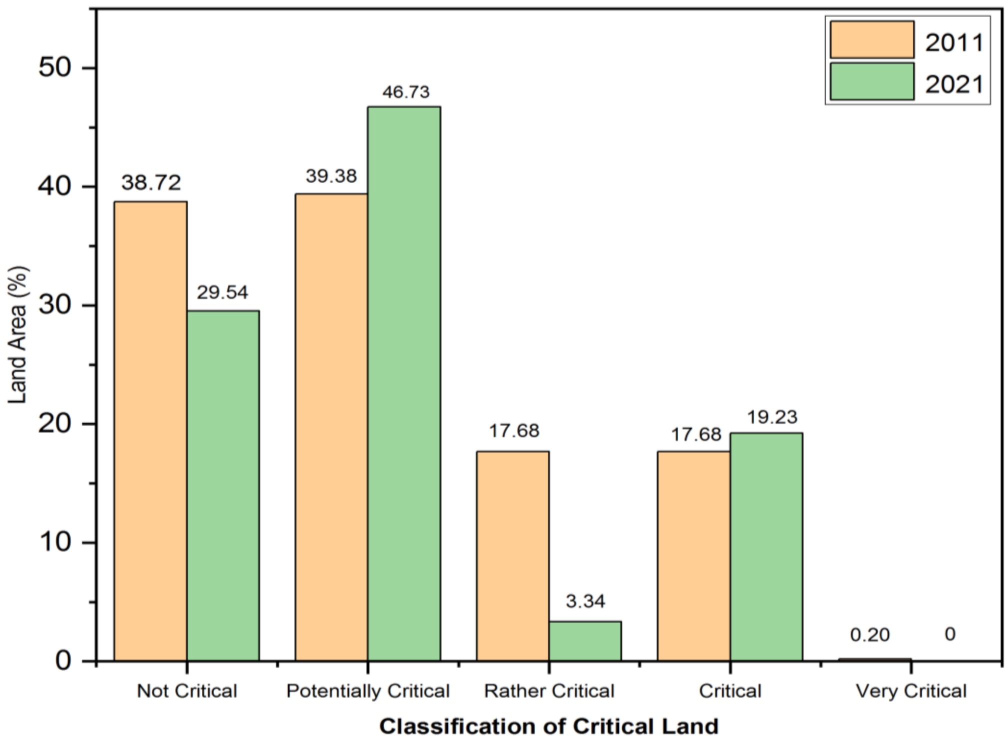


Figure 8. Classification of Critical Land

In forest areas, ricefields, cropland, and built-up areas, the amount of not-critical land has decreased by 11,608.43 ha; in cropland and built-up areas, the amount of potential critical land has increased by 47,330.45 ha; in cropland and built-up areas, the amount of slightly critical land has increased by 858.30 ha; and in cropland and built-up areas, the amount of critical land has increased by 1,885.51 ha. Surpsringly, there is no record of very critical land in 2021. The changes in land use between 2011 and 2021 reveal significant implications for land criticality. The disappearance of primary dryland forests suggests possible deforestation or conversion to alternative land uses, undermining the crucial role these forests play in stabilizing soil and preventing erosion. This loss heightens erosion hazard, especially in areas where settlements have expanded. Concurrently, the expansion of secondary dryland forests, while indicating reforestation efforts, introduces younger forests that are less effective in erosion prevention, thus contributing to overall erosion hazard. Furthermore, the significant decline in rice fields, typically managed to reduce erosion, exacerbates erosion hazard as these areas are replaced by less erosion-resistant land uses like settlements or plantations. The expansion of settlement areas, coupled with forest loss, amplifies erosion hazard due to increased surface runoff from urbanization. Additionally, the expansion of plantation areas implies a transition to commercial agriculture, potentially increasing erosion risks depending on crop types cultivated. However, the rise in water body areas may signify improved water management practices, as study by Shah et al. (2022) stated that improved water management can offering some mitigation against erosion by controlling water flow and storage more efficiently.

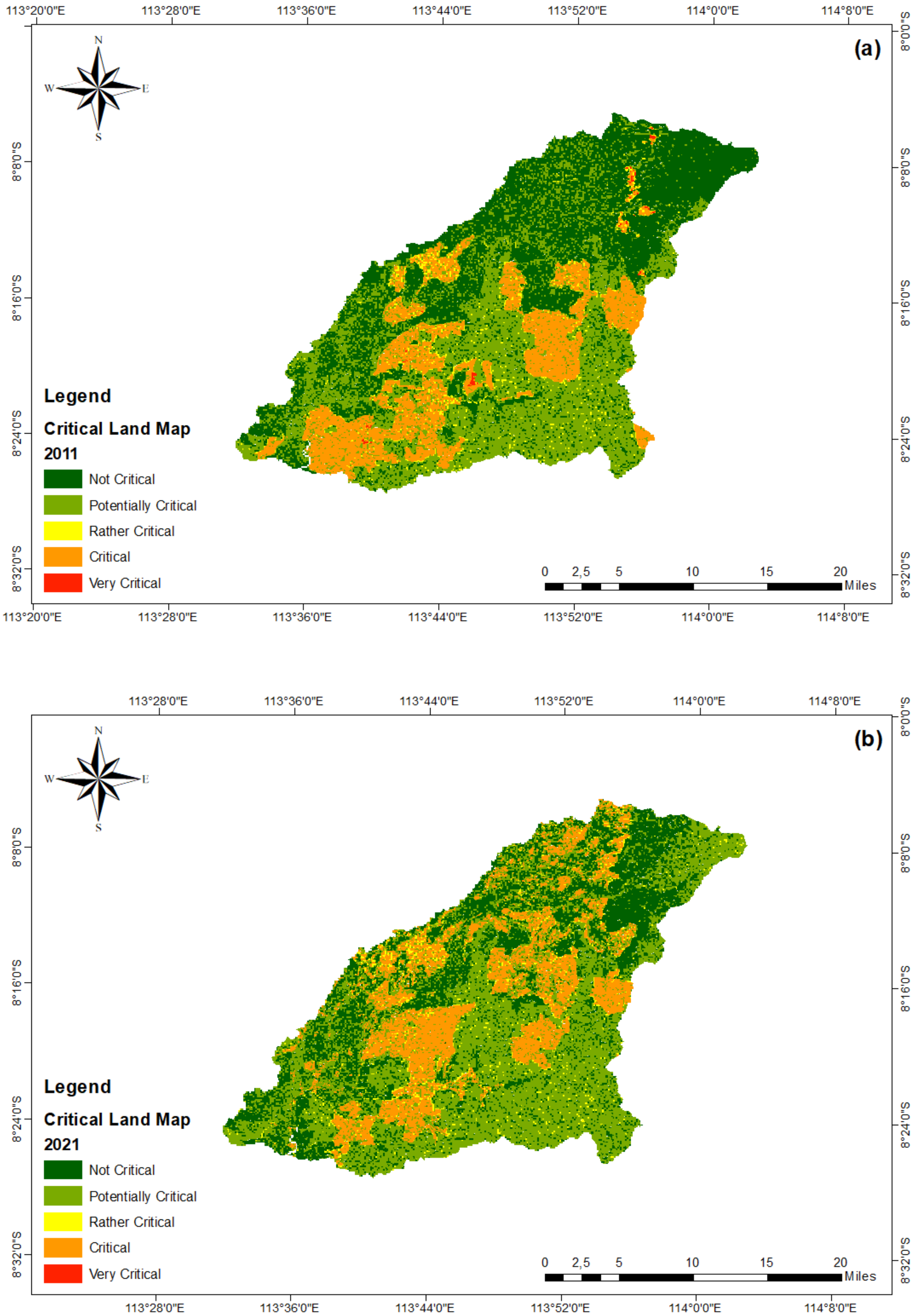


Figure 9. (a) 2011 Critical Land Map and (b) 2021 Critical Land Map

In addition to land use change, the integration land use change with level of erosion also contribute to the criticality of an area of land. Both very critical and critical land happened in high erosion hazard level. Based on Setyawan et al. (2023), areas designated as highly critical generally have elevated levels of erosion hazard, which in this study is due to a combination of adverse conditions, including high rainfall erosivity (R), high soil erodibility (K), steep slope length and steepness (LS), low cover and management (C), and poor support practices (P). For example, based on Santos et al. (2020), slopes that have been cleared of trees in an area that receives a lot of rain and where there are inadequate measures to protect the soil are very susceptible to significant erosion. Thus, in this study, very critical land that occurred in 2011 was in the land use type class 5, or bare land with. As similar by pervious study of Cutler et al. (2023), which stated that the lack of vegetation cover could led soil exposed and highly susceptible to erosion. Furthermore, very critical land areas are also found at several points in the upstream Mayang watershed area with higher slopes. Steeper slopes accelerate the process of erosion, which based on Luo et al., (2023), gravity produces a substantial influence in causing the downward movement of loose soil and rocks, particularly in the presence of intense precipitation, therefore, as the slope increases in steepness, the rate of erosion accelerates.

The results of the model's accuracy analysis use a comparison of critical land maps with Google Earth Pro to validate the critical and very critical land levels. In 2011, the criticality level was very critical, one of which occurs in the Tempurejo District, located in an arid and secondary dryland forest as shown in Figure 10. In 2021, it decreased to a critical level due to changes in land use to cropland. A comparison of critical land maps with Google Earth Pro as shown in Figure 11.

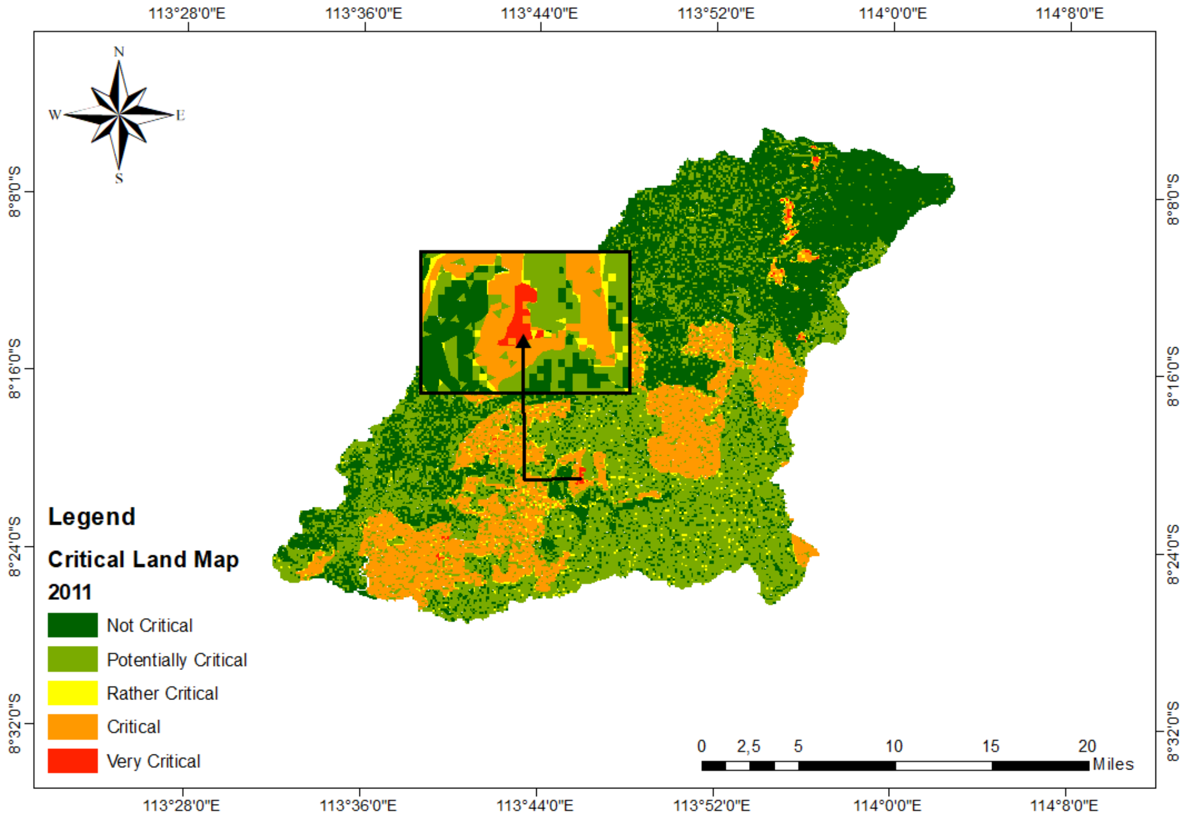
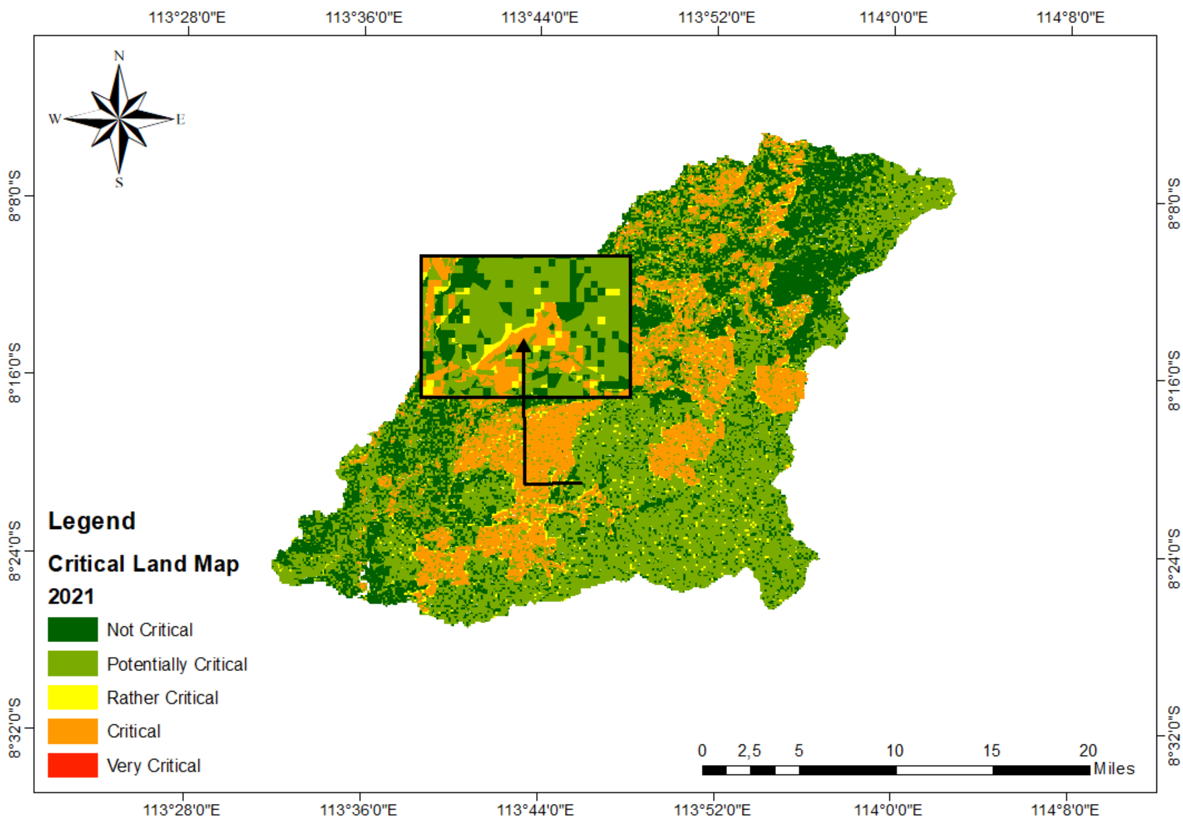


Figure 10. 2011 Critical Land and Validation



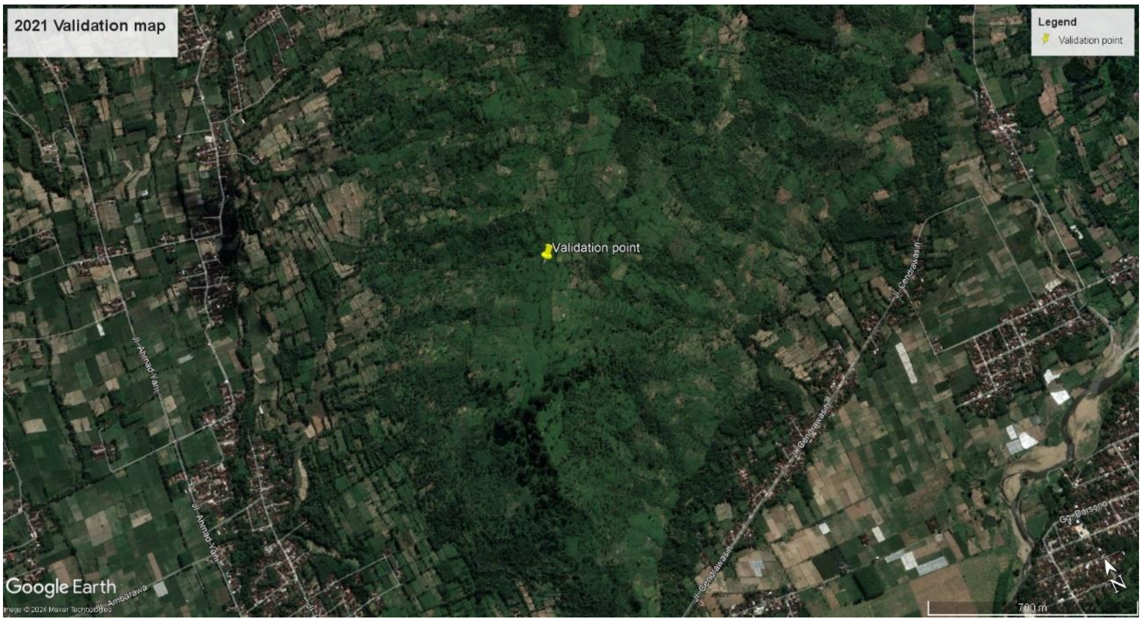


Figure 11. 2021 Critical Land and Validation

CONCLUSION

The integration of spatially distributed raster data reveals diverse patterns in erosion danger levels from 2011 to 2021. While areas with very low and low erosion levels remained relatively stable, indicating effective land management practices, significant declines were observed in regions categorized as having medium and high erosion. Conversely, there was a concerning rise in areas affected by very high erosion, suggesting expanding regions of severe erosion potentially due to factors such as deforestation and urbanization. Changes in land use between 2011 and 2021, show significant ecological alterations, including the disappearance of primary dry land forests and the expansion of secondary forests, settlements, and plantations. These changes have substantial implications for erosion hazard, especially as younger forests and urban areas contribute to increased surface runoff, exacerbating erosion hazard. Additionally, the integration of land use change with erosion levels underscores the criticality of certain areas, particularly those with steep slopes upstream, which are more susceptible to erosion due to gravity and intensified water flow. The model's accuracy analysis, validated against Google Earth Pro, confirms the critical and very critical levels of land, highlighting the need for comprehensive land management plans to mitigate erosion risks and preserve environmental sustainability.

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DECLARATIONS

Conflict of Interest

We declare no conflict of interest, financial or otherwise.

Ethical Approval

On behalf of all authors, the corresponding author states that the paper satisfies Ethical Standards conditions, no human participants, or animals are involved in the research.

Informed Consent
On behalf of all authors, the corresponding author states that no human participants are involved in the research and, therefore, informed consent is not required by them.

DATA AVAILABILITY

Data used to support the findings of this study are available from the corresponding author upon request.

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