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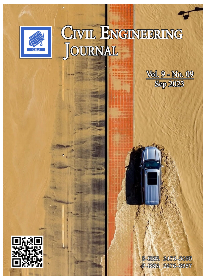

Potential Erosion in Mining, Oil Palm Plantations, and Watersheds Reforestation Areas

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Abstract

Erosion forecasting is a complex issue generated by numerous causes, the extent of which varies based on the unique area and conditions. Changes in rainfall, land cover, and watershed function are the primary causes of increased erosion. This study aims to scrutinize the actual and potential erosion in the mining area (MA), oil palm plantations (OPP), and watersheds reforestation (WR) in Asoloe, South Konawe, Indonesia. We utilized qualitative research methods and surveys with the USLE model. MA shares the highest actual erosion with 332.30 tons/ha/year, with an average erosion of 27.69 tons/ha/year from 2011 to 2022. Meanwhile, the potential erosion is 4747.19 tons/ha/year, with an average of 395.60 tons/ha/year. In terms of current conditions, 44.6% of rainfall engenders erosion with more than 0.5 t/ha and 33.9% with more than 1 t/ha. This study successfully demonstrates that for given location and area characteristics, high amounts of rainfall and changes in land function eminently affect soil erosion and that the potential erosion changes that occur in the Asoloe watershed every year are exceptionally influenced by changes in land use and land function. Therefore, some mitigation strategies and policies must be taken to reduce the risk of future erosion.

Keywords: Erosion Potential; Watershed; Land-Use Change; Rainfall.

1. Introduction

Erosion, as a geologically significant and environmentally relevant phenomenon, manifests itself in distinct ways across diverse landscapes, necessitating comprehensive investigations to unravel the underlying drivers and assess the associated socio-environmental consequences. Common causes of increased runoff and erosion include improper land development, mining, and excessive precipitation [1]. In non-agricultural regions, poor management, steep slopes, and tree removal exacerbate soil erosion [2]. Consequently, all activities can change natural conditions, including land surface circumstances in mining, agricultural, and residential regions, which can harm land, lower soil productivity, and increase the amount of essential land [3]. Mining areas are dynamic landscapes where erosion processes intersect with human activities, necessitating a comprehensive examination of the complex interaction between natural and anthropogenic factors and mining conditions and processes that cause severe land degradation, decreased soil production, and ecological environmental changes [4].

Erosion in mining areas is a consequence of complex and interrelated processes, such as land disturbance, the removal of vegetation, the alteration of hydrological regimes, and the exposure of vulnerable soils. Potentially damaging processes include landslides, soil degradation, drought, flooding, erosion, and water volume [1]. Excavation activities,

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such as open-pit mining and overburden removal, disrupt natural topography and expose previously protected subsoils, making them vulnerable to erosion by wind and water. Likewise, transferring land to road use areas can diminish vegetation and accelerate erosion due to rapid surface flow [5], as topography, soil vegetation, climate, and human activities influence erosion events [6].

Moreover, the construction of roads and tailing dams modifies surface hydrology, leading to increased runoff and sediment transport. The impacts of erosion in mining areas extend beyond the immediate vicinity, affecting downstream water quality, aquatic ecosystems, and adjacent agricultural lands. Land subsidence in mining areas has an impact on changes in ecological and environmental factors due to mining activities [4]. Understanding the intricate mechanisms and spatial patterns of erosion in mining areas is essential to implementing effective erosion control and sediment management measures, minimizing environmental impact, and promoting sustainable land rehabilitation practices. In addition, hydrological investigators must examine soil erosion, vital land, and probable runoff discharge [7]. Consequently, a comprehensive investigation of erosion in mining areas is warranted to inform evidence-based strategies and enhance the resilience of these dynamic landscapes. Dramatic changes in land shape and condition due to open-pit mining greatly affect environmental conditions [8]. While erosion in mining areas is driven by land disturbance, the removal of vegetation, the alteration of hydrological regimes, and the exposure of vulnerable soils, erosion in plantation areas, such as oil palm plantations, is primarily influenced by a multitude of factors, including land clearing, monoculture practices, and alterations to hydrological regimes [9]. On the other hand, in oil palm plantation areas, reduced vegetation results in increased erosion and sedimentation [10].

The extensive removal of native vegetation during land preparation disrupts the natural soil cover and exposes the underlying soil to erosion agents. Subsequent plantation establishment involves extensive soil disturbance, compaction, and alterations in hydrological patterns, leading to increased surface runoff, reduced infiltration, and heightened erosion susceptibility against vegetation land cover, surface water conditions, and erosion conditions, which are environmental elements [11]. The widespread use of heavy machinery, chemical inputs, and irrigation systems further exacerbates erosion risks by altering soil structure, nutrient cycling, and water movement. The consequences of erosion in plantation areas extend beyond the boundaries of the plantations, impacting downstream water quality, aquatic ecosystems, and overall landscape stability. Therefore, a comprehensive investigation of erosion processes in plantation areas is essential to inform evidence-based management strategies, foster sustainable agricultural practices, and safeguard the integrity of these important landscapes.

Nevertheless, watershed erosion is a significant environmental concern that necessitates extensive research to comprehend its complex dynamics and the potential for reforestation to reduce erosion risks. Watersheds are prone to erosion due to steep gradients, intensive land use, and fluctuating hydrological regimes. Erosion of a watershed can harm water quality, sedimentation, and topsoil. Erosion can result from annual plant cultivation in elevated, flat locations [12]. Reforestation of watersheds can reduce erosion and preserve soil integrity. In land conservation, soil erosion is contingent on soil texture, type, climate, and precipitation [13]. The reintroduction of vegetation through reforestation facilitates soil stabilization, enhances root systems that bind the soil, promotes infiltration, and reduces surface runoff. This leads to reduced erosion and sediment transport, thereby safeguarding water resources and fostering ecological resilience within watersheds. Reforestation efforts can also contribute to the restoration of biodiversity, improved habitat quality, and carbon sequestration, further enhancing the overall sustainability and ecosystem services provided by watersheds. Innovative greening is required, with the methods of planting, maintenance, and conventional plantations as an alternative form of management [11]. To thoroughly understand reforestation, erosion, and watershed dynamics, hydrological modeling, soil analysis, and long-term monitoring are required. Watershed management, restoration, and sustainable land use techniques based on scientific evidence can help preserve and restore these vital ecosystems. Erosion is caused by precipitation, settlements, and watershed conditions. Energy, catchment form, soil type, land cover, and use all influence the concentration of sediment in a river. Increasing concentrations exacerbate river erosion [14]. In all watersheds, hydrological models must be resistant to hydro-geomorphology that promotes erosion [15].

It is essential to distinguish between actual erosion, the measurable loss of soil or sediment, and potential erosion, the predictive indicator of erosion risk, because the magnitude of actual and prospective erosion impacts quality. According to Kolesar et al. [16], global soil erosion can alter the impacts of climate change on soils. Erosion of watershed soil is caused by a decrease in soil fertility, vegetation growth, water quality, and watershed characteristics, which alters watershed conditions and land use [17]. In addition, poor soil conditions influence land erosion rates [18], and rainfall affects soil conditions, erosion control, and poor land use [19]. Actual erosion is the quantifiable loss of soil or sediment caused by erosion forces such as water, wind, or gravitation over a specific time period. It quantifies the immediate influence of erosional forces and reveals the current erosion status of a landscape. Potential erosion, on the other hand, estimates an area's erosional capacity or susceptibility under particular conditions based on soil properties, topography, land use, and meteorological variables. Guswa et al.'s model predicts landscape vulnerability and erosion rates [20]. Annual precipitation influences watershed sensitivity by 40 to 60%, with flow conditions becoming 80% more sensitive as precipitation and land characteristics increase. Extreme precipitation and discharge modify and sensitize watersheds, such as the Cocheco River. Ovreiu et al. [21] reported that soil erosion is affected by soil texture, soil type, climate, the amount of rainfall that occurs, and uniform slope conditions and heights. Furthermore, slope changes in land conservation become the effect of changes in land erosion [13].

The differentiation between actual erosion and potential erosion becomes particularly significant when comparing different landscapes. Changes in soil permeability, varying rainfall intensity, and duration can lead to high rates of erosion [22]. Meanwhile, potential erosion increases due to changes in erosion events and topographic factors [23]. For instance, in a mining area, erosion can cause soil loss, sediment runoff, and water quality changes. However, slope gradient, soil erodibility, and rainfall patterns can be used to assess long-term erosion hazards and influence mitigation solutions. In plantations, land removal, intensive agriculture, and changing hydrological regimes can cause soil erosion and sedimentation. Unsuitable plantations deplete water sources, subside groundwater, and lose land cover [24]. Potential erosion, on the other hand, can be assessed by considering soil erodibility, slope, and rainfall patterns, helping to anticipate erosion vulnerabilities and guide land management decisions. Soil erodibility against aggregate release reveals the soil's susceptibility and resistance to rainfall-induced erosion [25]. Moreover, rainfall, surface discharge, and streamflow all contribute to watershed erosion, which is the gradual loss of soil or sediment. It manifests as observable changes in channel morphology, sediment deposition, and the degradation of water quality. On the other hand, the potential erosion of a watershed is dependent on its soil, terrain, land use, and climate. It calculates watershed erodibility under specified conditions. Predicting erosion rates and locating high-risk sites necessitates slope steepness, soil erodibility, and precipitation intensity. Guswa et al. [20] discovered that forest changes led to a decrease in water levels (1-2%), a low decline, and (4%) a moderate decline, and that this occurred in approximately 96% of watersheds, whereas high declines were 22% or 78% of low flows. In the USLE equation, rainfall erosion is a significant variable that hinges on the amount of data. Precipitation's effect on erosion influences analytical accuracy [26].

The study of erosion in mining areas, oil palm plantations, and reforestation watersheds has made significant progress, yet several critical knowledge areas remain underexplored. Firstly, there is a notable absence of comprehensive investigations that explicitly address the distinction between observed erosion processes and the potential for erosion occurrence in these specific landscapes. The influence of soil properties, surface fixtures, infiltration rates, precipitation, land use change, overdevelopment, improved soil management can be environmental problems and identify increasingly severe and widespread erosion processes [27]. While numerous studies have focused on quantifying actual erosion rates and impacts, limited attention has been given to evaluating the susceptibility and vulnerability of these areas to erosion under varying conditions. Understanding this differentiation is crucial for developing targeted erosion control strategies and formulating effective land management practices. Furthermore, a research deficiency exists concerning the long-term implications of erosion in these landscapes. Most studies have predominantly concentrated on short-term erosion assessments, providing limited insights into the cumulative effects of erosion over extended periods. Long-term monitoring and analysis are imperative to evaluate the sustainability of erosion control measures, comprehend erosion dynamics, and forecast future erosion risks accurately. Moreover, the complex interactions between erosion and other environmental factors, such as biodiversity loss, water quality degradation, and carbon sequestration, necessitate further investigation. Although erosion can have cascading effects on ecosystem services, the precise mechanisms and extent of these impacts in mining areas, oil palm plantations, and reforestation watersheds have not yet been comprehensively elucidated. Holistic studies that encompass the multifaceted ecological and socio-economic ramifications of erosion are warranted to guide integrated management approaches. Lastly, there is limited knowledge regarding the effectiveness and feasibility of erosion control and mitigation measures specifically tailored to these landscapes.

The Revised Universal Soil Loss Equation (RUSLE) assesses the environmental effects of land use within a watershed. Precipitation and slope determine erosion. Erosion suppression and increased erosion generation enhanced flow route modifications in yellow rivers [28-30]. Land use within a watershed is affected by plant factors and watershed conservation [31, 32]. For example, Soil erosion attributed to precipitation decreases agricultural land utilization, soil productivity, and watershed utilization. Zhou et al. [19] implied that rainfall-induced land loss is caused by poor land use and its alterations. To calculate fundamental flow, sub-watershed land use area, and rainfall-induced flow, land use maps, sub-watershed maps, maps of rain measuring stations, and rainfall data are required [33]. While various erosion control practices have been proposed and implemented, their efficacy and long-term viability remain uncertain. Evaluating the efficiency of different erosion control techniques, such as terracing, vegetation management, and sediment trapping, in specific contexts is imperative to inform evidence-based management strategies. Addressing these knowledge gaps will contribute to a more comprehensive understanding of erosion processes, inform evidence-based decision-making, and facilitate the development of sustainable land management practices in mining areas, oil palm plantations, and reforestation watersheds.

The situation of the Asoloe watershed is depicted in Figure 1. Asoloe watershed is located in South Konawe Regency, Southeast Sulawesi Province, Indonesia. The watershed has upstream coordinates 3°56'5.77"S 122° 6'17.29"T, and downstream coordinates 4°18'57.06"S 122°22'15.04"E with the length of the main river 17,5 km with a watershed area of 59 km^2. In the upstream region, there are forest and reforestation regions in excellent condition. In the middle portion of the watershed are mining and oil palm plantation regions. In the downstream portion of the catchment, sediment deposits are visible in the river. The annual expansion of the mining area in the subject area has a negative impact on the forest cover. This condition can influence changes in the surface of the land and the volume of erosion observed in the downstream areas of the river, which are becoming shallower due to sedimentation and have the potential for flooding due to the smaller volume of the river basin, as well as residential areas where floods occur annually. In the Asoloe River Basin, there are also community oil palm plantations whose land area increases annually. Land that was formerly forested has been converted into oil palm plantations, creating the potential for changes in land use and increased erosion in the Watershed. Currently, the government is planning the re-greening of the Asoloe River Basin, particularly in the upstream and critical areas, so that the greening reduces the rate of erosion in the watershed. This condition is exacerbated by rivers with greater sedimentation rates. There have been previous studies with the USLE method by analyzing actual and potential erosion conditions but did not examine land cover conditions in mining, oil palm plantations, and reforestation conditions. Therefore, this study aims to determine the actual amount of erosion and potential erosion caused by mining conditions, oil palm plantations, and watershed reforestation, especially in the Asoloe watershed, South Konawe Regency, Southeast Sulawesi Province, Indonesia.

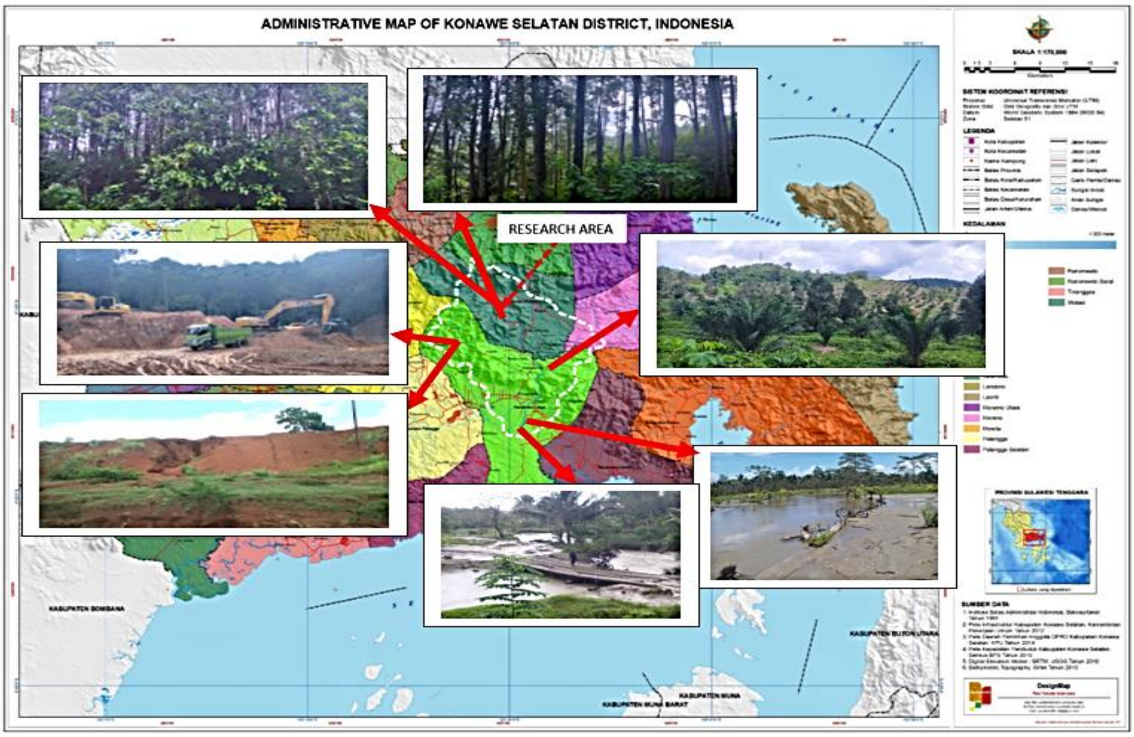

Figure 1. Watershed Conditions of Asoloe, Indonesia

2. Research Method

Bensekhria & Bouhata [34] affirmed that rain is a significant factor in water erosion. Therefore, each of the major analyses of erosion in the watershed was integrated into the analysis of land circumstances. This study employs a qualitative approach and survey techniques. This study utilizes data on precipitation, topography, watersheds, land cover, and soil conditions. Figure 2, shows the flowchart of the research methodology through which the objectives of this study were achieved. Current conditions are prone to erosion, and prospective large flood events such as those in 2013 and 2019 have resulted in landslides, flash floods, and submerged residential areas in the river's lower reaches. This study employs the USLE model, which identifies erosion intensity and factors influencing the frequency of erosion events [34]. We ascertained high rainfall, existing land conditions, and land slope levels in order to calculate the amount of potential erosion, with following USLE formula:

$$A = R \times K \times L \times S \times C \times P \quad (1)$$

where, A is Annual soil erosion (ton/ha), R is Rainfall erosivity, dependent on rainfall and runoff of the region, K is Erodibility factor of soil, L is slope length (m), S is slope (%), C is Plant Management Factor, and P is Land Management Factor.

The sequence of this study was as follows:

1. To collect hydrological data, topographic measurements, watershed data, soil data, and land cover condition data.
2. To determine the length of the slope (l), slope (s), plant factors and land conservation (C & P), and soil erodibility (R).
3. To determine the slope length and slope factor (LS) obtained from the results of slope length (l), slope, and soil grain diameter (d) with the formula $LS = (1.38 + 0.985(s) + 1.38(s)^2)\frac{\sqrt{L}}{22}$.

4. To determine the rain erosivity factor from rainfall data, number of rainy days, maximum rainfall, and erosivity index ($EI30 = 6.119 \times Rain \times 1.12 \times days - 0.747 \times Max.Rain \times 0.526$).
5. To determine the erosion magnitude by USLE formula.
6. To determine potential erosion ($EP = R \times K \times LS$).

Rainfall analysis aims to determine the draft rainfall for each return period of 2, 5, 10, 25, and 50 years recurrence periods, which will be used in analyzing flood discharge plan equations used by the Gumbel and Log person type III method. The accuracy validation of the planned rainfall data was tested using the Chi-squared test.

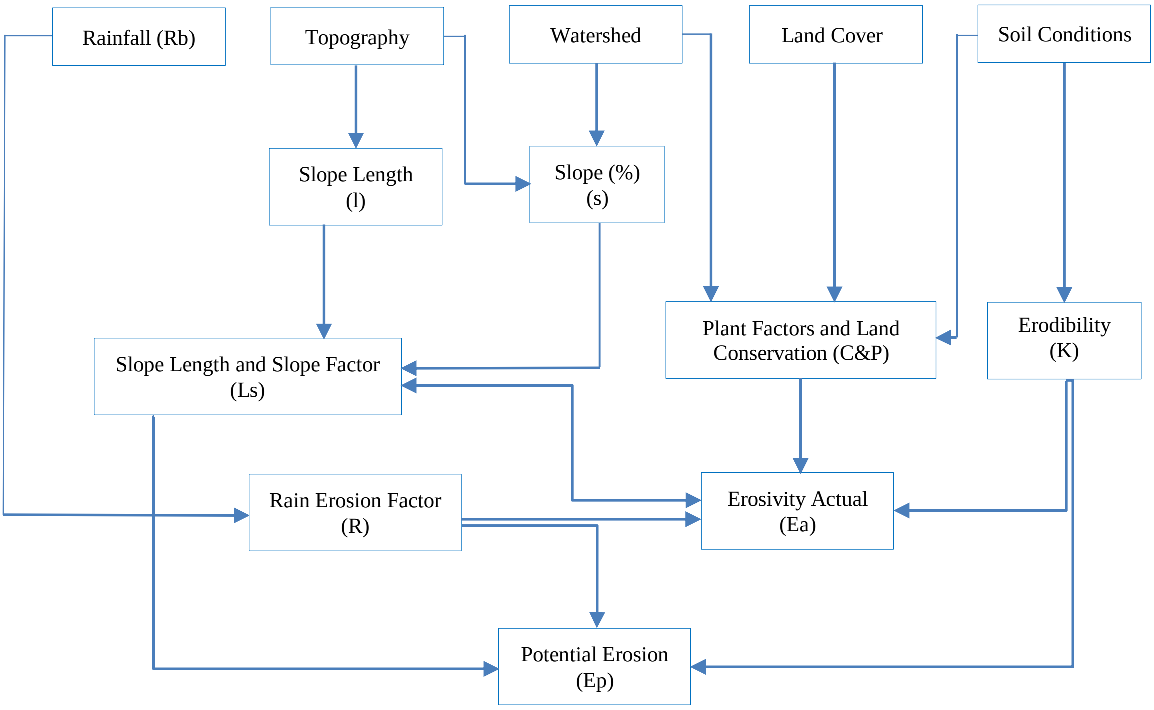

Figure 2. Flowchart of the research methodology

3. Results and Discussion

3.1. Rainfall Intensity

The topography of the Asoloe watershed is hilly, undulating, and straight, and the annual precipitation fluctuates. From 2011 to 2022, moderate to significant precipitation was recorded at the Onembute and Boito rainfall stations in this study area. Table 1 provides a summary of average precipitation, while Table 2 presents precipitation with various return periods derived from three formulation methodologies. As floods occurred during the years 2011 (137 mm) and 2018 (185 mm) there were significant increases in precipitation. As the maximal rainfall trend increases over the next seven years, the Gumbel approach appears applicable for a return period of 50 years.

Table 1. Average rainfall of watershed station around Aosole

No.	Year	Station		Average of Rain Intensity (mm)
		Onembute	Boito	
1	2011	63	211	137
2	2012	65	70	67.5
3	2013	67	75	71
4	2014	59	63	61
5	2015	63	64	63.5
6	2016	56	75	65.5
7	2017	44	81	62.5
8	2018	120	250	185
9	2019	54	73	63.5
10	2020	34	96	65
11	2021	33	95.5	64.25
12	2022	56	97	76.5

Table 2. Precipitation with return period

No.	Return Period (years)	Gumbel	Log Person III	Log-Normal
1	2	78.672	71.814	78.779
2	5	118.768	97.290	103.789
3	10	145.312	121.421	119.915
4	25	178.860	161.817	131.848
5	50	203.744	200.630	154.397

Based on the results of the probability distribution analysis, the values of $X_2 < X_{2Cr}$ (the pertinent method and meet the watershed circumstances) are compatible with Gumbel method. R_2 = 78.672 millimeters, R_5 = 118.768 millimeters, R_{10} = 145.312 millimeters, R_{25} = 178.860 millimeters, and R_{50} = 203.744 millimeters were among the results obtained; subsequent rainfall analysis determines the magnitude of intensity that occurs from 1 hour to 24 hours (Figure 3).

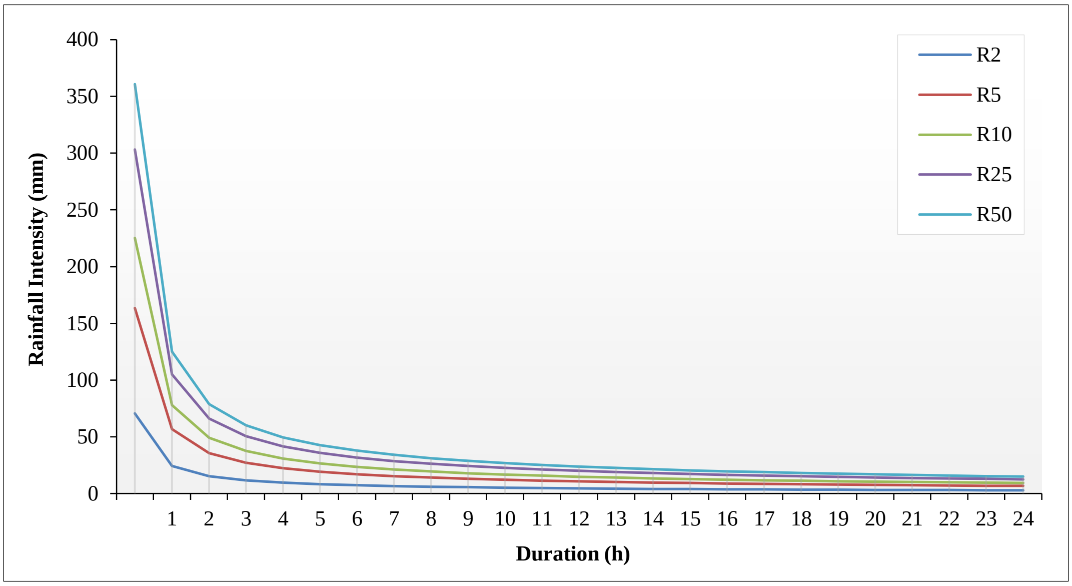

Figure 3. Rainfall intensity calculation

3.2. Erosivity

There are also shifts in the erodible surface conditions of the soil. Soil classification of the Asoloe watershed is untisol (with yellow-red Podzol soil types), and the slopes range from flat to steep, with class I = 0 to 8%, class II = 8 to 15%, class III = 15 to 25%, and class IV = 25 to 40%. This region's evapotranspiration can reach 53.7% due to the catchment rate of 9.7% and the runoff flow of 35.4%. Due to the soil water content and a potential infiltration flow rate of 5%, which is significantly influenced by the amount of available rainfall, the potential change is 1,2%. Table 3 demonstrates calculation of erosivity in Onembute station in 2011, as an example of high rainfall intensity. The results of erosivity analysis for both stations can be seen in Figure 4.

Table 3. Onembute Station Erosivity Analysis in 2011

Year	Month	Rb	N	Rb Max	Rb 1.21	N-0.47	Rb Max 0.525	EI30	R
2011	January	18.40	13	3.60	33.92	0.30	1.96	121.79	946.7
	February	24.00	15	6.30	46.78	0.28	2.63	210.68	
	March	14.40	14	2.30	25.21	0.29	1.55	69.11	
	April	24.90	18	4.10	48.91	0.26	2.10	161.37	
	May	32.60	20	6.30	67.76	0.24	2.63	266.59	
	June	9.20	13	1.50	14.66	0.30	1.24	33.25	
	July	9.10	12	2.00	14.47	0.31	1.44	39.62	
	August	2.40	4	1.20	2.88	0.52	1.10	10.12	
	September	0.00	0	0.00	0.00	0.00	0.00	0.00	
	October	0.00	0	0.00	0.00	0.00	0.00	0.00	
	November	0.00	0	0.00	0.00	0.00	0.00	0.00	
	December	6.40	7	2.10	9.45	0.40	1.48	34.21	

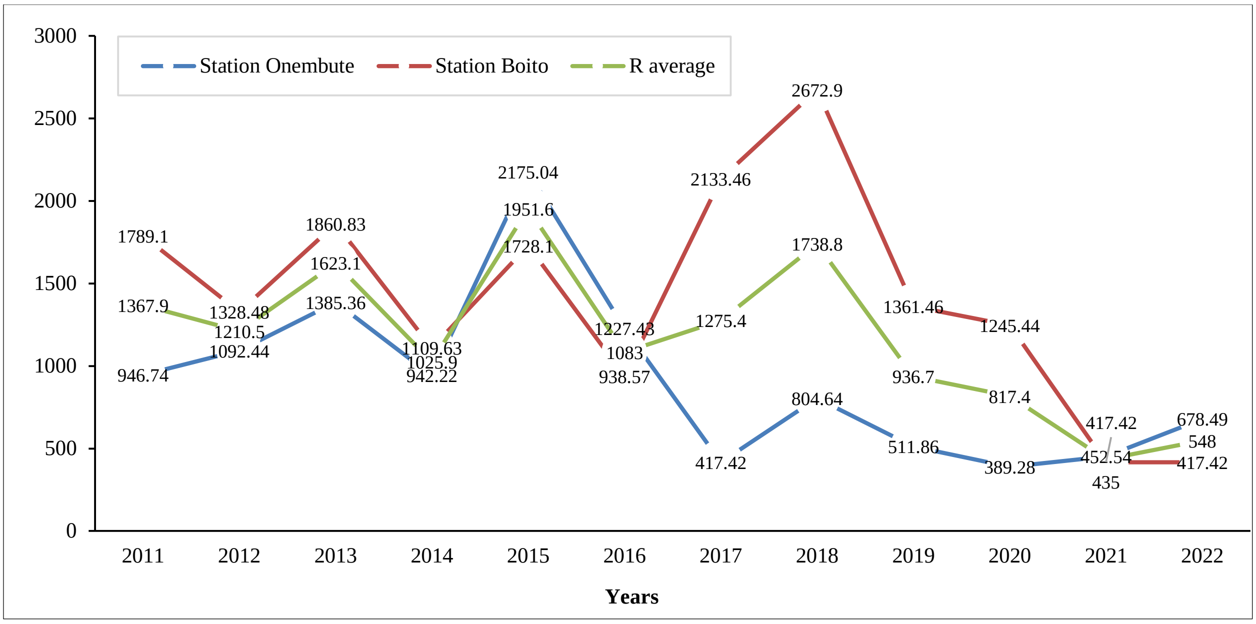

Figure 4. Erosivity 2011 - 2022 based on rainfall data

At Onembute station (blue line), the lowest annual rainfall erosivity event occurred in 2020 with 389.28 tons/ha/cm of rain, while at Boito station (red line), the lowest range occurred in 2022 with 417.42 tons/ha/cm of rain and the highest occurred in 2018 with 2672.90 tons/ha/cm of rain. The lowest level of average erosion in the Asoloe watershed occurred in 2021 when it was 453.51 and the maximum level occurred in 2015 when it was 1951.60. Changes in the number of rainy days over the past three years have substantially reduced the potential for erosion. Some studies suggest that rainfall conditions will partially percolate into the soil and some will become surface runoff or evaporate, with the annual rainfall rate being the daily average of precipitation and the number of rainy days determining the rate of percolation in the watershed represented by each existing rainfall station.

3.3. Potential Erosion

Soil Erodibility Factor (K) can be determined from the soil type in the Aosole sub watershed, based on the condition of the yellow-red Podzol soil type (Ultisol) with a value of 0.15 for Soil Erodibility Factor (K). The majority of the downstream Aepodu sub-watershed area is classified as slope class I with a slope of 0 to 8%, followed by slope class II with a slope of 8 to 15%, slope class III with a slope of 15 to 25%, and slope class IV with a slope of 25 to 40%, based on the results of the slope length and slope factor analysis. The classification of slope is then modified according to the Long Learning (LS) value. LS values (0.162) are derived from the slope length and slope of the watershed slope parameters.

Aspects of Crop Management and Land Conservation (CP) Plant management factors are the ratios of eroded soil in a type of soil management that is eroded on the same land surface, but without crop management to get an annual C value, it is necessary to pay attention to changes in land use each year; conditions in the Asoloe watershed land use are mining land, oil palm plantation land, rice fields, and forests, according to the survey results. In order to prevent an increase in the frequency and number of erosion events, it is necessary to routinely implement watershed management and conservation measures, as well as observe soil and water conservation regulations. For forest land cover conditions, CP values ranged from 0.01 to 0.07, with 0.07 being used in this study. For good watershed cover conditions, CP values ranged from 0.2 to 0.4, with 0.4 being used in this study. Secondary forests, primary forests, or land improvement with reforestation had a value of 0.01 to 0.05, with 0.05 being used in this study. While the value of the CP mining area is between 0.6 and 0.8 and the value used in this study is 0.8, the rate of erosion in each land use will vary depending on the CP value.

Figure 5 depicts the magnitude of Aosole Watershed erosion. The highest magnitude of erosion occurred in 2015 at 46.26 tons/ha/year and the lowest magnitude occurred in 2021 at 10.31 tons/ha/year. The parameters that greatly affect this analysis are erosivity, slope length, and slope. The more sloped the slope conditions, the greater the potential for erosion transport, but the greater the slope length, the lower the magnitude of erosion. Figure 6 depicts the erosivity, potential erosion, and actual erosion magnitude for each change in CP value, including mining, oil palm plantations, and reforestation. Large erosivity will have a negative impact on all aspects of land cover change, as depicted in the figure.

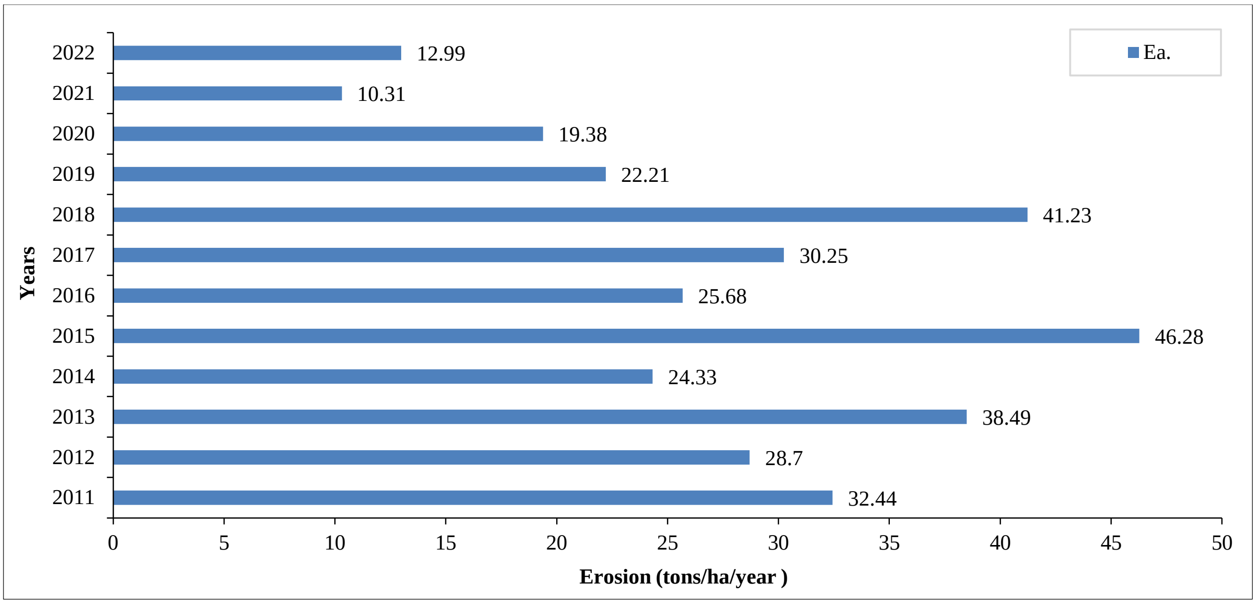

Figure 5. Results of calculation of erosion magnitude

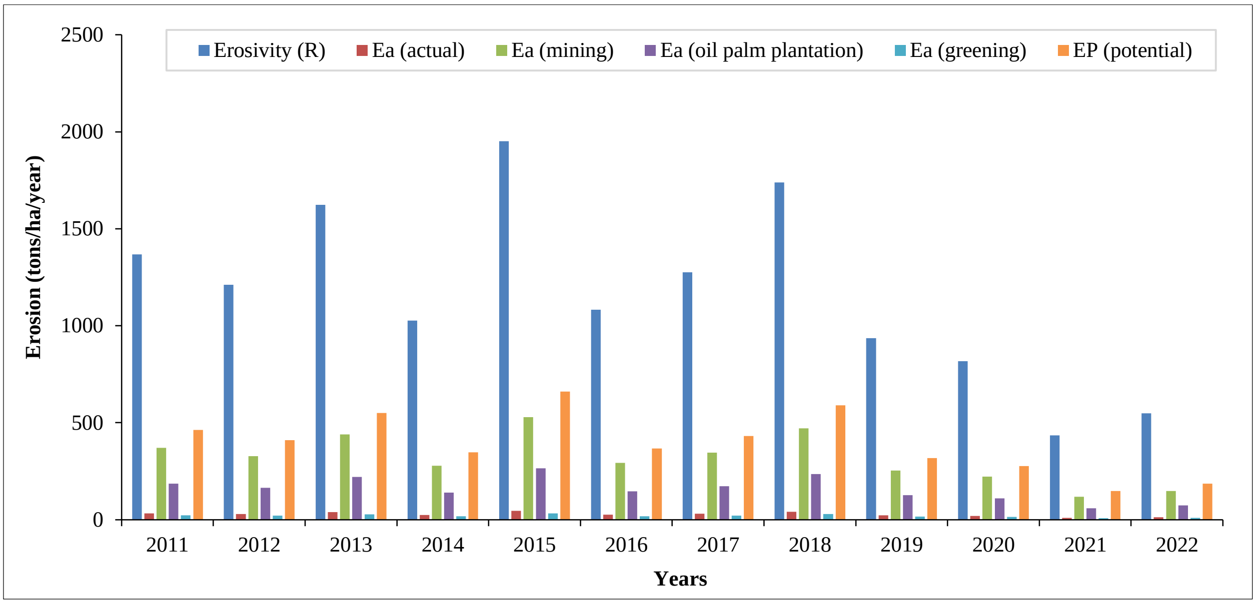

Figure 6. Erosion magnitude and potential erosion in land use

The results of the actual erosion analysis of the Aosole watershed, which are influenced by the values of R, K, l, s, and CP, vary from year to year due to the amount of precipitation. The lowest value of actual erosion occurred in 2021, when Ea = 10.31 tons/ha/year, while the highest value occurred in 2015, when Ea = 46.28 tons/ha/year. In contrast, the minimum value for land cover conditions with mining land conditions and a CP value of 0.8 is Ea = 117.87 tons/ha/year in 2021, while the maximum value was Ea = 528.81 tons/ha/year in 2015. In the condition of oil palm plantation land with a CP value = 0.4, the lowest Ea value was obtained in 2021 at Ea = 58.97 tons/ha/year and the highest was obtained in 2015 at Ea = 264.40 tons/ha/year, while in reforestation land cover the CP value = 0.05 and the lowest Ea value was obtained in 2021 at Ea = 7.37 tons/ha/year and the highest occurred in 2015 at Ea = 33 tons/ha/year. This condition is strongly influenced by the erosivity (R) and land cover (CP) values. In mining land conditions, the Ea value is very high relative to other Ea values due to a low infiltration rate and a high run-off rate.

3.4. Discussion

The findings in the preceding section are consistent with Siddiq's [6] study, where erosion is influenced by a land slope as done in the Lower Lake in rainfall erosion conditions (R) with Cambisol and Andosol soil with soil erodibility values (K) 0.22 and 0.20 with soil slopes around the lake by 28 - 40% with a total erosion reduction in the Lower lake of 1061.36 tons/year and can reduce sediment rates by 31.08%. The analysis was carried out in steep, bumpy, hilly, and flat topographic areas with high levels of rainfall. Determining watershed conditions is a top priority in addressing erosion and changes in land degradation. Determination of survey points in sub-watersheds using a picture of the potential for stable rainfall can utilizes the Geographic Information System (GIS) to effectively determine the path and condition of the sub-watershed area to help obtain water sources with water quality parameters and water quantity in the sub-watershed [35].

In accordance with research conducted by Brychta & Janeček [26], obtained Parameters that have a significant effect on the amount of erosion are rainfall, rain intensity, and erosion resulting in large soil loss using the USLE method obtained large erosion resulting in large countermeasures costs, the similarity in this study is the influence of rainfall and erosion can increase erosion that occurs. The difference in this study is the determination of the cost of handling erosion, while in our study we took into account changes in land cover that resulted in changes in erosion. The potential for rainfall that occurs affects the rate of erosion so the rate of erosion will also increase. The results proved that if the parameters I15 > 6.25 mm and H > 12.5 mm were met, then rainfall 84.2% caused erosion> 0.5 t/ha and 73.7% ≥ 1 t/ha. In the case of existing conditions, only 44,6% of rainfall caused erosion > 0.5 t/ha and 33.9% ≥ 1 t/ha. This study proved that high rainfall rates affect soil erosion and actual erosion in watersheds with different cover conditions. Fan et al. [23] has reported changes and increases in erosion that occurred in hilly areas, and the preservation of agricultural land to reduce erosion potential, using the USLE method conventionally. Although excessively conservative, the watershed reforestation strategy will be effective in preventing future erosion in the mining, oil palm plantation and watershed areas.

Prevention and reduction of erosion are dependent on mitigation management. Erosion control is essential in mining sites to delay the erosion caused by land disturbance. Reforestation with indigenous plants, contour tillage, and terracing can stabilize soil, reduce runoff, and prevent sediment movement. Around waterways, buffer zones and riparian vegetation filter detritus and pollutants. During mining operations, sedimentation ponds, barriers, and basins can capture sediment and prevent its flow into adjacent ecosystems. Soil conservation and appropriate land management minimize erosion in oil palm fields. Cover crops, contour tillage, and terracing reduce surface runoff and stabilize soil. Filter strips and riparian vegetation can prevent the entry of sediment and nutrients into waterways. Channels and bunds that are constructed and maintained correctly can reduce soil erosion caused by surplus water flow. Best practices for managing fertilizers and pesticides prevent soil erosion and water contamination, making oil palm cultivation more sustainable. Watershed reforestation mitigation measures encourage forest ecosystem conservation and restoration. Reforestation should employ native tree species with extensive root systems that stabilize the soil. Enhanced natural regeneration can save money and enhance reforestation efforts. Additionally, riparian barriers can prevent sedimentation and nutrient runoff. Plan and manage reforestation to prevent deforestation and forest degradation. Implementation, monitoring, evaluation, and adaptation are key to the success of erosion control measures. Monitoring erosion rates, sediment transport, and water quality can enhance mitigation techniques. Involving local communities, landowners, and stakeholders in the planning and implementation of erosion prevention promotes ownership and sustainable land management. Erosion can be mitigated by integrating erosion control strategies tailored to particular land-use scenarios. These measures preserve the soil, water, biodiversity, and long-term viability of ecosystems that have been harmed by mining, oil palm plantations, and watershed restoration.

4. Conclusion

Erosion in the Aosole catchment is triggered by R, K, L, S, and CP, which are affected by precipitation, slope, and land cover. In the region under study, mining areas, oil palm plantations, and reforestation areas experienced the least actual erosion in 2021 Ea = 10.31 tons/ha/year and the most in 2015 Ea = 46.28 tons/ha. The smallest mining land cover (Ea) is 117.87 tons/ha/year, whereas the highest is 528.81 tons/ha/year. Oil palm plantation land had Ea = 58.97 and 264.40 tons/ha/year, while reforestation land cover had Ea = 7.37 and 33.05 tons/ha/year. Erosion (R) and land cover (CP), particularly on mining land, have a substantial effect on this. The potential for erosion in the Asoloe catchment ranges between 147.36 and 661.13 tons/ha/year. Using the USLE method, the patent erosion rate in the Aosole watershed was calculated to be 332.30 tons/ha/year, with an average erosion rate from 2011 to 2022 of 27.69 tons/ha/year. The total EP is 4747.19 tons/ha/year, and the average EP is 395.6 tons/ha/year. 44.6 % of precipitation results in erosion > 0.5 t/ha and 33.9% t/ha.

This study demonstrates that excessive precipitation, changes in land function, and land cover influence erosion potential. Considering that reforestation has the lowest erosion value within the catchment, it should be expanded. Reforestation of watersheds employs native trees with deep roots to stabilize soil and preserve forest ecosystems. Reduce sedimentation and nutrient discharge with regeneration and riparian barriers. Implementation, evaluation, and adaptation are required for erosion control. Through local communities, proprietors, and stakeholders, erosion prevention promotes land ownership and sustainable land management. After mining, oil palm plantations, and watershed restoration, soil, water, biodiversity, and ecosystem viability can be preserved by erosion control techniques tailored to land-use scenarios.

5. Declarations

5.1. Author Contributions

Conceptualization, A.S.S., S.M., and R.T.; methodology, A.S.S., S.M., and N.; software, A.S.S. and S.M.; validation, A.S.S., S.M., and N.; formal analysis, A.S.S. and R.T.; investigation, N. and R.T.; resources, A.S.S., S.M., N., and R.T.; data curation, A.S.S., N., and R.T.; writing—original draft preparation, A.S.S. and S.M.; writing—review and editing, A.S.S., S.M., and N.; visualization, A.S.S. and R.T.; supervision, A.S.S. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available in the article.

5.3. Funding

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5.4. Acknowledgements

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5.5. Conflicts of Interest

The authors declare no conflict of interest.

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