Pol. J. Environ. Stud. Vol. 32, No. 4 (2023), 3617-3626
DOI: *10.15244/pjoes/163499* ONLINE PUBLICATION DATE: 2023-06-09

Original Research

Mapping Analysis for Vulnerable Areas and Erosion Rate of Laut Tawar Lake, Peusangan Watershed

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Received: 13 December 2022
Accepted: 21 April 2023

Abstract

Having an area of approximately 57,8 km^2, a perimeter of 46,12 km, and a water catchment area of about 246,5 km^2, Laut Tawar Lake has undergone siltation which was allegedly caused by soil erosion from the water catchment area, leading to sedimentation of water bodies. This study aims to map vulnerable areas and calculate the erosion rate of the Laut Tawar Lake for the purpose of providing information on the spatial layout and development design of the lake water catchment area. We use remote sensing and geographical information system to map areas vulnerable to erosion. For analyzing the potential erosion rate, we adopt the Universal Soil Loss Equation (USLE) approach. Our result showed erosion rate occurred in the Laut Tawar Lake ranged from very low to very high. In addition, erosion is also sparsely distributed in Laut Tawar Lake. The high erosivity index, domination of area more than 45% slope, and land use change from forest to the agricultural area in the study area become the main driver of the erosion. Analysis of the potential erosion rate of Lake Laut Tawar shows an increase from 1990 to 2019. Erosion was 12.4 tonnes/ha/year in 1990, 11.0 tonnes/ha/year in 2000, 14.6 tonnes/ha/year in 2009, and 27.4 tonnes/ha/year in 2019. The spatial distribution of erosion shows an increasing trend from year to year. The results of the overlay with villages in lake catchments show that 66 percent of villages are in the high and very high categories in the last year. The study suggested conservation through revegetation using local species as the best solution for the erosion issue

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in the lake cliff area. The vegetation also plays a crucial role as a soil cover that protects the soil from rainfall kinetic energy that led to erosion.

Keywords: landslide, land use, sedimentation, soil, slope

Introduction

Lake is one of the essential ecosystems providing various freshwater resources for life and being a susceptible indicator to climate change [1-4]. Despite functioning ecologically and biologically, the lake provides freshwater, resources, and material production, beneficial to power plants, tourism, and other functions for human life. These indicate the primary role of the lake in the socioeconomic development of the cities around the ecosystem [5, 6]. Lake is directly and indirectly affected by the land use change, climate change, and human activity [5, 2, 7], and every lake is responding differently to environmental changes [7-9].

Laut Tawar lake is one of Indonesia's lakes located in Aceh Tengah District. The total area of the lake is approximately 5.742,10 ha and becomes the water supply for around 64.147 population living around the lake area. The exquisite landscape of the lake become the main attraction for international and domestic tourists. Laut Tawar Lake also holds an important ecosystem function for endemic fish, known as depik fish, which was declared by the International Union for the Conservation of Nature (IUCN) as an endangered species. Moreover, Laut Tawar lake also functions as the water balance of the Krueng Peusangan watershed, the water source of the four districts of Central Aceh, Bener Meriah, Bireuen, and North Aceh.

Pressures from population growth to the land demand, labor, and settlement, slowly modified the environmental condition surrounding the lake area. Land use change in the lake water catchment area causes erosion and sedimentation. The watershed area is experiencing destructive condition from human interaction and intervention that affects hydrological balance and cause disaster [10, 11]. Disturbance in watershed ecology and hydrology is highly related to disruption to the ecosystem part [12-14]. This has caused a reduction in water discharge, shrinkage of the surface area, decrease of the biota, and reduction in the lake water quality. [15] stated that there are 46 plankton types in Laut Tawar Lake that were categorized into 11 classes. Three Phylum fauna were found in Laut Tawar Lake, including Molluska (Soft-bodied organisms), Annelida (segmented worms), and Pisces (fish). For Pisces, 22 fish types were found in Laut Tawar Lake. Moreover, according to [16] there are two endemic species in Laut Tawar Lake, namely Rasbora tawarensis and Poropuntius tawarensis, known as gule depik and gule kawan in a local name. In the terrestrial ecosystem of the Laut Tawar Lake, terrestrial fauna can also be found (e.g., Insecta, aves, and Mammalia). Agricultural activity potentially pollutes lake water if fertilizer and pesticide residue were flowing into the lake and affecting the growth of algae and other aquatic plants (eutrophication). The stilting process from erosion in Laut Tawar lake shows an increasing trend yearly, as depicted by the actual condition of the upstream of Krueng Peusangan River, as provided in Fig. 1. The upstream was the point of the Regulating Weir for the Peusangan water powerplant and upstream of the Krueng Peusangan River.

Sedimentation in Laut Tawar Lake (Fig. 1) has been of concerned and requires a rapid yet comprehensive solution for the mitigation effort. The ecosystem function where the erosion area be identified should be rehabilitated and improved, followed by the limitation on expansion for development around the area [17]. Increasing the landscape function by conserving the forest area can increase the soil water content, bulk density, and soil porosity; hence, preventing soil erosion [18]. This study aims to analyze the erosion rate and map water catchment areas that are vulnerable to erosion. This study offers fundamental information to be used for spatial layout for the development plan. We argue that the study is significant to support the sustainability of the Laut Tawar Lake, and deliver proper knowledge for policy making at the government level of Aceh Tengah District.

Study Area

The study was conducted in Laut Tawar Lake, Krueng Puesangan watershed (Fig. 2), Aceh Tengah District, Aceh Province. Geographically, Laut Tawar Lake is located at 04°34'43" N and 96°55'25" E with 1.205 m elevation above mean sea level (AMSL). Laut Tawar Lake extended for 57,8 km^2 with a perimeter area of 46,12 km and the water catchment area of approximately 246,5 km^2.

Data and Analysis

This study used (Table 1): 1). Input data for GIS, comprises spatial and numeric data. The spatial data input consists of Digital Elevation Model (DEM) data, land use, soil, and slope. 2). Numeric data comprises climate data (e.g., rainfall).

Method for Analysis

Analyzing Areas Vulnerable to Erosion

In this study, we value areas vulnerable to erosion using the approach of linear morphometric parameter

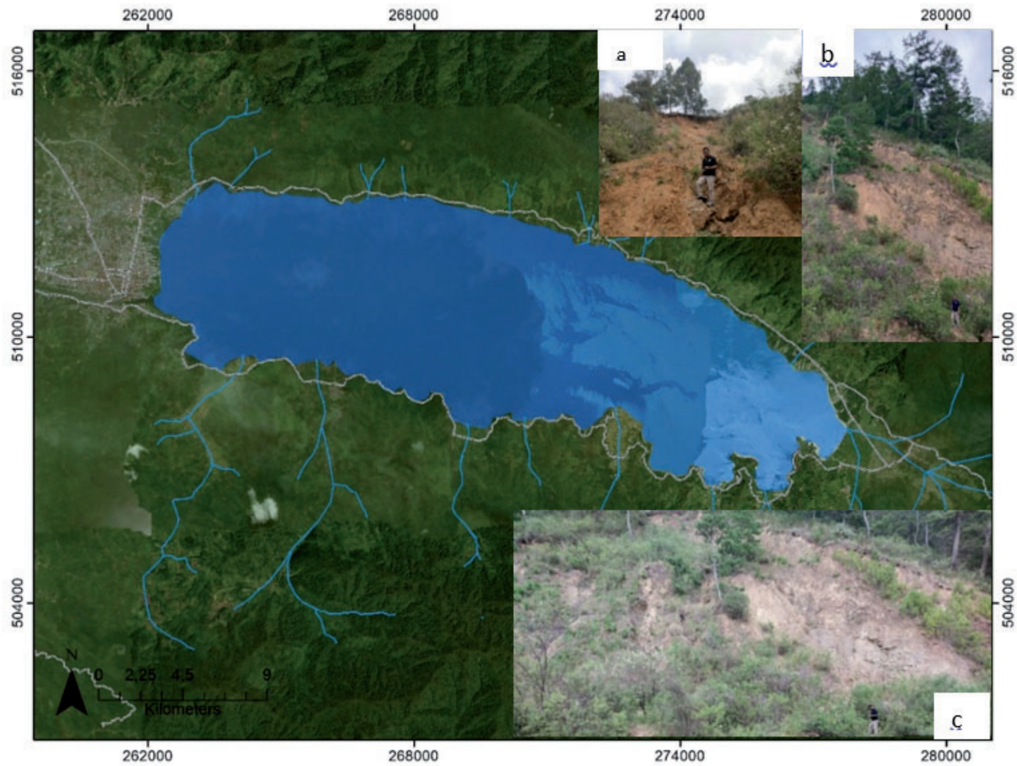

Fig. 1. Laut Tawar Lake, Takengon, Aceh Tengah District. a), b), and c) Erosion points that occurred along the Lake Laut Tawar causeway caused road access to be disrupted.

Table 1. Data description.

Data Type	Source	Description
Digital Elevation Model (DEM)	Advanced Spaceborne Thermal Emission Reflection Radiometer (ASTER) DEM USGS	30 m of spatial resolution
Soil map	Soil Research Institution and field sample	Scale 1:250.000
Land use	Forestry Planning Agency (Baplan)	Land use for the years 1990, 2000, 2009, and 2019
Rainfall	Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS)	The year 1981-2021

extraction from the water catchment area. The approach is combining the physiography characteristic of the water catchment area to determine the hydrological response, which represents the tendency to generate an area vulnerable to erosion. Factors used for the process comprise slope, soil type, and land use.

Steps to determine the area vulnerable to erosion were: (1) extraction of the linear morphometric parameter, shape, and relief of the catchment area, using the Digital Elevation Model (DEM) from ASTER; (2) land use map composed from Baplan; (3) determination of slope class; (4) determination of soil classification class; and (5) determination of area vulnerable to soil erosion and its classification to five vulnerability class: very high, high, medium, low, and very low.

Analyzing Erosion Rate

We analyze erosion rate using ArcGIS 10.8 software and the USLE model with five factors and formulation as follows:

$$A = R\ K\ L\ S\ C\ P$$

Where A is the amount of the eroded soil (ton/ha/year), R is the rainfall factor index (erosivity), K is the soil erodibility factor, L is the slope length factor, S is the slope factor, C is the factor of soil vegetation cover and cultivation management, and P is the factor of soil conservation measures. For the case of Indonesia climatic condition, erosivity were estimated using Bols : $E.I_{30} = 6{,}119\ (RAIN)^{1{,}21}.\ (DAYS)^{-0{,}47}.\ (MAXP)^{0.53}$

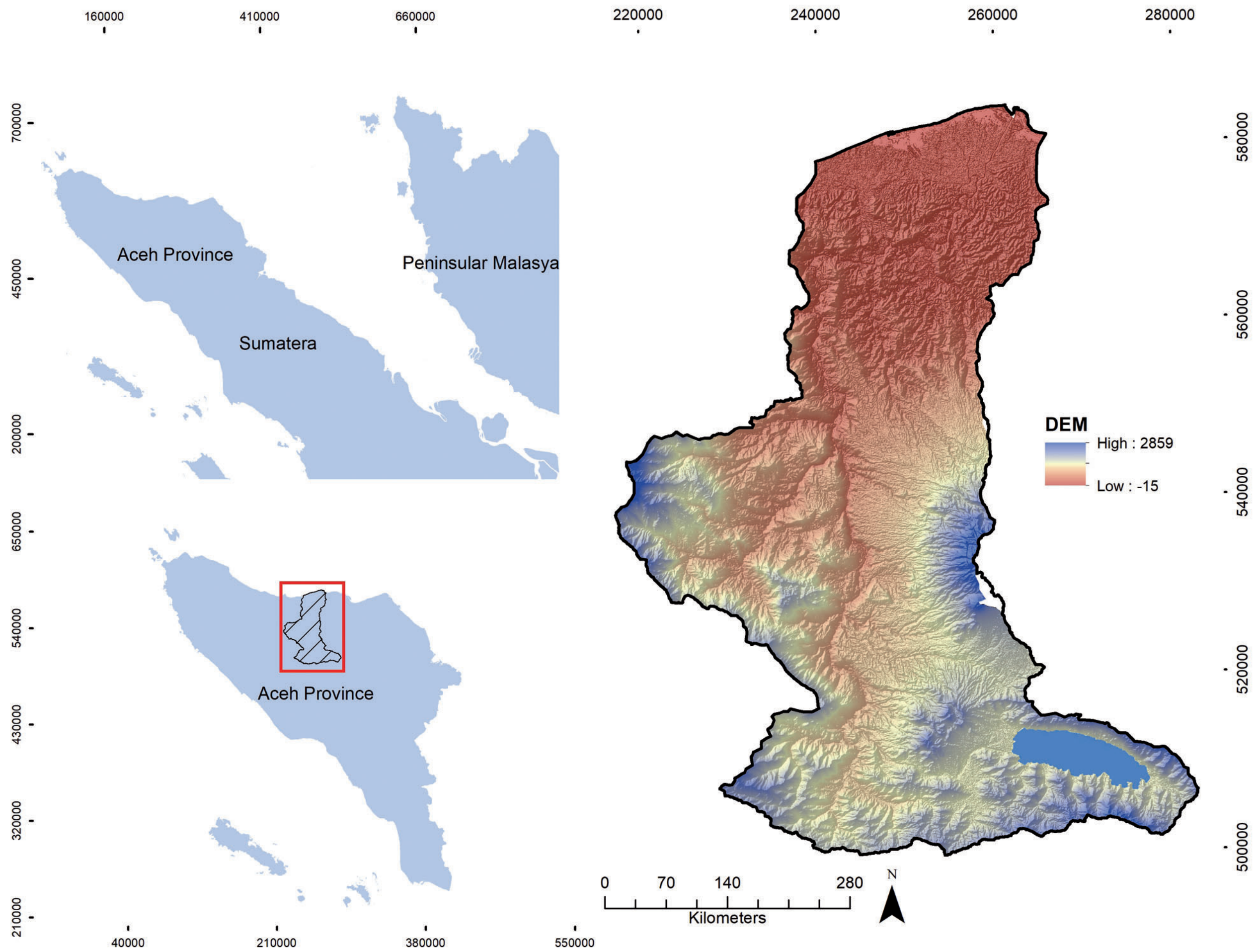

Fig. 2. Area for Erosion Study in The Catchment Area of Laut Tawar Lake, Takengon, Central Aceh. Laut Tawar Lake crossing four districts in Aceh Province is part of the upstream Peusangan watershed.

Where:
EI_{30} = Rainfall erosivity index
RAIN = Annual rainfall (cm)
DAYS = Number of rainy days on annual average (days)
MAXP = Average of maximum rainfall in a day or 24 h

Results and Discussion

Rainfall Erosivity Index

One of the factors that determine the prediction of soil erosion is the rainfall erosivity index. Rainfall characteristic (e.g., rainfall amount, number of rain days, and maximum rainfall) affects the type of erosion in a region [19]. [20] stated that the amount of rainfall, rainfall intensity, and rainfall distribution determine the dispersion strength of rain against the ground, the amount and strength of the surface runoff, as well as the level of destruction from erosion occurrence.

According to the result from rainfall analysis for four decades (1981-2020), the highest rainfall was found in the first decade of 1981 to 1990 with an erosivity index of 2.041,5 mm/year. The second highest is the third decade , with erosivity amounting to 1.883,1 mm/year during the period of 2001 to 2010, followed by the fourth decade period of 2011 to 2020, amounted to 1.842,8 mm/year, and the lowest is during the second period of 1991 to 2000 with erosivity index of 1.808,6 mm/year.

The erosivity index value indicates rainfall's potential capacity on causing soil degradation; thus, has the potential to cause erosion, flooding, and landslide in Wae Batu Merah watershed [21]. The higher the rainfall index, the higher the erosivity, which indicates a great rainfall capacity for causing erosion. The different levels of rainfall erosivity across soil will lead to varied runoff and erosion potential [22]. Excess annual rainfall in the western region of the highland will increase the hazard of soil erosion, including landslides [23].

Slope and Landslide Points

The slope factor with the highest influence on erosion is the tilt and the slope length. The results of

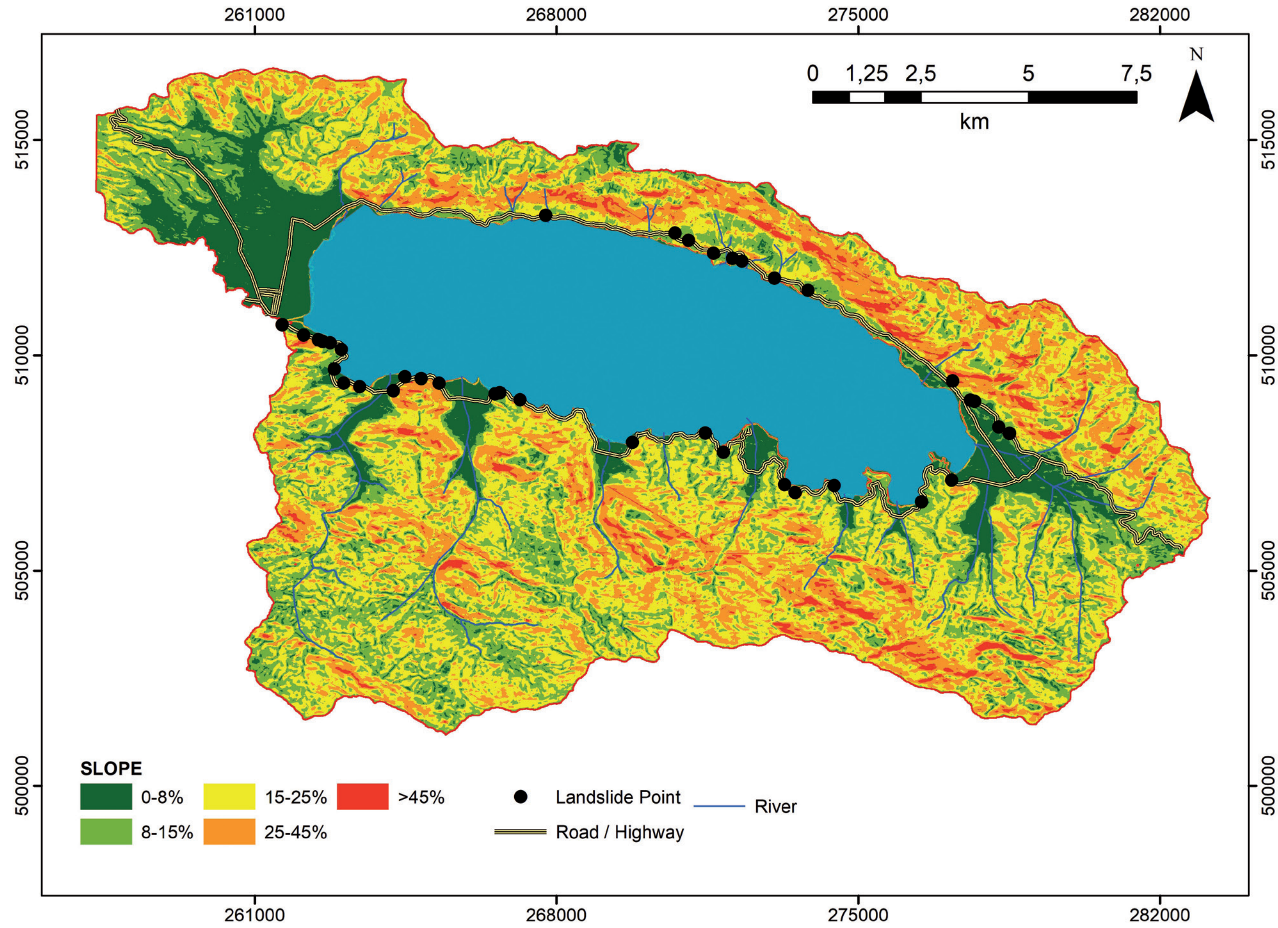

Fig. 3. Slope and Landslide Points of Laut Tawar Lake. Points of landslides (erosion) occur along the causeway Laut Tawar Lake.

the slope analysis in the Lake Laut Tawar area show that the area around the lake is dominated by very steep (50.1%), steep (28.7%) and rather steep (8.1%) areas (Fig. 3). The flat and tilt areas (7.6% and 5.6%) are found in the lower reaches of the lake, which are land areas that often experience flooding along the rivers that flow into the lake.

A slope of more than 45% is dominating Laut Tawar Lake watershed with approximately 50,1% of the total lake area. [24] has stated that areas with steep topography and sparse land use allow the soil to be dispersed from rainfall kinetic energy. The amount of rainfall that infiltrates or flows as surface run-off is highly affected by the topography factor or slope. The steeper the slope, the lower the amount of infiltrated rainfall and the greater the run-off [25]. A slope of more than 45% is more vulnerable to landslides (Fig. 3), where landslide points were distributed surrounding the lake area. Landslides were found to occur in the area frequently crossed by local communities and tourists.

Land Use and Landslide Points

Land use in an area plays an important role in covering soil surface from run-off dan erosion hazards. Vegetation cover affects the erosion rate, of which open area will have a greater erosion rate while dense vegetation areas have the least erosion probability [25]. Land use in Laut Tawar Lake (Fig. 4) is dominated by Secondary Dryland Forest (58,7 km^2), Forest Plantation (45,4 km^2), Dryland Agriculture (40,0 km^2), Shrubs (13,2 km^2), Settlement area (10,5 km^2), Primary Dryland Forest (8,7 km^2), Paddy Field (7,6 km^2), and open area/bare ground (0,1 km^2).

Land use change affected natural disaster hazards, for instance, erosion and landslide that commonly occurred in Laut Tawar Lake. Landslides frequently occur in shrubs and bare ground land use. Landslides and flash floods in Laut Tawar Lake have become an annual event and causing mortality and loss of assets [26]. This was mainly due to environmental changes, specifically deforestation, in Laut Tawar Lake, which were also altering the water quality of the lake [25].

The [27] research stated that as many as 37 points of landslides in the freshwater lake area were caused by land use change from forests to plantations, slopes, especially in the cliff area carved for development roads, the volcanic geology of the Bukit Barisan mountain, rainfall, and the characteristics of equatorial rainfall.

Land use change in a few decades has impacted the increasing trend of erosion events. Forest land use

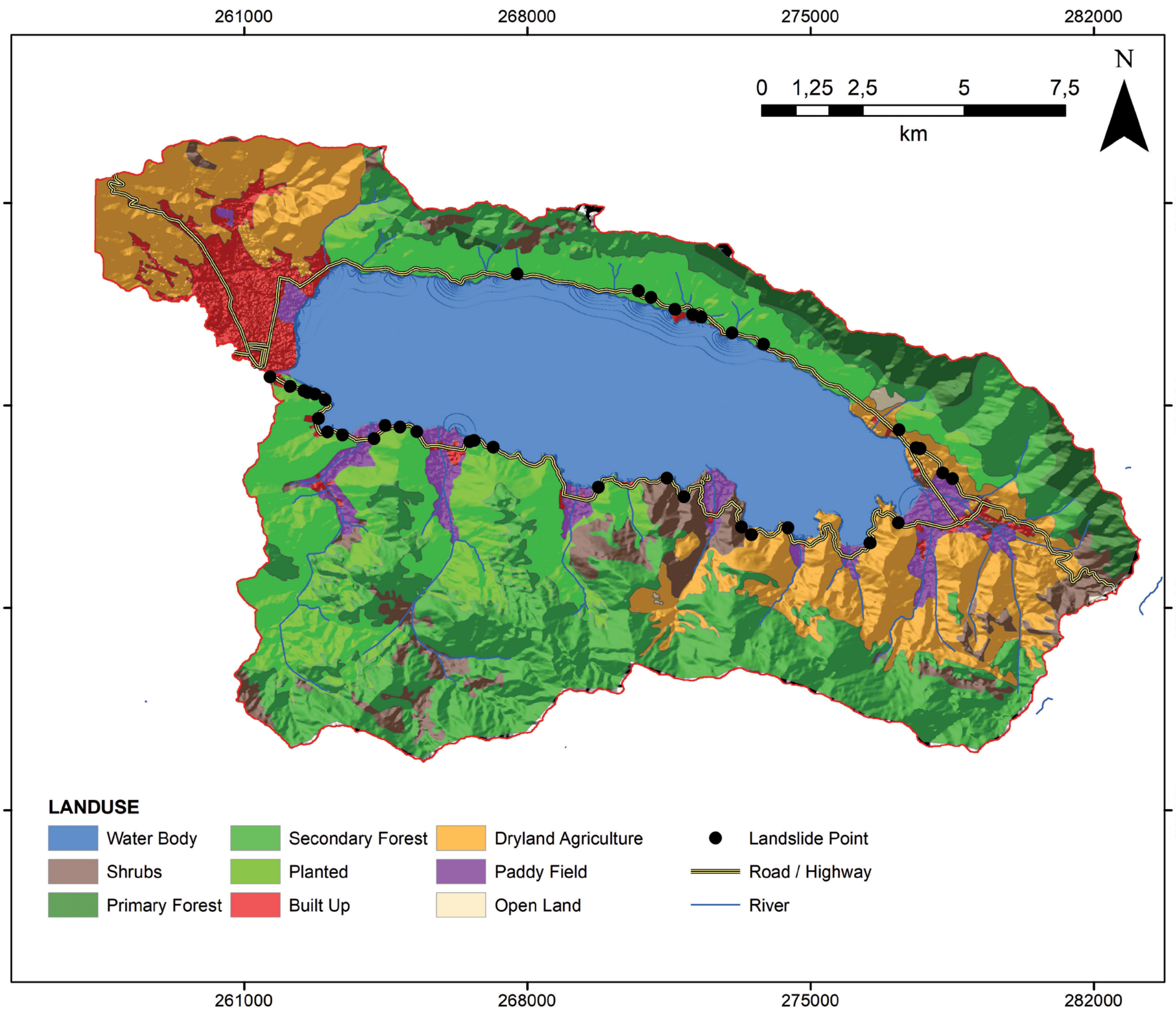

Fig. 4. Land Use and Landslide Points in Laut Tawar Lake. This image also shows the catchment area Laut Tawar Lake.

that previously dominated the lake area was reduced over time. The reduction of forest cover is mainly for agricultural expansion, which is against the conservation principle for slope areas. These have aggravated the soil erosions in the area.

Potential Erosion Rate

Our result from the predicted erosion rate for 4 periods is showing an increasing trend (Table 2). In addition, the distribution was found in almost the entire part of Laut Tawar Lake (Fig. 5). Potential erosion was spreading in Laut Tawar Lake from an area with a slope of 0% to more than 45% in various land use types.

An analysis of Lake Laut Tawar's potential erosion rate reveals a rise from 1990 to 2019. In the years 1990, 2000, 2009, and 2019, erosion was 12.4 tonnes/ha/year, 11.0 tonnes/ha/year, 14.6 tonnes/ha/year, and 27.4 tonnes/ha/year, respectively. The catchment of Danau Laut Tawar has undergone changes in land use that have contributed to this rise in erosion [27]. One of the causes of the rise in erosion is the 40-year process of turning forest area into agricultural land [27]. The intensity of cliff landslides has grown as main forest on the cliffs of Lake Laut Tawar has given way to coffee and pine plantations [27]. This is consistent with research findings that show a connection between higher erosion rates and changes in the land cover of the Lake Tondano catchment [28]. The [29, 30] potential erosion in the Laut Tawar Lake was affected by the index of soil length and slope (LS), while the actual erosion was derived by the index of soil length and slope (LS) and index of conservation and land management (CP).

Decreasing forest area, specifically, converted land to estate crops becomes the main driver for the class of heavy erosion [31]. The main factor for heavy erosion is the unsuitable land use with the land topography condition [24]. Laut Tawar Lake area that was dominated by a slope of more than 45% (50,1% of the total study area) has the most probability for erosion events under the high to very high category, as reinforced by the unsuitable land use according to the principle of soil and water conservation technology.

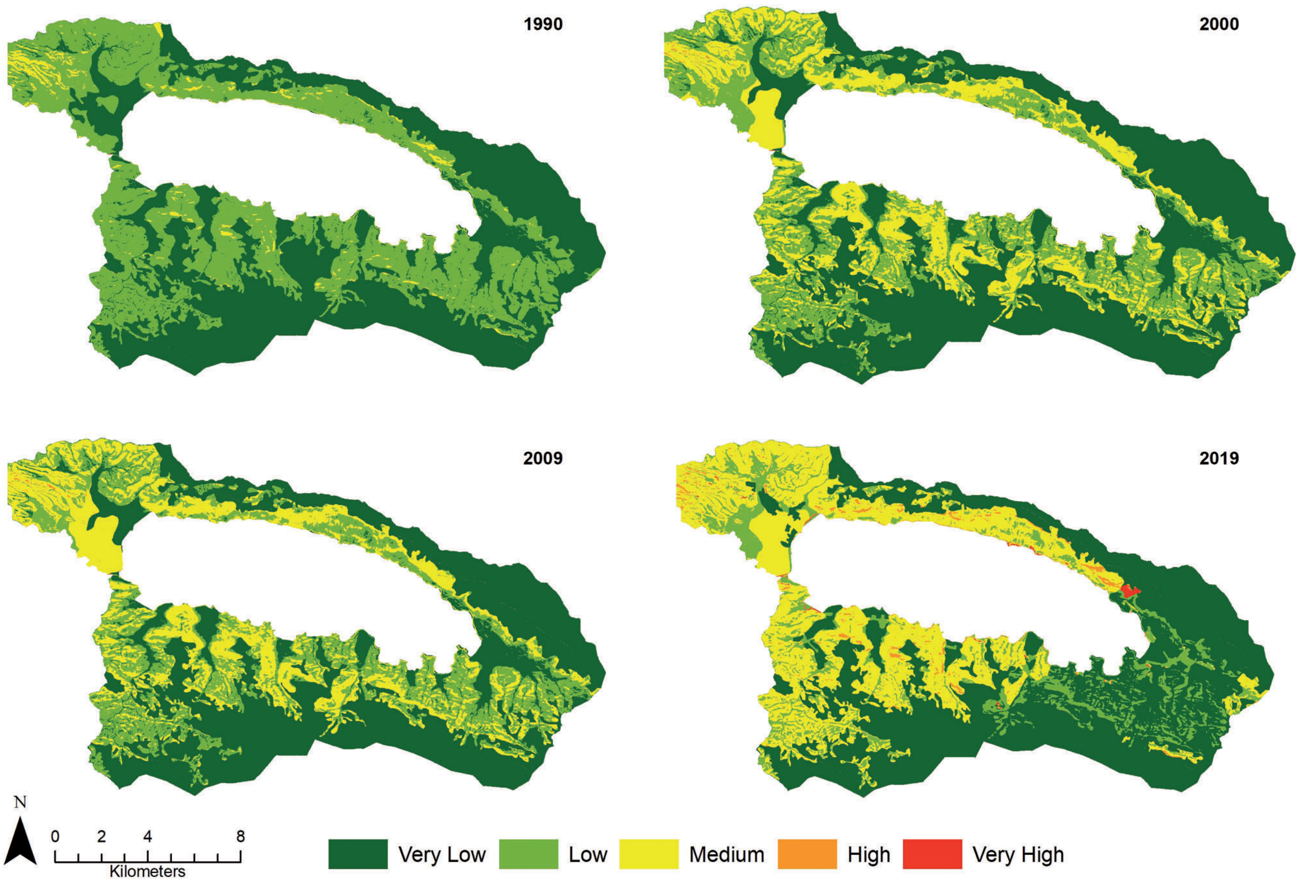

Fig. 5. The distribution of soil erosion four periods (year period 1990, 2000, 2009 and 2019).

Table 2. Distribution of erosion for four periods (1990, 2000, 2009, and 2019.)

Erosion class	Distribution of soil erosion (ha)			
	1999	2000	2009	2019
Very low	9,562.1	8,928.1	8,918.2	9,641.6
Low	8,625.8	5,433.7	5,149.3	2,729.0
Medium	481.8	4,296.3	4,583.6	5,945.5
High	0.7	11.5	18.5	300.7
Very high	0.5	1.2	1.2	54.0

The actual condition in Laut Tawar Lake was exacerbated by the hilly soil contour, high rainfall, forest loss, and domination of community settlement in some parts of the slope area [26, 28] has confirmed that a steep slope with an absence of conservation effort will reduce the infiltration capacity of the soil, increase surface runoff and its rate and increase the transport energy of the surface run-off that leads to high erosion.

Distribution of the erosion for the years 1990, 2000, and 2009 is not showing a distinctive condition for a different study area, of which very high soil erosion is dominating many parts of the lake. The area under high and very high erosion in 2019 was majorly found in dryland agriculture land use. This has shown the high influence of land use on erosion events.

Based on Table 2, the erosion distribution area shows an increasing trend. During the 1990 period, erosion occurrence was dominated by very low erosion, which reached an area of 9,562.1 ha, while during the period 2000 to 2009, wide erosion occurrence was dominated by low to medium with an area of 10,583 ha and 8,879.9 ha respectively. Then, in 2019 the distribution of high and very high erosion has occurred in the Fresh Sea Lake area. The trend of increasing erosion in Lake Laut Tawar from very low to very high erosion is caused by land conversion [27]. Erosion peaks were found in 2019, with a very high erosion

Table 3. Villages that are contributing to the erosion in Lut Tawar Lake.

Villages	Erosion category	Villages	Erosion category	Villages	Erosion category
Bale Nosar	H-EH	Kala Lengkio	EH	Pedemun One One	H-EH
Bamil Nosar	H-EH	Kala Segi	H-EH	Pinangan	H-EH
Bewang	H-EH	Kejurun Syiah Utama	H	Rawe	H-EH
Blang Kolak Ii	H	Kelitu Sintep	H-EH	Simpang Iv	H
Bukit Ewih Tami Delem	H-EH	Kenawat	H-EH	Sintep	H-EH
Bukit Sama	H-EH	Kuala I	H	Takengon Timur	H-EH
Burbiah	H-EH	Kute Baru	H	Tebuk	H
Daling	H-EH	Lelabu	EH	Teluk One-One	H-EH
Dedamar	H-EH	Linung Bulen I	H-EH	Tensaran	H-EH
Empus Talu	H	Linung Bulen Ii	H	Timangan Gading	H-EH
Gegarang	H-EH	Lot Kala	H-EH	Toweran Toa	H-EH
Genuren	H-EH	Mendale	H-EH	Toweren Antara	H
Gunung Bahgie	H-EH	Mengaya	H-EH	Toweren Uken	H
Gunung Suku	H-EH	Merodot	H-EH	Waq Toweren	H
Hakim Bale Bujang	H-EH	Mongal	H	Wihlah Setie	H
Ie Reulop	H	Nunang Antara	H	Kala Kemili	H-EH
Jongkok Bathin	H	Paya Reje Tami Dalem	H	Paya Tumpi I	H-EH
Jongok Meluem	H	Paya Tumpi	H-EH	Paya Tumpi Baru	H-EH
Kala Bintang	H-EH				

Note: H = Heavy, EH =Extremely heavy

of 54 ha. High erosion did not occur during the period 1990 to 2009 as there was no significant amount of land conversion in the area.

Erosion distribution, from low to high category, was found to occur in villages near the Laut Tawar Lake area (Table 3) in 2019. Around 66% (55 villages) of the total villages (84 villages) in Laut Tawar Lake were identified as having high and very high erosion. The potential for hazard erosion was found in the village area, even though it is a small percentage of the total area of the village. This makes it easier for the government to prevent erosion.

These villages were mainly facing a massive shift in land use change and land management. The most apparent pattern of land use change is the conversion from forest to agriculture and estate crop area. Continuous land use change, specifically from forest to estate crops area, will cause natural disasters (e.g., erosion and landslide) in the lake cliff area. Villages that were detected experiencing high and very high erosion were in urgent need of a policy or village law related to land management aligned with conservation principal. Under the condition where no proper management and intervention to the villages identified under high and very high erosion, erosion will negatively impact the local economy. This was due to a reduction in soil nutrients from erosion which affected soil fertility; hence, decreasing land productivity [31, 32]. One of the policies can be the implementation of conservation efforts through revegetation using local species in Laut Tawar Lake. The local species can act as soil cover from rainfall kinetic energy, one of the drivers for soil surface erosion.

Conclusions

Our result for soil erosion in Laut Tawar Lake indicates very low to very high erosion events. The erosion was distributed in the study with a slope of more than 45%. The high erosivity index in the Laut Tawar Lake area has become the main cause of high and very high erosion. In addition to the erosivity index, the topography factor or slope of the Laut Tawar Lake area, which was dominated by more than 45% slope (50,1% of the total area), contributed to the erosion occurrence. From 1990 to 2019, Lake Laut Tawar's potential erosion rate increased, according to analysis. In 1990, erosion was 12.4 tonnes/ha/year; in 2000, 1 1.0 tonnes/ha/year; in 2009, 14.6 tonnes/ha/year; and in

2019, 27.4 tonnes/ha/year. The distribution of erosion shows an increasing trend for 4 periods. Around 55 villages (66% of the total villages) were under high to very high erosion. These factors were aggravated by the land use change in the area, from forest to agricultural land; hence, leading to high and very high erosion in the lake area.

One of the solutions for the erosion in Laut Tawar lake cliff is conservation efforts through a revegetation activity using the local species. The use of the local vegetation will highly benefit the soil from rainfall kinetic energy that causes erosion. The government and community can conserve the agricultural area surrounding the Laut Tawar Lake.

Acknowledgments

This research was funded by Directorate of Research and Community Service Deputy for Research and Technology Strengthening Ministry of Education, Cultural, Research and Technology with LLDIKTI Region XIII with Number: 041/LL13/AKA/PM/2022, 340/LPPM-Umuslim/KP-PTM/2022, and part of the framework of the Krueng Peusangan Watershed Study Center for the Graduate Program of Almuslim University. Acknowledgments were also conveyed to the Regional Governments of Aceh Tengah District.

Conflict of Interest

We have no conflicts of interest to disclose in this article.

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