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JOURNAL OF WATER AND LAND DEVELOPMENT

e-ISSN 2083-4535

Polish Academy of Sciences (PAN) Institute of Technology and Life Sciences – National Research Institute (ITP – PIB)

JOURNAL OF WATER AND LAND DEVELOPMENT
DOI: 10.24425/jwld.2023.145348
2023, No. 57 (IV–VI): 181–187

Soil erosion rate and hazard level at the Sianjo-anjo Reservoir watershed in Indonesia

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RECEIVED 11.08.2022 ACCEPTED 13.02.2023 AVAILABLE ONLINE 02.06.2023

Abstract: The Sianjo-anjo reservoir is used to meet the need for downstream clean water. Land activity at the Sianjo-anjo reservoir watershed can potentially increase the rate of erosion and the silting of rivers and reservoirs due to sedimentation. Reservoir siltation is a crucial challenge for reservoir management because it can reduce its function and affect its service life. However, sediment yield is often overlooked in reservoir planning and environmental assessment. This study aims to predict the rate of land erosion and sediment yield, and create an erosion hazard map of the Sianjo-anjo reservoir watershed. The study used a Geographic Information System, GIS-based Universal Soil Loss Equation (USLE) method and discovered that the erosion rate of the Sianjo-anjo reservoir watershed was between 35.23 $\text{Mg·ha}^{-1}\text{·y}^{-1}$ until 455.08 $\text{Mg·ha}^{-1}\text{·y}^{-1}$, with 95.85% classified as the low level, 0.03% as moderate, and 4.12% as high. Meanwhile, the sediment yield from the Sianjo-anjo reservoir watershed was 218,812.802 Mg·y^{-1}. USLE is vital to identify areas susceptible to erosion and crucial for reservoir sustainability. Furthermore, it is necessary to plan good sediment management. Long-term land conservation is required to maintain storage capacity and ensure effective operation of the reservoir.

Keywords: erosion modelling, reservoir, sediment yield, soil erosion

INTRODUCTION

Erosion is one of major causes of soil damage (Andriyani, Wahyuningsih and Suryaningtias, 2019). Soil erosion is the separation and transfer of soil particles by wind or water, which may cause sedimentation elsewhere and lead to the formation of new soil, water, and pools of water in water basins (Alalwanya *et al*., 2021). Erosion requires special attention in watersheds because it can worsen soil and water quality. This can reduce upstream land productivity, cause downstream sedimentation, and trigger flooding (Azmeri, 2020).

Previous studies have estimated the rate of soil erosion. Lal (2001) and Merritt, Letcher and Jakeman (2003) summarised soil erosion models, namely the Universal Soil Loss Equation (USLE), and its variations, such as Revised Universal Soil Loss Equation (RUSLE) and Modified Universal Soil Loss Equation (MUSLE). The USLE method has advantages due to its simplicity and accuracy; therefore, this empirical model is the most widely used (Lal, 2001; Merritt, Letcher and Jakeman, 2003; Lim *et al*., 2005; Xu *et al*., 2008; Zhang *et al*., 2008; Alexakis, Hadjimitsis and Agapiou, 2013; Perović *et al*., 2013; Chatterjee, Krishna and Sharma, 2014; Kourgialas *et al*., 2016; Azmeri *et al*., 2017; Azmeri, Legowo and Rezkyna, 2020; Azmeri *et al*., 2022). The USLE method predicts the average soil loss over a specific period in an area covered by a planting and management system (Alalwanya *et al*., 2021). The USLE and RUSLE models estimate the average annual gross erosion as a function of rainfall energy. Meanwhile, the MUSLE's rainfall energy factor is replaced by a runoff factor for sediment mapping (Shi *et al*., 2022).

The GIS application has been widely used to characterise soil erosion in large areas (Pandey, Chowdary and Mal, 2007; Dabral, Baithuri and Pandey, 2008; Rahman, Shi and Chongfa, 2009; Benzer, 2010; Meusburger, Bänninger and Alewell, 2010; Sheikh, Palria and Alam, 2011; Biswas, 2012). The GIS consists of hardware, software, geographic data, and human resources that coordinate to enter, store, improve, update, manage, manipulate, integrate, analyse, and display data as geographically-based information (Wibowo, Kanedi and Jumadi, 2015). The rate of soil erosion based on previous studies had good accuracy. GIS allows users to analyse spatial data in a user-friendly manner to identify locations at risk of soil erosion (Kamuju, 2016).

Reservoirs are used to meet downstream water needs and provide water conservation, including the Sianjo-anjo reservoir in the Aceh Singkil Regency. This reservoir has a role in fulfilling the need for raw water. The building of a reservoir is expected to fulfil the needs according to its operational service life plan. However, reservoir sedimentation can result in silting, affecting the reservoir's capacity and operational service life (Namr and Mrabet, 2004; Tatipata *et al.*, 2015; Azmeri *et al.*, 2017; Zarfl and Lucia, 2018). Primary sources of sedimentation are watersheds (Azmeri, Legowo and Rezkyna, 2020; Azmeri *et al.*, 2022), reservoir slope and landslides (Legowo, Hadihardaja and Azmeri, 2009).

The sedimentation at the Sianjo-anjo reservoir is most likely to occur from its watershed soil erosion. Sediment flows through rivers and is then trapped in the reservoir (Mulu and Dwarakish, 2015). Changes in land use, i.e. conversion into oil palm plantations upstream of the Sianjo-anjo reservoir watershed potentially leads to erosion due to increased peak runoff. An increase in the erosion rate can also cause accumulation of sediment deposits in rivers and reservoirs. Reservoir silting at a certain period can change its capacity and reduce its effective life time.

The erosion rate at the reservoir watershed should be controlled to reduce erosion hazards, and thus, maintain the conservation of the Sianjo-anjo reservoir as the most significant source of water in Aceh Singkil. This study needs to be supported by spatially accurate modelling with an erosion-sedimentation rate method using the GIS-based Universal Soil Loss Equation (USLE) method.

MATERIALS AND METHODS

STUDY LOCATION

This study was conducted at the Sianjo-anjo reservoir watershed of 4.52 km^2. The Sianjo-anjo reservoir watershed is located at the Aceh Singkil Regency at 02°25'09.63"–02°26'30.5"N and 97°58'51.91"–98°1'7.82"E (Fig. 1).

DATA COLLECTION AND PROCESSES

The data required for the study include rainfall, slope and slope length, land use, soil type, and watershed boundaries. The data were used to calculate the USLE factors as follows:
1) ten-year (2010–2019) satellite rain data from the TRMM (Tropical Rainfall Measuring Mission) on Giovanni's website; rainfall data is presented in monthly rainfall in cm;
2) digital elevation model (DEM) data from satellite images sourced from the National DEM website; the data was used to obtain topographical data and determine watershed boundaries; the DEM data has a spatial resolution of 0.27 arcseconds or 8.1 meters using the EGM2008 vertical datum;

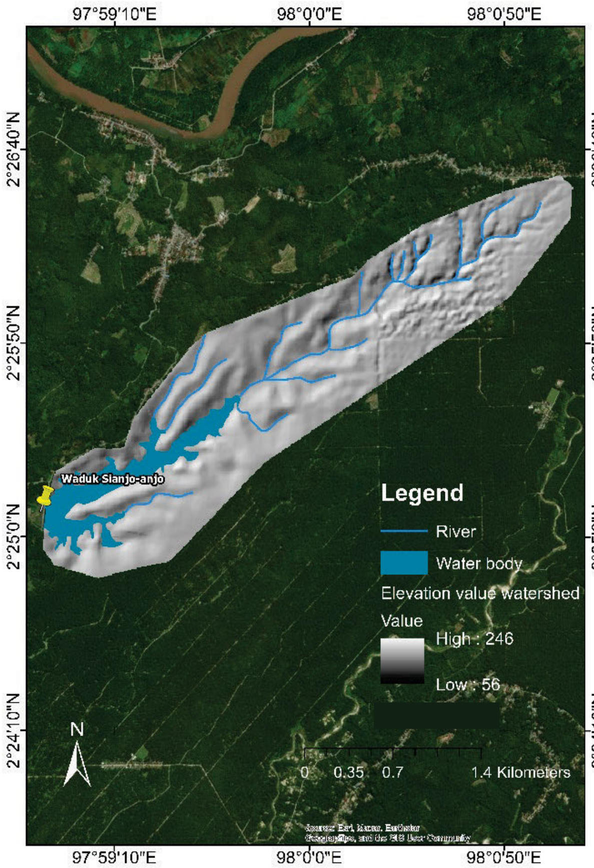

Fig. 1. The study location – Sianjo-anjo reservoir watershed; source: own elaboration

3) 2019 Aceh soil type map shapefile was obtained from the Aceh Web GIS Portal; soil type data was used to obtain soil erodibility factor (K);
4) 2019 Aceh land cover map shapefile was obtained from Indonesian the Ministry of Environment and Forestry (Ind. Kementerian Lingkungan Hidup dan Kehutanan Republic Indonesia); the data was used to obtain land use information at the Sianjo-anjo reservoir watershed, which was subsequently used to determine the land use and processing factor (CP).

METHOD

The modelling was carried out using ArcGIS 10.7.1 for data analysis. The average annual soil loss rate was estimated using the Universal Soil Loss Equation (USLE) method developed by Wischmeier and Smith (1978). The annual soil loss rate was compiled as a soil erosion hazard map. This model used four input factors in the USLE model as Azmeri *et al.* (2022) described (Eq. 1, Fig. 2).

$$A = R \cdot K \cdot LS \cdot CP \tag{1}$$

where: A = amount of soil loss per unit area ($Mg \cdot ha^{-1} \cdot y^{-1}$), R = rainfall erosivity factor, K = soil erodibility index, LS = slope length factor, C = crop management factor, P = soil conservation factor.

The calculation was conducted by determining the rain erosivity value (Eq. 2), which was then entered into the ArcGIS

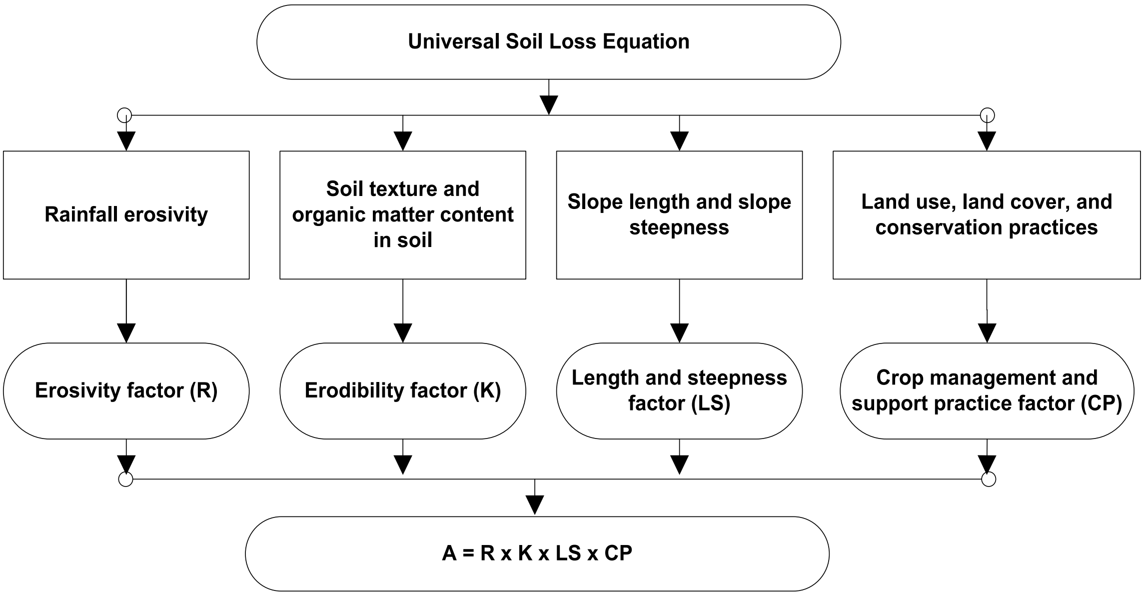

Fig. 2. Methodology flowchart; A = amount of soil loss per unit area (Mg·ha^{-1}·y^{-1}); source: Azmeri *et al.* (2022)

10.7.1 calculator to determine the R factor and obtain the soil erosion rate. The erosivity factor is a rainfall factor affecting erosion. The kinetic energy of raindrops when raining causes erosion when the raindrops touch the ground (Azmeri, 2020; Azmeri *et al.*, 2022). The ten-year rainfall data was obtained from Giovanni's website.

$$R = 2.21{P_m}^{1.36} \tag{2}$$

where: R = rain erosivity factor, P_m = monthly rainfall level (cm).

The soil erodibility factor (K) indicates the resistance of soil particles to erosion or peeling and transport of soil particles due to the kinetic energy of rainwater and surface runoff (Huda, Arief and Nurhadi, 2020). Topographic factors that significantly affect the rate of erosion are length (L) and steepness (S) (Azmeri, Legowo and Rezkyna, 2020; Azmeri *et al.*, 2022). The slope factor (LS) is the ratio between the soil lost from a plot of land having a certain length and steepness with a standard plot located on bare soil, a slope length of 22.1 m and steepness of 9% (Andriyani, Wahyuningsih and Suryaningtias, 2019). The length and slope factor (LS) were determined from the topographic map of the Sianjo-anjo reservoir watershed using the ArcGIS 10.7.1 software. Topographic raster data was projected into the UTM. Meanwhile, slope data was generated from the DEM. The crop management factor (C) shows the overall effect of vegetation, plant litter, soil surface condition, and land management on the level of erosion (Arifandi and Ikhsan, 2019). The soil conservation action factor (P) reflects physical or mechanical soil management (Azmeri *et al.*, 2020).

CLASSIFICATION OF SPATIAL EROSION HAZARD

The soil erosion hazard reflects the danger of erosion (Azmeri, Legowo and Rezkyna, 2020). The erosion hazard level can be determined based on the amount of soil eroded if crop management and soil conservation techniques are unchanged. The classification of erosion hazards based on the rate of erosion is presented in Table 1.

Table 1. Erosion hazard classes

Class	Soil erosion hazard (Mg·ha^{-1}·y^{-1})	Classification
I	<15	low
II	15–60	low-moderate
III	60–180	moderate
IV	180–480	high-moderate
V	>480	high

Source: Peraturan (2013).

RESULTS AND DISCUSSION

RAINFALL EROSIVITY

Rainfall erosivity indicates the potential for rainfall to erode soil and it is a critical factor in understanding landscape hydrologic and geomorphological processes (Thomas, Joseph and Thrivikramji, 2018). It is caused by surface runoff and raindrops that fall on the ground (Huda, Arief and Nurhadi, 2020). This monthly rainfall data (in cm) is regional rainfall data used to calculate the rain erosivity factor. The erosivity values varied from 53.225 to 260.806. The total erosivity of rain for ten years (2010–2019) is 1,834.995. A high rainfall erosivity index indicates a higher ability to cause erosion.

SOIL ERODIBILITY (K) FACTOR

The soil erodibility depends on soil texture, structural profile, permeability, and organic matter. This factor indicates soil vulnerability to erosion (Panagos *et al.*, 2015). A higher soil erodibility index indicates that the soil is more vulnerable to erosion. The soil type map of the Sianjo-anjo reservoir watershed is presented in Figure 3.

The soil erodibility factor was determined based on the soil type in the Sianjo-anjo reservoir watershed and analysed using

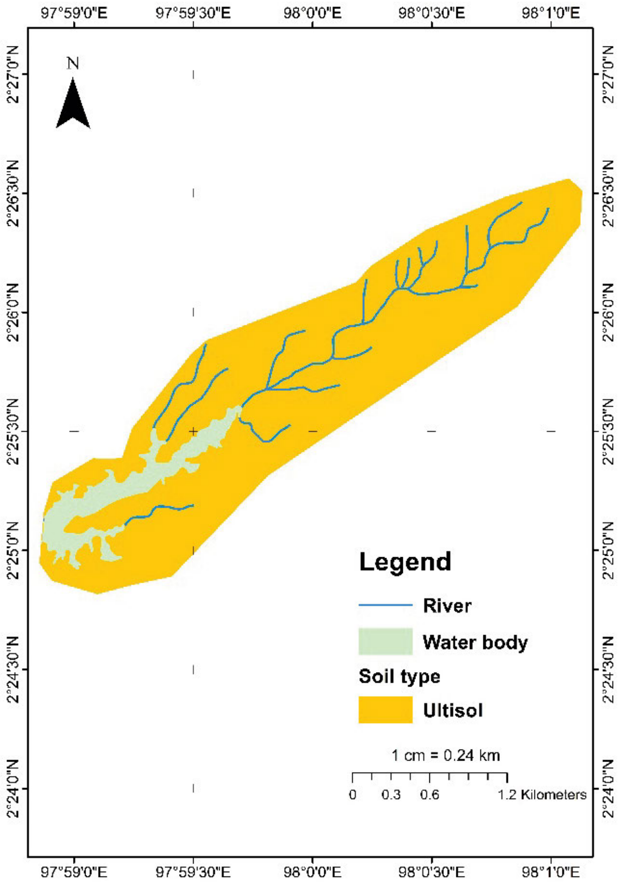

Fig. 3. Soil erodibility map of Sianjo-anjo reservoir watershed; source: own study

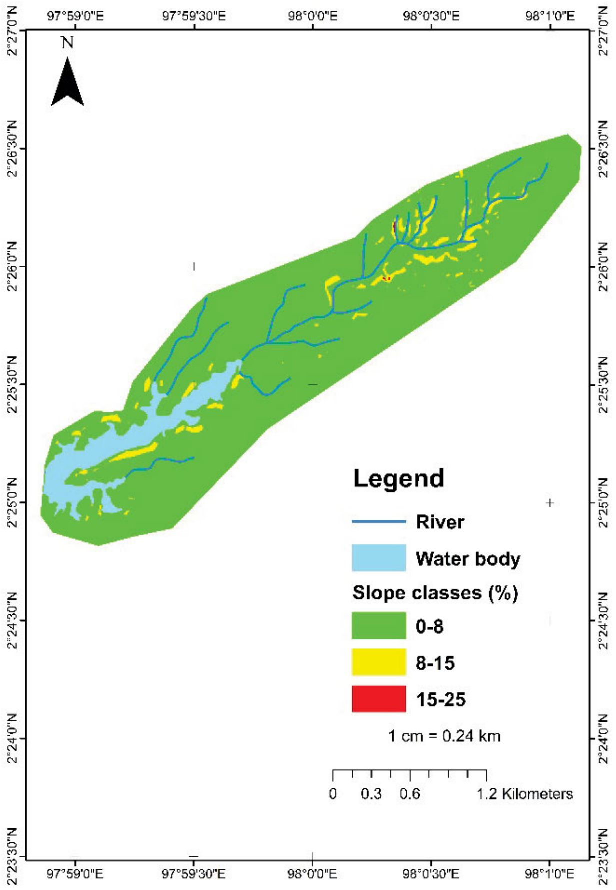

Fig. 4. Slope steepness map for the Sianjo-anjo reservoir watershed; source: own study

ArcGIS 10.7.1. The soil type identification showed that the entire area of 451.66 ha had the Ultisols soil with a *K* value of 0.16. Ultisols is characterised by the accumulation of clay at the subsurface, reducing water absorption and increasing surface runoff and soil erosion (Prasetyo and Suriadikarta, 2006). The low aggressiveness and weak stability of the aggregate make the soil susceptible to erosion, which is a problem especially in sloping areas. This is an obstacle, particularly for agricultural land. However, Ultisols soil is the most common soil in plantations (Notohadiprawiro, 1986).

SLOPE LENGTH AND STEEPNESS (*LS*) FACTOR

The distribution of the slope length and steepness factor (*LS*) in the Sianjo-anjo reservoir watershed is shown in Table 2 and Figure 4.

Table 2. Distribution of slope length and steepness factor (*LS*) in the Sianjo-anjo reservoir watershed

No.	Slope (%)	Area (ha)	*LS*	Percentage
1	0–8	434.2	0.4	96.1
2	8–15	17.2	1.4	3.8
3	15–25	0.2	3.1	0.05
Total		**451.6**	–	**100.0**

Source: own study.

Based on Table 2, 96.14% of the Sianjo-anjo reservoir watershed steepness, located from upstream to downstream of the watershed, is mostly 0–8%. Meanwhile, a 15–25% steepness upstream of the Sianjo-anjo reservoir watershed has the lowest percentage, i.e. 0.05%. The steepness affects the number of runoffs and the level of erosion. A steep-sloped land has a more significant potential for gravitational movement than a less-steep land because the pull increases with the steepness of the ground surface (Arham, Lopa and Bakri, 2017).

CROP MANAGEMENT AND SUPPORT PRACTICE (*CP*) FACTOR

Human activities on the land affect crop management and soil conservation measures. The classification of the Sianjo-anjo reservoir watershed land use and management is shown in Table 3 and Figure 5.

Table 3. Distribution of crop management and support practice factor (*CP*) in the Sianjo-anjo reservoir watershed

Land cover	Area (ha)	*CP*	Percentage
Shrub	5.87	0.3	1.49
Settlement	27.20	0.5	6.89
Plantation	361.42	0.5	91.62
Total	**394.48**	–	**100.00**

Source: own study.

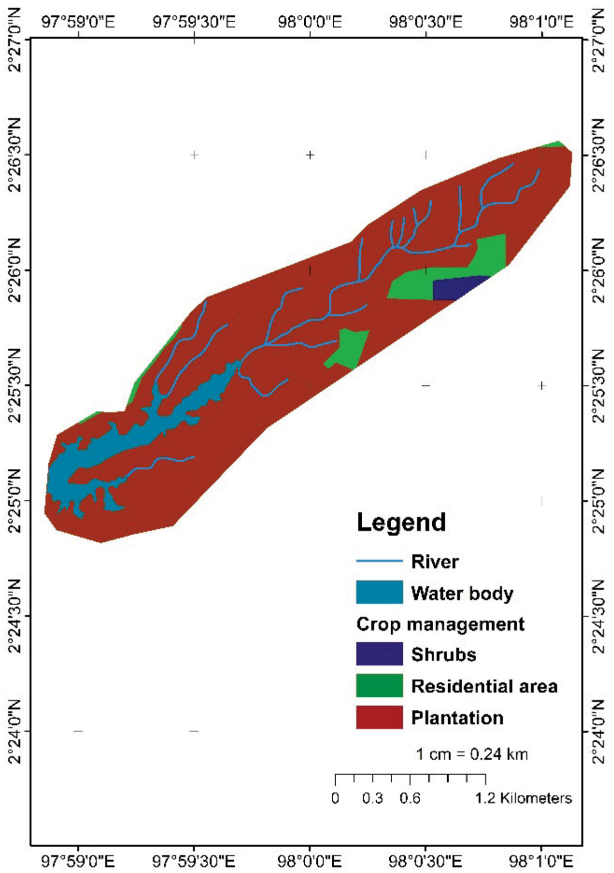

Fig. 5. Crop management and support practice factor (*CP*) map for the Sianjo-anjo reservoir watershed; source: own study

In terms of land use, the Sianjo-anjo reservoir is predominantly covered by plantations occupying 361.42 ha with the *CP* value of 0.5. The plantations are spread from upstream to downstream of the watershed. The middle to the downstream watershed had various land cover types, such as shrubs and settlements. Land without cover crops has higher *CP* values because it lacks water-holding capacity. This promotes damage to soil layers (Thomas, Joseph and Thrivikramji, 2018).

ANNUAL SOIL EROSION ESTIMATION

The soil erosion hazard in the Sianjo-anjo reservoir watershed (Tab. 4, Fig, 6) is caused by overlapping erosion factors, such as rain erodibility (*R*), soil erodibility (*K*), slope length and steepness (*LS*), as well as crop management and soil conservation measures (*CP*). In the overlay analysis, the four layers are combined using the union tools to generate maps and attributes that include data from the four layers. Based on Equation (1), the erosion rate for the Sianjo-anjo reservoir watershed is between 35.23 $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$ and 455.08 $\text{Mg}\cdot\text{ha}^{-1}\cdot\text{y}^{-1}$.

Table 4 and Figure 6 show that the erosion at the Sianjo-anjo reservoir watershed is classified from low to high. The area not included in the land erosion review is the 57.18-hectare reservoir pool. The high erosion hazard in the Sianjo-anjo reservoir watershed concentrates around the inter-rills leading to the Sianjo-anjo River. The internal groove erosion (inter-rills) is concentrated when the soil diverts water into small grooves. Flow velocity increases on more accessible paths and erodes to form shallow grooves. Such a groove is temporary, since a short rain can erode inter-rills. The erosion process at the edge of inter-rills leads to displacement of mini grooves (out of their original path). As soon as sheet erosion begins, runoff rapidly forms small rills, and part of the runoff flows between the rills. Some soil particles in the form of thin sheets are transferred by runoff, while others settle in small rills. This type of soil erosion is the most common. About 70% of the total soil is affected by land and inter-rill erosions, predominating through the initial erosion process (Bashir *et al.*, 2017).

Table 4. Soil erosion hazard in the Sianjo-anjo reservoir watershed

Soil erosion hazard	Area (ha)	Percentage
Low	378.09	95.85
Moderate	0.13	0.03
High	16.26	4.12
Total	**394.48**	**100.00**

Source: own study.

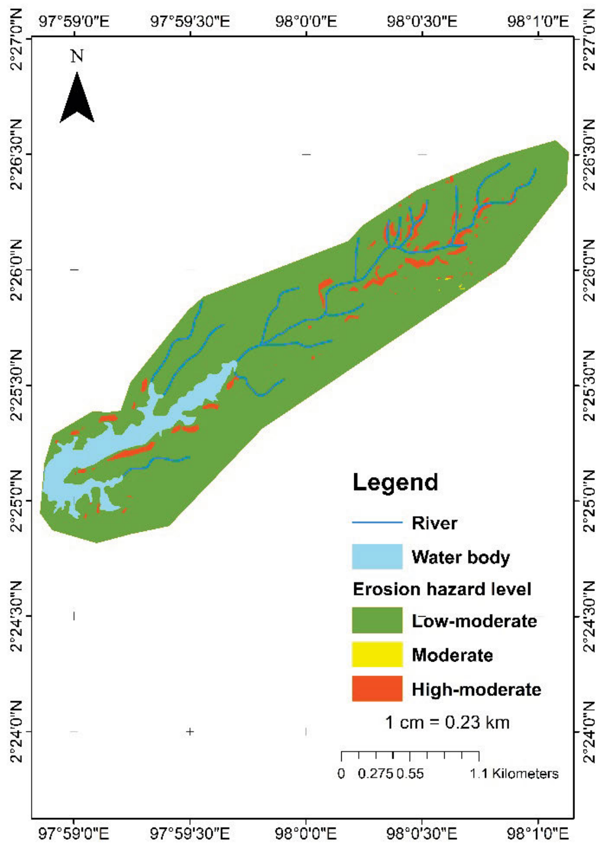

Fig. 6. Soil erosion hazard map for the Sianjo-anjo reservoir watershed; source: own study

Low soil erosion hazard is spread in most of the Sianjo-anjo reservoir watershed, with the highest percentage on plantation land cover. The plantation land cover has a high erosion index because of the high plantation *CP* value and its Ultisols soil type, which has a high *K* value. However, since most of the land in the Sianjo-anjo reservoir watershed (96.14%) has a gentle slope (<8%), the palm oil plantations, which are widespread at the reservoir watershed, have a low erosion rate (Arham, Lopa and Bakri, 2017).

The areas of moderate soil erosion hazard were spread upstream and downstream of the Sianjo-anjo reservoir watershed, covered by plantations, shrubs, and settlements. Each of these covers had a high *CP* value, an Ultisols soil type with a high erodibility factor, and several had moderate steepness (8–15%). The condition resulted in a higher erosion index.

The information on the potential erosion rate is expected to be used to plan actions that can reduce erosion at several points in the Sianjo-anjo reservoir watershed area with moderate and high erosion hazard. The strategy is to use mechanical or vegetative measures for land conservation. Real soil erosion can be prevented by counter farming. Counter farming strengthens plant roots and can hold soil, so it does not erode easily during heavy rains. In addition, the terracing system is very important, especially in keeping rainwater from flowing down and causing erosion. With terraced land, soil is more stable and plants grow better.

CONCLUSIONS

The soil erosion modelling shows that the erosion hazard upstream to downstream of the Sianjo-anjo reservoir watershed is classified from low to high. The erosion hazard is very low in 95.85%, moderate in 0.03%, and high in 4.12% of the watershed. The soil erosion index obtained using the GIS-based USLE method is between 35.23 $Mg \cdot ha^{-1} \cdot y^{-1}$ and 455.08 $Mg \cdot ha^{-1} \cdot y^{-1}$, while the sediment yield at the Sianjo-anjo reservoir watershed outlet is 218,812.802 $Mg \cdot y^{-1}$. Plantations, shrubs, and settlements mainly cover this location. The plantation area has a high crop management and support practice factor (*CP*) value. It is located on Ultisols soil with a high erodibility factor; therefore, it is classified in the moderate and heavy erosion categories, although it is on a gentle slope (<8%). This study shows that actions are required to handle land erosion at the Sianjo-anjo reservoir. The high erosion hazard of this reservoir watershed concentrates around the inter-rills leading to the Sianjo-anjo River. The internal groove erosion (inter-rills) becomes more intensive when soil diverts water into small grooves. Flow velocity increases on more accessible paths and erodes to form shallow grooves. The inter-rills erosion requires preventive measures in crop management and support practice measures involving human activities on the land. This vital information takes into account nature, intensity, spatial distribution, and sediment volume at the Sianjo-anjo reservoir watershed. Sediment accumulation in the Sianjo-anjo reservoir will eventually reduce the reservoir's storage capacity. The information that identifies areas susceptible to erosion and sediment yield benefits long-term land management.

FUNDING

The Ministry of Education, Culture, Research, and Technology of the Syiah Kuala University funded this study through the professor incentive grants no. 002/UN11.2/PT.01.03/PNBP/2022 on February 14, 2022.

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