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Article

Remote Sensing-Based Soil Erosion Rate Estimation Using the E30 Model and Sentinel-2 Imagery

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Abstract. Estimating the rate of soil erosion generally takes time, money, and energy. There are many parameters that must be accommodated, such as the physical properties of the soil, land cover, rainfall, topography, and so on. One alternative method for estimating erosion rates is to use a remote sensing approach. The aim of this research is to estimate the rate of soil erosion in the Special Purpose Forest Area of the University of Lambung Mangkurat (KHDTK ULM) Mandiangin, using the E30 model and Sentinel-2 imagery. The erosion rate are measured directly in the field with a number of sample points. According to the E30 model concept, field erosion samples are only measured on land that has a slope of 30^0. The topographic data itself is extracted from DEMNAS data. Meanwhile, soil bulk density data was obtained from https://soilgrids.org/, and solum data was taken from https://daac.ornl.gov/. From the Sentinel-2 imagery, Normalized Difference Vegetation Index (NDVI) data was extracted, which is one of the parameters in the E30 model. The estimated results of the erosion rate at KHDTK ULM Mandiangin show that, in general, the highest erosion rate at KHDTK ULM Mandiangin is around 480 tons/ha/year. Additionally, almost 80% of the KHDTK ULM Mandiangin area has a very serious erosion hazard level. Of course, the fastest rate of erosion is located on hill slopes with steep topography. Apart from having steep topography, one of the factors causing the high rate of erosion at KHDTK ULM is the thin soil layer and the lack of dense forest cover. This finding indicates the need to conserve vegetation cover on steep lands.

Keywords: Geospatial, Remote sensing, Sentinel-2, Soil erosion, Watershed

INTRODUCTION

Erosion is the event of moving or transporting soil or parts of soil from one place to another by natural media. Naturally, the earth's surface will always experience an erosion process, where in one place the process of erosion occurs while in another place, accumulation occurs. This natural event can occur very slowly, and without human intervention to form a dynamic balance. Erosion can be a serious problem in certain watershed ecosystem, where there is no vegetation that is able to intecept rainwater, and therefore can cause the increase in amount of surface flow (Yanti et al., 2017). The amount of kinetic energy in rain can be reduced by the role of vegetation, which can inhibit the rate of rainwater. Land cover factors can influence erosion in terms of vegetation density, which is known based on land cover information (Lathifah & Yunianto, 2013). The Special Purpose Forest Area (KHDTK) at the University of Lambung Mangkurat Education and Training Forest is an area that is vulnerable to erosion. This is because, apart from the hilly topography, several locations also have minimally dense vegetation cover. Some of the hills are only covered by grassland. In addition, this area is prone to forest and land fires every dry season. Consequently, the vegetation cover that functions to reduce erosion rate is often diminishedor even completely lost when burned. During the rainy season, post-fire data shows that bareland that has been burned will be easily eroded by raindrops. This causes a fairly high erosion rate.

The rate of erosion can be estimated using various methods, including the Universal Soil Loss Equation (USLE) or Revised Universal Soil Loss Equation (RUSLE). The USLE and RUSLE methods use several parameters, such as slope, soil type, vegetation type and cover, rainfall, and land use, to calculate the level of erosion hazard. The results of these calculations will produce an erosion index value, which is then used to determine the level of erosion hazard in an area. The erosion estimation method using USLE or RUSLE generally takes a lot of time, money, and energy. This is because there are many biophysical parameters involved in the calculations, and some parameters even have to be sampled directly in the field, such as soil samples.

One alternative approach for more efficient erosion estimation is to use remote sensing technology. Currently, the development of remote sensing technology has advanced very rapidly. This includes aspectsrelated to image resolution, namely spatial resolution, spectral resolution, temporal resolution, and radiometric resolution. Some of these remote sensing images are available for open access to the public throughout the world and are available in real time on the internet. Sentinel-2 Multispectral Instrument (MSI) is a satellite imaging technology provided by the European Space Agency (ESA) free of charge to the public. Sentinel-2 imagery has a fairly good spatial resolution, namely 10 meters. With this kind of spatial resolution, if Sentinel-2 is used for erosion mapping, it will be able to produce geospatial erosion data at a scale of 1:20,000. This refers to Tobler (1987) regarding the relationship between map scale and the spatial resolution of the image that is the data source.

The purpose of this research is to estimate the rate of soil erosion in the Special Purpose Forest Area of the University of Lambung Mangkurat (KHDTK ULM) Mandiangin, using the E30 model and Sentinel-2 imagery. From the results of this research, it is hoped that data on the geospatial distribution of erosion rates at KHDTK ULM Mandiangin will be obtained, as well as the level of erosion hazards. It is hoped that this geospatial information will later become the basis for conservation actions to restore local environmental conditions, especially soil conditions. It is also hoped that the use of remote sensing technology in this research will become a reference for updating geospatial data on erosion rates at KHDTK ULM in the future.

MATERIAL AND METHODS

Research Location and Ground Survey

This research was conducted in part of the Forest Areas with Special Purposes (KHDTK) Education and Training Forests of the University of Lambung Mangkurat, Mandiangin, South Kalimantan Province, Indonesia. The KHDTK ULM Mandiangin itself is located between 3°30'10.47" S and 3°32'58.03" S and between 114°54'54.11" E and 114°57'27.13" E. The research location and the Sentinel-2 imagery can be seen in Fig. 1.

As the name suggests, the E30 model means using a land surface with a slope of 300 as a reference. The basic principle of the E30 model is to use data on minimum and maximum erosion rates on land with a slope of 300 as input parameters. And this data must be measured directly in the field. In this research, based on the results of direct measurements in the field, it was found that the minimum erosion rate on slope 300 was 29.23 mm/year, and the maximum erosion rate on slope 300 was 83.67 mm/year. This data was obtained at six measurement points in the field, which were distributed purposefully across forest land cover, bareland, and bushes. Due to the research time limit that must be met in this research, field data collection only lasted four months, specifically from June 2023 to September 2023. Meanwhile, the rate of erosion in a year is calculated using the extrapolation method. Of course, good field data collection should be carried out throughout the entire year.

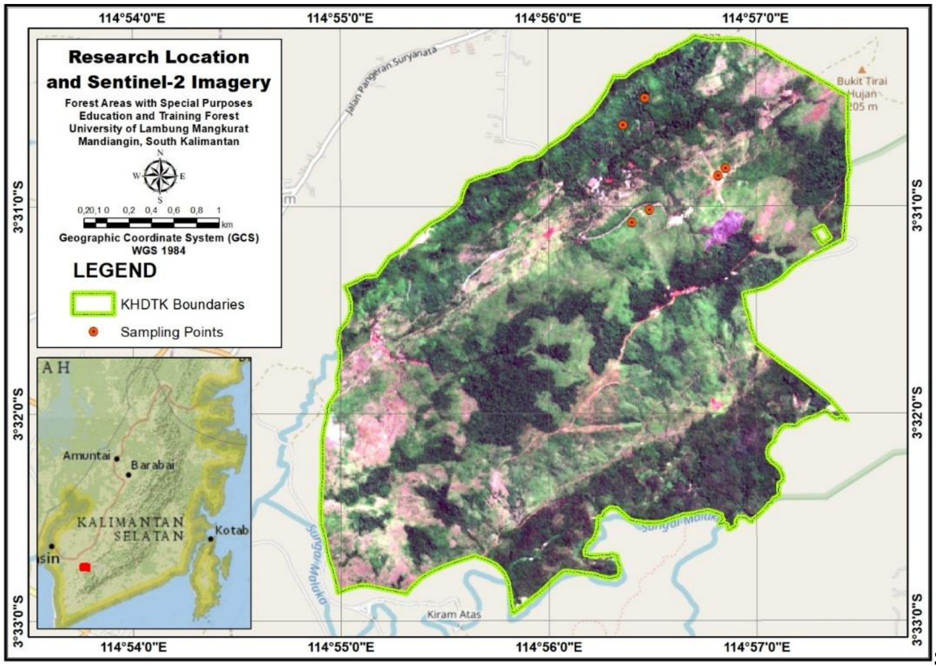

Figure 1. Research location, sampling points, and Sentinel-2 imagery

Sentinel-2 Image Processing and NDVI

The Sentinel-2 imagery used in this research is Sentinel-2 level 2A (atmospherically corrected) on acquisition on August 3, 2023. The time of this acquisition coincides with the time the field data was collected. Natively, Sentinel-2 imagery has three variations of spatial resolution, namely 10 meters, 20 meters, and 60 meters. For the purposes of inter-band analysis, all bands must have the same spatial resolution; in this research, all bands were resampled so that the spatial resolution was 10 meters. The resampling process was carried out using ESA SNAP software.

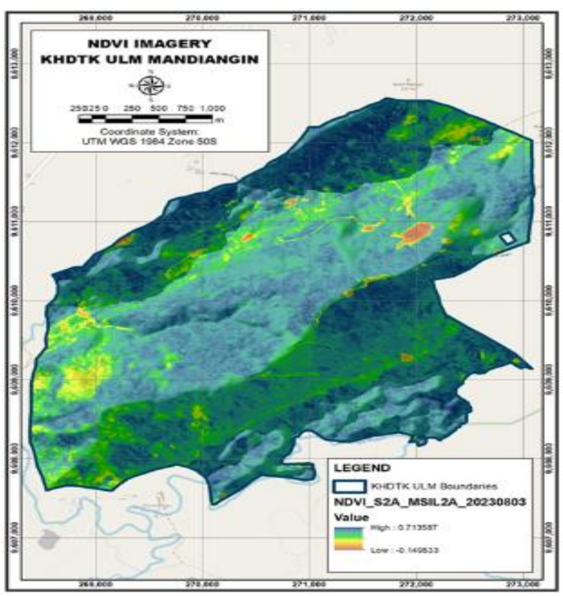

Figure 2. NDVI imagery

One of the input parameters in the E30 model is the Normalized Vegetation Index (NDVI) (Rouse et al., 1974). In this case, NDVI is extracted from Sentinel-2 imagery using the formula in equation 1.

$$\text{NDVI} = \frac{NIR - Red}{NIR + Red} \tag{1}$$

where Red = Red band or band 4 in Sentinel-2 imagery, and NIR = Near infrared band or band 8 in Sentinel-2 imagery.

NDVI imagery itself can be seen in Fig. 2. Normally, NDVI imagery has a range of pixel values from -1 to 1. Theoretically, if the pixel values are greater than 1, then it is certain that they are vegetation features. Open dry lands generally have pixel values around 0, and water features generally have minus pixel values in NDVI.

Estimation of Erosion Rate Using the E30 Model

The E30 model was developed in 1993. It is called the E30 model because it uses data on the rate of soil erosion on a 30^0 slope as one of the input parameters in estimating the rate of soil erosion. Data on the rate of soil erosion on a 30^0 slope must be measured directly in the field. In addition to data on soil erosion rates, this model uses topographic data and vegetation density as input parameters for estimating soil erosion rates (Honda, 1993; Honda et al., 1996; Honda et al., 1998). The E30 model is formulated as in equation 2.

$$\text{E} = E30\left(\frac{S}{S_{30}}\right)^{0.9} \tag{2}$$

where E = Soil erosion rate, E_{30} = Estimated rate of soil erosion on slope 30^0, S = Slope angle (in degrees), and S30 = Tangent 30^0.

For E30 itself, it is formulated as in equation 3.

$$\text{E30} = exp\left[(Log\ E30min - Log\ E30max)\left(\frac{NDVI - NDVImin}{NDVImax - NDVImin}\right) + Log\ E30max\right] \tag{3}$$

where E30min = Minimum soil erosion rate on slope 30^0 (field measurement results), and E30max = Maximum soil erosion rate on slope 30^0 (field measurement results).

According to the basic formula, the E30 model will provide estimates of the rate of erosion in units of soil thickness eroded in units of time, namely millimeters per year. This unit is less commonly used in Indonesia. Modeling the level of erosion hazards or critical land in Indonesia generally requires erosion data in mass units, namely tons per hectare per year. Therefore, the estimation results of the E30 model, which have units of mm/year, must be converted into units of tons/ha/year. To convert the soil erosion rate unit from mm/year to tons/ha/year, the formula in equation 4 is used.

$$E\ in\ tons/ha/year\ = 10\ x\ E\ in\ mm/year\ xBD(gr/cm^3) \tag{4}$$

where BD = Soil Bulk Density

The BD spatial data in this study is the result of spatial interpolation of BD data downloaded from https://soilgrids.org/ (Hengl et al., 2017). The soil bulk density from SoilGrids is a global soil dataset, so it can be used for all research locations around the world. The BD spatial data at KHDTK ULM Mandiangin can be seen in Fig. 3. The higher the BD value, the higher the soil density.

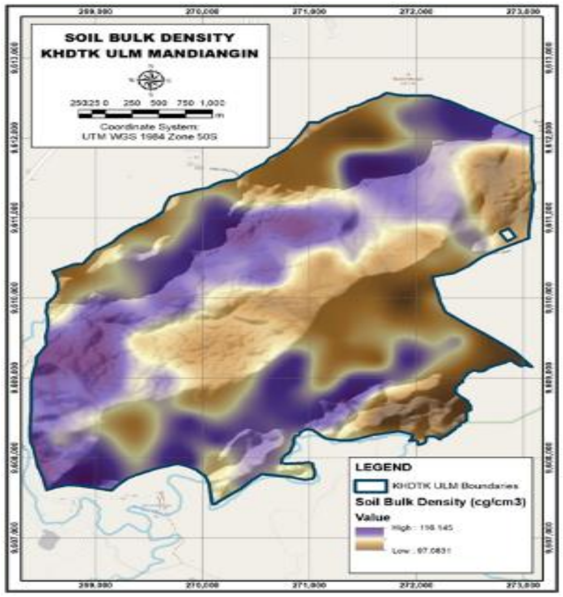

Figure 3. Soil Bulk Density

Analysis of the Erosion Hazard Level

For certain purposes, estimates of erosion rates are categorized into erosion hazard levels (TBE) using certain parameters, namely the depth of the soil layer or solum. This is because a fast rate of erosion does not always indicate a dangerous situation, especially if the soil layer is thick. Slow erosion rates can be dangerous if the soil layer is very shallow or thin. In this study, solum data was taken and interpolated from Global 1-km Gridded Thickness of Soil, Regolith, and Sedimentary Deposit Layers data downloaded from https://daac.ornl.gov/ (Pelletier et al., 2016). Spatial interpolation is applied to adjust the coarse-spatial resolution of the dataset used to meet the scale criteria for the research location. The interpolation method implemented is Inverse Distance Weighted (IDW). The spatial distribution of the KHDTK ULM Mandiangin soil solum can be seen in Fig. 4.

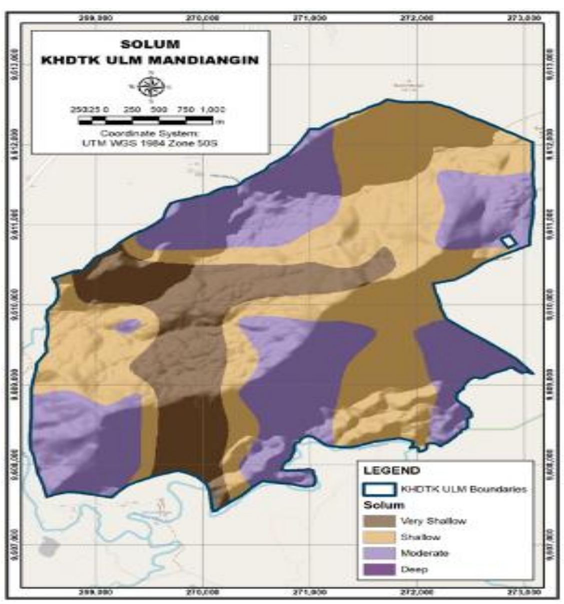

Figure 4. Solum

The criteria used to determine the level of erosion hazard are based on the Regulation of the Minister of Forestry of the Republic of Indonesia Number: P32/Menhut-II/2009. The details can be seen in Table 1.

Table 1. Classification of erosion hazard levels

Solum	Erosion Hazard Class				
	I	II	III	IV	V
	Erosion Rate (tons/ha/year)				
	<15	15-<60	60-<180	180-480	>480
Deep	0 - VL	I - L	II - M	III - H	IV - VH
Moderate	I - L	II - M	II - H	IV - VH	IV - VH
Shallow	II - M	III - M	IV - VH	IV - VH	IV - VH
Very Shallow	III - H	IV - VH	IV – VH	IV - VH	IV - VH

Note: VL : Very Low; M : Moderate; VH : Very High; L : Low; H : High

RESULTS

The fundamental difference between erosion estimation using variants of the USLE model and the E30 model is that the USLE model uses many parameters, such as topography, soil, vegetation, rainfall, and human activities. Meanwhile, in the E30 model, the parameters are relatively simpler, namely only topography and vegetation density, or biomass. The vegetation biomass, in this case, is represented by the Normalized Difference Vegetation Index (NDVI). Hence, the E30 model is an erosion rate estimation model that is completely based on geospatial information and geospatial modelling.

The E30 model eliminates climatic factors such as rainfall and human activity, with the assumption that rainfall and human activity are represented by the condition or greenness of vegetation. If rainfall is high and human activity is minimal, the vegetation will be greener or the biomass will be higher, and the NDVI value will also be higher. On the other hand, if there is low rainfall in a place or if there is human activity clearing land there, then the greenness or vegetation biomass will be low, and the NDVI value will also be low. However, the E30 model still accommodates slope as a topographic parameter. Bearing in mind that NDVI values or vegetation biomass generally do not correlate directly with slope. In this research, elevation as a topographic parameter was taken from DEMNAS data belonging to the Geospatial Information Agency (BIG), as shown in Fig. 5.

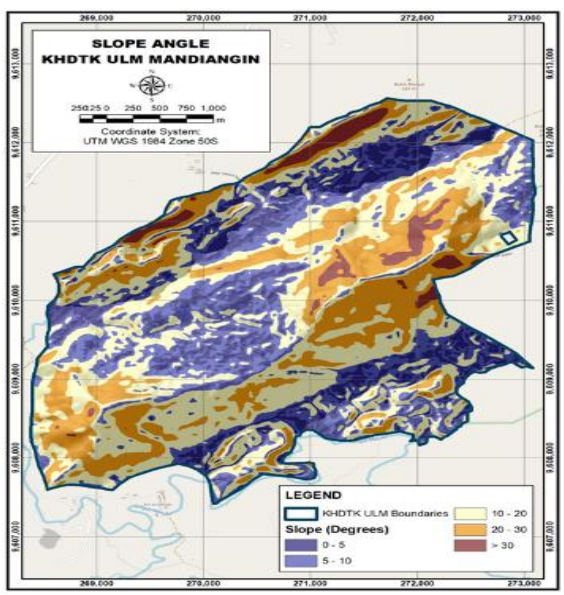

Figure 5. Slope angle

Facts on the ground and images in Fig. 1 show that Mandiangin hill is the greenest area among the other hills. Unlike Besar hill and Pematon hill, which only have dense forests at the tops. The presence of fairly dense vegetation on the ground surface will reduce the rate of erosion. Fig. 1 is a Sentinel-2 MSI image acquired on August 3, 2023. In this image, on the northern part of Besar hill, there are open land, degraded forest, and land after fire that recently occurred. This is also clearly visible in the NDVI-transformed image in Fig. 2. Areas where vegetation is torn apart like this will automatically increase the soil's vulnerability to erosion.

The NDVI image in Fig. 2 shows that dense and healthy vegetation is commonly found on the tops and slopes of hills. Meanwhile, in valley areas, the vegetation tends to be open. This is because there are a many human activities that occurs there. Especially tourism and agricultural activities by local residents.

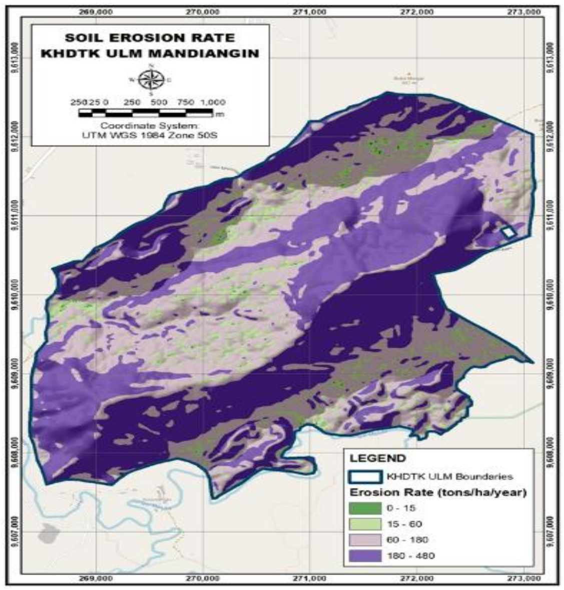

Figure 6. Soil erosion rate

Fig. 6 shows the final results of the estimated erosion rate of KHDTK ULM Mandiangin after the units were converted to tons/ha/year. The spatial distribution of erosion rates, as seen in Fig. 6, shows that, in general, the highest erosion rate at KHDTK ULM Mandiangin is around 480 tons/ha/year. The fastest rate of erosion is located on hill slopes that have steep topography, as shown in Table 2. In general, only valley areas have slow erosion rates. However, on Pematon hill, which is relatively gentle, a slow rate of erosion was also found on the slopes and around the top of the hill. Apart from the slopes being quite gentle, these areas also have dense vegetation. So, to reduce the rate of erosion on hill slopes, it is important to maintain the presence of forest cover there. So that the rate of surface water flow, which has the potential to erode the soil surface, can be slowed down by vegetation.

Table 2. The extent of the erosion hazard level of KHDTK ULM Mandiangin according to slope classes

No.	Slope (Degrees)	Soil Erosion Rate (ton/ha/year)		
		Minimum	Maximum	Average
1	0 – 5	2.99	420.63	245.75
2	5 – 10	328.99	766.64	518.39
3	10 – 15	605.59	1,105.95	828.15
4	15 – 20	871.35	1,416.18	1,123.99
5	20 – 25	1,139.26	1,715.77	1,394.80
6	25 – 30	1,395.47	2,023.92	1,635.86
7	30 – 35	1,651.28	2,239.68	1,864.23
8	35 – 40	1,897.67	2,326.42	2,068.12
9	40 – 45	2,143.62	2,358.83	2,270.10

As can be seen in Fig. 4, in general, the soil solum in the KHDTK ULM area is very shallow. This can also be seen directly in the field, where the soil layer in Mandiangin, especially on the hill areas, is generally thin. Soil conditions like this are quite dangerous when eroding, even when the rate of erosion is slow.

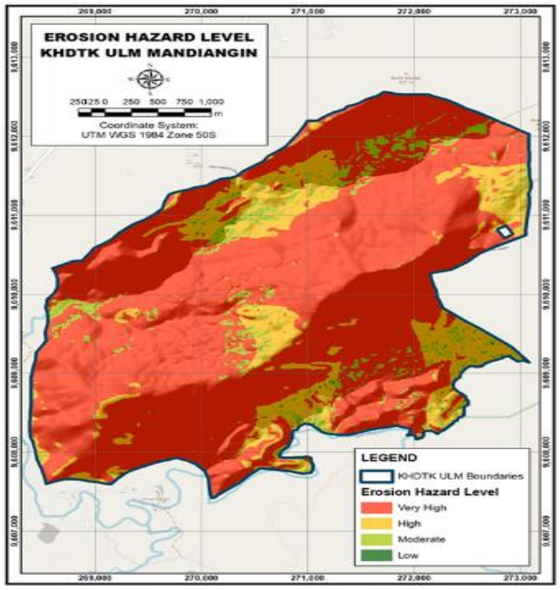

Figure 7. Erosion hazard level

Because it is dominated by shallow soil layers, KHDTK ULM Mandiangin is an area threatened by erosion, even though the rate of run of is not too high, as can be seen in Fig. 7. The erosion hazard level is very high almost on the 80% of the KHDTK ULM area, as seen in Table 3 and Fig. 8. Erosion with a light hazard level is only found in a small part of the areas that have thick solum. Especially valley areas, which are locations for soil deposits when erosion occurs.

Table 3. The extent of the erosion hazard level of KHDTK ULM Mandiangin

No.	Erosion Hazard Level	Area (hectares)
1	Very High	1,292.56
2	High	236.98
3	Moderate	106.32
4	Low	2.43

Unlike vegetation cover, which can be restored by humans through reforestation activities, the shallow solum layer is almost impossible to modify. So the only thing humans can do to reduce the level of erosion danger is to maintain or increase vegetation cover. Mechanical action by through terracing techniques may be implemented to reduce the steepness of the slope, and in turn reduce the rate of erosion.

DISCUSSION

KHDTK ULM is completely located within a conservation forest area, so in general, the condition of the vegetation is quite well maintained. However, this area is vulnerable to forest and land fires during the dry season, as has been happened in 2023. In addition to the potential in reducing or even eliminating vegetation cover, forest and land fires can also burn organic layers on the ground. The long-term impact can cause a reduction in the solum layer. In several places in the KHDTK ULM area, there are also farming and plantation activities in the surrounding community. The human activities in agricultural can also affect the solum layer.

KHDTK ULM is also one of the ecotourism destinations that is quite crowded with visitors. Various natural attractions, such as camping activities and several sports activities, are carried out in the area. These massive activities require land clearing and infrastructure development. Even some buildings are built on hilltops and steep slopes. Therefore, tourism activities may damage the vegetation cover and compact the surface soil layer. These can potentially increase the rate of surface water flow and erosion on the slopes. Liu (2019) reported that these impacts can be categorized into both environmental and ecological effects, with soil erosion being a primary concern. High trekking and camping activity in protected areas, like in Malaysia's Pahang National Park, leads to increased soil compaction, which exacerbates soil erosion (Sabri et al., 2018). This physical disturbance disrupts soil structure, reducing its capacity to retain water and nutrients, further contributing to erosion (Panagos et al., 2015).

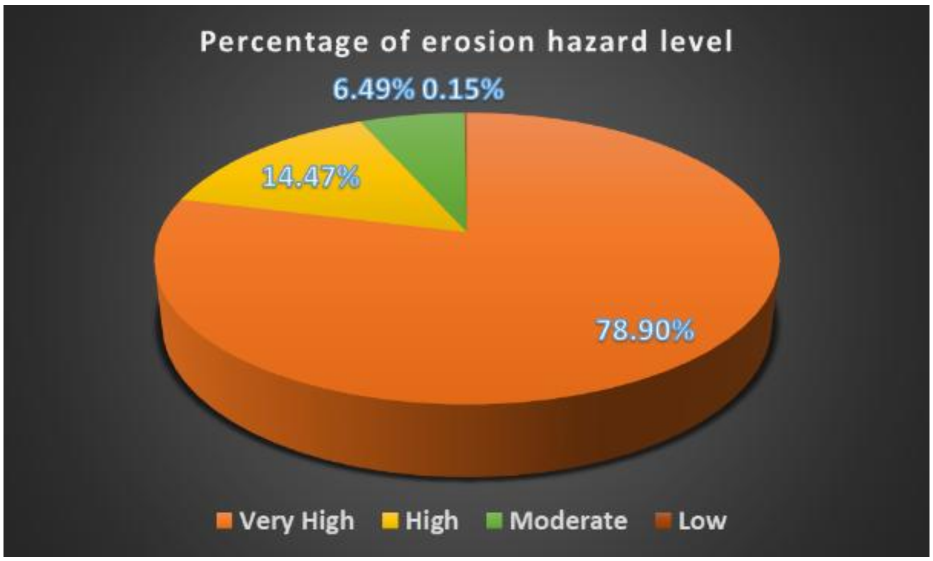

Figure 8. Percentage of erosion hazard level at KHDTK ULM Mandiangin

The E30 model is an erosion estimation model based on remote sensing. The advantage of the model for extracting information on the earth's surface based on remote sensing technology lies in their practicality in producing information quickly and covering large areas, as is the case with mapping erosion rates. We can even extract geospatial information on the erosion of one province, one island, or even the whole world using remote sensing imagery. We can also update information, such as erosion rates, at any time without having to carry out field surveys again. Of course, there are weaknesses in remote sensing technology when compared to direct measurements in the field. Among other things, the accuracy of the information is a significant concern. The ability of remote sensing images to provide information on the earth's surface is limited by the image resolution. This is particularly true for Sentinel-2, which has a spatial resolution of 10 m, the geospatial information on the rate of erosion or the level of erosion hazard that it can provide is a maximum of up to an area of 10 m x 10 m in the field. If we want more detailed erosion information than this, then Sentinel-2 will not be able to provide it. Perhaps we can use imagery with higher spatial resolution, such as NICFI or SPOT-7.

CONCLUSIONS

The results of the estimation of the rate of erosion and the level of erosion hazard in this study clearly show that KHDTK ULM Mandiangin is in a critical condition regarding erosion. This is because some areas are dominated by very high erosion hazard levels. Apart from the steep topography, the cause of high erosion at KHDTK ULM is due to the lack of vegetation cover in several places and the thin surface soil layer. Therefore, the erosion of rainwater, no matter how small, will have an impact on a large percentage of surface soil loss. To reduce the impact of erosion hazards at KHDTK ULM, of course, actions must be taken, such as revegetation in open areas. In the long term, revegetation or reforestation will also improve the quantity and quality of the surface soil layer.

The field erosion rate data uncovered though this research was too short, namely only a few months. This is due to research deadlines that must be met by researchers. Ideally, measurements of field erosion rates should be carried out for at least one year. In fact, in the future, it is recommended that some kind of permanent erosion measurement and monitoring tool or station be built at several points in the field, within the KHDTK ULM area. This way, the actual rate of erosion can actually be monitored in real time and geospatial information on erosion can be extracted at any time when needed.

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AUTHOR CONTRIBUTIONS

Badaruddin: research coordinator, data analysis, data interpretation, manuscript writing; Shamani: contributor, research member, research implementer, data analysis, data interpretation.

CONFLICTS OF INTEREST

The authors declare no conflict of interest related to financial funding and authorship order for this article.

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