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Erosion Hazard Analysis Using the RUSLE Model in the Upper Opak Sub Watershed

Analisis Bahaya Erosi Menggunakan Model RUSLE di Daerah Aliran Sungai Opak Hulu

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ABSTRACT

The increase of population causes changes in land use patterns that are not always suitable with conservation rules. This condition makes erosion risk higher, especially in the upstream area of Opak Sub-watershed, which has an important role to keep hydrological function from upstream to downstream. This research aims to analyze the erosion hazard level in the upstream part of Opak Sub-watershed by using the Revised Universal Soil Loss Equation (RUSLE) model with Geographic Information System (GIS) and remote sensing data. The R factor was calculated from 10 years of rainfall data, the K factor was obtained from physical and chemical analysis of 10 soil samples, the LS factor was calculated from DEMNAS image, while the C and P factors were taken from Sentinel-2A image using supervised classification with Maximum Likelihood method and MSAVI vegetation index analysis. The result shows that erosion rate is between 0 and 163.892 tons/ha/year. From the total area of 6.785,33 ha, about 2.585,08 ha (38,10%) is in the Very Severe erosion hazard category (>480 tons/ha/year). In general, 92,43% of the total area in the upstream of Opak Sub-watershed has erosion rate above the allowed limit (T_m = 10,89 tons/ha/year), which means that comprehensive conservation actions are needed.
Keywords: erosion, RUSLE, watershed

ABSTRAK

Peningkatan jumlah penduduk menyebabkan perubahan pola penggunaan lahan yang tidak selalu sesuai dengan kaidah konservasi. Kondisi ini meningkatkan risiko erosi, terutama di bagian hulu Sub DAS Opak yang memiliki peran penting dalam menjaga fungsi hidrologis dari hulu hingga hilir. Penelitian ini bertujuan untuk menganalisis tingkat bahaya erosi di bagian hulu Sub DAS Opak dengan menggunakan model Revised Universal Soil Loss Equation (RUSLE) yang terintegrasi dengan Sistem Informasi Geografis (SIG) dan data penginderaan jauh. Faktor R dihitung berdasarkan data curah hujan selama 10 tahun, faktor K diperoleh dari analisis sifat fisik dan kimia 10 sampel tanah, faktor LS dihitung dari citra DEMNAS, sedangkan faktor C dan P diperoleh dari citra Sentinel-2A melalui klasifikasi terawasi menggunakan metode Maximum Likelihood serta analisis indeks vegetasi MSAVI. Hasil penelitian menunjukkan bahwa laju erosi berkisar antara 0 hingga 163,892 ton/ha/tahun. Dari total luas 6.785,33 ha, sekitar 2.585,08 ha (38,10%) termasuk dalam kategori bahaya erosi Sangat Berat (>480 ton/ha/tahun). Secara keseluruhan, 92,43% dari luas wilayah hulu Sub DAS Opak memiliki laju erosi di atas batas toleransi (Tm = 10,89 ton/ha/tahun), sehingga diperlukan tindakan konservasi yang komprehensif.

Kata kunci: erosi, RUSLE, daerah aliran sungai

INTRODUCTION

The rapid growth of population pushes intensive land use change, especially in the upstream area of watershed, which often ignores land conservation principles. This situation gives serious impact to watershed hydrological functions, such as increasing surface runoff and decreasing base flow, which finally raises erosion risk (Sumarlin et al., 2021; Nurcahyo et al., 2024). The Opak Watershed, which covers Sleman District in Yogyakarta and Klaten District in Central Java, is an area that faces high pressure from land conversion in its upstream part (Widiatmoko et al., 2020; Farikha et al., 2023).

Erosion in tropical areas like Indonesia is mostly caused by high rainfall, which makes surface runoff faster and carries soil particles (Arsyad, 2010). Estimation of erosion potential can be done efficiently using the Revised Universal Soil Loss Equation (RUSLE), which is a development of USLE and already adapted for tropical conditions (Benavidez et al., 2018). RUSLE calculates erosion rate based on erosivity factor (R), erodibility factor (K), slope length and steepness (LS), land cover (C), and conservation practice (P) (Harliando et al., 2023).

The combination of RUSLE with remote sensing data and Geographic Information System (GIS) makes it possible to do spatial analysis in wide and complex areas in an efficient way (Sukristiyanti et al., 2010; Rumbiak et al., 2023). This research aims to map the erosion hazard level in the upstream part of Opak Sub-watershed by using RUSLE with remote sensing and GIS approach, and to evaluate the spatial distribution of its causal factors to support sustainable watershed management.

MATERIALS AND METHODS

This research uses a quantitative descriptive approach by combining spatial analysis with remote sensing and Geographic Information System (GIS) and field survey. The spatial data used are Sentinel-2A image from the European Space Agency (ESA) and the National Digital Elevation Model (DEMNAS) from Geospatial Information Agency (BIG). Sentinel-2A image was used to make land cover map and calculate vegetation index value. The land cover map was produced using supervised classification with Maximum Likelihood Classification (MLC), and then tested with accuracy using confusion matrix table based on visual reference from Google Earth image in 2025. The vegetation index was calculated using Modified Soil Adjusted Vegetation Index (MSAVI) method as parameter for C factor in the RUSLE model. DEMNAS data was used to delineate the boundary of the Sub-watershed and to calculate topographic factors such as slope length and steepness (LS factor).

Field sampling points were chosen using purposive sampling method based on land unit from overlay of land cover map and slope map. Field survey was conducted at 10 sample points to get data of soil physical and chemical properties. At each point, disturbed and undisturbed soil samples were taken for laboratory analysis, including texture, structure, permeability, and organic matter content. The data from this analysis were used to estimate K factor (soil erodibility) in the RUSLE model. The location of sampling points based on land unit map can be seen in the following figure.

Estimation of erosion potential was done by calculating five main parameters in RUSLE: R (rainfall erosivity) from historical rainfall data; K (soil erodibility) from laboratory test; LS (slope length and steepness) from DEMNAS; C (land cover factor) from MSAVI vegetation index; and P (land conservation practice) determined from actual land use. All spatial processes were conducted using ArcGIS 10.8 software.

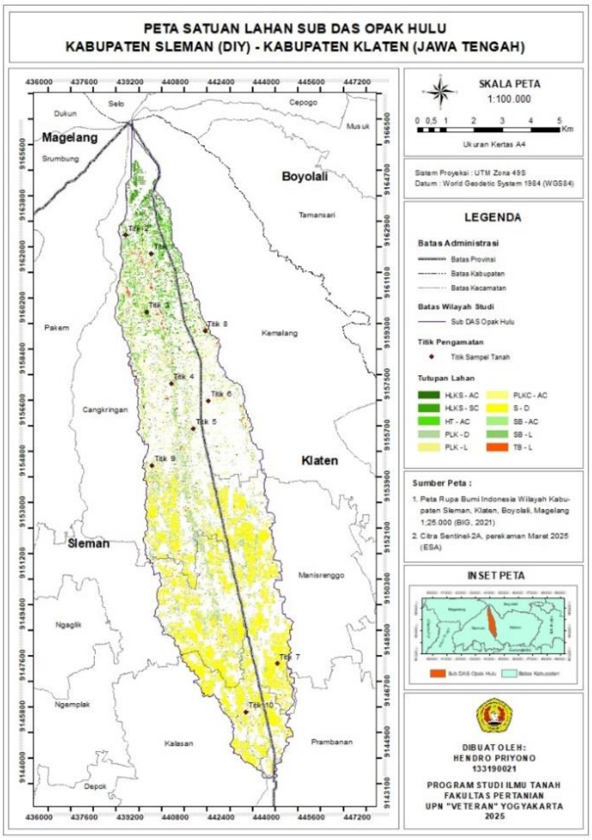

Figure 1. Land unit map

RESULTS AND DISCUSSIONS

A. Satellite Imagery Analysis

The upstream part of Opak Sub-watershed has an area of about 6.837,11 ha, located in Sleman District, Yogyakarta, and Klaten District, Central Java. The topography varies from flat to very steep, with the north part dominated by steep slopes and the south part more gentle. The soil types include Grey Regosol Complex and Lithosol in the upstream, and Brownish Grey Regosol in the middle to southern part, which comes from young volcanic material. The study area has climate type C (rather wet) based on Schmidt and Ferguson classification, with Q value of 48,61%. Agricultural activities and built-up land dominate the land cover in the upstream of Opak Sub-watershed

Land cover analysis was done using supervised classification with Maximum Likelihood Classification (MLC) method. To measure the accuracy of the classification result, an accuracy test was done using confusion matrix table (Simamora et al., 2015). This matrix compares the classification result with reference data from Google Earth image in 2025, which is assumed to represent field condition. After that, Kappa index (κ) value was calculated to know the agreement level between classification result and reference data. The result of accuracy test is shown in Table 1.

Table 1. Accuracy Test of MLC Supervised Classification Land Cover Map

Klasifikasi	HLKS	HT	P	BA	PLK	PLKC	S	SB	TB	Total	*User Accuracy*	*Commission*
HLKS	6	0	0	0	0	0	0	0	0	6	100%	0%
HT	0	13	0	0	0	0	0	0	0	13	100%	0%
P	0	0	23	0	0	0	0	1	0	24	95,8%	4,2%
BA	0	1	0	3	0	0	0	0	0	4	75%	25%
PLK	1	0	0	0	4	0	0	1	0	6	66,7%	33,3%
PLKC	0	0	0	0	0	11	0	0	0	11	100%	0%
S	0	0	0	0	0	0	17	0	1	18	94,4%	5,6%
SB	0	0	0	0	0	0	1	6	0	7	85,7%	14,3%
TB	0	0	0	0	0	0	1	1	9	11	81,8%	18,2%
Total	7	14	23	3	4	11	19	9	10	100		
Producer Accuracy	85,7%	92,9%	100%	100%	100%	100%	89,5%	66,7%	90%	*Overall Accuracy*		92%
Omission	14,3%	7,1%	0%	0%	0%	0%	10,5%	33,3%	10%			

Kappa index equation (κ):

$$\kappa = \frac{(N \times \sum x) - \sum y}{N^2 - \sum y} x\ 100\% \quad (1)$$

Where:
κ : Kappa index
N : total sample
$\sum x$: number of correct classifications (diagonal)
$\sum y$: the sum of the cross products between the total columns and rows per class

Calculation of the multiplication of the total row by the total column for each class:

$\sum y$ = (6x7)+(13x14)+(24x23)+(4x3)+(6x4)+(11x11)+(18x19)+(7x9)+(11x10)

$\sum y$ = 1.448

Calculation of the kappa index (κ):

$$\kappa = (\frac{[(92x100) - 1.448]}{[(100^2) - 1.448]}\ x\ 100\%$$

κ = 90,65%

Classification accuracy reached a Kappa value of 0,9065, indicating a very high level of agreement, suitable for spatial erosion analysis.

B. Rainfall Erosivity Factor

Erosivity is the power that moves soil particles so they are detached and carried by surface runoff to lower areas. Erosivity was calculated using the Lenvain equation (1989, in Asdak, 2010). The erosivity factor (R) was calculated from the average annual rainfall of the last ten years from four rainfall stations provided by BPDAS Serayu Opak Progo (2023). The result of erosivity calculation are summarized in Table 2.

The highest value was recorded at Kaliurang Station (2.855,39 MJ.cm/ha.hour.year), while the lowest was at Plataran Station. The high R value in the upstream of Opak Sub-watershed is caused by high annual rainfall intensity. This is supported by Hanum et al. (2024), who explained that rainfall distribution is strongly influenced by elevation, especially in mountain areas, because it triggers air mass rising, cooling, and condensation. The spatial distribution of R was then modeled using Inverse Distance Weighting (IDW) interpolation.

Table 2. Erosivity Factor (R) of Each Rainfall Station

Erosivity Factor (R) of Each Rainfall Station (MJ.cm/ha.jam.tahun)				
Month	Kaliurang Station	Kemput Station	Bronggang Station	Plataran Station
January	444,26	317,93	351,67	266,80
February	389,62	272,77	363,74	255,84
March	467,15	351,21	296,73	212,70
April	250,47	225,31	199,15	112,52
May	111,87	83,39	61,26	35,92
June	49,63	64,64	51,13	26,49
July	27,09	20,74	21,40	8,94
August	18,83	0,00	0,00	0,00
September	82,81	49,38	34,98	18,35
October	156,89	90,47	60,55	31,03
November	479,20	366,25	281,15	132,53
December	377,56	420,25	340,03	259,19
Total R Annual	**2.855,39**	**2.262,36**	**2.061,79**	**1.360,30**

C. Soil Erodibility Factor

Soil erodibility (K factor) shows the sensitivity of soil to erosion, which is influenced by soil texture, organic matter, structure, and permeability. The K value was calculated from physical and chemical parameters based on laboratory analysis of 10 soil samples selected by purposive sampling. The result of soil erodibility calculation are presented in Table 3.

Table 3. Erodibility Analysis using the Wischmeier and Smith Equations

No	Sampel	Kedalaman Efektif Tanah (cm)	Bo (a)	Fraksi Tanah			M	Struktur Tanah		Permeabilitas Tanah		K	Rata-rata
				Debu %	Lempung %	Pasir halus %		Struktur	Nilai Struktur (b)	Permeabilitas (cm/jam)	Nilai Permeabilitas (c)		
1	HLKS-AC	56	5,95	20,92	20,82	58,26	6.269,47	Granular Sedang	3	2,39	4	0,41	0,50*
2	HLKS-SC	52	2,98	17,24	22,56	60,20	5.996,95	Granular Sedang	3	3,31	4	0,55	
3	HT-AC	48	5,60	18,76	20,10	61,14	6.384,01	Granular Kasar	3	2,23	4	0,43	
4	PLK-D	52	3,15	26,50	21,54	51,96	6.155,97	Granular Sedang	3	3,21	4	0,56	
5	SB-AC	9	3,33	19,36	20	60,64	6.400	Granular Sedang	3	3,32	4	0,57	
6	PLK-L	26	2,98	12,18	18,20	69,62	6.691,24	Granular Kasar	3	2,99	4	0,62	0,57**
7	PLKC-AC	49	5,78	11,38	22,74	65,88	5.969,11	Granular Kasar	3	2,84	4	0,40	
8	S-D	35	3,15	22,76	19,08	58,16	6.548,05	Gumpal	4	2,18	4	0,63	
9	SB-L	71	1,98	24,28	21,24	54,48	6.203,14	Granular Sedang	3	2,43	4	0,63	
10	TB-L	15	1,98	15,72	22,44	61,84	6.015,55	Granular Kasar	3	3,56	4	0,61	

*Rata-rata K dari jenis tanah Kompleks Regosol Kelabu dan Litosol (sampel 1-5) ** Rata-rata K dari jenis tanah Regosol Coklat Kekelabuan (sampel 6-10)

Keterangan:

HLKS-AC: Hutan Lahan Kering Sekunder, Agak Curam
HLKS-SC: Hutan Lahan Kering Sekunder, Sangat Curam
HT-AC: Hutan Tanaman, Agak Curam
PLK-D: Pertanian Lahan Kering, Datar
SB-AC: Semak Belukar, Agak Curam
PLK-L: Pertanian Lahan Kering, Landai
PLKC-AC: Pertanian Lahan Kering, Agak Curam
S-D: Sawah, Datar
SB-L: Semak Belukar, Landai
TB-L: Tanah Terbuka, Landai
Bo: Bahan organik
M: Ukuran partikel tanah
K: Erodibilitas tanah

The K values range from 0,4 to 0,63, with the highest values found in Brownish Grey Regosol soil, which is mostly used for agriculture. Samples with higher K values in Brownish Grey Regosol are mostly agricultural land. This is in line with Agustin (2015), who stated that intensive agricultural activity can increase soil erodibility due to decreasing organic matter content and changes in soil structure.

D. Slope Length and Steepness Factor

The LS factor is a combination of slope length (L) and slope steepness (S), which affects the speed of surface runoff and its ability to transport soil particles. The LS factor in the study area is influenced by the varied topography. The result of LS factor calculation using Moore and Burch equation is presented in Table 4.

Table 4. Results of LS Factor Calculations using the Moore and Burch Equations

No	Sample	FA	*cell size* (m)	θ (rad)	LS
1	HLKS-AC	6	8,30	0,26	5,38
2	HLKS-SC	8	8,30	0,58	16,41
3	HT-AC	3	8,30	0,20	2,97
4	PLK-D	10	8,30	0,02	0,23
5	SB-AC	2	8,30	0,18	2,24
6	PLK-L	24	8,30	0,11	3,08
7	PLKC-AC	4	8,30	0,16	2,53
8	S-D	1	8,30	0,03	0,20
9	SB-L	3	8,30	0,14	1,82
10	TB-L	5	8,30	0,13	2,02

Based on LS calculation at 10 sampling points, the lowest value was found at S-D (Flat Rice Field), which was 0,20. The highest value, 16,41 was at HLKS-SC (Very Steep Secondary Dryland Forest). The overall LS factor has a value range from 0 to 201,457. This value was kept in raster form to be used in erosion calculation with raster-based model. The LS factor in RUSLE is the integration of slope length and slope steepness, which strongly influences erosion intensity. LS value increases with slope angle and flow length, which raises the energy and volume of runoff (Esa et al., 2018).

E. Vegetation Factor

The vegetation factor shows the effect of vegetation, litter, land cover, and crop management on erosion rate. The C factor in RUSLE represents the influence of land cover on soil erosion vulnerability. The C factor values in this study were derived from MSAVI vegetation index. The MSAVI values in the study area range from -0,32 to 0,81 and then classified into intervals and C values based on Sulistyo et al. (2011), which are shown in Table 5.

Results indicate that most of the study area exhibited moderate (32,16%) to high (47,77%) vegetation density, which correlates with lower erosion potential. Dense canopy cover in forested land was particularly effective in reducing erosion risk, confirming Sulistyo et al.'s (2011) conclusion that increased vegetation density leads to reduced C-values and enhanced erosion control.

Table 5. Vegetation factors based on the criteria of Sulistyo *et al.* (2011)

No	Interval	C value	Vegetation Density	Area	
				ha	%
1	0 - 0,2	0,9	No Vegetation	208,6	3,05
2	0,2 - 0,4	0,7	Low Density	1.163,37	17,01
3	0,4 - 0,6	0,5	Medium Density	2.199,08	32,16
4	0,6 - 0,8	0,3	High Density	3.266,74	47,77

5	0,8 - 1	0,1	Very High Density	0,08	0,001
			Total	**6.837,11**	**100**

Source: Sulistyo *et al* (2011)

F. Conservation Practice Factor

Conservation is an effort to reduce the potential of soil loss. The P factor is the ratio between soil loss from land with conservation practices compared to land without conservation practices, with the assumption that all other factors remain the same (Asdak, 2010). The P factor was derived from the combination of slope data interpreted from DEMNAS and land cover data from Sentinel-2A imagery, based on Sulistyo et al., (2011). The result of P factor calculation are presented in Table 6.

Table 6. P Value Based on Agricultural and Non-Agricultural Areas

No	Slope (%)	Land Use	P value	Land Area	
				ha	%
1	0-8%	Non-agricultural	1	2.763,69	40,70
2	0-8%	Agricultural land	0,5	2.792,87	41,13
3	8-20%	Non-agricultural	1	636,42	9,37
4	8-20%	Agricultural land	0,75	310,99	4,58
5	>20%	Non-agricultural	1	265,78	3,91
6	>20%	Agricultural land	0,9	21,02	0,31
		Total		**6.790,78**	**100**

P-values ranged from 0,1 to 1. Lower P-values were generally observed on agricultural land with gentle slopes, indicating effective soil conservation. Conversely, non-agricultural areas lacked specific conservation measures and thus retained maximum P-values. These findings support the conservation assessment framework of Abdurachman et al. (1985).

G. Soil Loss Estimation

Soil loss was calculated using the RUSLE model in raster format, integrating all five factors (R, K, LS, C, and P) through ArcGIS's raster calculator. Estimated erosion rates ranged from 0 to 163.892 tons/ha/year. These were classified according to the Erosion Hazard Level (EHL) system of the Ministry of Forestry (1998, in Yusuf et al., 2020), as shown in Table 7.

The result shows that Very Light erosion (<15 tons/ha/year) covers 657,17 ha (9,69%), Light (15-60 tons/ha/year) covers 661,74 ha (9,75%), Medium (60-180 tons/ha/year) covers 1.271,35 ha (18,74%), Heavy (180-480 tons/ha/year) covers 1.609,99 ha (23,73%), and Very Heavy (>480 tons/ha/year) covers the largest area, 2.585,08 ha (38,10%). This means that more than one-third of the study area experiences very high erosion, which can cause serious land degradation if not controlled with proper conservation practices.

Table 7. Erosion Hazard Classification

No	Soil Loss ton/ha/year	Erosion Hazard Classification	Area	
			ha	%
1	<15	Very Light	657,17	9,69
2	15-60	Light	661,74	9,75
3	60-180	Moderate	1.271,35	18,74
4	180-480	Heavy	1.609,99	23,73
5	>480	Very Heavy	2.585,08	38,10
Total			**6.785,33**	**100%**

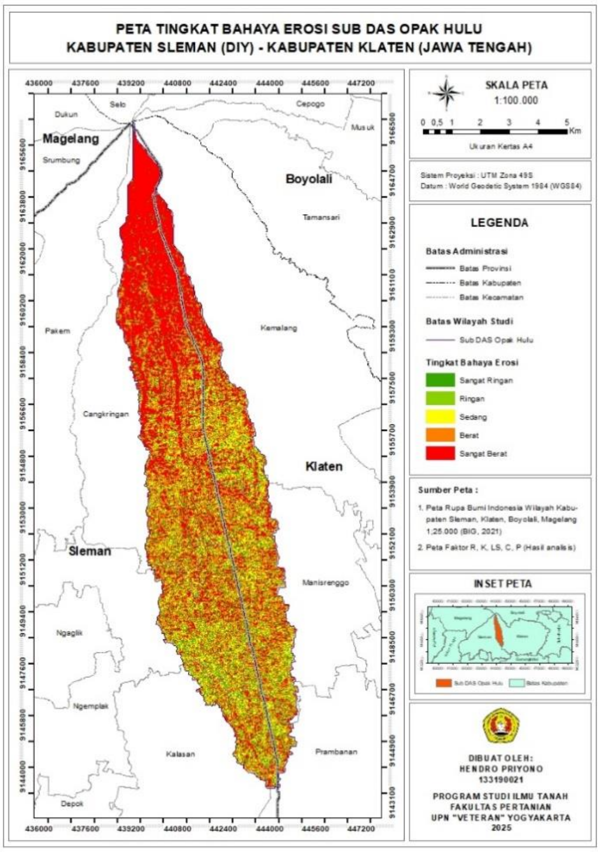

Figure 2. Erosion Hazard Level Map

Following the calculation of the RUSLE model's erosion rate, it is necessary to determine the tolerable erosion (T_m) value, expressed in tons/hectare/year. The T_m value represents the permissible erosion threshold, used to assess whether the rate of soil loss remains within acceptable conservation limits. This T_m value is derived by converting the T_k value, which signifies the tolerable erosion in mm/year. The T_k values are obtained from the guidelines for determining T_k for soils in Indonesia (Arsyad, 2010). A comparison between the erosion rate and the T_m value is crucial for evaluating the risk of land degradation and identifying appropriate conservation measures (Hanafi & Pamungkas, 2021). The calculated T_m values are presented in Table 8.

Table 8. Average T_m Value

No	Sample	Effective Soil Depth (cm)	Soil Depth Categories	T_k	BV (g/cm3)	T_m
1	HLKS-AC	56	Moderate	1,2	1,03	12,41
2	HLKS-SC	52	Moderate	1,2	1,15	13,81
3	HT-AC	48	Shallow	0,8	0,84	6,74
4	PLK-D	52	Moderate	1,2	1,43	17,14
5	SB-AC	9	Very Shallow	0,4	1,24	4,96
6	PLK-L	26	Shallow	0,8	1,39	11,12
7	PLKC-AC	49	Shallow	0,8	1,35	10,80
8	S-D	35	Shallow	0,8	1,37	10,94
9	SB-L	71	Moderate	1,2	1,30	15,59
10	TB-L	15	Very Shallow	0,4	1,36	5,46
Average						**10,89**

To assess land degradation risk, erosion rates were compared with Tolerable Soil Loss (TML) values. TML (in tons/ha/year) was converted from soil loss tolerance (Tk) values in mm/year, as specified in Arsyad (2010). The average TML was 10,89 tons/ha/year (Table 8). Based on this, 6.271,62 ha (92,43%) exceeded tolerable limits, while only 513,39 ha (7,57%) remained below.

The extreme maximum erosion value (163.892 tons/ha/year) suggests potential overestimation, likely due to the 30 m resolution limitations of DEMNAS. Benavidez et al. (2018) emphasized that flow accumulation methods are highly sensitive to DEM resolution, particularly in complex terrain. In two of the ten sites, slope class derived from DEMNAS diverged from field observations, further indicating resolution limitations. Sharma et al. (2010) showed that high-resolution DEM such as LiDAR can improve erosion estimation accuracy, especially in complex terrain. In addition, C and P factors estimated only from land cover and spectral indices, without field validation, may result in lower C values and higher erosion (Sulistyo et al., 2011).

The high percentage of land with Heavy to Very Heavy erosion is attributed to a combination of moderate to low vegetation cover, highly erodible soils, steep slopes, and intensive land use (e.g., farming, settlement, bare land). These results align with Hanafi and Pamungkas (2021), who reported that 85,86% of the Garang Sub-watershed area exceeded the erosion threshold. Similarly, Barbosa et al. (2024) found that low vegetation, steep slopes, and lack of conservation drove extreme erosion (118,9 tons/ha/year) in Brazil's Cerrado basin. Therefore, areas with heavy and very heavy erosion should be the main priority for soil conservation techniques, such as cover crops, terracing, or sustainable land management. Areas with very light to light erosion should still maintain their ecological function to sustain watershed stability.

CONCLUSION

Based on the research conducted, it can be concluded that:

1. Remote sensing provides accurate and comprehensive spatial data for analyzing the Upper Opak Sub-watershed. Sentinel-2A imagery effectively generates land cover and vegetation index (MSAVI) maps, while DEMNAS supports slope analysis, LS computation, and watershed delineation.
2. RUSLE parameters showed significant variability: R ranged from 1.361,85 to 2.768,06 MJ.cm/ha.h.year, K from 0,31 to 0,63, LS from 0 to 201,46, C from 0,1 to 0,9, and P from 0,5 to 1,0. The highest LS values were observed in steep terrain.
3. Annual soil loss estimates ranged from 0 to 163.892 tons/ha/year. Very Heavy erosion (>480 tons/ha/year) accounted for the largest area (38,10%). A total of 92,43% of the region exceeded the tolerable erosion threshold (TML = 10,89 tons/ha/year), especially in steep slopes and low vegetation area.

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