

EROSION HAZARD MAPPING IN SLEMAN REGENCY BASED ON RUSLE AND REMOTE SENSING

Rochmad Bayu Purnomoaji¹, Surya Murdani², Hamzah Saifuddin³, M. Fadel Pahleva Yacoeb⁴

^{1,2}Geography, Spatial Planning and Environment Department, Radboud University

³Master of Business Administration and Digital Transformation, International University of Japan

⁴Master of Urban and Environmental Planning, Griffith University

bayu.rochmadbayupurnomoaji@ru.nl

ABSTRAK

Erosi tanah merupakan persoalan degradasi lahan yang berimplikasi terhadap daya dukung wilayah, risiko hidrologis, produktivitas lahan, dan efektivitas pembangunan daerah. Penelitian ini bertujuan memetakan bahaya erosi di Kabupaten Sleman dan merumuskan implikasinya bagi perencanaan pembangunan. Metode yang digunakan adalah pendekatan kuantitatif-spasial berbasis Revised Universal Soil Loss Equation (RUSLE) yang diintegrasikan dengan Sistem Informasi Geografis dan penginderaan jauh. Data dikumpulkan dari data curah hujan CHIRPS selama sepuluh tahun, DEMNAS untuk topografi, peta jenis tanah, Sentinel-2 untuk NDVI, serta peta penggunaan lahan Kabupaten Sleman tahun 2024. Pengolahan dilakukan dengan menyusun peta faktor R, K, LS, C, dan P, yang kemudian dihitung menggunakan persamaan $A = R \times K \times LS \times C \times P$. Akurasi dan konsistensi data diuji melalui penyesuaian sistem koordinat, standarisasi resolusi raster, validasi rentang nilai, pemeriksaan spasial, dan pengecekan luas hasil klasifikasi. Hasil penelitian menunjukkan bahwa wilayah teranalisis seluas 56.862,54 ha didominasi oleh kelas erosi sangat ringan seluas 22.766,04 ha atau 40,04%. Namun, kelas sedang, berat, dan sangat berat mencakup 27.524,70 ha atau 48,40%, dengan konsentrasi utama pada lereng utara Merapi dan perbukitan Prambanan. Temuan ini menegaskan bahwa peta bahaya erosi perlu menjadi dasar pengendalian pemanfaatan ruang, rehabilitasi lahan, perencanaan drainase, serta pengarusutamaan konservasi tanah dan air dalam pembangunan Kabupaten Sleman.

Kata Kunci: Erosi, RUSLE, Sleman

ABSTRACT

Soil erosion is a land degradation issue with implications for regional carrying capacity, hydrological risk, land productivity, and the effectiveness of local development. This study aims to map erosion hazards in Sleman Regency and formulate their implications for development planning. A spatial-quantitative approach was applied using the Revised Universal Soil Loss Equation (RUSLE) integrated with Geographic Information Systems and remote sensing. Data were collected from ten-year CHIRPS rainfall records, DEMNAS topographic data, soil-type maps, Sentinel-2 NDVI, and the 2024 land-use map of Sleman Regency. The analysis produced R, K, LS, C, and P factor maps, followed by erosion estimation using $A = R \times K \times LS \times C \times P$. Data accuracy and consistency were assessed through coordinate harmonization, raster resolution standardization, value-range validation, spatial inspection, and area-tabulation checks. The results show that the analyzed area covers 56,862.54 ha and is dominated by the very low erosion class, covering 22,766.04 ha (40.04%). However, moderate, high, and very high erosion classes cumulatively reach 27,524.70 ha (48.40%), with major concentrations on the northern



slopes of Merapi and the Prambanan hills. These findings indicate that erosion hazard maps should be used as a basis for land-use control, land rehabilitation, drainage planning, and mainstreaming soil-water conservation in Sleman Regency development planning.

Keywords: *Erosion, RUSLE, Sleman*

INTRODUCTION

Soil erosion is one of the most decisive forms of land degradation affecting the sustainability of regional development because it influences the function of soil as a medium for production, a regulator of water systems, a carbon store, and an ecosystem support system. At the landscape level, erosion causes the loss of topsoil, reduces soil fertility, increases surface runoff, and intensifies sedimentation in river networks and drainage infrastructure. Therefore, erosion is not merely a soil conservation issue, but also a development planning issue related to land carrying capacity, ecological security, and the efficiency of public investment (Lal, 2001; Pimentel et al., 1995; Montgomery, 2007).

Sleman Regency has complex biophysical characteristics because it extends from the slopes of Mount Merapi in the north to the urban-peri-urban plains of Yogyakarta in the south. Variations in rainfall, slope, young volcanic soils, vegetation, and land-use intensity create uneven levels of erosion susceptibility. At the same time, the development of settlements, educational facilities, trade, services, and

infrastructure increases pressure on the land surface. Under such conditions, an erosion hazard map is needed as a spatial basis for identifying locations whose ecological functions need to be controlled, rehabilitated, or maintained.

Direct erosion estimation requires long-term field measurements, which are often difficult to conduct at the regency scale. Therefore, the Universal Soil Loss Equation (USLE) and the Revised Universal Soil Loss Equation (RUSLE) are widely used because they are able to integrate rainfall erosivity, soil erodibility, slope length and steepness, land cover, and conservation practices into a simple and operational parametric model (Wischmeier and Smith, 1978; Renard et al., 1997). The integration of RUSLE with Geographic Information Systems and remote sensing enables erosion analysis to be conducted spatially, making the results more relevant for spatial planning and location-based development programs (Benavidez et al., 2018; Phinzi and Ngetar, 2019).

The development of geospatial data strengthens the feasibility of RUSLE-based erosion mapping. CHIRPS provides long-term spatial rainfall data that combine



satellite information and rain-gauge observations (Funk et al., 2015). DEMNAS can be used to derive slope steepness and slope length. Sentinel-2 provides multispectral bands that can be used to calculate the Normalized Difference Vegetation Index (NDVI) as an indicator of vegetation condition. NDVI can then be converted into the C factor using an empirical approach that has been applied in RUSLE monitoring in tropical regions (Durigon et al., 2014; Pettorelli et al., 2014).

The main problem addressed in this study is the suboptimal use of erosion maps as an instrument of development planning in Sleman Regency. Many erosion analyses stop at the classification of erosion rates, while their implications for land-use control, rehabilitation priorities, protection of recharge areas, and the design of green-blue infrastructure have not been explicitly formulated. In fact, erosion hazard information can serve as a biophysical risk layer in spatial plans, detailed spatial plans, strategic environmental assessments, medium-term development plans, annual development work plans, and technical recommendations for land use.

Based on this background, this study aims to: (1) develop maps of the R, K, LS, C, and

P factors in Sleman Regency; (2) map the distribution of erosion hazard levels using RUSLE; and (3) formulate development planning implications for land-use control, soil and water conservation, and land rehabilitation priorities. The scope of this study is limited to soil erosion hazards in Sleman Regency.

RESEARCH METHOD

Research Design and Study Area

This study employed a quantitative-spatial design, with raster pixels within the administrative boundary of Sleman Regency serving as the unit of analysis. The model used was RUSLE because it is able to link climatic, soil, topographic, vegetation, and land management factors within a single equation for estimating average annual soil loss. All parameters were prepared as raster layers with standardized coordinate systems, spatial resolutions, and administrative boundaries before the spatial multiplication operation was conducted.

The equation used was $A = R \times K \times LS \times C \times P$. A represents the estimated average annual soil loss in tons/ha/year; R is the rainfall erosivity factor; K is the soil erodibility factor; LS is the slope length and slope steepness factor; C is the vegetation cover and management factor; and P is the conservation practice or land management



factor. The final output was classified into five erosion hazard classes, namely very low, low, moderate, high, and very high.

Table 1. Research Data and Data Sources

No.	Data	Source/Resolution	Map output
1	Rainfall	Ten-year CHIRPS	Annual rainfall map and R-factor map
2	Topography	DEMNAS	Slope map and LS-factor map
3	Soil type	Soil type map of Sleman Regency	K-factor map
4	Multispectral imagery	Sentinel-2A/Sentinel-2 MSI	NDVI map and C-factor map
5	Land use	2024 land-use map of Sleman Regency	P-factor map
6	Administrative boundary	Boundary of Sleman Regency	Masking and area tabulation of erosion classes

Source: Research data processing, 2026.

Method for Developing the Rainfall Map and Rainfall Erosivity Factor (R) from CHIRPS

The rainfall map was developed from ten-year monthly CHIRPS rainfall data. CHIRPS was selected because this study required a spatially continuous rainfall surface covering the entire administrative area of Sleman Regency. The use of gridded rainfall data is considered appropriate for regional-scale erosion modelling because rainfall stations are commonly limited in number, unevenly distributed, and may not fully represent the strong orographic rainfall gradient between the southern plains and the northern slopes of Mount Merapi. Interpolating point-based station data under such conditions may introduce spatial artefacts, particularly in areas with complex topography. Therefore, CHIRPS was used as the primary rainfall input, while station-based rainfall data, when

available, is more suitable as a reference for checking the reasonableness of the rainfall pattern rather than as the main source for generating the spatial rainfall surface.

Monthly CHIRPS rainfall data were downloaded for the area covering Sleman Regency and clipped using the administrative boundary of Sleman. All raster layers were standardized in terms of coordinate system, spatial resolution, extent, and no-data values so that they could be overlaid with the other RUSLE parameters. Monthly rainfall values were summed into annual rainfall and then averaged over the ten-year period to obtain the mean annual rainfall map. The spatial consistency of the rainfall surface was examined by checking whether the resulting pattern followed the expected rainfall gradient of Sleman, namely lower



rainfall in the southern and central plains and higher rainfall toward the northern Merapi slope.

The R factor was calculated using the Lenvain empirical approach, which is commonly applied in tropical rainfall erosivity studies. Operationally, monthly rainfall was converted into monthly erosivity using the formula $R_m = 2.21 \times P_m^{1.36}$, where P_m represents monthly rainfall in centimeters. The monthly erosivity values were then summed to obtain annual erosivity and averaged over the ten-year period. This procedure produced the R-factor map, which represents the spatial variation in the ability of rainfall to detach and transport soil particles. Because the R factor was derived from gridded rainfall data, the resulting map should be interpreted as a regional rainfall erosivity surface suitable for spatial screening and planning analysis, rather than as a substitute for plot-scale rainfall erosivity measurement.

Method for Developing The Soil Type Map and Soil Erodibility Factor (K)

The K-factor map was developed from the soil type map of Sleman Regency. In RUSLE-based spatial modelling, the soil erodibility factor can be derived by converting soil-type classes into representative K values when detailed laboratory-based soil property data are

not available for the entire study area. This approach is commonly used for regional-scale erosion hazard mapping because soil texture, structure, organic matter, and permeability data are rarely available continuously at pixel level. Therefore, the soil type map was used as the most operational spatial proxy for representing the relative susceptibility of different soils to particle detachment and transport.

The topology of the soil type vector data was first checked to ensure that there were no spatial inconsistencies such as gaps, overlaps, or invalid geometries. The soil type data were then clipped according to the administrative boundary of Sleman Regency. Each soil class was subsequently reclassified into a K value based on published soil erodibility conversion references used in USLE/RUSLE modelling. The K values used in this study were Cambisol 0.14, Grumusol 0.16, Mediterranean soil 0.16, Latosol 0.26, and Regosol 0.31. After the reclassification process, the K-factor layer was rasterized and standardized to match the coordinate system, spatial resolution, extent, and no-data values of the R, LS, C, and P layers before being used in the RUSLE calculation.

The conversion from soil type to K value was not intended to represent laboratory-measured erodibility at plot scale. Rather, it was used as a regional erodibility



indicator suitable for spatial screening and erosion hazard mapping at regency scale. This interpretation is important because the actual erodibility of a soil may vary within the same soil class depending on local texture, aggregate stability, organic matter, permeability, land management, and moisture condition. Consequently, the K-factor map produced in this study should be interpreted as a spatial approximation of soil erodibility for planning analysis, while detailed conservation engineering in priority areas should still be supported by site-level soil sampling and field verification.

Method for Developing The Slope Map and LS Factor from DEMNAS

The slope map and LS factor were derived from DEMNAS. The initial stages involved clipping the DEM to the boundary of Sleman Regency, filling local depressions (sink filling), and adjusting the coordinate system. Slope was calculated in percent units to examine the distribution of slope classes. The LS factor was then calculated using the LS Factor (one-step) tool in QGIS, which integrates slope gradient and flow accumulation information.

Conceptually, the LS factor represents the influence of slope length and slope steepness on the acceleration of surface runoff. High LS values indicate steeper slopes or longer flow paths, which increase

the energy of surface flow. The LS results were checked by comparing their spatial pattern with the slope map and landform characteristics: high values should appear on the Merapi slopes, the Prambanan hills, and geomorphologically plausible surface-flow channels.

Method for Developing The NDVI Map and Cover-Management Factor (C) from Sentinel-2

The NDVI map was developed from Sentinel-2 imagery selected under minimum cloud-cover conditions. The red and near-infrared bands were used to calculate NDVI using the formula $NDVI = (NIR - Red) / (NIR + Red)$. In Sentinel-2, the NIR band is represented by Band 8, while the red band is represented by Band 4. The NDVI values were then clipped to the boundary of Sleman Regency and classified to examine variations in vegetation density.

The C factor was calculated from NDVI using the equation $C = (1 - NDVI) / 2$, as used by Durigon et al. (2014) for monitoring the RUSLE cover-management factor in tropical regions. The relationship between NDVI and C is inverse: the higher the NDVI, the lower the C factor, and thus the greater the vegetation protection of the soil surface. The C-factor map was checked to ensure that its values fell within a logical range and that its spatial pattern was



consistent with the NDVI map, with densely vegetated areas having lower C values and open or built-up areas having higher C values.

Method for Developing The Land-Use Map and Management/Conservation Factor (P)

The P-factor map was developed from the 2024 land-use map of Sleman Regency. Each land-use class was simplified and converted into a management/conservation factor value based on the level of land-surface protection. Forests, water bodies, and areas with high surface protection were assigned low values; irrigated rice fields were assigned low values; shrubs and

gardens were assigned intermediate values; while settlements, built-up areas, sand, and open land were assigned high values. After conversion, the data were rasterized and their resolution was standardized with the other parameters.

The P factor in this study represents a regional land-use-based proxy, not a direct measurement of conservation practices on each land parcel. Therefore, the interpretation of P in built-up areas was conducted cautiously. High P values in built-up areas primarily indicate weakened surface hydrological functions, reduced infiltration, and increased runoff, rather than implying that all built-up surfaces experience natural soil erosion.

Table 2. Conversion of K and P Factors Used in The Modelling

Parameter	Class	Value
K	Cambisol	0.14
K	Grumusol	0.16
K	Mediterranean soil	0.16
K	Latosol	0.26
K	Regosol	0.31
P	Forest/water body/river/lake	0.001
P	Irrigated rice field/grass-covered vacant land	0.02
P	Rainfed rice field	0.05
P	Shrubland	0.10
P	Garden/plantation	0.30
P	Dry field	0.28
P	Settlement/building/sand/open land	1,00

Source: Adapted from the conversion of soil erodibility and land cover/management factors in Sadewo, et al (2023), adjusted to the Sleman data classes.

Method for Developing The Erosion Hazard Map and Testing Data Accuracy-Consistency

The erosion hazard map was developed using raster calculator with the equation A

= $R \times K \times LS \times C \times P$. All input rasters were checked to ensure that they had the same extent, cell size, coordinate system, and no-data values. The calculated A values were classified into five classes: very low (0-15



tons/ha/year), low (>15-60 tons/ha/year), moderate (>60-180 tons/ha/year), high (>180-480 tons/ha/year), and very high (>480 tons/ha/year). The area of each class was calculated from the number of pixels multiplied by the pixel area and then converted into hectares and percentages.

The accuracy test in this study was conducted as a spatial-logical accuracy and data-consistency test, rather than field

validation of soil loss. The checks included: (1) consistency of raster projection and resolution; (2) examination of the value range of each factor; (3) visual verification that the R pattern follows rainfall, K follows soil type, LS follows slope, C is inversely related to NDVI, and P follows land use; (4) checking the total classified area against the analyzed area; and (5) assessing spatial plausibility against the geomorphological conditions of Sleman.

Table 3. Classification of erosion hazard levels

Class	Erosion range (tons/ha/year)	Hazard level	Planning meaning
1	0-15	Very low	Maintaining land cover and controlling land-use change.
2	>15-60	Low	Land-use supervision and basic conservation in vulnerable areas.
3	>60-180	Moderate	Medium priority for vegetation strengthening, micro-drainage, and soil conservation.
4	>180-480	High	High priority for rehabilitation, restrictions on land clearing, and runoff control.
5	>480	Very high	Very high priority for structural-vegetative conservation and strict spatial control.

Source: Ministry of Forestry of the Republic of Indonesia, Regulation No. P.32/Menhut-II/2009 on Technical Planning Procedures for Forest and Land Rehabilitation in Watersheds (RTkRHL-DAS), Table 17.

RESEARCH RESULTS

Rainfall and Rainfall Erosivity

The CHIRPS processing results show that the average annual rainfall in Sleman Regency reaches 2,570 mm/year, with a minimum value of 2,200 mm/year and a maximum value of 3,363 mm/year. The spatial pattern shows a gradient from south to north. Southern areas such as Depok, Berbah, Kalasan, and parts of Mlati tend to have lower rainfall, whereas the

northern areas associated with the Merapi slopes show higher rainfall.

The resulting R factor has an average value of 1,962, with a minimum of 1,588 and a maximum of 2,780. The increase in the R factor toward the north indicates that rainfall on the Merapi slopes is not only greater in quantity but also has higher erosivity potential. In the RUSLE context, this factor represents an initial pressure that can increase erosion risk when interacting with steep slopes, erodible



soils, low vegetation cover, and less protective land management.

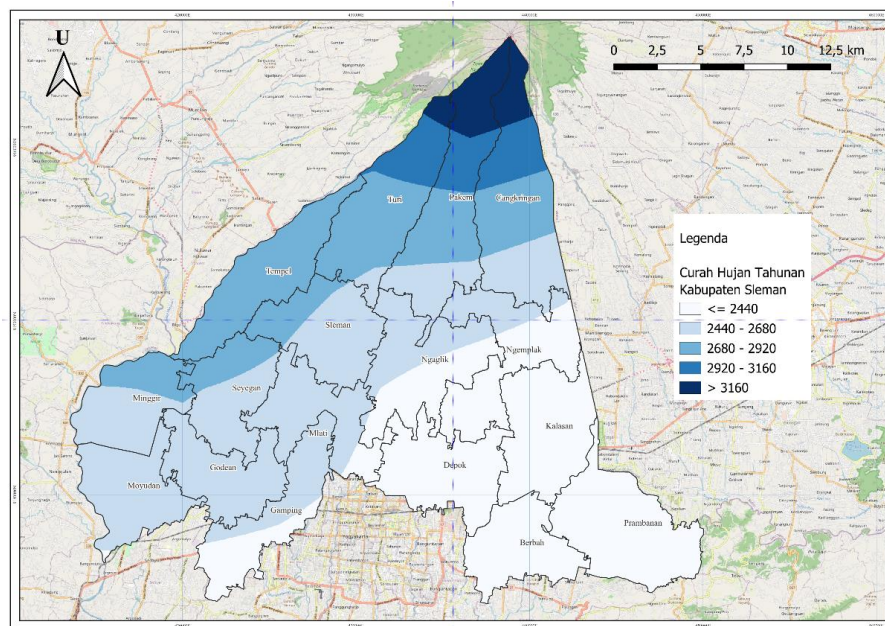


Figure 1. Annual Rainfall Map of Sleman Regency

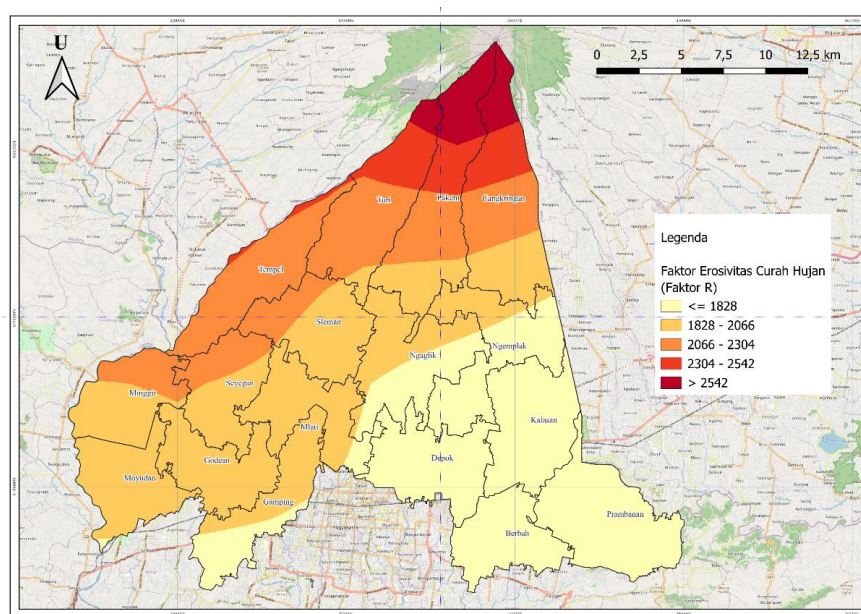


Figure 2. Rainfall Erosivity Factor (R) Map of Sleman Regency

Soil Type and Soil Erodibility Factor

The K-factor map shows that Sleman Regency is dominated by Regosol, with an erodibility value of 0.31. This is the highest value among the soil classes used in this study. Spatially, Regosol is widely

distributed across the central to northern parts of Sleman Regency. This condition is important because young volcanic soils can support land productivity but are also relatively vulnerable to particle

detachment when located on steep slopes and exposed to high rainfall.

Other soil classes, such as Cambisol, Grumusol, Mediterranean soil, and Latosol, have more limited distributions. The K value does not operate independently; it

becomes more decisive when it coincides with high R and LS factors. Therefore, areas with Regosol, high rainfall, and steep slopes need to be treated as priority zones for soil conservation in development planning.

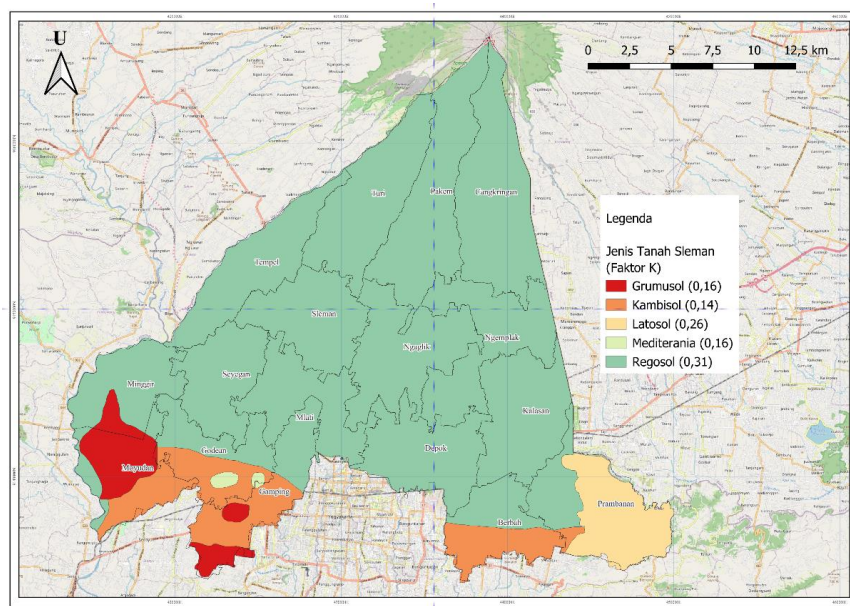


Figure 3. Soil Type and Soil Erodibility Factor (K) Map of Sleman Regency

Slope and LS Factor

The slope map shows a strong contrast between the southern plains and the northern slopes of Sleman Regency. The southern and central areas are dominated by low slopes, whereas the northern and southeastern areas show moderate to very steep slopes. This pattern follows the morphology of the Mount Merapi slopes and the Prambanan hills.

The LS factor of Sleman Regency has an average value of 3.8, with a minimum value of 0.0002 and a maximum value of 851. The high maximum value indicates local sites with a combination of steep slopes and extreme flow accumulation. In the RUSLE model, LS is one of the most decisive factors because it controls runoff velocity and the ability of water to transport soil particles.

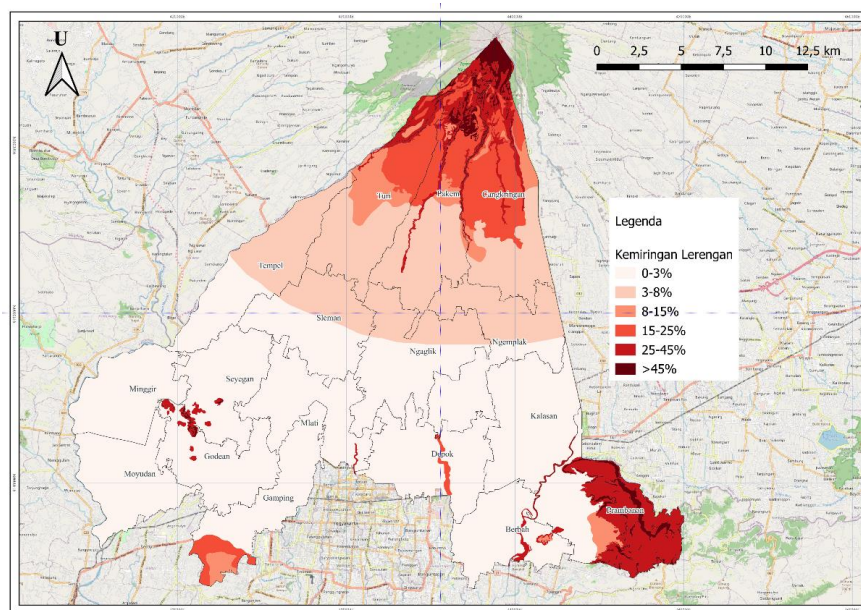


Figure 4. Slope Map of Sleman Regency

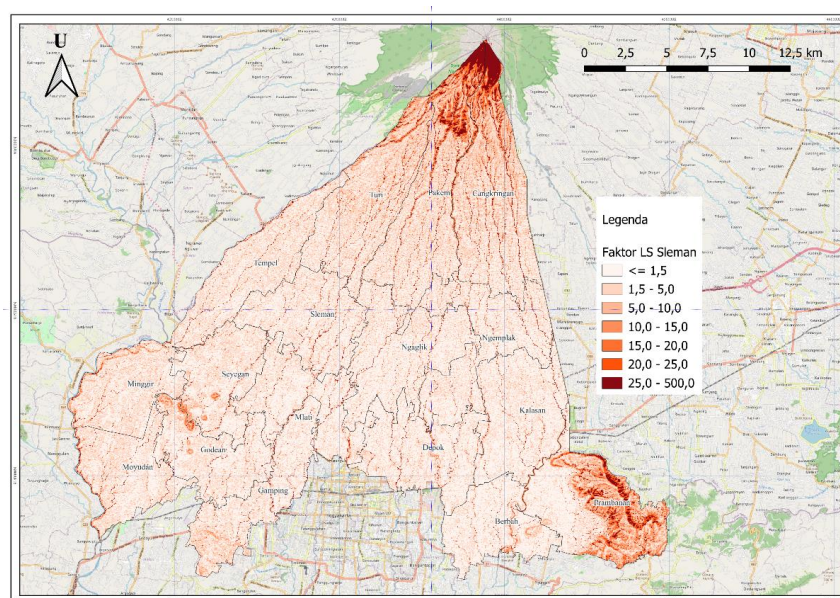


Figure 5. Slope Length and Steepness Factor (LS) Map of Sleman Regency

NDVI and C Factor

The NDVI value of Sleman Regency has an average of 0.355, with a minimum value of -0.265 and a maximum value of 0.724. This average value indicates moderate vegetation cover, but the range reveals strong landscape heterogeneity. The more urbanized central-southern area tends to have lower NDVI due to vegetation

fragmentation, whereas parts of the western and northern areas show better vegetation cover.

The conversion of NDVI into the C factor shows an average value of 0.322, with a minimum value of 0.1487 and a maximum value of 0.59. Areas with high NDVI have low C values and are therefore more capable of protecting the soil surface from

raindrop impact and runoff. Conversely, areas with low NDVI have higher C values

and are more vulnerable to soil particle detachment.

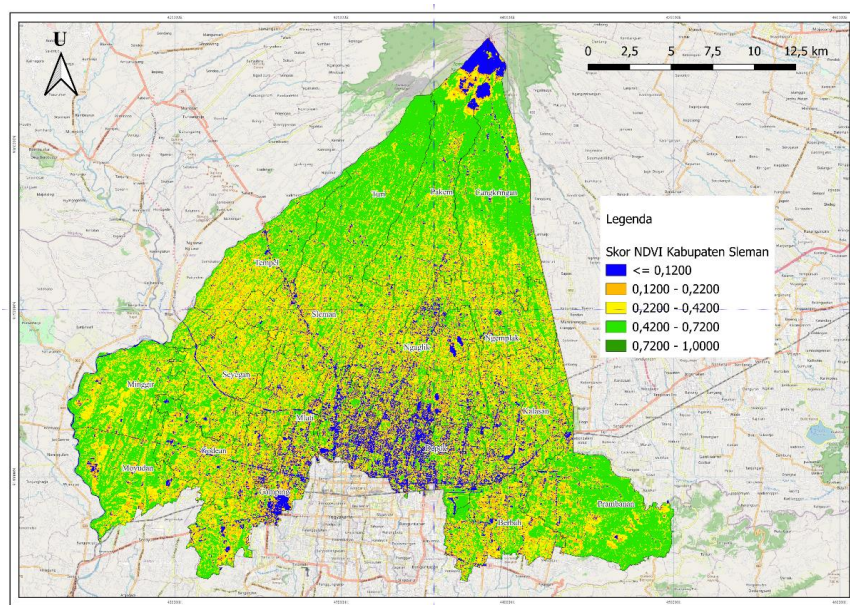


Figure 6. NDVI Map of Sleman Regency

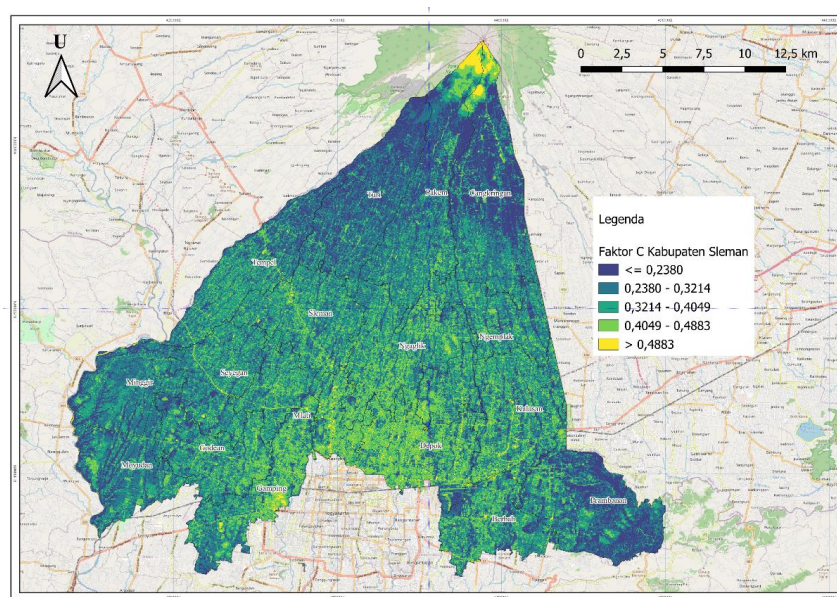


Figure 7. Cover-Management Factor (C) Map of Sleman Regency

Land Use and P Factor

The land-use map shows that Sleman is a heterogeneous landscape. The southern and central areas are dominated by settlements, buildings, public facilities, road networks, and urban-peri-urban activities. The central-western area still

shows a mosaic of rice fields, gardens, dry fields, and rural settlements. The northern area shows a combination of vegetated areas, forests, gardens, dry fields, slope settlements, and open areas.

The P factor shows variation in the capacity of land use to reduce erosion. Low

P values are associated with forests, water bodies, rice fields, and land uses with better surface protection. High P values often appear in settlements, buildings, open land, and surfaces with weakened

hydrological functions. In development planning, this map is important for identifying spatial-use patterns that may increase runoff and the need for conservation interventions.

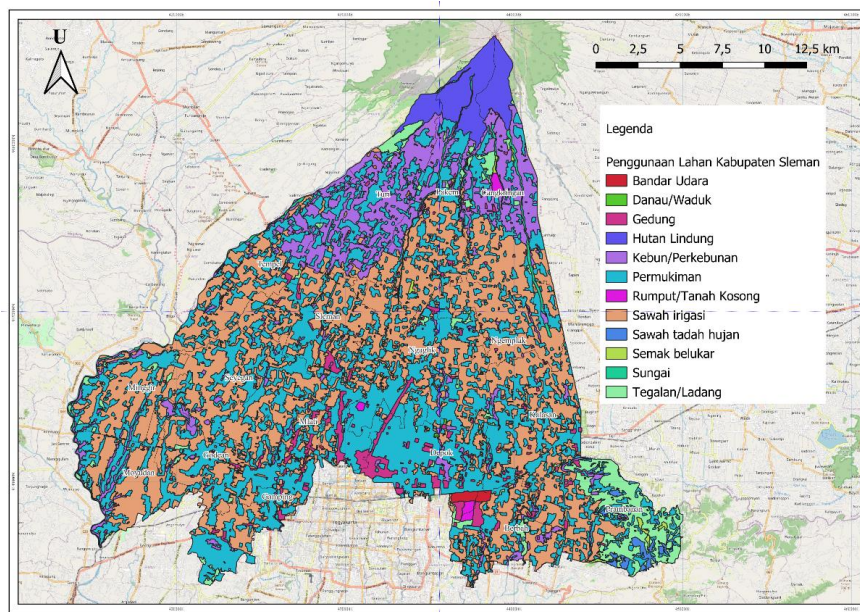


Figure 8. Land-Use Map of Sleman Regency

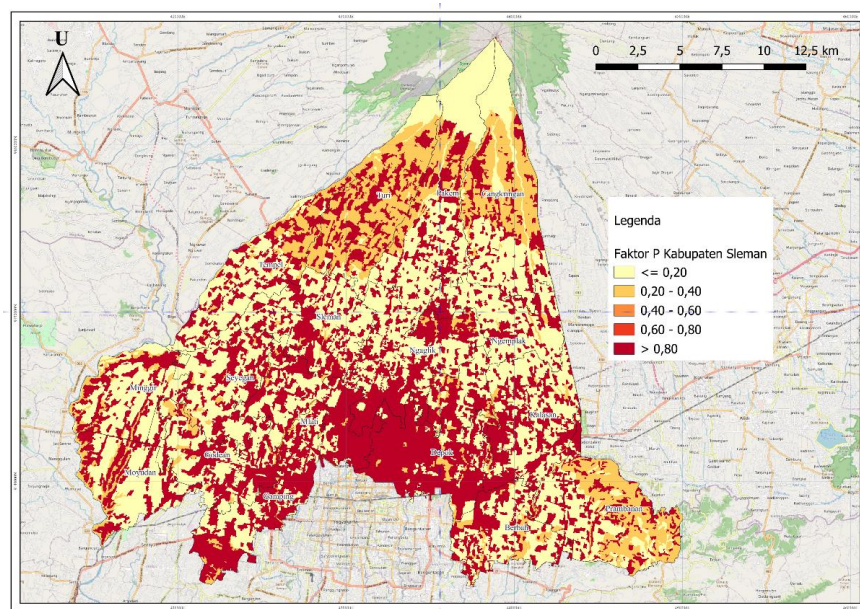


Figure 9. Land Management/Conservation Factor (P) Map of Sleman Regency

Distribution of Erosion Hazard Levels

The spatial multiplication of R, K, LS, C, and P produced the erosion hazard level map of

Sleman Regency. The analyzed area covers 56,862.54 ha. The very low class is the largest class, covering 22,766.04 ha or 40.04% of the total analyzed area. The low



class covers 6,571.80 ha or 11.56%. The moderate class covers 10,038.60 ha or 17.65%. The high class covers 10,735.56 ha or 18.88%, while the very high class covers 6,750.54 ha or 11.87%.

The dominance of the very low class does not mean that the erosion problem in Sleman is low overall. If the moderate, high,

and very high classes are combined, areas with moderate to very high erosion hazard reach 27,524.70 ha or 48.40%. The high and very high classes alone cover 17,486.10 ha or 30.75%. Thus, nearly one-third of the analyzed area requires serious attention in soil-water conservation and land-use control.

Table 4. Distribution of Erosion Hazard Classes in Sleman Regency

Class	Erosion hazard level	Erosion range	Area (ha)	Percentage
1	Very low	0-15 tons/ha/year	22.766,04	40,04%
2	Low	>15-60 tons/ha/year	6.571,80	11,56%
3	Moderate	>60-180 tons/ha/year	10.038,60	17,65%
4	High	>180-480 tons/ha/year	10.735,56	18,88%
5	Very high	>480 tons/ha/year	6.750,54	11,87%
	Total		56.862,54	100,00%

Source: Results of RUSLE raster processing for Sleman Regency.

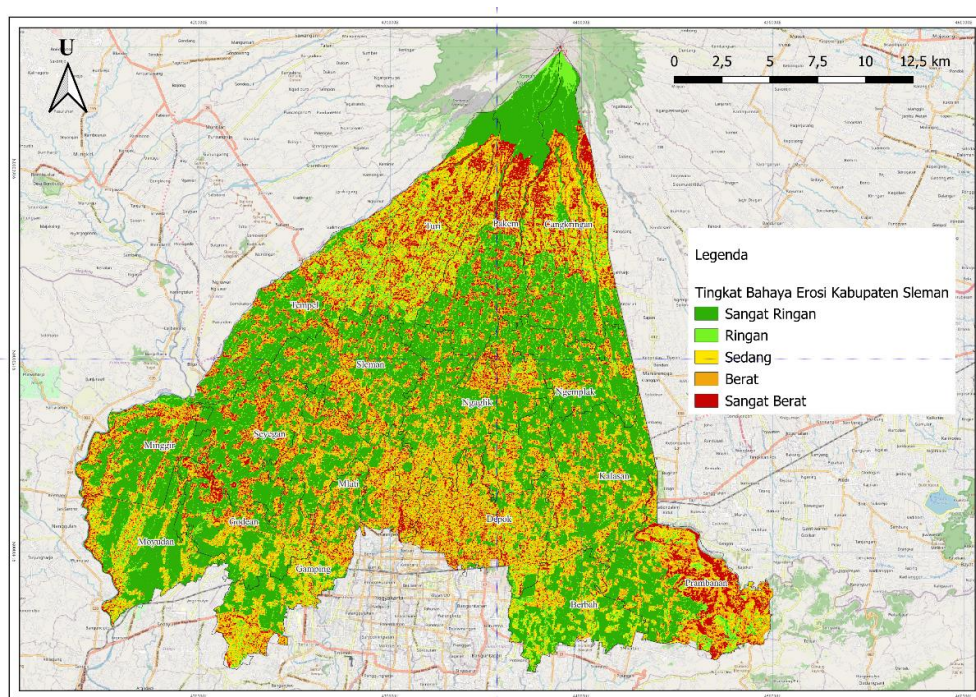


Figure 10. Erosion Hazard Level Map of Sleman Regency

DISCUSSION

The results show that erosion hazards in Sleman Regency are the outcome of interactions among climatic pressure, soil

material, landform, vegetation cover, and land use. Areas with high rainfall do not necessarily become high-erosion zones if they have good vegetation cover and protective

surface management. Conversely, areas with moderate slopes can experience increased risk if the soil is relatively erodible and the surface is exposed. This finding is consistent with the logic of RUSLE, which positions erosion as the result of multiplicative factors rather than a single cause (Renard et al., 1997; Alewell et al., 2019).

The concentration of high and very high erosion on the northern Merapi slopes demonstrates the importance of topography and orographic rainfall in shaping erosion risk. The increase in R values toward the north intensifies rainfall energy, while high LS values accelerate surface flow. When these two factors coincide with Regosol soils that have high K values, the risk of soil loss increases significantly. A similar condition is also observed in the Prambanan hills, where the LS factor is the main driver of the increase in erosion class. These areas should therefore be treated not only as biophysical erosion-prone zones, but also as spatial planning concern areas because they may constrain future land-use allocation, infrastructure development, and slope-based cultivation.

The role of vegetation is evident in the presence of areas that remain in low erosion classes despite being located on slopes and receiving high rainfall. This indicates that NDVI and the C factor are not merely indicators of land cover, but also indicators of the ecological capacity of the landscape to withstand degradation. Theoretically,

vegetation reduces raindrop impact energy, slows runoff, increases infiltration, and strengthens soil structure through root systems. Therefore, declining vegetation cover in areas with high R and high LS values can rapidly increase erosion hazard classes (Borrelli et al., 2017; Phinzi and Ngetar, 2019). In spatial planning terms, this finding confirms the importance of maintaining vegetated areas, riparian buffers, agroforestry systems, and green open spaces as part of erosion-sensitive land management.

In the context of regional development, the results of this study shift the understanding of erosion from a technical-conservation issue to a spatial governance issue. Indonesian spatial planning policy places RTRW and RDTR as instruments for directing land-use allocation, spatial utilization, and spatial control, while KLHS is used to ensure that environmental carrying capacity and sustainability principles are integrated into policies, plans, and programs (Government of Indonesia, 2016, 2021; Ministry of Agrarian Affairs and Spatial Planning/National Land Agency, 2021). Therefore, the erosion hazard map produced in this study can be used as a biophysical risk layer to support the implementation of RTRW, RDTR, KLHS, technical land-use recommendations, and annual development planning. This is particularly relevant for Sleman Regency because the regional spatial plan already regulates spatial structure, spatial pattern,



strategic areas, spatial utilization directions, and spatial control provisions (Government of Sleman Regency, 2021).

High and very high erosion zones need to be treated as priority control zones, especially when they overlap with steep slopes, natural drainage channels, recharge areas, open land uses, planned settlement expansion, tourism areas, infrastructure corridors, or intensive cultivation zones. Such overlaps may indicate potential conflicts between development objectives and land conservation requirements. In these locations, spatial planning instruments should direct stricter land-use control, vegetation protection, slope stabilization, runoff management, and restrictions on land clearing. Thus, the erosion hazard map is not only an output of RUSLE-based modelling, but also an evidence-based planning instrument for identifying areas where development should be controlled, conditioned, or accompanied by conservation measures.

Areas in the moderate class are also important because they function as transition zones. Without adequate management, the moderate class can shift into the high class due to land clearing, infrastructure development without contour-based drainage, declining vegetation cover, or conversion of permeable surfaces into impervious areas. Therefore, moderate zones need to be positioned as prevention areas through permit supervision, green open space requirements, strengthening of riparian

vegetation, surface runoff control, and integration into RDTR zoning provisions. In this sense, moderate erosion areas should not be interpreted as safe areas, but as early-warning zones for preventive spatial management.

Built-up areas in southern and central Sleman need to be interpreted differently. In flat areas, LS values are relatively low, so natural soil erosion is not always dominant. However, urbanization can increase impervious surfaces, reduce infiltration, increase runoff, and add to the drainage burden. Therefore, erosion-control strategies need to be integrated with green-blue infrastructure such as infiltration wells, retention parks, environmentally sensitive drainage, riverbank vegetation, and control of building coverage ratios and impervious surfaces. These strategies are relevant for RDTR-based development control because detailed spatial plans can regulate site-level development intensity, drainage requirements, green space provision, and environmental management conditions.

These findings also demonstrate the need for a sub-watershed- and landscape-based approach. Erosion follows slopes and flow paths, so interventions are insufficient if they are based only on district or village administrative boundaries. Protection of upper slopes, control of land clearing on middle slopes, and sediment management downstream must be designed as a single



upstream-downstream system. In this way, soil-water conservation can directly contribute to reducing flood risk, drainage sedimentation, and infrastructure damage. The integration of erosion hazard information into RTRW, RDTR, and KLHS can therefore strengthen the practical relevance of erosion mapping by connecting biophysical risk assessment with spatial planning, environmental safeguards, and development policy.

CONCLUSIONS

AND

RECOMMENDATIONS

Conclusions

RUSLE mapping based on GIS and remote sensing shows that erosion hazards in Sleman Regency have strong spatial variation. The very low class is the largest class, covering 22,766.04 ha or 40.04% of the analyzed area. However, the moderate, high, and very high classes cumulatively reach 27,524.70 ha or 48.40%, while the high and very high classes cover 17,486.10 ha or 30.75%.

The distribution of high erosion is primarily concentrated on the Merapi slopes in the north and the Prambanan hills in the southeast. This pattern is formed by the interaction of rainfall erosivity, the LS factor, the dominance of Regosol soils, vegetation variation, and land use. Thus, erosion in Sleman cannot be explained by a single factor, but by the

simultaneous configuration of biophysical conditions and spatial use.

Recommendations

The Government of Sleman Regency needs to use the erosion hazard map as a biophysical risk layer in spatial plans, detailed spatial plans, strategic environmental assessments, medium-term development plans, annual development work plans, and permit control. High and very high zones should become priorities for vegetative-structural rehabilitation, slope stabilization, protection of channel buffers, and restrictions on land clearing. Moderate zones should be treated as prevention zones so that they do not develop into areas of severe degradation.

The erosion map needs to be updated periodically because the R, C, and P factors are dynamic. The local government can develop an annual monitoring system based on CHIRPS, Sentinel-2, DEMNAS, and the latest land-use maps. For technical design in priority locations, this mapping needs to be complemented by field surveys, soil property measurements, drainage inspection, and direct evaluation of land conservation practices.

ACKNOWLEDGEMENTS

The authors express their gratitude to the parties that provided spatial data and supporting documents for this study,



particularly the providers of CHIRPS, DEMNAS, Sentinel-2, soil type maps, and the land-use map of Sleman Regency. The authors also thank all parties who provided input during the preparation of this scientific manuscript.

REFERENCES

- Alewell, C., Borrelli, P., Meusburger, K. & Panagos, P. (2019) 'Using the USLE: Chances, challenges and limitations of soil erosion modelling', *International Soil and Water Conservation Research*, 7(3), pp. 203–225. <https://doi.org/10.1016/j.iswcr.2019.05.004>
- Angima, S.D., Stott, D.E., O'Neill, M.K., Ong, C.K. & Weesies, G.A. (2003) 'Soil erosion prediction using RUSLE for central Kenyan highland conditions', *Agriculture, Ecosystems & Environment*, 97(1–3), pp. 295–308. [https://doi.org/10.1016/S0167-8809\(03\)00011-2](https://doi.org/10.1016/S0167-8809(03)00011-2)
- Benavidez, R., Jackson, B., Maxwell, D. & Norton, K. (2018) 'A review of the (Revised) Universal Soil Loss Equation ((R)USLE): With a view to increasing its global applicability and improving soil loss estimates', *Hydrology and Earth System Sciences*, 22(11), pp. 6059–6086. <https://doi.org/10.5194/hess-22-6059-2018>
- Borrelli, P., Alewell, C., Alvarez, P., Anache, J.A.A., Baartman, J., Ballabio, C., Bezak, N., Biddoccu, M., Cerda, A., Chalise, D., Chen, S., Chen, W., De Girolamo, A.M., Gessesse, G.D., Deumlich, D., Diodato, N., Efthimiou, N., Erpul, G., Fiener, P. & Panagos, P. (2021) 'Soil erosion modelling: A global review and statistical analysis', *Science of the Total Environment*, 780, 146494. <https://doi.org/10.1016/j.scitotenv.2021.146494>
- Borrelli, P., Robinson, D.A., Fleischer, L.R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schutt, B., Ferro, V., Bagarello, V., Van Oost, K., Montanarella, L. & Panagos, P. (2017) 'An assessment of the global impact of 21st century land use change on soil erosion', *Nature Communications*, 8, 2013. <https://doi.org/10.1038/s41467-017-02142-7>
- Borrelli, P., Robinson, D.A., Panagos, P., Lugato, E., Yang, J.E., Alewell, C., Wuepper, D., Montanarella, L. & Ballabio, C. (2020) 'Land use and climate change impacts on global soil erosion by water (2015–2070)', *Proceedings of the National Academy of Sciences*, 117(36), pp. 21994–22001. <https://doi.org/10.1073/pnas.2001403117>
- Durigon, V.L., Carvalho, D.F. de, Antunes, M.A.H., Oliveira, P.T.S. & Fernandes, M.M. (2014) 'NDVI time series for monitoring RUSLE cover management factor in a tropical watershed', *International Journal of Remote Sensing*, 35(2), pp. 441–453. <https://doi.org/10.1080/01431161.2013.871081>
- Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A. & Michaelsen, J. (2015) 'The climate hazards infrared precipitation with stations: A new environmental record for monitoring extremes', *Scientific Data*, 2, 150066. <https://doi.org/10.1038/sdata.2015.66>
- Kinnell, P.I.A. (2010) 'Event soil loss, runoff and the Universal Soil Loss Equation family of models: A review', *Journal of Hydrology*, 385(1–4), pp. 384–397. <https://doi.org/10.1016/j.jhydrol.2010.01.024>
- Lal, R. (2001) 'Soil degradation by erosion', *Land Degradation & Development*,



- 12(6), pp. 519–539.
<https://doi.org/10.1002/ldr.472>
- Montgomery, D.R. (2007) 'Soil erosion and agricultural sustainability', *Proceedings of the National Academy of Sciences*, 104(33), pp. 13268–13272.
<https://doi.org/10.1073/pnas.0611508104>
- Panagos, P., Ballabio, C., Borrelli, P., Meusburger, K., Klik, A., Rousseva, S., Tadic, M.P., Michaelides, S., Hrabalíková, M., Olsen, P., Aalto, J., Lakatos, M., Rymaszewicz, A., Dumitrescu, A., Begueria, S. & Alewell, C. (2015) 'Rainfall erosivity in Europe', *Science of the Total Environment*, 511, pp. 801–814.
<https://doi.org/10.1016/j.scitotenv.2015.01.008>
- Panagos, P., Borrelli, P., Meusburger, K., Yu, B., Klik, A., Lim, K.J., Yang, J.E., Ni, J., Miao, C., Chattopadhyay, N., Sadeghi, S.H., Hazbavi, Z., Zabihi, M., Larionov, G.A., Krasnov, S.F., Gorobets, A.V., Levi, Y., Erpul, G. & Ballabio, C. (2017) 'Global rainfall erosivity assessment based on high-temporal resolution rainfall records', *Scientific Reports*, 7, 4175.
<https://doi.org/10.1038/s41598-017-04282-8>
- Pettorelli, N., Laurance, W.F., O'Brien, T.G., Wegmann, M., Nagendra, H. & Turner, W. (2014) 'Satellite remote sensing for applied ecologists: Opportunities and challenges', *Journal of Applied Ecology*, 51(4), pp. 839–848.
<https://doi.org/10.1111/1365-2664.12261>
- Pettorelli, N., Vik, J.O., Mysterud, A., Gaillard, J.M., Tucker, C.J. & Stenseth, N.C. (2005) 'Using the satellite-derived NDVI to assess ecological responses to environmental change', *Trends in Ecology & Evolution*, 20(9), pp. 503–510.
<https://doi.org/10.1016/j.tree.2005.05.011>
- Phinzi, K. & Ngetar, N.S. (2019) 'The assessment of water-borne erosion at catchment level using GIS-based RUSLE and remote sensing: A review', *International Soil and Water Conservation Research*, 7(1), pp. 27–46.
<https://doi.org/10.1016/j.iswcr.2018.12.002>
- Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R. & Blair, R. (1995) 'Environmental and economic costs of soil erosion and conservation benefits', *Science*, 267(5201), pp. 1117–1123.
<https://doi.org/10.1126/science.267.5201.1117>
- Sadewo, W., Subagiada, K. & Djayus (2023) 'Analysis of erosion rate classification using the Universal Soil Loss Equation (USLE) method with Geographic Information Systems in Samarinda City', *Jurnal Geosains Kutai Basin*, 6(1), pp. 1–12.
- Teng, H., Liang, Z., Chen, S., Liu, Y., Rossel, R.A.V., Chappell, A., Yu, W., Shi, Z. & Wang, B. (2018) 'Current and future assessments of soil erosion by water on the Tibetan Plateau based on RUSLE and CMIP5 climate models', *Science of the Total Environment*, 635, pp. 673–686.
<https://doi.org/10.1016/j.scitotenv.2018.04.146>
- Tucker, C.J. (1979) 'Red and photographic infrared linear combinations for monitoring vegetation', *Remote Sensing of Environment*, 8(2), pp. 127–150. [https://doi.org/10.1016/0034-4257\(79\)90013-0](https://doi.org/10.1016/0034-4257(79)90013-0)
- Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K. & Yoder, D.C. (1997) *Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE)*. Agriculture Handbook No. 703. Washington, DC: U.S. Department of Agriculture.



- Wischmeier, W.H. & Smith, D.D. (1978) *Predicting rainfall erosion losses: A guide to conservation planning*. Agriculture Handbook No. 537. Washington, DC: U.S. Department of Agriculture.
- Rouse, J.W., Haas, R.H., Schell, J.A. & Deering, D.W. (1974) 'Monitoring vegetation systems in the Great Plains with ERTS', in Freden, S.C., Mercanti, E.P. & Becker, M.A. (eds.) *Third Earth Resources Technology Satellite-1 Symposium*. NASA SP-351. Washington, DC: NASA, pp. 309–317.
- Government of Indonesia (2016) *Government Regulation Number 46 of 2016 concerning Procedures for Conducting Strategic Environmental Assessment*. Jakarta: Government of Indonesia.
- Government of Indonesia (2021) *Government Regulation Number 21 of 2021 concerning Spatial Planning Implementation*. Jakarta: Government of Indonesia.
- Government of Sleman Regency (2021) *Regional Regulation of Sleman Regency Number 13 of 2021 concerning the Spatial Plan of Sleman Regency 2021–2041*. Sleman: Government of Sleman Regency.
- Ministry of Agrarian Affairs and Spatial Planning/National Land Agency (2021) *Regulation of the Minister of Agrarian Affairs and Spatial Planning/Head of the National Land Agency Number 11 of 2021 concerning Procedures for Preparing, Reviewing, Revising, and Issuing Substantive Approval for Provincial, Regency, Municipal Spatial Plans and Detailed Spatial Plans*. Jakarta: Ministry of Agrarian Affairs and Spatial Planning/National Land Agency.
- Ministry of Forestry of the Republic of Indonesia (2009) *Regulation of the Minister of Forestry No. P.32/Menhut-II/2009 concerning Technical Planning Procedures for Forest and Land Rehabilitation in Watersheds (RTkRHL-DAS)*. Jakarta: Ministry of Forestry.
- European Space Agency (n.d.) *Sentinel-2*. Available at: https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-2 (Accessed: 25 May 2026).
- Geospatial Information Agency (n.d.) *DEMNAS: National Digital Elevation Model*. Available at: <https://tanahair.indonesia.go.id/> (Accessed: 25 May 2026).

