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Estimation of soil water erosion based on RUSLE, GIS and remote sensing

Estimación de la erosión hídrica del suelo basada en RUSLE, SIG y teledetección

Dayma Sadami Carmenates Hernández[1*], Maiquel López Silva[1],
Oscar Brown Manrique[2] and Rider Riveras Hernández[2]

[1]*Universidad Católica Sedes Sapientiae, Facultad de Ingeniería, Departamento de Investigación, Los Olivos, Lima, Perú. E-mail: mlopezs@ucss.edu.pe*
[2]*Universidad de Ciego de Ávila Máximo Gómez Báez, Ciego de Ávila, Cuba. E-mail: obrown@unica.cu*

[*]Author for correspondence: Dayma Sadami Carmenates Hernández, e-mail: dcarmenates@ucss.edu.pe

ABSTRACT: Soil degradation is the main ecological challenge in hydrographic units, as it leads to a decrease in soil fertility. Climate change and anthropogenic factors exacerbate this problem. Based on this, the purpose of this research was to estimate soil loss due to water erosion in the Rímac River basin. To this end, various tools were used, such as remote sensing (RS), Geographic Information Systems (GIS), and the Revised Universal Soil Loss Equation (RUSLE). The findings revealed that the basin has an annual soil loss of 135 t ha^{-1} $year^{-1}$. A classification of water erosion was proposed in which 15.30%, 50.43%, and 34.27% of the area are classified as high, medium, and low priority, respectively. By integrating the RUSLE model with GIS and remote sensing, it was possible to accurately calculate and locate soil erosion caused by water, identifying the most urgent intervention areas and thus strengthening decision-making for the sustainable management of soil resources.
Keywords: agricultural soils, soil degradation, spatial analysis, NDVI.

RESUMEN: La degradación del suelo constituye el principal desafío ecológico en las unidades hidrográficas, debido a que provoca una disminución en la fertilidad del suelo. El cambio climático y los factores antropogénicos empeoran este problema. Con base en lo anterior, el propósito de la investigación fue estimar la pérdida del suelo por erosión hídrica en la cuenca del río Rímac. Para esto, se usaron diversas herramientas, como la teledetección (RS), el Sistema de Información Geográfica (SIG) y la Ecuación Universal de Pérdida de Suelo Revisada (RUSLE). El hallazgo reveló que la cuenca tiene una pérdida de suelo anual de 135 t ha^{-1} $año^{-1}$. Se propuso una clasificación de erosión hídrica en la que el 15,30%, el 50,43% y el 34,27% del área está clasificado como de alta, media y baja prioridad, respectivamente. Al integrar el modelo RUSLE con SIG y teledetección, se pudo calcular y ubicar con exactitud la erosión del suelo por agua, señalando las zonas de intervención más urgentes y reforzando así la toma de decisiones para manejar el recurso suelo de manera sostenible.
Palabras clave: suelos agrícolas, degradación del suelo, análisis espacial, NDVI.

INTRODUCTION

Watersheds are affected by significant challenges, such as extreme droughts, deforestation, flooding, and inadequate agricultural practices that cause soil erosion. Erosive processes lead to the removal of organic matter, nutrient retention capacity, and water in the topsoil, resulting in low food production and food insecurity. Consequently, soil erosion is a global environmental problem that negatively impacts the productivity of natural ecosystems and sustainable agriculture in watersheds (Negese *et al.*, 2021).

The process of soil erosion is the detachment, transport, and deposition of particles from the topsoil layer caused by various natural processes (Ugese *et al.*, 2022).

Water erosion, in particular, is significant because the topography and rainfall intensity carry particles at higher speeds to rivers. Furthermore, the transport of large volumes of sediment caused by erosion reduces the capacity of river intake structures, drinking water treatment plants, storage capacity, and the lifespan of reservoirs (Alí, *et al.*, 2023).

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The Revised Universal Soil Loss Equation (RUSLE) is the most widely used model for predicting soil loss due to its compatibility with geospatial technologies, its reliability, simplicity, and accuracy (Ghosh *et al.*, 2022). Currently, the use of Geographic Information Systems (GIS) and Remote Sensing (RS) has significantly increased the accuracy and efficiency of the RUSLE model (Efthimiou *et al.*, 2020).According to Phinzi y Ngetar (2019), the RUSLE equation, by integrating GIS and RS, allows for a reliable and practical representation of the spatial distribution of soil erosion. Therefore, the objective of this study is to estimate soil loss in the Rímac River basin in Peru, based on RUSLE, GIS, and RS.

MATERIALS AND METHODS

The study was conducted in the Rímac River basin, which covers an area of 3503.95 km² and is 145 km long. Its source is located on the western slopes of the Andes Mountains, at an altitude of 5508 meters above sea level, and it flows into the Pacific Ocean (Figure 1). Located in an arid and semi-arid zone, natural vegetation is only found in the upper basin. The middle and lower basin lacks vegetation and is easily eroded by rainfall, leading to mudslides, landslides, and rockfalls. The Rímac River basin plays a crucial role as it is the main source of fresh water for the Peruvian capital.

First, data collection was carried out using remote sensing techniques. This enabled the creation of a digital elevation model (DEM), which was extracted from https://www.idep.gob.pe/geovisor/VisorDeMapas/. The data was processed using the ArcGIS Pro 3.0 GIS platform. Additionally, a 25-year (1998-2022) historical series of precipitation data from nine rain gauge stations, provided by the National Meteorology and Hydrology Service of Peru (SENAHMI), was used. Figure 2 shows the methodological model.

The R factor was estimated using the Renard y Freimund (1994) equation, which is expressed in equation (1). Equations (2) and (3), developed by Renard (1997).were applied to the K factor.

The LS factor, representing the ratio of slope length to slope inclination, was obtained from the flow direction using the DEM, as expressed in equation (4). The C factor was obtained using the Normalized Difference Vegetation Index (NDVI), as shown in equations (5) and (6).

$$R = 0.0483 \times P^{1.61} \quad (1)$$

$$K = 0.034 + 0.0405 x exp\left[-0.5\left(\frac{logD_g + 1.659}{0.7101}\right)^2\right] \quad (2)$$

$$D_g = exp\left(\sum f_i I_n\left(\frac{d_i + d_i - 1}{2}\right)\right) \quad (3)$$

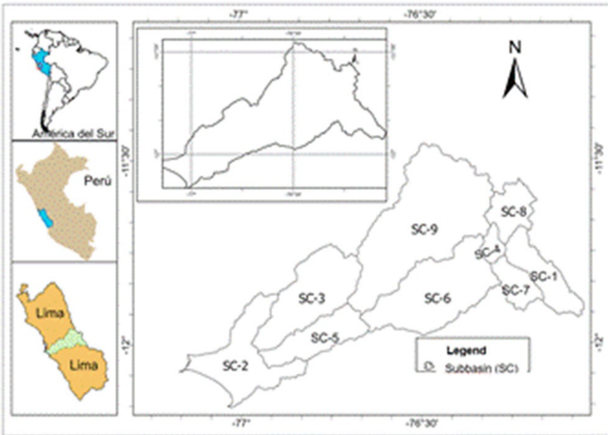

Figure 1. Rimac River Basin.

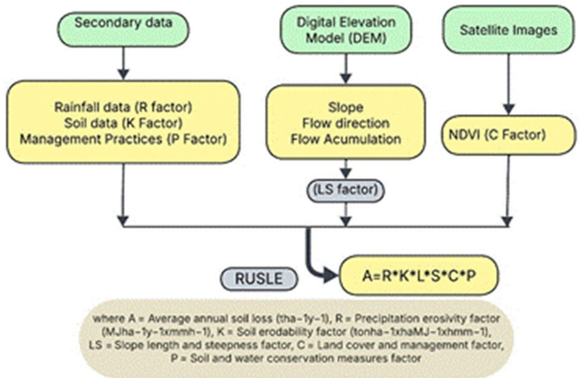

Figure 2. The methodology model.

$$LS = \{FA \times (tamaño \quad de \quad celda/23.13)\}^{0.4} \times \{Sin \quad (pendiente \quad de \quad DEM \times 0.01745)/0.09\}^{1.3} \times 1.6 \quad (4)$$

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \quad (5)$$

$$C = exp\left[\alpha \frac{NDVI}{(\beta - NDVI)}\right] \quad (6)$$

Where R is the measure of rainfall erosivity expressed in (MJ mm ha^{-1} h−1 year^{-1}), P is the average annual precipitation (mm), Dg is the geometric mean of the particle size, for the clay, silt and sand texture classes, di, di$_{-1}$ are the maximum and minimum particle size diameters, respectively and fi are the mass fractions, LS is the slope length and slope factor, FA is the flow accumulation, NIR and RED are the near infrared and red bands, respectively, the NDVI value varies between (−1 and 1), where −1 implies bare soil and 1, forest, α and β are adjusted coefficients with values of α =2, β =1. Finally, the P factor was analyzed from the support practices by Mckague (2023).

RESULTS AND DISCUSSION

Nine sub-basins (SBs) were established within the basin. RUSLE parameters were determined for each SB. One of the most important parameters of the RUSLE model is the Rainfall Erosivity Factor (R), since raindrops contribute to soil erosion. Rainfall in the basin, within this framework, shows a significant spatial and temporal distribution. The rainfall stations for the basin are illustrated in Table 1. It is evident that rainfall increases with altitude above sea level, due to the cooler air, which promotes water condensation. Therefore, SB-8 has recorded the most notable average annual rainfall over the last 25 years, reaching 925.7 mm.

he results indicate significant spatial variability in the rainfall erosivity index across the basin, with the highest values located in the upper northwest area, particularly in sub-basin SC-9, where a maximum of 933.73 MJ mm ha^{-1} h^{-1} yr^{-1} is reached. The combination of heavier and more concentrated rainfall, linked to the orographic effect typical of higher elevations, along with steep slopes that increase the energy of surface runoff and, therefore, the erosive potential, may explain this behavior. In contrast, sub-basins SC-2 and SC-5, located in the southwest part of the basin, have significantly lower erosivity at 42.72 MJ mm ha^{-1} h^{-1} yr^{-1} or less. This is mainly due to the fact that these drier areas have a reduced and less intense rainfall regime. Furthermore, the low frequency of extreme events and the limited kinetic energy of rainfall in this area restrict the development of significant erosive processes, even with sparse vegetation cover. In summary, these results show that rainfall erosivity in the watershed is highly influenced by topographic and climatic factors, highlighting the importance of considering the spatial diversity of the R factor when estimating soil erosion.

The Soil Erodibility Factor (K) was calculated for soil classes using soil texture and color classifications according to FAO standards by Schoeneberger *et al.* (2012). The study region presented only three soil types: Eutric Regosol, representing 5.74% of the total watershed area; Leptosol, covering 82.70%; and Eutric Fluvisol, covering 11.56%. Regarding Leptosol soils, these are formations developed by erosion and consolidated by limestone, volcanic rocks, sandstone, shale, and quartzite. In the Rímac River basin, the K factor varies between 0.001 and 0.02 t MJ^{-1} Ja^{-1} mm^{-1}. A high K value indicates greater vulnerability to soil erosion, while a lower K value indicates less vulnerability (Gitima *et al.*, 2023).

The C factor was determined according to the associated Land Use/Land Cover (LULC) value, which allowed for the generation of Land Use/Land Cover (LULC) maps and Normalized Difference Vegetation Index (NDVI) maps (Ugese *et al.*, 2022). The weighted C factor in the defined sub-basins ranged from 0.001 to 1. Low values were observed in sub-basins SC-3 and SC-5, indicative of soils without vegetation cover and more prone to erosion.

The P factor, obtained from the slope of crop management practices in strips, terraces, and contours, ranged from 0.66 to 0.97 due to the predominance in regions SC-4 and SC-6 of areas lacking conservation practices. The analysis of the RUSLE method parameters (Table 2) showed that the average annual loss due to water erosion in the Rímac River basin during the study period was 135 tons per hectare per year.

"Within the sub-basin analysis, sub-basin SC-9 exhibited the highest average annual percentage of water erosion, at 35.58 t ha^{-1} $year^{-1}$. This percentage encompassed approximately 30% of the total eroded area and ranked highest in vulnerability to land loss within the Rímac River basin (Figure 3). The presence of very steep slopes, high rainfall erosivity, and sparse or seasonal vegetation cover are conditions that increase the energy of surface runoff and promote the transport and detachment of soil particles. This behavior can be explained by the simultaneous presence of these unfavorable factors. In comparison, sub-basin SC-2 showed a much lower average annual water erosion rate of only 0.12 t ha^{-1} $year^{-1}$. This represents 12.59% of the eroded area and places it ninth in the ranking. and reduced, in addition to less steep slopes that limit runoff formation and, therefore, emergence of significant erosive processes. These disparities demonstrate the significant impact of topography and rainfall patterns on how water erosion is spatially distributed in the basin.

Table 1. Rain gauge stations and R factor of the sub-basins

Station	Altitude (*msnm*)		Average annual rainfall			R (MJ mm ha^{-1} h^{-1} $año^{-1}$)
			Minimum	Maximum	Average	
Casapalca	4294	1	469.10	1159.8	724.6	439.17
Campo de Marte	117	2	2.90	180.80	16.70	3.50
Ñaña	460	3	1.00	240.0	13.60	4.00
Matucana	2479	4	211.70	474.20	320.3	136.99
Chosica	867	5	1.10	106.50	28.70	5.16
Autisha	2220	6	4.30	440.20	219.3	85.18
San Jose de Parac	3829	7	415.90	795.30	674.8	393.32
Milloc	4384	8	522.20	1369.60	925.7	619.77
Carampoma	3424	9	252.80	705.00	495.3	255.53

Table 2. Values of the estimated soil water erosion by micro-basins

Subbasin	RUSLE (t ha^{-1} año^{-1})	Area (km^2)	Area (%)	Classification
SC-1	27.14	235.75	6.73	3
SC-2	0.12	441.03	12.59	9
SC-3	0.99	492.31	14.05	7
SC-4	4.02	55.92	1.60	6
SC-5	0.82	267.60	7.64	8
SC-6	12.01	633.71	18.09	5
SC-7	24.70	130.43	3.72	4
SC-8	29.92	169.81	4.85	2
SC-9	35.58	1 077.37	30.75	1
Total	**135.30**			

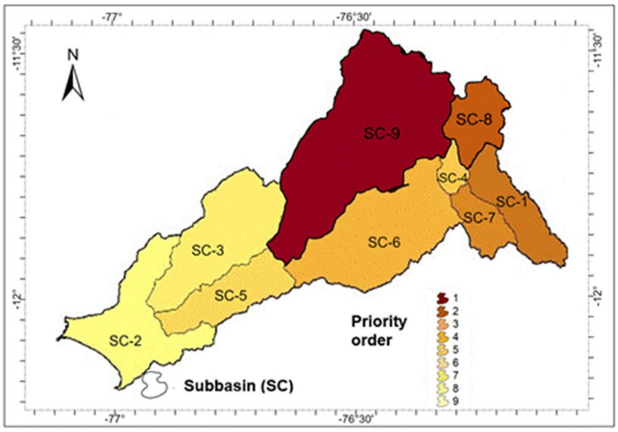

Figure 3. Spatial distribution of priority order by subbasin.

CONCLUSIONS

- The current study enabled a comprehensive assessment of soil erosion due to water in the Rímac River basin. This was achieved through the combined use of the RUSLE model, GIS, and remote sensing techniques, which facilitated the definition of nine sub-basins and the spatial characterization of the factors governing land loss. The findings show that the basin has an average loss of 135 t ha^{-1} year^{-1}, highlighting a significant spatial variability in the erosion process. In particular, sub-basin SC-9 exhibits the highest levels of degradation, with a maximum loss of 35.58 t ha^{-1} year^{-1}. This is equivalent to approximately 30% of the total basin area and indicates that it is a critical area with a high risk of water erosion.
- The watershed was categorized into three zones: 535.99 km² (15.30% of the total area) with high priority, 1.767.0 km² (50.43%) with medium priority, and 1.200.94 km² (34.27%) with low priority.
- These findings highlight the combined importance of topographic, climatic, and vegetation cover factors in erosion, and underscore that integrated perspectives based on GIS and remote sensing are effective tools for determining priority areas for sustainable soil management and conservation planning in Andean watersheds.
- To improve the spatial prioritization of sub-basins and optimize decision-making in sustainable soil management, it is recommended that future research incorporate multi-criteria analysis approaches into the RUSLE method, such as Composite Value (CV), Weighted Sum Analysis (WSA), and the Analytic Hierarchy Process (AHP). Furthermore, it is recommended to include Principal Component Analysis (PCA) to determine the interaction and relative impact among the factors R, K, LS, C, and P. This would decrease uncertainty and strengthen the statistical robustness of the erosion model.

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