

Estimation of soil loss using the USLE model and GIS tools in the Chillón river basin, Lima, Peru

Estimación de la pérdida de suelos utilizando el modelo USLE y herramientas SIG, en la cuenca del río Chillón, Lima, Perú

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Cite as: Delgado, J. (2020). «Estimation of soil loss using the USLE model and GIS tools in the Chillón river basin, Lima, Peru». *South Sustainability*, 1(1), e007
DOI: 10.21142/SS-0101-2020-007

Article received: 6/12/2019
Peer review
Article approved: 15/5/2020



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ABSTRACT

Poor land planning, where the potential and limitations of land use are not considered in planning and spatial organization, has in recent years become one of the main sources of environmental degradation. This research presents a diagnosis and estimation of water erosion in the Chillón river basin, applying the Universal Soil Loss Equation (USLE) mathematical model, and analysis employing Geographic Information System (GIS) tools, in order to understand the geospatial behavior of this phenomenon. The USLE factors considered for this research include rainfall erosivity (R), soil erodibility (K), the topographic factor (LS), the conservation factor and human management (C and P). A spatial database was built containing rainfall information from 14 weather stations, data extracted from the 1:125 000 soil map «Land Use Plan for the Chillón River Basin», the ASTER Global Digital Elevation Map (GDEM), current land use in the area, the interpretation of satellite imagery, IGN mapping, and geo-referenced information collected through fieldwork. The processing of spatial information was made using GIS, which enabled the superimposing of erosion factors and potential erosion behavior in the Chillón river basin.

Keywords: GIS tools, spatial geo, water erosion, USLE

RESUMEN

La poca planificación del territorio, donde no se consideran el potencial ni las limitaciones del uso de la tierra en su ordenamiento y organización espacial, se ha convertido en los últimos años en una de las principales fuentes de degradación del medioambiente. La presente investigación realiza un diagnóstico y una estimación de la erosión hídrica en la cuenca del río Chillón, mediante la aplicación del modelo matemático de la ecuación universal de pérdida de suelos (USLE), analizado mediante el uso de herramientas de sistemas de información geográfica (SIG), que permiten entender de manera geoespacial el comportamiento de dicho fenómeno. Los factores USLE considerados para la presente investigación toman en cuenta la erosividad de las lluvias (R), la erodabilidad del suelo (K), el factor topográfico (LS) y el factor de conservación y manejo antrópico (C y P). Se construyó una base de datos espacial, que contiene la información de precipitaciones de 14 estaciones meteorológicas, datos de suelos extraídos del mapa de suelos 1:125 000 del «Plan de ordenamiento territorial de la cuenca del río Chillón», datos topográficos del satélite ASTER GDEM, cobertura y uso actual de suelos y de la interpretación de imágenes de satélite, cartografía del IGN e información georreferenciada recopilada en trabajos de campo. El procesamiento de la información espacial utilizó un *software* SIG, lo que permitió realizar las superposiciones de los factores de erosión y del comportamiento de la erosión potencial en la cuenca del río Chillón.

Palabras clave: herramientas SIG, geoespacial, erosión hídrica, USLE



Introduction

Peru is a country with a characteristic geography influenced mainly by the Andes mountain range. The interaction of climatological, lithological, topological, edaphic and anthropogenic phenomena governs the erosive processes exerted upon that geography. Soil erosion is one of the main indicators of ecosystemic deterioration, with major environmental and socio-economic implications, including the potential for desertification in the most susceptible areas (Galilea, 2015). The rate of soil erosion produced by human activities significantly exceeds the formation rate of soil (Guo et al., 2018). Soil use and management are the main factors influencing erosion and sediment transport at the basin level (Zhang, L. et al., 2016).

Poor land planning in Peru has meant that the most productive and flat soils have mostly been dedicated to urban uses. The United States Food and Agriculture Organization (FAO) has indicated (1996) that soil degradation processes result in reduced yield and fertility for all crops. In this context, conservation and rehabilitation measures are essential for sustainable agricultural development and the avoidance of negative effects upon the local economies directly dependent upon farming income (FAO, 1980). Soil erosion has been shown to constitute one of the main risks to the productivity of cultivatable land (Lee et al., 2010).

The Chillón River is one of the principal hydrological systems of western Peru. Flowing into the Pacific Ocean, the Chillón River is located in the central zone of the Lima region. The river basin covers a total area of 2444 square kilometers. The wet basin accounts for 42% of the total area, due to its location over 2500 meters above sea level, which is the lowest limit that effectively contributes to surface runoff (Amiel, 1964).

Combining GIS tools and empirical models, total soil erosion and its distribution across river basins can be efficiently estimated (Lin et al., 2014). The Universal Soil Loss Equation (USLE) was developed in the 1950s as a mitigation and soil conservation measure. Subsequently, from 1978 to 1985, this equation was reformulated and improved thanks to new erosion research in the United States. Today, it is acknowledged as one of the best-adapted geographical system models for soil erosion prediction; in fact, it is widely accepted in several countries that have analyzed interpretative data and obtained positive results, including Mexico, Colombia, Peru, Chile and Ecuador. Many soil researchers consider the USLE model to be the empirical method best adapted to interpretation of erosion results (Jaramillo, 2015). Furthermore, it has been stated that application of the USLE method in a major basin, using GIS tools combined with limited data, can provide practical results for adequate soil management (Kim et al., 2005).

Erosion control should be conducted using preventative measures, and where soil erosion has occurred corrective actions are required. Information regarding soil use and occupation is obtained from an erosion risk map (Ribeiro, 2002).

The aim of this study was to estimate soil loss due to water erosion employing the USLE model and GIS tools, and to identify the relationship between erosion and soil management and conservation techniques in the Chillón river basin (Peru).

Materials and methods

Study area cartographic information: The Chillón River is one of the principal hydrological systems of western Peru. Flowing into the Pacific Ocean, the Chillón River is located in the central zone of the Lima region. The river basin covers a total area of 2444 square kilometers. Sources consulted included maps produced by Peru's National Geographic Institute (IGN), specifically maps numbers 23-i, 23-k, 24-i and 24-j (scale 1:100 000), and the Digital Elevation Model (DEM) produced by the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite, in its Global DEM version 2 (G-DEM 2). Slope, geological and soil maps of the Chillón river basin were also used.

Satellite images: The ASTER G-DEM 2: S012W077 and S012W078, geoid EGM96, was used, at a spatial resolution of 30 m. «World Imagery by ESRI» was also used for its high-resolution satellite images (0.3 to 1.5 m), produced in recent years (from 2010 to 2017), of the Chillón river basin, which facilitated the identification of current soil coverage and use. Taken together, this information was used to update data on the Chillón river basin, where previously the only information available had come from Peru's National Water Authority (ANA). Additionally, the area's drainage network was identified using GIS tools.

Soil analysis data: Soil data for the years 2013 and 2014 was retrieved from the Metropolitan Municipality of Lima (MML) and the Metropolitan Planning Institute (IMP).

USLE methodology

SIG ArcGis v10.4 and QGIS v3.0.1 software was used for the present study. The USLE model is an internationally accepted methodology, constituting an empirical process which enables the calculating and predicting of approximate soil erosion results (Wischmeier and Smith, 1978). The Universal Soil Loss Equation is as follows:

$$A = R * K * L * S * C * P$$

Where: A = Average annual soil loss in tons per hectare; R = Rainfall erosivity index ($MJ \text{ mm ha}^{-1} \text{ h}^{-1}$); K = Soil erodibility factor ($t \text{ ha h MJ}^{-1} \text{ ha}^{-1} \text{ mm}^{-1}$); L = Topographical factor, where L is for slope length (m); S = Slope steepness factor ($m \text{ m}^{-1}$); C = Cropping, or cover and management

factor; P = Conservation practice factor (cultivation contouring, strip cropping or terracing).

The USLE mathematical model was employed in analysis at a territorial basin level, and different geo processing techniques for different data were employed, including weather, topography, soil type and soil use. In addition, high-resolution satellite images were analyzed.

DEM correction: In order to correctly study the topography of the Chillón river basin, it was necessary to use DEM. IGN maps 23-i, 23-k, 24-i and 24-j were complemented with topographic data from the ASTER GDEM (S012W077 and S012W078). Subsequently, topographic and hydrographic data layers were derived using ArcGIS software, in order to obtain slope (S), drainage network, flow direction and flow accumulation data.

Current soil use and plant cover: This map was produced by combining data from different sources: ESRI high-resolution color satellite imagery, and MML and IMP (2013) soil use layer data (Supplementary Table 1), while crop details from the middle and lower sections of the basin were obtained through fieldwork conducted up until November 2017.

Rainfall erosivity estimation (R factor): The equation proposed by Arnoldus (1978) was used to estimate the R factor through application of the Fournier Index (FI). Precipitation data was retrieved from the 14 weather stations closest to the study area and managed by Peru's National Meteorology and Hydrology Service (SENAMHI) (retrieved from: <http://www.senamhi.gob.pe/?p=descarga-datos-hidrometeorologicos>) for the period 1988-2008.

$$FI = P^2/P$$

Where FI = Fournier Index; P² = Monthly precipitation (mm); P = Annual precipitation (mm)

The information status selected came from the released values available via the SENAMHI online service, while the methodology incorporated a minimum of 20 years of permanent records. A filter of stations with null values and those lacking 12 months of continuous records was conducted.

Soil erodibility estimation (K factor): The K factor was calculated for the studied basin using the methodology described by Wischmeier and Smith (1978). The physical and mechanical properties of the soils were retrieved from MML and IMP records (2013).

$$K = 2.1 M^{1.14} (10^{-4})^{(12-a)} + 3.25(b-2) + 2.5(c-3) / 100$$

$$M = (\% \text{ slime} + \% \text{ fine sand}) (100\% - \text{clay})$$

K = Soil erodibility factor; M = Particle associated - textural factor (% slime + % fine sand) (100% - clay)); a: Organic matter (%); b: Type of structure (granular, very fine =1: granular, medium to coarse= 3; Rocky, laminar,

massive =4); c: Type of permeability (fast = 1; moderately fast = 2; moderate = 3; slow to moderate = 4; slow = 5; very slow = 6).

Slope length factor (L factor). The average slope length was obtained using the method described by Wischmeier and Smith (1978). It was calculated using the DEM, IGN maps 23-j, 23-k, 24-i and 24-j, and the following equations:

$$L = (\lambda/22.13)^m$$

$$\lambda = \sqrt{PS^2 + PS^2}$$

L = Slope length factor; λ = Slope length (m); PS = DEM pixel size; m = Exponential influenced by the degree of slope (raster); 22.13 = Standard length of slope used for the area studied.

Slope steepness factor (S factor): The S factor was calculated according to the method used by Lal and Elliot (1994). Three relations were proposed to estimate this factor; two of them are better adapted to the steep slopes found in the Chillón river basin.

- Slopes less than 9 % and lengths greater than 4 m:

$$S = 10.8 * \text{Sine } \Theta + 0.03$$

- Slopes greater than 9 % and lengths greater than 4 m:

$$S = 16.8 * \text{Sine } \Theta - 0.50$$

S = Slope steepness factor; Seno Θ = Sine of the slope of the land (degrees °)

LS factor determination: Non-dimensional factor.

$$LS = L * S$$

L = Slope length factor; S = Slope steepness factor.

Soil use cover factor (C factor): This represents the efficiency of plant cover as a protector of soil against rainfall and surface runoff. It was obtained from the soil use map of the study area (MML, IMP, 2013) as well as from the agricultural cadastre of the area. Both data were evaluated according to base values previously published (Wischmeier, 1978) and the estimate based on the soil map (MML, IMP, 2013), combined with cultivation plot information for the middle and lower sections of the river basin, and the ESRI image (Supplementary Table 2).

Soil conservation techniques factor (P factor): To estimate the P factor, soil conservation techniques were evaluated in the upper, middle and lower sections of the river basin. For this purpose, different parameters were taken into account. These included cultivation contouring, strip cropping, and terracing. The estimated P factor values were based on Supplementary Table 3. In addition, field data was collected directly from June to November 2017.



USLE application

To correctly estimate the soil erosion conditions in the river basin using USLE methodology, a spatial analysis was conducted using information layers in raster format corresponding to each factor (R, K, L, S, C and P). ArcGis v10.4 software was used for this analysis. Finally, the results were reclassified according to Supplementary Table 4.

Results and discussion

The integration of predictive models into the GIS tools and the use of DEM result in a qualitative shift in the temporary and spatial scale in the analysis of soil erosion risk.

These methodologies enable the application of models over large basins as well as smaller basins, although at a greater spatial resolution. They also enable the incorporation of data retrieved from other cartographical sources, mostly derived from satellite image analysis (Pérez-Cabello et al., 2006) and airborne sensors (Beguería, 2006).

Rainfall erosivity (R factor)

One of the most significant consequences of global warming is the rise in the magnitude and frequency of maximum precipitation, resulting from the increase in humidity levels and/or storm activity (Huang et al., 2013). Analysis of rainfall data from the Chillón river basin showed an average annual value of 496.3 mm. The highest monthly average occurred in March, with 172.5 mm, while the lowest monthly average was recorded in July, with 0 mm. Rainfall was concentrated from October to April, with 93% of the annual total.

The weather stations were grouped together according to altitude and the prevailing climate. Thus, in the lower part of the Chillón river basin (0 to 1000 meters above sea level) the average value for annual precipitation was 17.85 mm, the highest monthly value was in February (4.87 mm), and the lowest value was in October (0.16 mm). Rainfall was concentrated from December to March (58.9 %) and from June to August (30.9 %), with decreased precipitation from April to May (3.5 %) and from September to November (5.7 %) (Figure 1a).

Rainfall erodibility (R) in the area of influence of the weather stations located in the lower river basin varied from 0.71 to 8.81 MJ mm ha⁻¹ h⁻¹.

In the middle section of the river basin (1000 to 3600 meters above sea level) average annual precipitation was 355.47 mm, the highest average monthly value was 89.17 mm (in March) and the lowest average value was 0.14 mm (in July). Most rainfall occurred from October to April (97.6%), during the temperate warm weather which characterizes the wet summer (Figure 1b).

Rainfall erodibility (R) in the area of influence of the weather stations located in the middle section of the river basin range from 18.35 to 95.52 MJ mm ha⁻¹ h⁻¹.

In the upper part of the river basin (3600 to 5000 meters above sea level) average precipitation was 679.46 mm, with the highest monthly average of 137.77 mm occurring in March and the lowest monthly average of 4.3 mm recorded in July. The majority of rainfall was found to occur from October to April (91.3%), in the temperate cold to high mountain glacier climate of the upper reaches of the basin (Figure 1c).

Rainfall erodibility (R) in the area of influence of the weather stations located in the upper reaches of the river basin range from 92.5 to 104.19 MJ mm ha⁻¹ h⁻¹.

Figure 2 shows a choropleth map of the Chillón river basin indicating the intensity of erosion caused by rainfall across the territory. The upper areas of the river basin display higher than the middle section (yellow) and coastal zones (red).

Erodibility factor (K)

Erodibility is the susceptibility of soil to erosion by rainfall. Soil erodibility is dependent upon different factors, including soil texture, aggregated material stability, shear strength, infiltration capacity and the organic and chemical materials content (Odunuga et al., 2018). To estimate the K factor in the area of the Chillón river basin, an analysis was made of the soil maps (1:125 000 scale) created by the Metropolitan Municipality of Lima (MML) as part of the «Territorial Management Plan for the Chillón basin» (2013). This digital map shows in detail the main soil groups and the predominant texture in each area, enabling reclassification and calculation of the K factor value and the erodibility of soils across the entire study area.

Erodibility calculations in the river basin produced K factor values ranging from 0.05 to 0.87 t ha h MJ⁻¹ ha⁻¹ mm⁻¹. The predominant K factor value in the study area was 0.37 t ha h MJ⁻¹ ha⁻¹ mm⁻¹, corresponding to sandy soil textures, sandy loam to silty loam, with a moderate susceptibility to landslide and runoff.

Figure 3 shows a choropleth map of the Chillón river basin where the most susceptible areas to soil erodibility are located near Canta and Obrajillo (dark blue), meanwhile the central and northern zones of the basin are moderate susceptible to erodibility (light blue and orange) and finally mountainous areas on the south and urban coastal zones are less susceptible (red).

Topographic Factor (LS)

The areas prone to erosion are the steep to very steep slopes with a high dissection index and ruggedness index (Gopal et al., 2015). In order to define the LS factor, it was necessary to estimate both the slope length factor (L) and the slope steepness factor (S). The combined result produces what is known as the topographic factor.

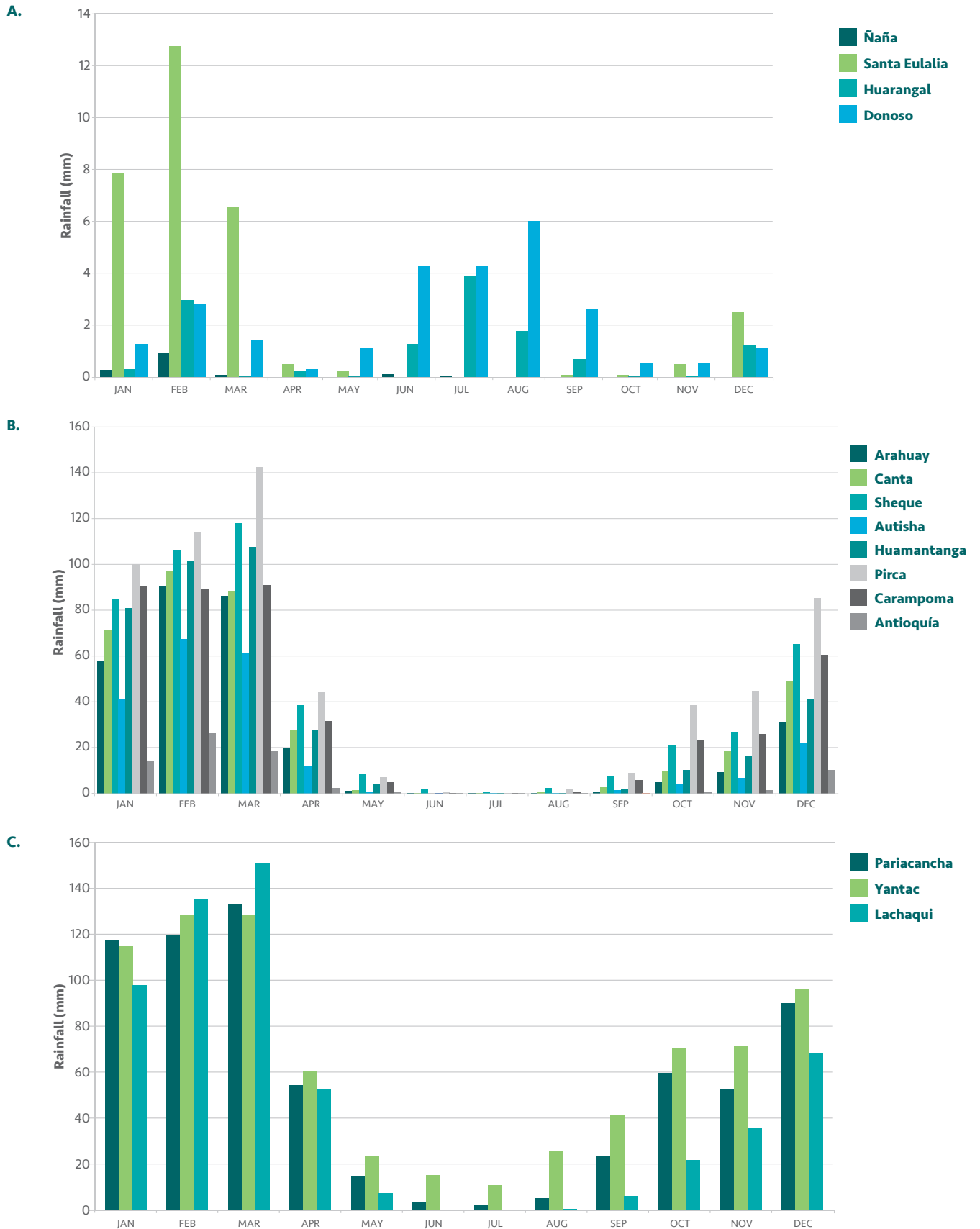


Figure 1. A. Annual rainfall histogram for warm climate areas in the lower Chillón river basin (0 to 1000 meters above sea level). B. Annual rainfall histogram for the temperate warm climate areas of the middle section of the Chillón river basin (1000 to 3600 meters above sea level). C. Annual rainfall histogram for the temperate cold to high mountain glacier climate areas in the upper reaches of the Chillón river basin (3600 to 5000 meters above sea level).



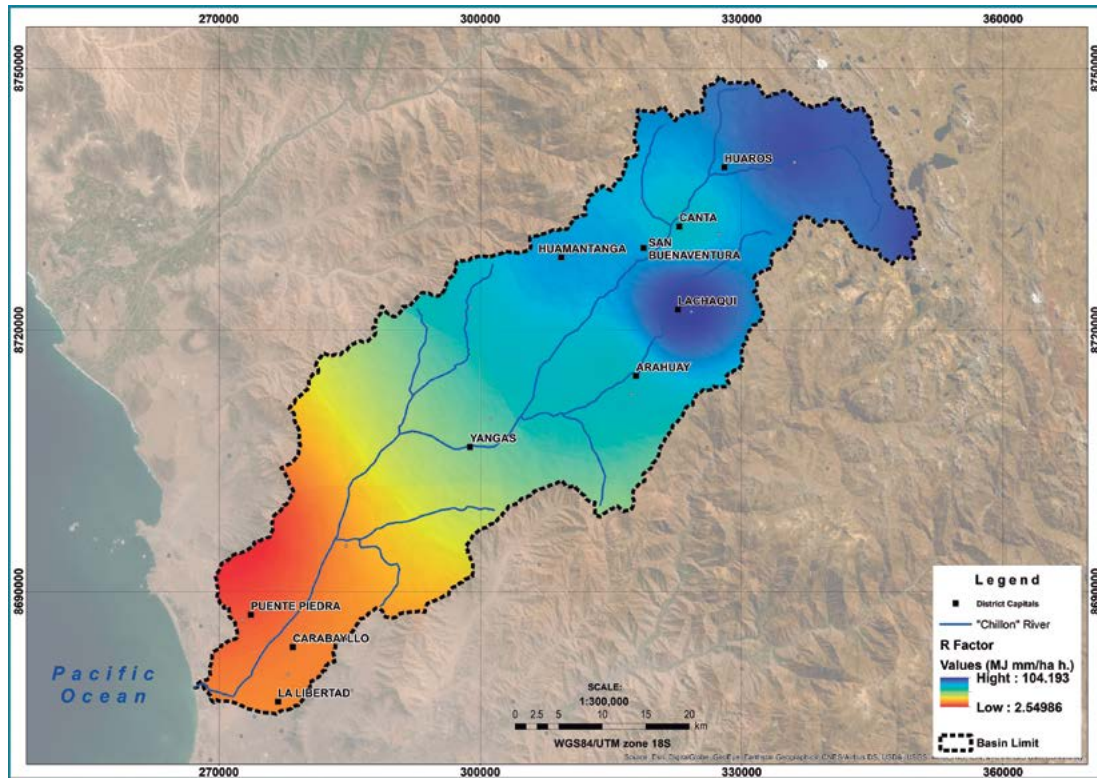


Figure 2. Spatial representation of R factor in the Chillón river basin.

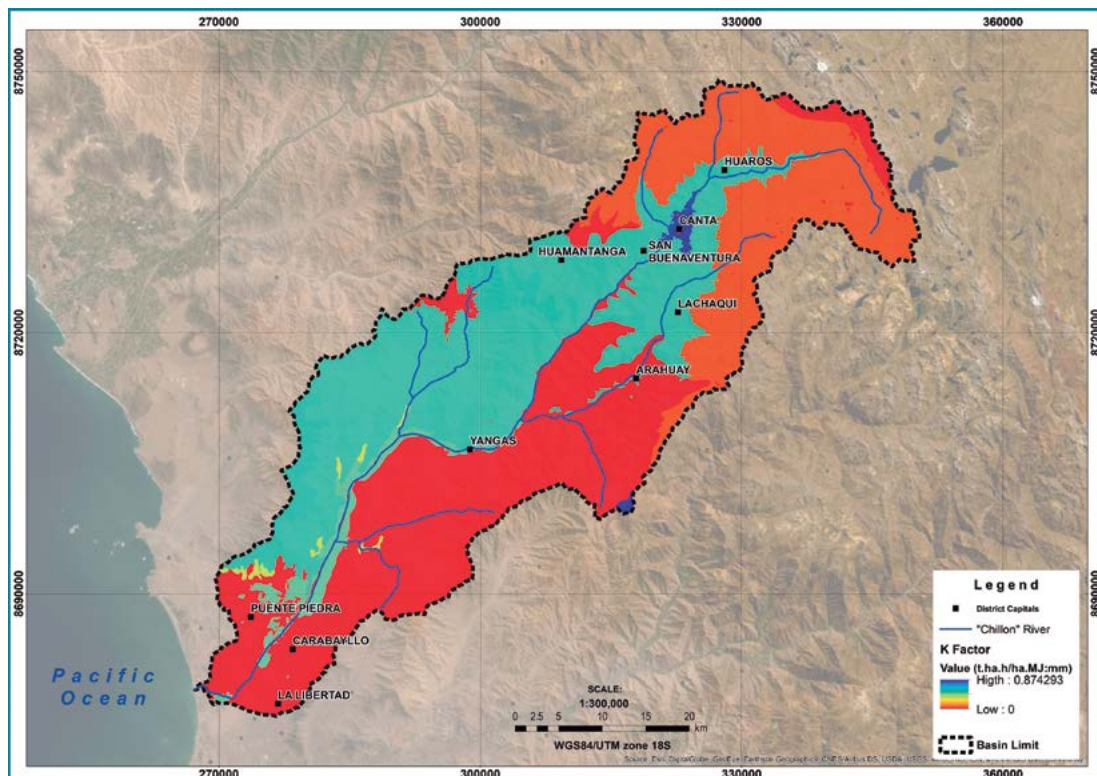


Figure 3. Spatial representation of K factor in the Chillón river basin.

With regard to the L factor, a slope map was obtained from the DEM, which was used to define the exponent «m» of the formula (Table 1).

In the same way, the S factor was derived from the slope maps, in both percentage and angular values.

The river basin contains high altitude and mountainous areas along most of its length. This generates considerable humidity, principally in the middle and upper areas of the river basin. Slope estimates exceed 200% in the steep areas, but fall to values below 5% in the flat areas close to sea level.

The LS factor was estimated and reclassified along the entire basin (Table 2), producing low values in 94.7% of its extension and moderate values in the remaining 5.3%.

Figure 4 shows a choropleth map of the Chillón river basin indicating the slope length factors. Areas with abrupt slopes located in the steep slopes of the basin (red) are more prone to erosive processes than medium areas (located in high mountains in yellow) and flatter areas (located in coastal zone in green).

Current soil use and plant cover (C)

Soil erosion can be reduced by employing biological measures that increase the plant cover in areas with steep slopes (Tian et al., 2009). C factor is related to the behavior of soil facing erosion, according to the extent that plant cover protects it by cushioning the impact of rainfall droplets and surface runoff. C factor values were estimated for the different soil uses within the basin (Supplementary Table 2). Using these values, the C factor map showing spatial distribution was obtained (Figure 5).

Soil conservation techniques factor (P)

In the fields within the river basin, use of crop rotation and appropriate farming techniques would increase plant cover and reduce soil loss through erosion (Ozsoy et al., 2012). The P factor serves as an indicator of the good soil conservation practices that residents can implement to reduce soil degradation. The P factor values were estimated for areas where conservation practices were applied to farming, and for slope protection. The P factor map was elaborated using these values (Figure 6).

Estimation of erosion using the USLE (A)

Once all the factor values were obtained, the calculation using the USLE method was conducted through the creation of corresponding raster layers. Soil loss (A) was found to range from 0 to 291.4 t ha⁻¹ year⁻¹ (Figure 7). According to this map, the middle section of the Chillón river basin recorded the highest rate of soil loss. These areas are vulnerable to landslides and contain slopes in excess of 70%, covering almost 30% of the total.

In order to validate the results of the model, identification of erosion areas was conducted through fieldwork. The studied areas were georeferenced (Table 3)

The fieldwork demonstrated that in the lower Chillón river basin area (near the villages of Punchauca, Cerro

Table 1 – Values for the exponent «m» (Wischmeier & Smith, 1978)

Slope value	Slope (%)
0.5	> 5
0.4	3 - 5
0.3	1 - 3
0.2	< 1

Table 2 - LS factor for the Chillón river basin. Based on *Instituto Espacial Ecuatoriano* (IEE) information. Data estimated by the author.

LS factor	Category	Area (Ha)	%
Low	< 15	210,452.27	94.7
Moderate	15- 30	11,778.22	5.3
High	30 - 45	-	-
Very high	> 45	-	-
Total		222,2230.49	100

Table 3. Fieldwork erosion data (November 2017).

Point	WGS 84/UTM – ZONE 18 S			Description
	North (m)	East (m)	Altitude (meters above sea level)	
1	8690485.0	282083.0	309	Crops on agricultural terraces (coriander, parsley, radish). Gravity irrigation. Low slope
2	8697430.0	283973.0	487	Zone of crops on terraces (Leek, strawberry). Gravity irrigation. Low slope
3	8706595.0	299682.0	955	Cultivated areas on narrow agricultural terraces (fruit trees: avocado and peach). Gravity irrigation. Low slope
4	8711057.0	305501.0	1192	Narrow terraces in urban areas (club). Occurrence of landslides on hillsides.
5	8729806.0	323101.0	2875	Hillside crops: trees and shrubs.
6	8732742.0	322926.0	2722	Livestock areas and crops (inter-Andean valley).
7	8741927.0	343216.0	4142	High Andean areas (lakes)

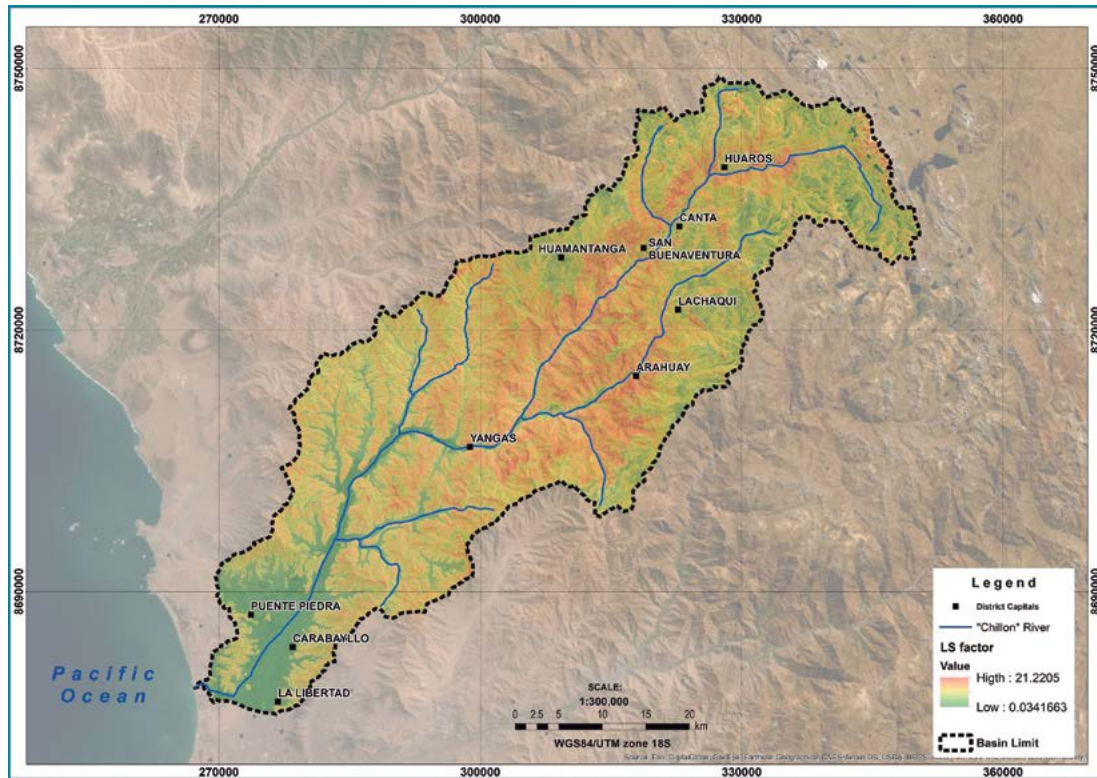


Figure 4. Spatial representation of LS factor values across the Chillón river basin.

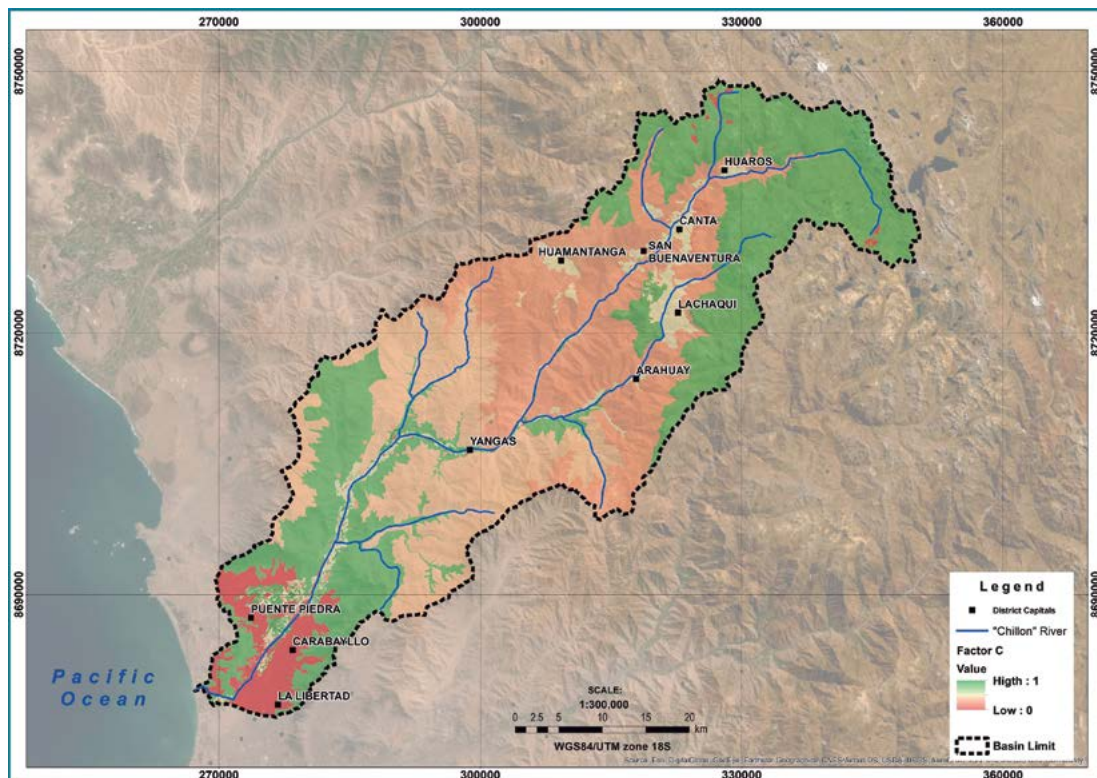


Figure 5. Spatial representation of C factors in the Chillón river basin.

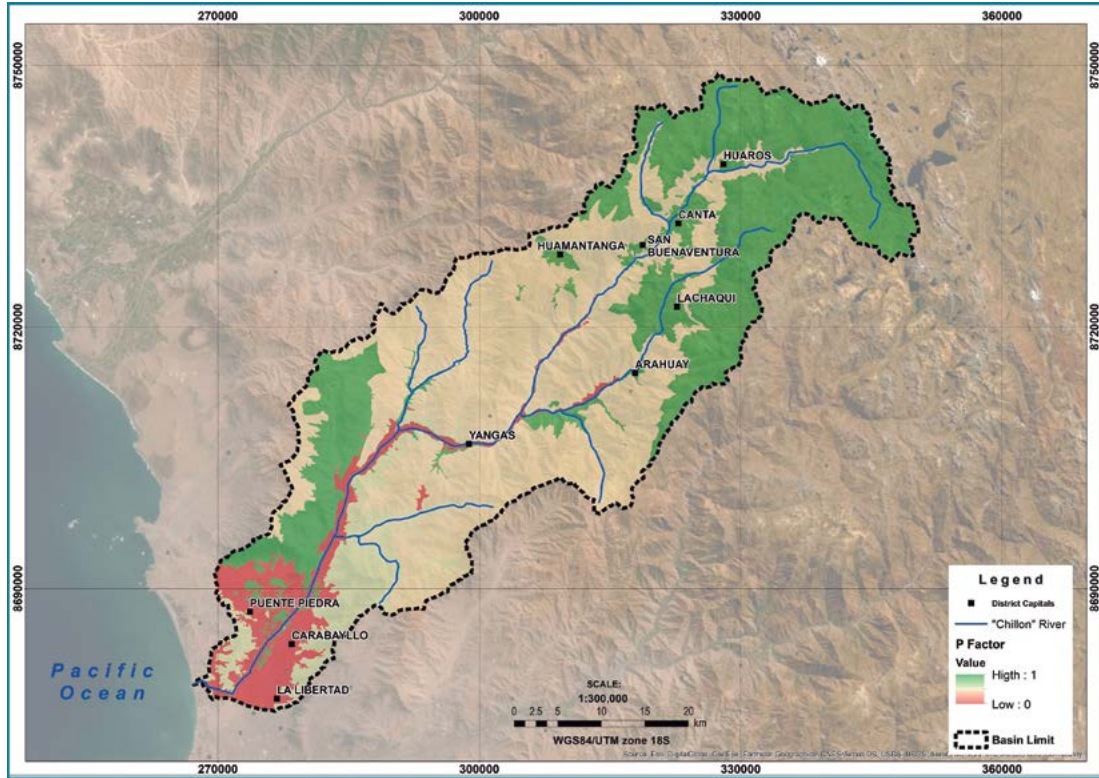


Figure 6. Spatial representation of P factors in the Chillón river basin.

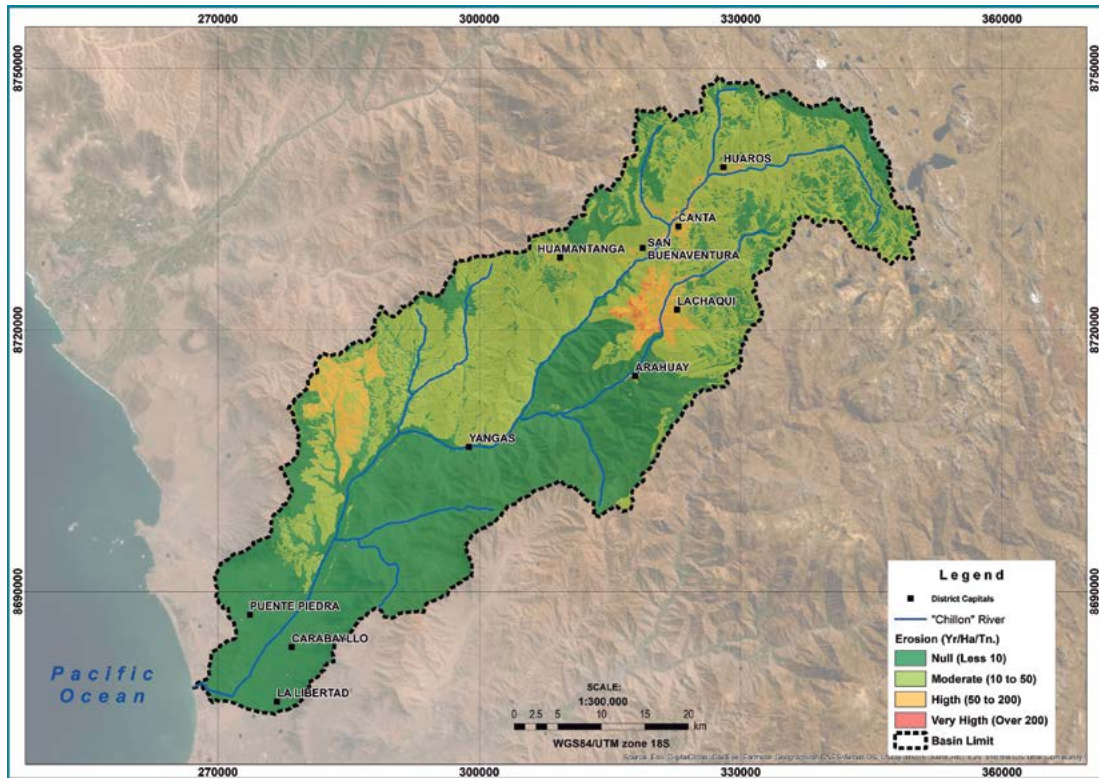


Figure 7. Spatial representation of A factors in the Chillón river basin.

Trapiche and Yangas) the soil erosion process was minimal, due to the limited precipitation record and minimal slopes (agricultural terraces).

In the middle section of the river basin (near the villages of Canta and Obrajillo), soil erosion areas were identified on hillsides. These areas have formed gullies that continue to expand. Rainfall was abundant from December to April and the slopes exceeded 50% and experienced moderate erosion.

In the upper section of the river basin (near the lakes Chuchon and Chun Chun) soil erosion was moderate in what are low temperature areas with abundant precipitation during the summer months and very steep slopes. As an additional factor, it should be noted that in these areas soils are sparse, with areas of rock outcrops.

Conclusions

The R factor results for the Chillón river basin oscillate between 0.71 and 8.81 MJ mm ha⁻¹ h⁻¹ in the lower basin, between 18.35 and 95.52 MJ mm ha⁻¹ h⁻¹ in the middle section, and between 92.05 and 104.19 MJ mm ha⁻¹ h⁻¹ in the upper part of the basin.

Precipitation is low in the lower area (0 to 1000 meters above sea level), with values of up to 10.5 mm from December to March, making it a low erodibility area. In the middle section of the river basin (1000 to 3600 meters above sea level) from December to April precipitation is 314.4 mm, making it a moderate erodibility area. In the upper area of the basin (> 3600 meters above sea level) precipitation is 516.2 mm between December and April, making it an area of moderate erodibility.

The estimated K factor range is from 0.05 to 0.87 t ha h MJ⁻¹ ha⁻¹ mm⁻¹. The K factor value of 0.37 t ha h MJ⁻¹ ha⁻¹ mm⁻¹ predominates throughout the area, corresponding to sandy soil textures, sandy loam to silty loam, which exhibit a moderate susceptibility to landslides and runoff.

Regarding LS factor results, 25.5 % of the river basin's extension exhibited values between 9.8 and 12.7. The slopes were between 25 and 75% (steep slopes), favoring hydrological erosion in the area. A total of 16% of the river basin's extension exhibited LS factor values of between 0 and 3.2. These soils exist on slopes ranging from 4 to 25%, classified as moderately steep slopes.

C factor values between 0.011 in areas associated with forestry plantations (in the middle section of the river basin) to 1 in fallow and prepared lands lacking plant cover to cushion soil erosion were recorded.

Where the P factor was estimated for the farmed area and the middle section of the river basin, management practices and slope protection by means of forestry species plantations were identified.

Estimated soil loss rates were 291.4 t ha⁻¹ year⁻¹ on moderate to very steep slopes in the middle and upper basin. In these areas the soil texture ranges from sandy to silty loam, and glacial erosion deposits constitute the origin of some of these soils. The influence of abundant precipitation in the summer months (December to April) led to moderate vulnerability to landslides in the villages of Canta and Obrajillo and at the Chuchon and Chun Chun lakes.

According to the USLE spatial model for the Chillón river basin, the lands adjacent to the villages of Obrajillo and Canta are exposed to land erosion processes. This is directly related to farming and livestock activities in areas with steep slopes (greater than 50%), where heavy rainfall is recorded from December to April. There is no indication of adequate projects to address erosion control in the area.

Soil is a natural strategic resource, unrecoverable in the presence of erosive processes, and of vital importance to humanity's food security. Climate change and increasingly intensive economic activities have accelerated the erosion process. This trend is seen in the results obtained from the Chillón river basin, where areas with considerable soil loss have been identified, and where land management and conservation processes should be prioritized.

Acknowledgements and sources of financing

Special thanks to my students on the physical geography courses who contributed to the conducting of this research. The research was self-funded.

Authorial contribution

JD was responsible for the conception, data gathering and writing of this article.

Potential conflicts of interest

The author has no potential conflicts of interest to declare.

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