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Assessment of soil erosion in the Cesar watershed, an initial step toward the restoration of the Cesar River

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Abstract

> The Magdalena River stands out as the largest contributor of sediment in South America. Although the Cesar River is one of the main tributaries of the Magdalena River, very few studies, if any, have focused on estimating soil erosion rates in the Cesar watershed. This contribution addresses this gap by presenting soil erosion rates calculated specifically for the Cesar watershed. It is based on the RUSLE-GGS (RUSLE-GIS-GLUE-SDR) erosion model at the watershed scale. The estimates cover a period from 1991 up to 2020, with a spatial resolution of 2.5 km. Different scenarios were modeled to assess and predict the variations in sediment yield and to fit the model to the sediment concentration data observed in local sediment gauging stations. By using the Getis-Ord statistical analysis, hotspots where soil erosion is most pronounced were identified. To the best of our knowledge, this contribution represents the first assessment of soil erosion in the Cesar watershed. In addition to providing a basis for future research, the results are expected to contribute to the formulation of appropriate scenarios to address the restoration of the Cesar River. Finally, the study triggers a discussion on the sustainable management of the basin to explore solutions aimed at preserving the integrity of this vital water resource.

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I. Introduction

River restoration is defined as an effort focused on restoring the ecosystem to its original state, with the purpose of rescuing ecosystem services that have been reduced over time [1]. The design of a river restoration plan requires an interdisciplinary approach in which knowledge and expertise are drawn from earth sciences and engineering, as well as social, economic, and cultural management sciences [2]. Water quality has long been the main concern in river restoration. In recent studies, the geomorphological aspect has gained significant importance in river management [3] due to its fundamental role in flood prevention, river maintenance, and floodplain restoration [4], [5].

It is recognized that soil erosion can have a range of significant impacts and effects on a watershed[6]. For instance, it can lead to the gradual loss of fertile topsoil, reducing its quality and nutrient and water-holding capacity, with negative impacts on agricultural productivity and natural vegetation [4], [7]. In addition, it leads to sediment accumulation in rivers and streams, which reduces the river transport capacity and affects water quality and aquatic life [8].

Watershed-scale erosion models are important tools for managing natural resources and planning for soil and water conservation [8]. Several empirical models are available for predicting soil erosion. These include USLE (Universal Soil Loss Equation) and RUSLE (Revised Universal Soil Loss Equation) [9]. These models differ significantly in the data they require and are updated according to the needs of each watershed. For example, in the Lo River (Vietnam), a variant of the RUSLE model based on the Loureiro and Coutinho equation is used [10]. In other cases, the RUSLE model is used in conjunction with geographic information system (GIS) image interpretation, such as in ArcGIS software, for the calculation of soil erosion rates [11], [12]. In addition, recent technological advances have made it possible to combine models that incorporate watershed morphological features and digital elevation data using algorithms to provide accurate data for river erosion assessment [13]. Models based on mass conservation and conservation equations for flow and sediment momentum have also been used for erosion estimation [5].

The Magdalena River is a larger river system that flows through most of the Colombian Andes[14]. The Magdalena sediment production varies from 128 to 2,200 t/km^2/year for watersheds ranging from 320 to 59,600 km^2 [15]. Thus, it stands out as the fluvial system exhibiting the largest sediment production in South America. In its lower section, the Cesar River is one of the main tributaries of the Magdalena River, the main water source of the Department of Cesar, and the second most important tributary of the Department of Guajira. Even though a very limited number of studies have reported sediment input from the Cesar River to the Magdalena River, in many cases, they are not freely available, or the fundamental input information is non-existent, especially from the low alluvial plains. Therefore, a better review and estimation of erosion rates in the watershed is possibly urgently required [15].

This study presents estimates of soil erosion rate for the Cesar watershed. They resulted from the application of the RUSLE-GGS (RUSLE-GIS-GLUE-SDR) erosion model [5]. The RUSLE-GGS erosion model provides a systematic and objective frame for assessing soil erosion at country or watershed scales in developing countries [5]. In the study, watershed RUSLE-GGS was used for the period from 1991 to 2020 with a spatial resolution of 2.5 km. Additionally, the Getis-Ord Gi^* statistical analysis was applied to identify hotspots where erosion is most severe. This provides an opportunity to implement targeted erosion control strategies in areas of the watershed most prone to erosion. This article presents a preliminary iteration of the soil erosion diagnosis for the Cesar watershed so that future work can analyze restoration scenarios for the Cesar River.

II. Methods

A. *Study Area*

Colombia is located in the northern section of South America (Fig. 1a) and in the Neotropical ecoregion. The Cesar River watershed covers an area of 22,930 km^2 and is part of the “Magdalena-Cauca” hydrographic area and the “Cesar” hydrographic zone. It is divided into 4 hydrographic subzones identified as Upper Cesar, Middle Cesar, Ariguaní River, and Lower Cesar [16], and its main surface stream is the Cesar River (Fig. 1b).

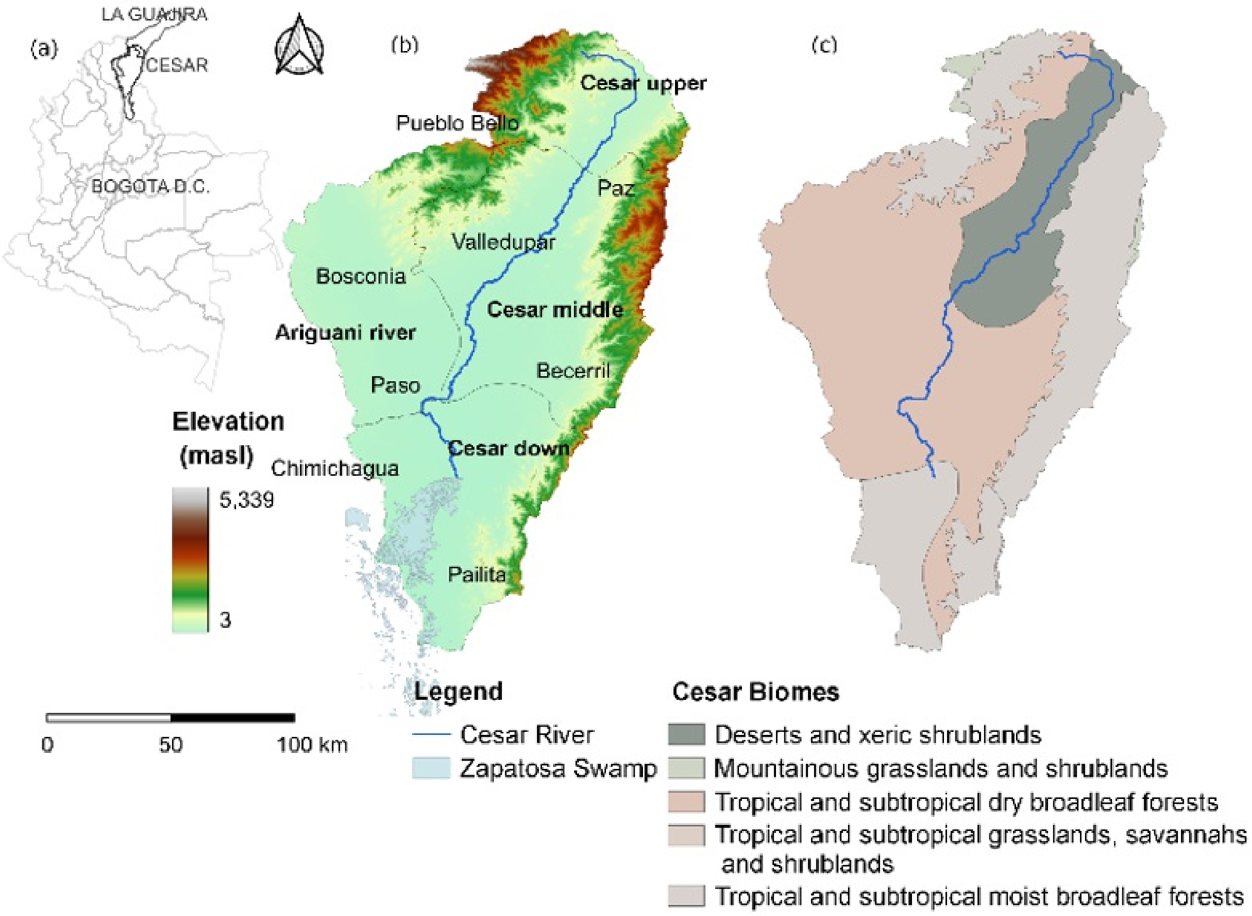

Fig. 1. (a) Location of the Departments of Cesar, Guajira, and the Cesar watershed. (b) Cesar watershed and its hydrographic subdivisions (c) Main biomes of Cesar from [16]. Author

The headwaters of the Cesar River are located southeast of the Sierra Nevada (Santa Marta) and west of the Serranía de Perija (municipality of San Juan del Cesar, Department of Guajira). It crosses the Department of Cesar from north to south and flows into the Zapatoza Swamp at the Momposina depression in the Magdalena River. The Cesar River is one of the main tributaries of the lower Magdalena River. It is the most important water source in the Department of Cesar and the second most important tributary in the Department of Guajira. The landscape and land use in the Cesar watershed are formed by a large piedmont area on the slopes of a mountainous ecosystem and lomerío terrain. The main biome of the Cesar River watershed (Figure 1c) is 50% tropical and subtropical dry broadleaf forest, 35% tropical and subtropical moist broadleaf forest, 14% desert and xeric scrub, and 1% grassland and montane scrub, based on [16].

B. *Data*

The data sources of fundamental parameters of the RUSLES-GGS model are presented in Table I. The meteorologic data comprises monthly precipitation records from 41 stations in the study area from 1990 to 2020. Land use maps were obtained for 2000, 2010, and 2018 provided by the Colombian Subdirection of Agrology. Global land use maps developed by MODIS and FAO were also used. The Corpenicus DEM digital elevation model with a spatial resolution of 30m from the European Special Agency (ESA) was used. Soil-type maps were also used. These were produced locally in Colombia using the Corine Land Cover methodology and obtained from the global and national soil databases of the International Soil Information Research Center (ISRIC).

The construction of the RUSLE-GGS model was generated for the years 2000, 2010, and 2020. All the resulting maps (Table I) have been post-processed in order to obtain a spatial resolution of 2.5 km. To calibrate the model, sediment yield observation (SSY) data were collected in the study area. These data were obtained by multiplying the monthly sediment concentration (expressed in kg/m³) by the monthly discharge (expressed in m³/s). The information was derived from two stations located in the Cesar Upper watershed (Reposo station [latitude: 10.52719444; longitude: -73.33636111]) with an area of influence 4,241 km² and Cesar Middle (Canoas Bridge station [latitude: 9.646333333; longitude: -73.65183333]) with an area of influence 749 km². It is important to mention that the monthly sediment concentration data presented information gaps. For this reason, only site-specific sediment yield (SSY) data collected between 1991 and 2000 were used to perform the model calibration.

Table I. Summary of Input Data for the Calculation of the Rusles-Ggs Model. Author

Name	Source	Resolution	Years	Reference
Total monthly precipitation	IDEAM[1]	Monthly	1991-2020	[17]
Sand, silt, and clay content maps	ISRIC-WSI [2]	1km	2013	[18]
Organic carbon content map	ISRIC-WSI [2]	1km	2013	[18]
Digital elevation model	ESA [3] -NASA	30m	2020-2021	[19]
Digital Soil Map of the Department of Cesar, Guajira, and Magdalena Republic of Colombia.	IGAC [4] - IDEAM	1:100.000	2013	[20]
Land Cover Map Corine Land Methodology Cover Colombia (shapefile, 29 classes)	IGAC - IDEAM	1:100.000	2000-2002 2010-2012 2018	[21]
The Global land cover facility	MODIS[5]	0.25°	2001	[22]
Global land cover share database (10 classes)	FAO[6]	1km	2014	[23]

1. Institute of Hydrology, Meteorology and Environmental Studies of Colombia; 2. Global soil information; 3. European Space Agency; 4. Agustín Codazzi Geographic Institute of Colombia. 5. Moderate Resolution Imaging Spectroradiometer; 6. Food and Agriculture Organization.

C. *RUSLE-GGS model*

Soil erosion diagnosis was carried out in the Cesar watershed using the method developed by[5] called RUSLE-GGS, which allows quantifying soil erosion dynamics at the watershed scale. The RUSLE erosion model is used in different studies worldwide to estimate the long-term soil erosion rate [23], [24]. Its use is fundamental in research related to soil conservation and water resource management. This model is represented by the following mathematical structure:

$$ER = K \times LS \times R \times C \times P$$

Where ER is the loss of soil (t/h/year); K is the erodibility of the soil (t×h/MJ/mm); LS is the topographic factor; R means annual rainfall (MJ×mm/h/year); C is the factor associated with soil cover; P reflects conservation practices.

The estimation of the rate of erosion was carried out after a number of calculations of the five fundamental parameters of the model, namely:

- Soil erodibility factor (K): It was estimated at continental scale from maps of soil texture, organic matter content, structure, and permeability available in soil databases (ISRIC-WSI) using the equation proposed by [25]:

$$K = \frac{0,1317\left[\left(2,1 \times 10^{-4} M^{1.14}(12 - OM) + 3,25(S - 2) + 2,5(PE - 3)\right]}{100}$$

M refers to the size of the soil particles (textural factor); OM is matter organic (%); S is a number attributed to soil structure; PE is a number attributed to soil permeability.

$$M = [(\text{silt }\% + \text{ fine sand }\%) \times (100 - \text{ clay content }\%)] \qquad (3)$$

$$OM\% = \frac{OC_{gr/kg} \times 1,724}{10} \qquad (4)$$

OC is the organic carbon (g/kg), and 1,724 is a constant to convert to OM in %.

- The topographic factor (LS): The topographic factor was based on the effect of topography on surface runoff and soil particle movement on the slope, which considers two components: slope length (L) and slope steepness (S). Using the DEM and the Qgis LS-TOOL tool, 24 realizations were made according to the equations proposed in Moore and Nieber, Desmet and Govers 1996 and Wischmeier and Smith 1978 and the different considerations in the tool.
- Rainfall erosivity factor (R): Based on monthly total precipitation data from the watershed's weather stations, the erosivity factor was calculated using the concepts of R1: Arnuldos (1977), R2: Renard and Freimund (1994), and R3: Rodríguez (2004) [24], resulting in a total of 3 realizations employing the Modified Fournier Index Method (IMF) as follows:

$$IMF = \sum_{I=1}^{12} \frac{P_I^2}{P_t}$$

Where $P_I =$ Average monthly rainfall (mm) and $P_t =$ Total annual rainfall (mm).

$$R1 = 0.264 \times IMF^{1.50} \qquad (6)$$
$$R2 = 0.07397 \times IMF^{1.847} \qquad (7)$$
$$R3 = 2.56 \times IMF^{1.065} \qquad (8)$$

The results were interpolated using the Ordinary Kriging tool in order to cover the entire watershed.

- Factor (C) and (P): The determination of the coverage factor (C) was carried out using land use maps published by local public offices (IGAC-IDEAM) and from global data (MODIS-FAO). The coverage (C) values of soil susceptibility evaluated by other authors in Colombia were adopted [26], [27]. Two implementations of the C factor were obtained, one for a local soil classification map and another for a global soil classification. The P factor was set to 1.0 for the whole area. This stems from the fact that no erosion control practices were applied in the watershed.

The above realizations included the estimation of 144 samples (combinations) of erosion rates (t/h/y) in the Cesar watershed with a spatial resolution of 2.5 km. The results have been calibrated by comparing the sediment concentration data obtained by the local stations with the sediment production estimated by the sediment transfer rates (SDR) (Table II). These indices reflect the proportion of soil erosion flux from the watershed to the streams. That is the relationship between sediment production and erosion rates [5].

Table II. SDR transfer functions are used to obtain SSY samples. Based On [5].

Equation	Parameter description
$SDR_1 = 0.627 \times (SLP)^{0.403}$	SLP: the slope of the main streaming channel in %
$SDR_2 = 1.817 \times A^{-0.132}$	A: Watershed area in km^2
$SDR_3 = \text{Exp}\{1.7935 - 0.14191 \times \text{Log } A\}$	A: Watershed area in km^2
$SDR_4 = 0.42 \times A^{-0.125}$	A: Watershed area in m^2
$SDR_5 = 0.51 \times A^{-0.110}$	A: Watershed area in m^2

D. Identifying erosion hotspots in the watershed using the Getis-Ord tool (G_i^*)

Based on the research done by [4][28], the Getis-Ord (G_i^*) statistical analysis is incorporated, to explore the spatial patterns in the features of the geospatial data. This method acts as an indicator of local autocorrelation, which helps to assess the degree to which each feature is surrounded by other features that have equally high or low values [28]. In this study, it was used to identify high values (hotspots) and low values (coldspots) concerning the results of estimated soil erosion rates. This allowed the clustering of highly representative erosion values within the watershed.

$$G_i^*(d) = \frac{\sum_{j=i}^{n} w_{ij}(d) x_j}{\sum_{j=i}^{n} x_j}$$

Where Gi_* (d) is the local G* statistic for feature i at distance d, expressed as a z-score. The variable xj denotes the attribute value of each neighboring feature, wij represents the spatial weight for the specific target neighbor pair i and j, and n represents the total number of samples in the dataset. Typically, a significance level of $P<0.05$ is considered statistically significant [28].

III. Results and Discussion

A. *Spatiotemporal analysis of soil erosion*

In total, 144 samples of erosion rates in the watershed were calculated by combining the basic variables of the RUSLE-GGS model. In addition, 720 sediment yield samples (SSY) were generated by applying the five transfer functions (SDR). These were evaluated for the period 1991-2000. These samples were compared with the sediment concentrations observed at each of the stations located in the area study.

Using a ±30% margin of error, it was determined that of the 144 simulations performed, samples 135-SDR$_4$ and 103-SDR$_4$ matched the average sediment concentration values observed at the Canoas Bridge station. However, for the Reposo station, the sediment concentration values were consistent with the samples 63-SDR$_2$ and 96-SDR$_1$, i.e., they were not in agreement with the samples generated for the Canoas Bridge station. However, the area of influence of the Reposo station in the watershed is relatively small, and the observation data are incomplete. Therefore, it is concluded that sample 135-SDR4, which has a better calibration and a lower percentage of error in the results, best represents the simulated erosion rate in the watershed.

Table III. Results of estimated sediment yields and sediment yields observed at local stations. Author

Samples	Canoas Bridge Station (t)	Reposo Station (t)
ER135 SDR$_4$	47.476,69	24.427,44
ER103 SDR$_4$	53.346,86	26.768,65
ER63 SDR$_2$	14.509,78	10.732,33
ER96 SDR$_1$	21.500,7	9.529,11
Average sediment concentration values observed	64.520,24	11.039,16

Taking sample ER135SR4 as a reference, the average soil erosion in the study area evaluated by the RUSLES-GGS model showed significant variations in different periods. During the period 1990-2000 (Fig. 2a), the maximum erosion rate reached 123,54 (t/h/yr). During the period 2000-2010 (Fig. 2b), this value decreased to 99,77 (t/h/yr), and between 2010-2020 (Fig. 2c), a value of 105,03 (t/h/yr) was recorded. In the last two periods studied, a significant increase in erosion rates is observed, with variations between 1-10 (t/h/yr). However, it is important to note that a decrease was observed in the period from 2000 to 2010. This could be interpreted as a function of changes in precipitation or other effects caused by land use.

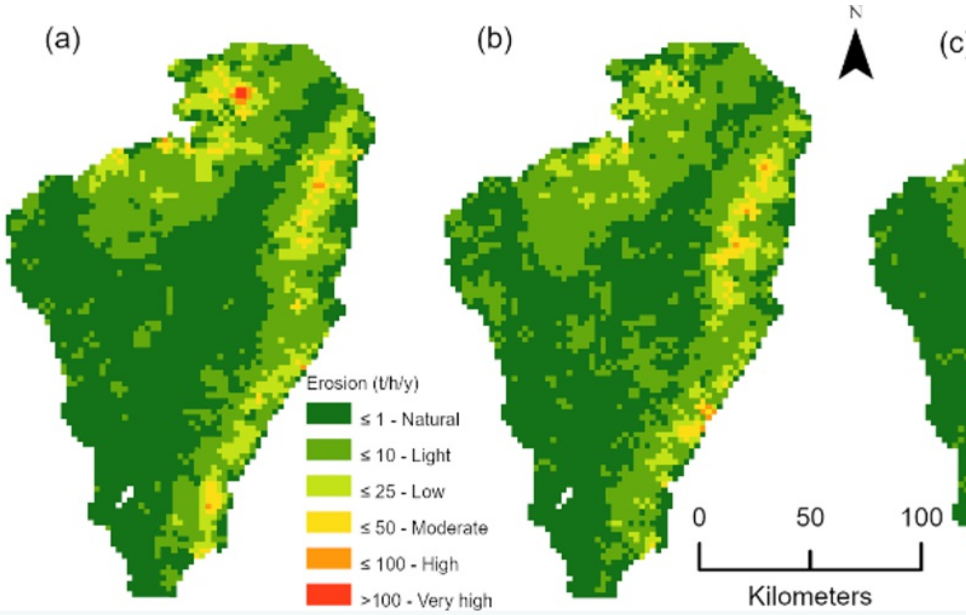

Fig. 2. (a) Erosion rate for the period 1991-2000; (b) erosion rate for the period 2001-2010; (c)erosion rate for the period 2010-2020. Author

In total, 8% of the watershed area has a low rate of erosion, while 2,30% has a moderate rate of erosion. The total moderate erosion rate in the watershed area gradually increased from 2,21% in 2000 to 2,03% in 2010 and finally to 2,65% in 2020 (Fig. 3). However, the areas with high and very high levels of erosion cover only 1% of the territory and are mainly concentrated in the mountainous areas of the watershed. It appears that these areas generate a significant amount of sediment, despite the relatively small proportion of high and very high erosion rates.

On the other hand, among the factors included in the erosion model, the slope was the most dominant factor in the periods studied. Therefore, due to the abrupt topography and probably the bare areas caused by landslides, the highest erosion rates are representative of the mountainous areas.

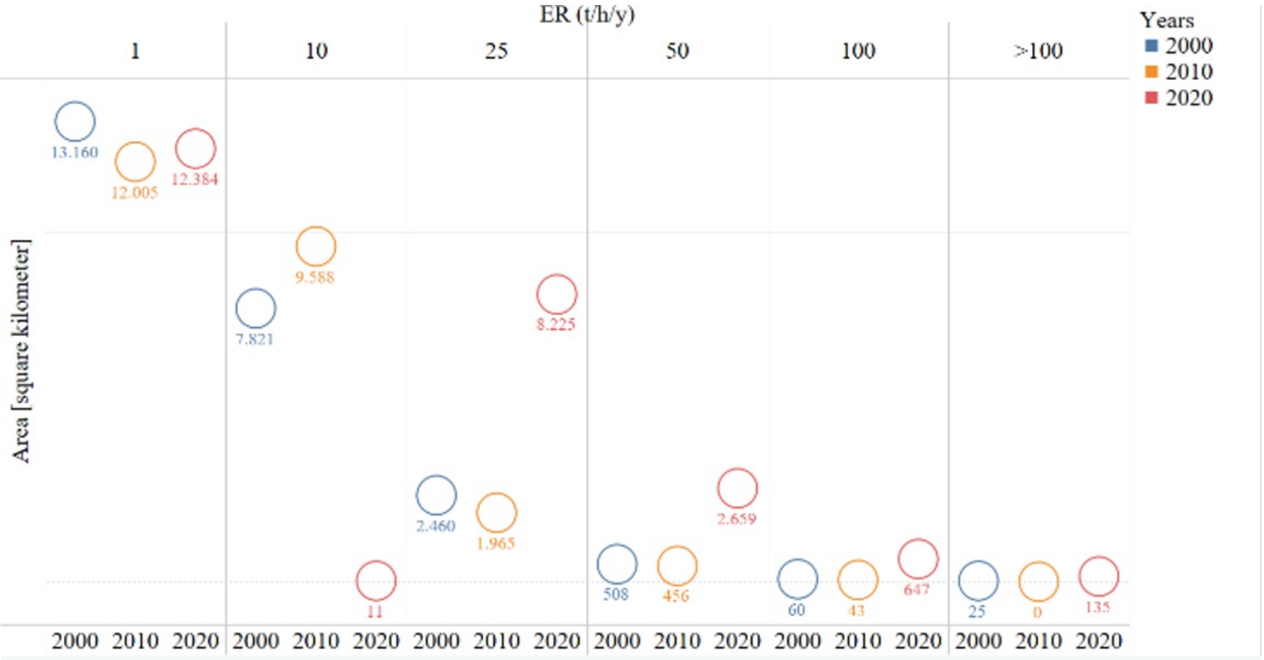

Fig. 3. Area (km^2) for each time period affected by erosion rates. Author

B. *Analysis of critical points of soil erosion*

Erosion hotspots in the watershed were statistically significant at a 99% confidence level. They represented approximately 1.25% of the study area (Fig. 4). These hotspots were mainly concentrated in the mountainous areas of the watershed. The hotspot areas coincided with regions with relatively high levels of erosion, including those in the very high erosion categories. Average soil erosion rates ranged from 100 (t/h/y) to more than 100 (t/h/y) in these hotspot areas.

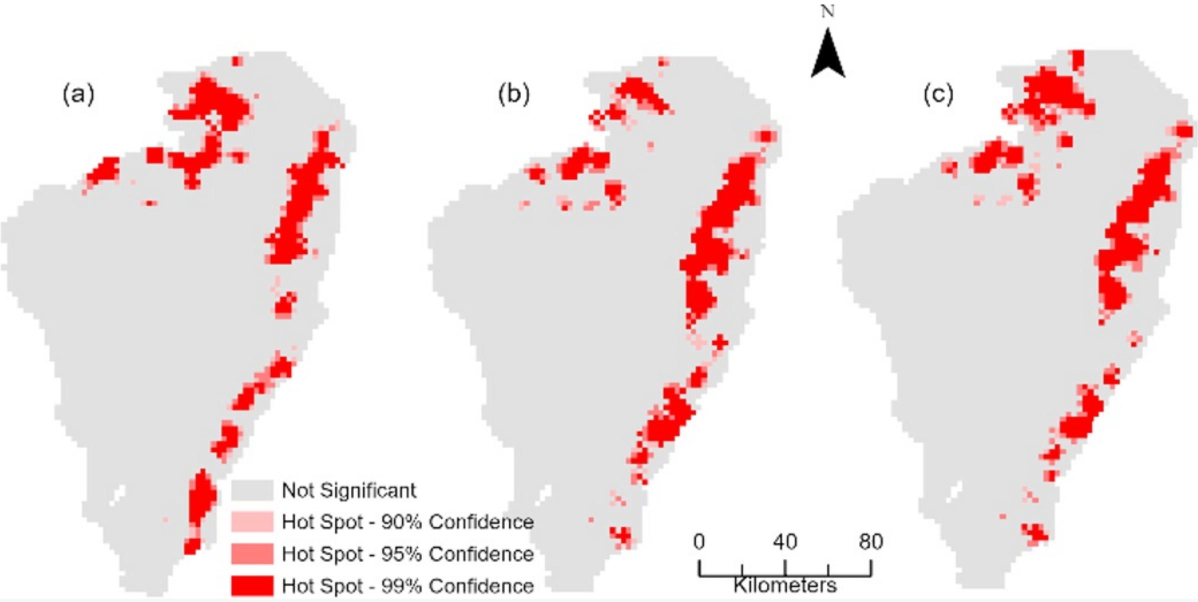

Fig. 4. (a) Hotspots for the period 1991-2000; (b) hotspots for the period 2001-2010; (c) hotspots for the period 2010-2020. Author

Although the hotspots depicted only overlap with the highest erosion rates in our research, it is crucial to also consider areas with lower erosion rates. These areas may play an equally important role in landscape dynamics and environmental quality, despite their smaller apparent impact.

In general, areas with relatively low erosion rates can be attributed to anthropogenic processes influenced by changing land use. However, these areas may show a less pronounced dispersion, possibly due to the uncertainty associated with the variables influencing the model, particularly the topographic factor [24].

The identification of these hotspots is an opportunity for the implementation of erosion control strategies with a targeted approach in the most vulnerable areas of the watershed [28]. Therefore, it is essential to consider the implementation of soil conservation measures on a relatively large scale and to pay special attention to areas affected by anthropogenic processes.

C. *Towards Cesar River Restoration*

In the department, recent research has confirmed that the Cesar River is facing one of the most alarming levels of soil degradation due to erosion, with a shocking 81.9% of the soils in the region being affected by this process [29]. However, in spite of this alarming diagnosis, the studies carried out in the Cesar watershed do not provide accurate data on erosion rates at the watershed level, and the information that does exist is categorized as "no evidence" [30], [31].

Possible solutions to address the problem of soil erosion have been proposed by research focused on the Cesar River. These solutions include strategies such as reforesting various areas and implementing conservation practices [29]. However, despite these proposals, a comprehensive roadmap has not yet been outlined. This roadmap should provide a broader and more specific approach to river restoration from an ecosystem services perspective.

Soil erosion has received sufficient attention in the context of developing countries. These countries have formulated policies and guidelines aimed at controlling soil erosion [32]. Implementing best management practices (BMPs) in watersheds, especially in critical areas or vulnerable subwatersheds, has been highlighted as a highly effective technique for achieving significant reductions in soil loss and sediment deposition [33], [34]. These techniques include restoring meanders and applying sustainable soil management practices. We posit that proper implementation of these strategies could provide a sound solution to address soil erosion and help restore the Cesar River watershed.

IV. Conclusions

A critical view of the soil dynamics in the region was obtained by analyzing the erosion rates caused by natural processes in the watershed. A significant increase in erosion rates was observed in the different studied periods, with values above 25 (t/h/y). This highlights the importance of addressing the factors that contribute to this soil degradation.

It is evident that although relatively low erosion rates do not represent a continuous distribution, their presence should not be overlooked. These areas could represent erosion influenced by anthropogenic activities, increasing the importance of implementing soil conservation strategies on a broader scale.

Identifying erosion hotspots using the Getis-Ord method has helped identify specific areas where control strategies should be focused because they are more vulnerable. The concentration of these hotspots in mountainous areas, in addition to their overlap with areas of high and very high erosion, underscores the need for targeted action in these areas to reduce soil loss and associated impacts.

In summary, an understanding of the erosion rates generated by natural processes in the watershed is essential not only for the identification of critical areas and the application of management practices but also for the development of comprehensive strategies that address both high and low-erosion areas. These findings underscore the need to promote soil conservation and overall river ecosystem health through holistic watershed management that considers natural and anthropogenic dynamics.

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