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SOIL EROSION DUE TO RAINFALL AND THE IMPACTS OF CLIMATE CHANGE IN AN ANDEAN HIGHLAND IN COLOMBIA

PEDRO SIMÓN LAMPREA-QUIROGA[1]*
OMAR JARAMILLO-RODRÍGUEZ[2]
WLADIMIR MEJÍA AYALA[3]

[1]*Forestry engineer, PhD in Geography; Independent investigator; Postal address: 111321000, Bogota, Colombia.*

[2]*Geographer, MSc in Geography; Independent investigator; Postal address: 111211, Bogotá, Colombia.*

[3]*Agroforestry engineer, PhD in Geography; Pedagogical and Technological University of Colombia (UPTC) in agreement with the Agustín Codazzi Geographic Institute (IGAC). Postal address: 101221, Bogotá, Colombia.*

ABSTRACT. Trends and median slope of daily rainfall that can affect rainfall aggressiveness and cause erosion in the Bogotá - Duitama corridor were studied. For this, the daily records of 26 stations (35 years, from 1980 to 2014) were evaluated, using the Sen's statistic and the Mann-Kendall test with confidence levels higher than 90%. The studied area covered about 8,100 km^2, located between 2,100 and 3,300 m a.s.l. in the Colombian Andes. Four stations with positive trends in median annual rainfall were found (from 6.90 mm/year to 28.80 mm/year) and one station with a decrease in median rainfall of -6.86 mm/year. In order to analyze the pluvial aggressiveness as the main agent of soil erosion, the Modified Fournier Indices (MFI) were generated for periods of 10 days. With the maximum decadal Modified Fournier Indices (MFI_{dmax}) of each year, it was possible to establish the median positive trend (Sen) of rainfall aggressiveness in five stations and three stations with negative trends. Through the correlation between the degree of erosion with the square of the decadal average maximum values of each year (MFI_{dmax}^2) and the negative annual precipitation, a coefficient of determination (R^2) greater than 0.50 was found. The validation of MFI_{dmax}^2 to explain the degree of soil erosion is a new useful methodology for land use planning and monitoring. In this way, developing countries have the possibility of using a tool to face the processes of pluvial erosion, vulnerability and adaptation to climate change.

Erosión del suelo por lluvias e impactos del cambio climático en un altiplano andino en Colombia

RESUMEN. Se estudiaron las tendencias y la mediana de la pendiente de las lluvias diarias que pueden afectar la agresividad de las lluvias y causar erosión en el corredor Bogotá - Duitama. Para ello, se evaluaron los registros diarios de 26 estaciones (35 años, de 1980 a 2014), utilizando el estadístico de Sen y la prueba de Mann-Kendall con niveles de confianza superiores al 90%. El área de estudio abarcó alrededor de 8.100 km^2, ubicada entre los 2.100 y 3.300 m s. n. m. en los Andes colombianos. Se encontraron cuatro estaciones con tendencias positivas en la precipitación media anual (de 6,90 mm/año a 28,80 mm/año) y una estación con una disminución en la precipitación media de -6,86 mm/año. Para analizar la agresividad pluvial como principal agente de erosión del suelo, se generaron los Índices de Fournier Modificado (IFM) para periodos de 10 días. Con los Índices de Fournier

Modificados (IFM_{dmax}) máximos decenales de cada año, fue posible establecer la mediana de la tendencia positiva (Sen) de la agresividad de la lluvia en cinco estaciones y tres estaciones con tendencias negativas. Mediante la correlación entre el grado de erosión con el cuadrado de los valores máximos medios decadales de cada año (MFI_{dmax}^2) y la precipitación anual negativa, se encontró un coeficiente de determinación (R^2) superior a 0,50. La validación de IFM_{dmax}^2 para explicar el grado de erosión del suelo es una nueva metodología útil para la planificación y el seguimiento del uso del suelo. De esta manera, los países en desarrollo tienen la posibilidad de utilizar una herramienta para enfrentar los procesos de erosión pluvial, vulnerabilidad y adaptación al cambio climático.

Keywords: Climate trends, rainfall aggressiveness, decadal modified Fournier index, Mann-Kendall.

Palabras clave: Tendencias climáticas, agresividad pluvial, índice de Fournier Modificado decadal, Mann-Kendall.

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***Corresponding author:** Pedro Simón Lamprea-Quiroga, Postal address: 111321000, Bogota, Colombia. E-mail address: pslamprea@yahoo.com

1. Introduction

With the global predictions projected for the year 2070 by Borrelli *et al.* (2020), based on a semi-empirical modelling approach and the Revised Universal Soil Loss Equation (RUSLE), soil erosion rates of $43 \cdot 10^9$ (+9.2 to -7) Mg yr^{-1} are predicted, with respect to a baseline of 2015. These projections for all global dynamics scenarios indicate a trend towards a more vigorous hydrological cycle (extreme values), which could increase global water erosion from 30% to 66 %. For their part, Arias-Muñoz *et al.* (2023) in the middle-upper basin of the Mira river, in the Andes of Ecuador, on the border with Colombia, estimated an average erosion rate of 32 t/ha/year, which can reach a maximum value of 812 t/ha/year.

Studies carried out by the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM *et al.,* 2015), indicate that 40% of the territory of Colombia presents some degree of erosion. The problem is especially relevant due to the large proportion of affected soils with some degree of erosion in the departments of Cundinamarca (80.3% of 23,984 km^2) and Boyacá (72.1% of 23,175 km^2). Severe erosion covers 6.8% of the department of Boyacá, while 5% occurs in the department of Cundinamarca. Due to erosion in the Colombian Andes, this soil degradation has been affecting more than 90% of the territory with agricultural vocation, which leads to the deterioration of the peasant productive base.

Additionally, the impacts of climate change, whose effects could initially be seen in rainfall erosion, may be related to the variations in rainfall patterns and the increase in winds, thus affecting drought. However, although some of the poor moisture conditions can be partially offset by heavy rains, erosion can affect soil and water resources due to increased storms (Basher *et al.,* 2012).

For their part, Almagro *et al.* (2017) argue that due to the variability and changes in rainfall, it is important to consider that the impacts of climate change on the erosivity of rainfall can lead to processes of greater soil degradation. Therefore, it is critical to identify ways and methods of how the country can adapt itself, reduce its vulnerability, and increase its resilience towards this phenomenon. For these reasons, the present study focuses on developing simple and practical methods with available daily precipitation data, which allow for improving soil conservation measures and adaptation processes to changes in rain erosivity. Likewise, it is worth taking into account that, although other authors (di Lena *et al.,* 2021)studied the trend of the Modified Fournier Index (MFI), no studies were found with the maximum annual values of MFI calculated for 10 days; together with its verification with the degree of soil erosion for the same period studied through regression equations.

However, despite the multiple scenarios evaluated and the numerous methods and models to assess erosion, it is not clear how to quantify the impact of climate change on soil erosion (Xiaofei *et al.,* 2021) and select the most appropriate erosion model for the Andean territory. Therefore, there is little knowledge of the implications of the model's conceptualization on projected soil erosion rates under climate change (Eekhout and de Vente, 2020).

Additionally, it is necessary to take into account that the soil can be affected by different rainfall regimens and intensities, which should be studied through indices developed by the institutions with the available information. Similarly, although from the review of previous studies, it has not been possible to establish any clear association of erosion with climate change, further research should be carried out based on the different ways environmental sustainability is impacted. This situation leads to the need for a better understanding of the benefit of the soils in climate regulation and ecosystem services (Lal *et al.,* 2021).

Based on the above, the objective was to determine the existence or absence of changes or trends in rainfall that may lead to soil erosion; with the hypothesis, in which: there is a relationship of soil erosion with the trend or change in the indices of pluvial aggressiveness.

2. Materials and methods

2.1. Study area

The study area was delimited to the rural corridor between Bogotá (the capital of Colombia in the department of Cundinamarca) and Duitama (the northeast city of the department of Boyacá), a territory that contains the representative customs of the Altiplano Cundiboyacense in terms of their agricultural practices (Lamprea Quiroga and Sanabria Marin, 2020). The shape of the land corresponds to a flat to gently undulating relief of the Colombian Andes, derived from water accumulation processes in lakes and swamps, with subsequent sedimentation processes from its steep edges; along the Bogotá, Suárez and Chicamocha rivers. This plateau also presents the largest population process in Colombia (Instituto Geográfico Agustín Codazzi [IGAC], 2014)

The corridor presents a relative geomorphological homogeneity with a gradual decline (fundamental to studying pluvial erosion and not making the analysis more complex with mass removal), over an altitudinal range of 2,100 to 3,300 meters above sea level. The main crops are potatoes, fruit trees and vegetables. Livestock is pasture-fed.

The land cover is dominated by agricultural activities (58%) and forests (29%). The soils belong to the order Entisols, Inceptisols and Andisols. The minimum temperatures oscillate between 6.5 to 11°C, and the maximum between 12 and 18 °C. (Instituto de Hidrología *et al.,* 2015). In the department of Cundinamarca, there are 28 municipalities (4,252 km^2) and 32 in Boyacá (3,847 km^2), covering an area close to 8,100 km^2, approximately 170 km long by 47 km wide (Fig. 1).

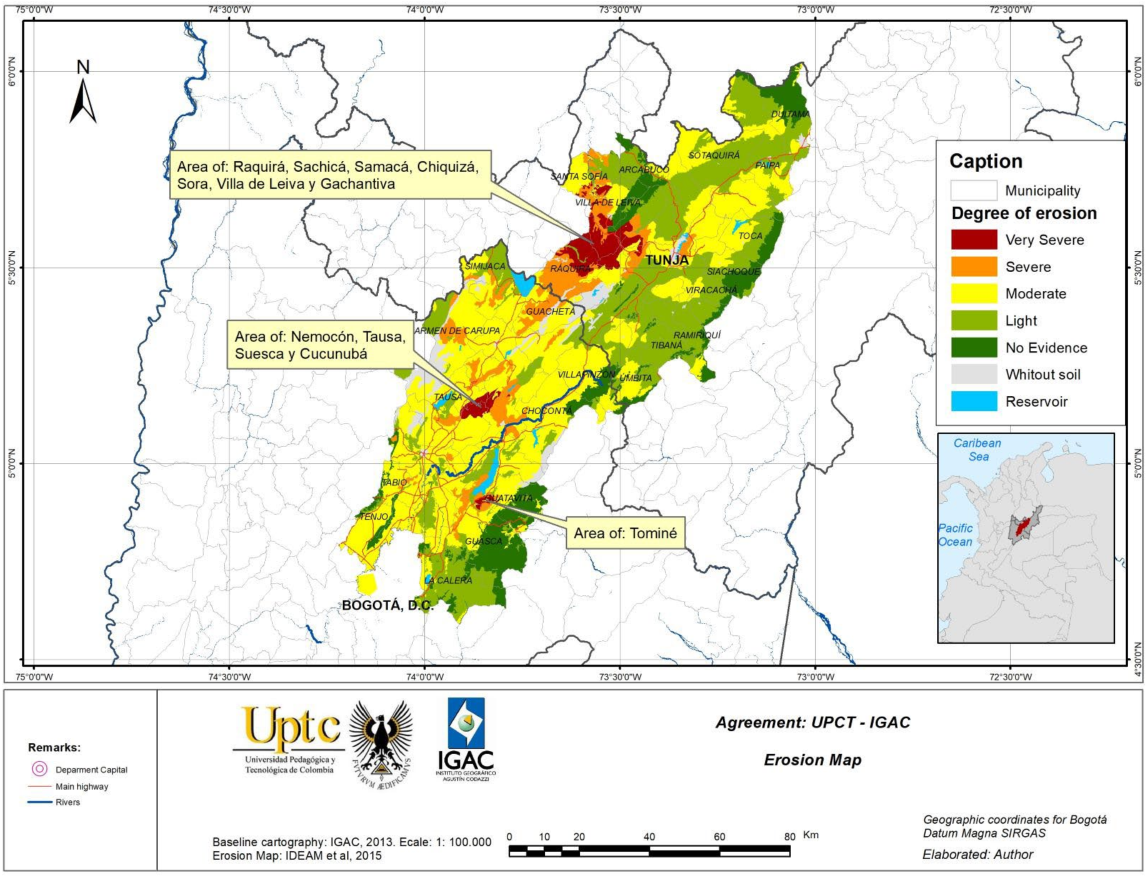

Figure 1. Distribution of the degree of erosion. Source: Own elaboration based on Instituto de Hidrología et al. *(2015).*

2.2. Erosion

The national study of soil degradation by erosion in Colombia (Instituto de Hidrología -IDEAM- *et al.,* 2015) provided reference information on the erosive process. In IDEAM *et al*. (2015, pp. 23-43) the methodological development is described. With this, the study area's classification and distribution of eroded surfaces were developed. Figure 1 shows the degree of very severe erosion in red. Very severe erosion, in Cundinamarca, affects the municipalities of Guatavita, Nemocón, Tausa, Suesca, Cucunubá and Guasca (between 240 and 1,080 ha), resulting in a total area close to 5,600 ha (1.3%) of the area study. This surface increases to more than 9% of the department of Cundinamarca, adding the areas with severe erosion (orange colour). In Boyacá, very severe erosion is found (between 400 and 7,120 ha) in the municipalities of Ráquira, Sáchica, Samacá, Chíquiza, Sora, Villa de Leyva, Gachantivá, Santa Sofía and Cucaita, which together add up to 20,570 ha (5.5 %). If severe erosion is added, it reaches about 12% affectation in the department of Boyacá.

2.3. Data source

2.3.1. Pluviometry

The climatic stations were selected based on the following: a) the largest number of stations (26 of 54) with records between 1980 and 2014 (35 years); b) Stations with more than 90% of the total daily precipitation records, although the methodology for trend analysis is not sensitive to missing value (Pal, 2009). Table 1 shows the selected stations.

The period from 1980 to 2014 was selected, mainly based on the collection of information from the erosion map (Instituto de Hidrología *et al.,* 2015). In contrast, the randomness of the series was verified with the Turning Point test, according to the methodology exposed by Clarke (1984, p. 26).

Table 1. Information from the weather stations used.

Name Station	Cat.	Elevation m a.s.l.	Latitude °	Latitude min.	Latitude s	Longitude °	Longitude min.	Longitude s	Depart.	Municipality
Arcabuco	PM	2600	5	45	38.1	73	26	38.9	Boy.	Arcabuco
Azulejos Los	PG	2780	5	39	4.9	73	12	3.6	Boy.	Tuta
Casa Amarilla	PM	3200	5	32	1.7	73	9	48.6	Boy.	Toca
Cerezo El	PM	2900	5	41	57.5	73	4	18.3	Boy.	Paipa
Cómbita	PM	2820	5	37	44.1	73	19	26.4	Boy.	Cómbita
Emporio Hacienda El	PM	2120	5	36	5.8	73	32	38.6	Boy.	Villa de Leyva
Nuevo Colón	AM	2438	5	21	13.7	73	27	23.4	Boy.	Nuevo Colón
Ráquira	PM	2290	5	32	19.6	73	37	52.9	Boy.	Ráquira
San Pedro de Iguaque	PG	2985	5	38	24.0	73	27	1.6	Boy.	Chíquiza
Siachoque	PM	2720	5	30	26.4	73	15	1.0	Boy.	Siachoque
Surbatá Bonza	AM	2485	5	48	8.8	73	4	28.1	Boy.	Duitama
Tibaná	PM	2115	5	18	55.0	73	23	45.4	Boy.	Tibaná
Turmequé	PM	2400	5	19	4.1	73	19	46.4	Boy.	Turmequé
U P T C	CP	2690	5	33	12.8	73	21	19.0	Boy.	Tunja
Úmbita	PM	2300	5	13	8.8	73	26	40.4	Boy.	Úmbita
Villa Carmen	CP	2600	5	30	42.1	73	29	44.8	Boy.	Samacá
Villa de Leiva	CP	2215	5	39	21.0	73	32	38.2	Boy.	Villa de Leyva
Amoladero El	PM	2963	4	51	28.7	73	44	43.4	Cundi.	Guatavita
Aepto. El Dorado	SP	2547	4	42	20.1	74	9	2.4	Cundi.	Bogotá
Cucunubá	PM	2620	5	15	3.7	73	46	14.7	Cundi.	Cucunubá
Hato El	PM	2575	4	52	0.0	74	9	13.9	Cundi.	Tenjo
Leticia	PM	2650	5	18	11.5	73	42	35.1	Cundi.	Lenguazaque
Potreritos	PM	2802	4	49	43.7	73	46	9.4	Cundi.	Guatavita
Silos	CO	2709	5	7	3.8	73	42	5.1	Cundi.	Chocontá
Simijaca	PG	2590	5	30	40.7	73	51	49.3	Cundi.	Simijaca
Santa Cruz de Siecha	PM	3100	4	47	3.4	73	52	14.9	Cundi.	Guasca

Source: Own elaboration based on information from IDEAM.
Notes: Depart: Department; Cundi.: Cundinamarca; Boy.: Boyacá; Cat: Station category; PM: Pluviometry; PG: Pluviographic; AM: Agrometeorological; CP: Climatic Principal; SP: Synoptic; °: degree; min: minute; s: seconds.

2.4. Precipitation analysis and comparison with the erosion map

The methodology developed with the daily values of precipitation by the station is summarized in the following major steps: a) Analysis of the daily precipitation, complete the series and generate the decadal Modified Fournier Indices (MFI_d). Rainfall analyses were carried out over periods of ten days, which is decisive for evaluating the short-term effects of the main erosive and productive agent. b) Obtaining the maximum annual value of the decadal Modified Fournier index (MFI_{dmax}). c) Evaluation of trends in annual precipitation and the MFI_{dmax}. d) Obtaining the multiannual mean value of the maximum values of the indices (MFI_{dmax}). e) Calculation of the weighted erosion level of the erosion map (IDEAM *et al.,* 2015) to obtain the correlation and regression with the multiannual average of the MFI_{dmax} and annual rainfall. Table 2 presents a synthesis of the methodology developed, based on the analysis of the behaviour of rainfall, to determine the existence of changes or trends that may affect the erosivity of rainfall.

The Pearson correlation coefficients between all stations were calculated to complete the daily rainfall. From this process, groups of five stations were formed to carry out the process of completing the daily precipitation data, with a) The Normal Ratio method used by Linsley *et al.,* (1977, p. 64), including the influence of the El Niño Ocean Indices from the National Weather Service Climate

Prediction Center (National Oceanic and Atmospheric Administration [NOAA], 2021) according to (Medina *et al.,* 2008); and b) Based on the least mean square error (RMSE) between the Homogeneous Fields Method of Antelo and Fernández (2014) and the Normal Ratio method, mentioned above, the way to complete the daily rainfall data for each station was chosen.

Table 2. Methodological synthesis process with its techniques and activities.

Techniques for daily precipitation analysis and MFI_d	**Techniques for trend analysis, compare with the erosion map, correlation and regression.**
Rainfall consistency analysis with the Turning Point or Gust Test (Clarke, 1984). Completion of the rainfall series with the Normal Ratio method (Linsley et al., 1977), including the influence of the ENSO adapted from Medina et al. (2008) or the Homogeneous Fields method (Antelo R. & Fernández, 2014) according to the lower value of the Root Mean Square Error (RMSE). Generation of decadal Modified Fournier Indices (MFI_d) (Gómez, 1999).	Obtaining the maximum annual value of the decadal Modified Fournier Index (MFI_{dmax}). Evaluation of the trends (Mann-Kendall, 1948) of annual rainfall and $MFI_{dmax,}$ with their Median slopes (Sen, 1968). Obtaining the multiannual average value of the maximum values of the MFI_{dmax}, by rain gauge station. Calculation of the weighted erosion level from the erosion map (IDEAM et al., 2015) to obtain the correlation and regression with the multiannual average of the MFI_{dmax} and annual rainfall.

2.4.1. Generation of decadal Modified Fournier Indices

Since pluviographs are scarcer in the developing countries of Latin America, the analysis of the aggressiveness of the rains was based on the availability of the records of the pluviometers, instead of the pluviographs. For this reason, Modified Fournier indices were used.

According to Kirby and Morgan (1984), in Gómez (1999), the analysis carried out by Fournier around the year 1960 with the sedimentary values of more than 140 rivers in Europe, Asia and the United States, obtained a high correlation between the sediment load and an index generated with annual and monthly rainfall. Although Fournier (1960) initially obtained a high correlation of the sediment load versus the relationship between the monthly precipitation of the rainiest month (p) and the average annual precipitation (P), this index (p^2/P) was later modified by Arnoldus (1977) in Renard and Freimund, (1994). With the modified Fournier index, the correlation of R^2 with the R factor (rain erosion factor in the universal soil loss equation -USLE-) increased from 0.55 to 0.91. The modification introduced by Arnoldus (1977) is illustrated in equation 1.

$$\boldsymbol{MFI = \sum_{i=1}^{12} \frac{p_i^2}{P}} \qquad \text{(Equation 1)}$$

Where MFI is Modified Fournier Index (mm), p_i is the rainfall for the i^{th} month (mm), P is the annual rainfall (mm), and i the month.

2.4.2. Obtaining decadal Modified Fournier Indices

Firstly, the rain patterns were divided into periods of ten days. Decade 1, from day 1 to 10; decade 2, from day 11 to 20; and decade 3, from the 21^{st} to the 28^{th} or 29^{th} or $30^{th,}$ or 31^{st}, depending on the number of days in each month, as proposed by Gómez (1991; 1999). With these decadal Modified Fournier indices (MFI_d), the monthly Modified Fournier indices (MFI_{dm}) and annual (MFI_{da}) can be obtained through the corresponding accumulation. The modified MFI_d at the decadal level (every 10 days) used in the present investigation was:

$$MFI_d = \sum_{i=1}^{10} \frac{P_i^2}{P} \quad \text{(Equation 2)}$$

Where MFI_d is the Decadal Modified Fournier Index (mm dec.$^{-1}$), p_i is precipitation of each of the 10 days (mm), P is the Average precipitation in the corresponding decade (mm), and i the day.

2.5. Obtaining the maximum annual value of MFIdmax

Of the 36 decadal Modified Fournier indices of each year (MFI_{dmax}), the maximum value of each year by rainfall station was selected. Thus, the aggressiveness trends of the rains were evaluated using the maximum annual value of the MFI_d of each station, according to the methodology of Chow *et al.* (1994, p. 394) and Suresh (2008, p. 563).

2.6. Evaluation of trends in annual precipitation and the MFIdmax

With the records of the total annual rainfall for each station, the trends were evaluated with different levels of statistical confidence (90.0%; 95.0%; 97.5%; 99.0% and 99.5%). These statistical confidence levels were applied to all the series analysed, taking into account the sensitivity of the method Mann (1945) and Kendall (1948). The value of the median slope was obtained with the method proposed by Sen (1968).

2.6.1. Trend analysis method with decadal Fournier indices

With this methodology (analysing the maximum annual values) it was intended to measure the potential impact of the acting agent (rain) on soil erosion over time (trend) as an expression of climate change.

2.6.2. Sen's test

Sen (1968) developed a non-parametric estimator to evaluate the magnitude of the data trend, which consists of evaluating the presence of a slope (positive or negative) of the time series (equidistantly distributed data, in days, months, years, etc.). For this, the algorithm proposed by Hirsch and Smith (1982) is used, which is an extension of those suggested by Theil (1950) and Sen. According to Hirsch and Smith (in Gallego, 2003), Sen's test is a robust method to doubtful values, the lack of records and atypical data since it is evaluated through the median for N pairs of data with the following expression:

$$Q_1 = \frac{X_{i\prime} - X_i}{i\prime - i} \quad \text{(Equation 3)}$$

Where Q_1 is the slope between the data pairs Xi' and X_i; $X_{i'}$ is the measurement at time i'; X_i is the measurement at the time i; i' is time after time I; and N' is the calculated number of slopes, between the data pairs.

The median of the *N* values of Q_1 is the estimator of the slope of Sen. The median slope (Q) is obtained with the estimator of the slope of Sen, through:

$$Q' = Q_{\left[\frac{N'+1}{2}\right]},\ if\ N' is\ odd; \quad y\ Q' = \frac{\left[Q_{\left(\frac{N'}{2}\right)} + Q_{\left(\frac{N'+2}{2}\right)}\right]}{2}, \text{ if } N' \text{ is even.} \quad \text{(Equation 4)}$$

2.6.3. Mann-Kendall (M-K) test

The Mann–Kendall test allows for the detection of the existence of a trend in a time series but does not provide an estimate of its magnitude. The M-K test is a nonparametric test based on a test earlier developed by Kendall (1948).

The null hypothesis (Ho) of the M-K test is that the data (x_1, x_2 ..., x_n) are identically and independently distributed random variables, and the alternative hypothesis (H_1) is that they are distributed with a decreasing or increasing trend, using the statistic called Sτ of Kendall, with the following expression:

$$S\tau = \sum_{i=1}^{n-1} = \sum_{j=i+1}^{n} sgn(X_i - X_j) \quad \text{(Equation 5)}$$

The function sgn (X) is the sign function, whose value is -1, 0 or 1; depending on whether the argument is negative, null, or positive, respectively.

The variance of (S) of the null hypothesis is obtained with the following equation:

$$Var\ (S) = \frac{n(n-1)*(2n+5) - \sum_{P=1}^{q} t_p\ (t_p - 1)*(2t_p + 5)}{18} \quad \text{(Equation 6)}$$

In equation 6, n is the Number of data; tp is the number of measurements equal to a particular value; and q el number of linked values (Number of linked groups). A linked group is a set of data from a sample that have the same value.

The range of levels for a specific confidence interval is carried out when evaluating C, through the following expression:

$$C_\alpha = Z_{1-(\frac{\alpha}{2})} * \sqrt{Var\ (S)} \quad \text{(Equation 7)}$$

Where C_α is distributed as a Normal distribution with mean 0 and variance 1. To test for an upward or downward trend, the confidence level is compared to the absolute value of Z; which is obtained from the Normal distribution tables. Based on the previous equation, the values, low (M_1) and high (M_{2+1}), can be found using the confidence limits with the following expressions:

$$M_1 = \frac{N' - C_\alpha}{2}; \qquad M_{2+1} = \frac{N' + C_\alpha}{2} \quad \text{(Equation 8)}$$

The selection of the slopes corresponds to M_1 and M_{2+1}, which are the respective Confidence Limits (CL_u and CL_l; upper and lower)

2.7. Obtaining the multiannual average value of the maximum values of the MFI_{dmax}

With the 35 maximum annual values of the MFI_{dmax}, the average quantity was obtained, with which the aggressiveness of the rains was characterized within the evaluated period (1980 to 2014).

2.8. Correlation between the level of erosion weighted vs. MFI_{dmax} and precipitation

Based on the erosion map in Figure 1, made by Instituto de Hidrología *et al.* (2015), the weighted average of the five degrees of erosion in the surrounding areas within a radius of 1 kilometre was calculated. The assigned weighting values, with the ranges of erosion levels obtained, are shown in Table 3.

Table 3. Weighting values and erosion levels.

Value applied to the degree of erosion in the weighting	Ranges of the levels of erosion generated	Degree of erosion
0.5	≤0.5	Without evidence of erosion.
1.0	0.6 to 1.0	Light
2.0	1.1 to 2.0	Moderate
4.5	2.1 to 4.5	Severe
5.0	4.6 to 5.0	Very severe

With the level of erosion obtained from the weighting of the areas around one kilometre from each rain measurement station, the correlation and regression process are subsequently carried out with the average value of the MFI_{dmax} and the annual precipitation.

Additionally, it should be noted that Microsoft Excel was used to calculate the previous equations and the median of the slope of Sen in the M-K test. Regarding the maps with isolines, these are generated through a Geographic Information System (GIS) and the inverse interpolation distance weighted (IDW) method.

3. Results and discussions

3.1. Pluviometry and rain trends

Most of the rain measurement stations record two periods, with the highest amounts in April and October, corresponding to the bimodal regime. The stations with a monomodal regime are located towards the southeast side, in the municipality of Guasca, Cundinamarca, concentrating rainfall in June and July. Figure 2 shows the map with the multiannual mean isohyets.

Additionally, Table 4 synthesizes the values obtained from the average annual accumulated daily rainfall and the results obtained with the slope trend tests (M–K and Sen). Positive trends were found in four stations, with more than 95% of the confidence level (CL) statistic. Similarly, the Potreritos station presented a negative trend with 90% *CL*. This station is located southwest of the corridor at 2,802 m a.s.l. in Guatavita, with high annual rainfall (1,717 mm), yielding a median decrease of about 6.9 mm/year.

Table 4 highlights the significant median increase of more than 28 mm of rain/year at the Tibaná station, followed by the El Dorado airport station (8.5 mm/year) in Bogotá, Silos in Chocontá (6.9 mm /year) and Surbatá Bonza in Duitama (6.4 mm/year). The increases in rainfall are located in stations that register sufficient contribution of annual rainfall for the plants and where severe or very severe erosive processes are not recorded.

The climate change in the rains patterns of the El Dorado airport (Bogotá) is consistent with the studies performed by Rojas *et al.* (2010), who reported a variation of 13.1 mm/year for the period 1985 to 2008. Although these authors found increases for the period 1987 to 2008, in the municipalities of Villa de Leyva (12.2 mm/year) and Tenjo (9.8 mm/year), with CL of 95% and 90%, respectively, in this study, these variations were not found. This lack of trend for the 35 years leads us to suggest that the difference concerning the positive trend could be derived from the relatively short period (22 years) selected in the study by Rojas *et al.* (2010). In other words, the employed tests are sensitive to the length and cut-off year of the period analysed.

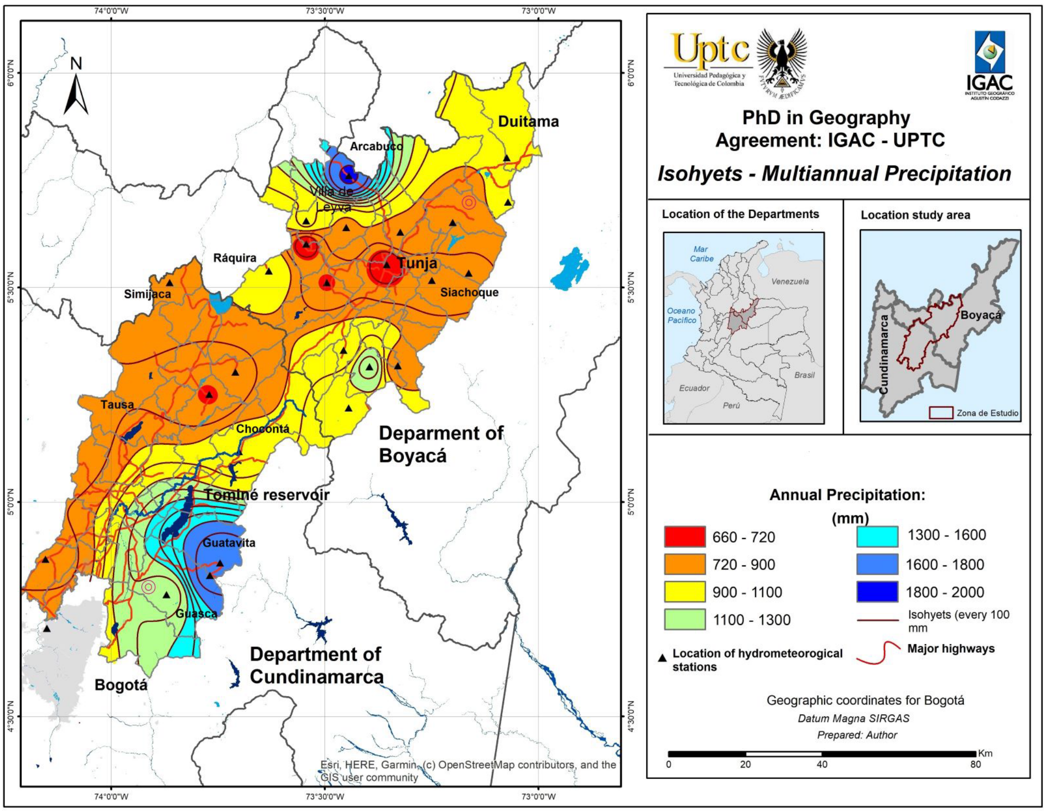

Figure 2 Multiannual mean total precipitation map 1980-2014.

Table 4. Sen and Mann-Kendall (M-K) test with Confidence Levels (CL) for annual rainfall.

Station	Median (Sen) (mm year^{-1})	M–K	Confidence Level (CL) (%)	CL_l Slope	CL_u Slope	Multiannual rain (mm)
El Dorado	**8.504**	**(+)**	**99.0**	**19.475**	**0.225**	**860**
Silos	**6.911**	**(+)**	**97.5**	**12.449**	**0.135**	**976**
UPTC	2.385			-1.500	5.780	660
Surbatá Bonza	**6.392**	**(+)**	**95.0**	**0.205**	**11.561**	**904**
Villa de Leiva	4.213			-1.150	10.273	1,017
Villa Carmen	1.011			-2.063	5.267	717
Casa Amarilla	-0.668			-4.777	4.129	790
El Emporio	-1.070			-4.800	3.077	665
Potreritos	**-6.868**	**(-)**	**90.0**	**-12.494**	**-1.427**	**1,717**
El Amoladero	7.673			-1.617	15.516	1,769
Úmbita	1.643			-2.171	5.950	1,077
Nuevo Colón	2.118			-0.681	5.318	930
Simijaca	1.851			-3.414	6.112	869
Ráquira	0.979			-6.933	7.675	994
Arcabuco	3.966			-10.820	19.444	1,813
Siachoque	-0.8600			-7.381	4.5027	759
Azulejos	-1.336			-6.839	3.797	826
Cómbita	5.850			-0.653	12.925	896
El Cerezo	-2.194			-7.566	3.841	915
San Pedro de Iguaque	-3.316			-11.378	4.381	890
Tibaná	**28.800**	**(+)**	**99.5%**	**11.750**	**47.465**	**1,234**
Turmequé	-5.565			-11.542	1.974	826
Cucunubá	1.940			-2.275	6.809	717
El Hato	3.795			-0.474	8.691	759
Leticia	3.817			-1.413	8.821	793
Santa Cruz de Siecha	3.154			-3.376	13.011	1,157

Notes: CLl: Lower confidence limit; CLu: Upper confidence limit; (+): Positive trend
(-): Negative trend with the MK test; CL: Confidence level. The records in bold showed a trend.

Additionally, it is necessary to take into account that despite having found negative median slopes (decrease in annual precipitation), several stations did not present a negative trend in precipitation, with a statistical CL greater than 90%. Figure 3 shows in red the stations with median negative slopes less than -1.0 – see. Table 4 for more information.

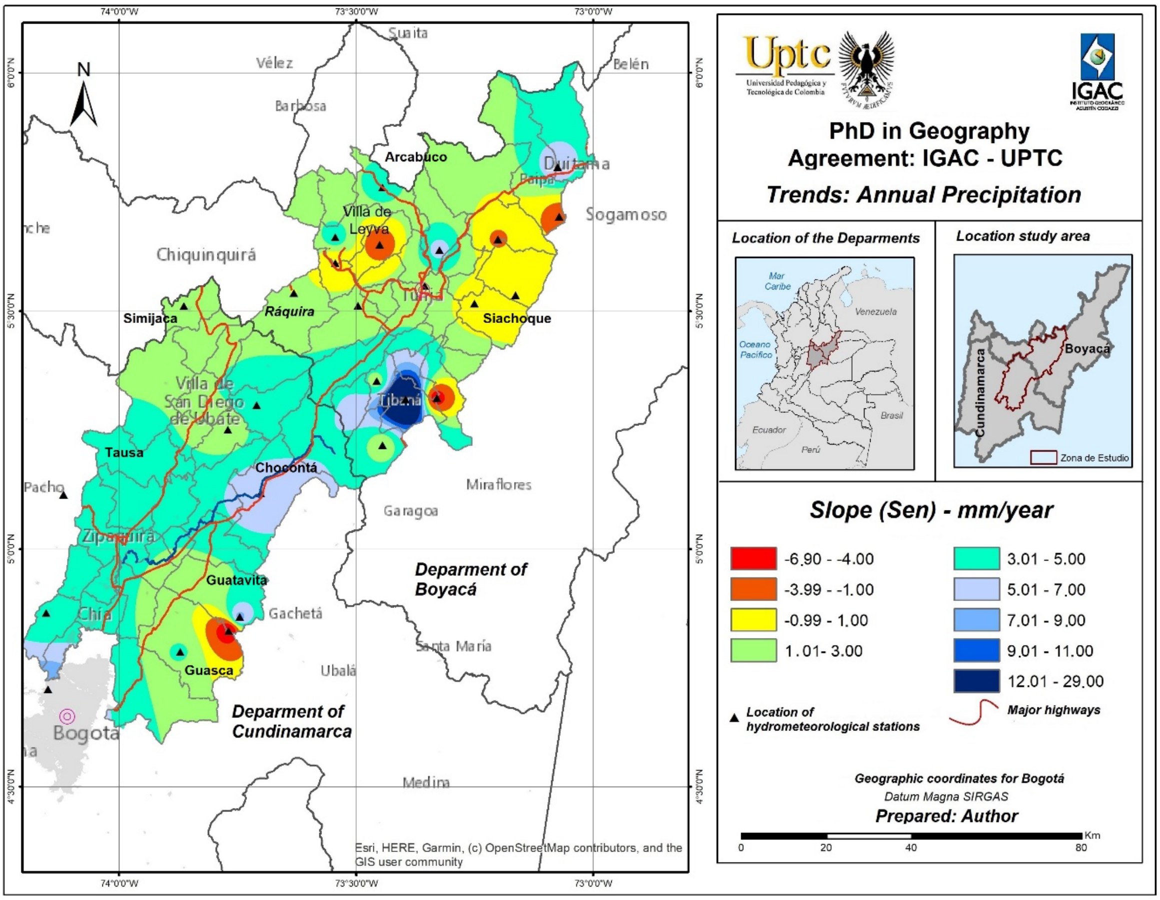

Figure 3. Distribution map of annual precipitation trends.

3.2. Rainfall aggressiveness considering the decadal modified Fournier Index (MFI_d)

For the study of the erosive aggressiveness of the rain, it is necessary to take into account that all the analysis was carried out based on the Modified Fournier index (MFI_d) for 10 days (decadal). Thus, to classify the aggressiveness of the rain through the Maximum decadal Modified Fournier Index of each year (MFI_{dmax}), the qualification made by Gómez (1975; in Gómez, 1999) is taken as a reference – see Table 5.

Although the classification made in Table 5 by Gómez (1975; in Gómez 1999) was based on studies in the Colombian coffee region (an area with greater amounts and intensities of rain than in the Cundiboyacense highlands), there is a coincidence of the stations classified with the MFI_{da} greater than 210 mm (medium degree of aggressiveness) with the areas that present degrees of severe and very severe erosion.

Next, the aggressiveness of the areas with the greatest rainfall was characterised by the average maximum annual values per station (MFI_{dmax}). The average spatial distribution of the MFI_{dmax} can be seen in Figure 4, where the map with the isolines with the greatest rainfall aggressiveness is shown in orange, red and purple colours.

Table 5. Rainfall aggressiveness rating with Modified Fournier Index (MFI).

MFI$_d$ (mm)	**MFI$_{da}$** (mm)	**MFI$_{dmax}$** (mm dec year^{-1}) (*)	**Degree of erosion**	**Precipitation characteristics**
< 5.0	< 140	< 20.0	Light	Light rains are well distributed.
5.1 - 8.0	140.1 - 210	20.1 - 25.0	Low	Low-intensity, frequent and well-distributed rains.
8.1 - 10.0	210.1 - 280	25.1 - 30.0	Moderate	Rains of medium intensity, frequent, of good to regular distribution.
10.1 - 14.0	280.1 - 350	30.1 - 35.0	Hight	Heavy rains, frequent or not, from good to bad distribution.
> 14.0	> 350	> 35.0	Very high	Heavy to very heavy rains, frequent or not, from good to bad distribution.

Notes: MFId: Decadal Modified Fournier Index; MFIda: Annual Decadal Modified Fournier Index; MFIdmax: Average annual maximum decadal Modified Fournier index; (*): Classification adopted with the present investigation. Source: Adapted from Gomez (1975) in Gómez (1999).

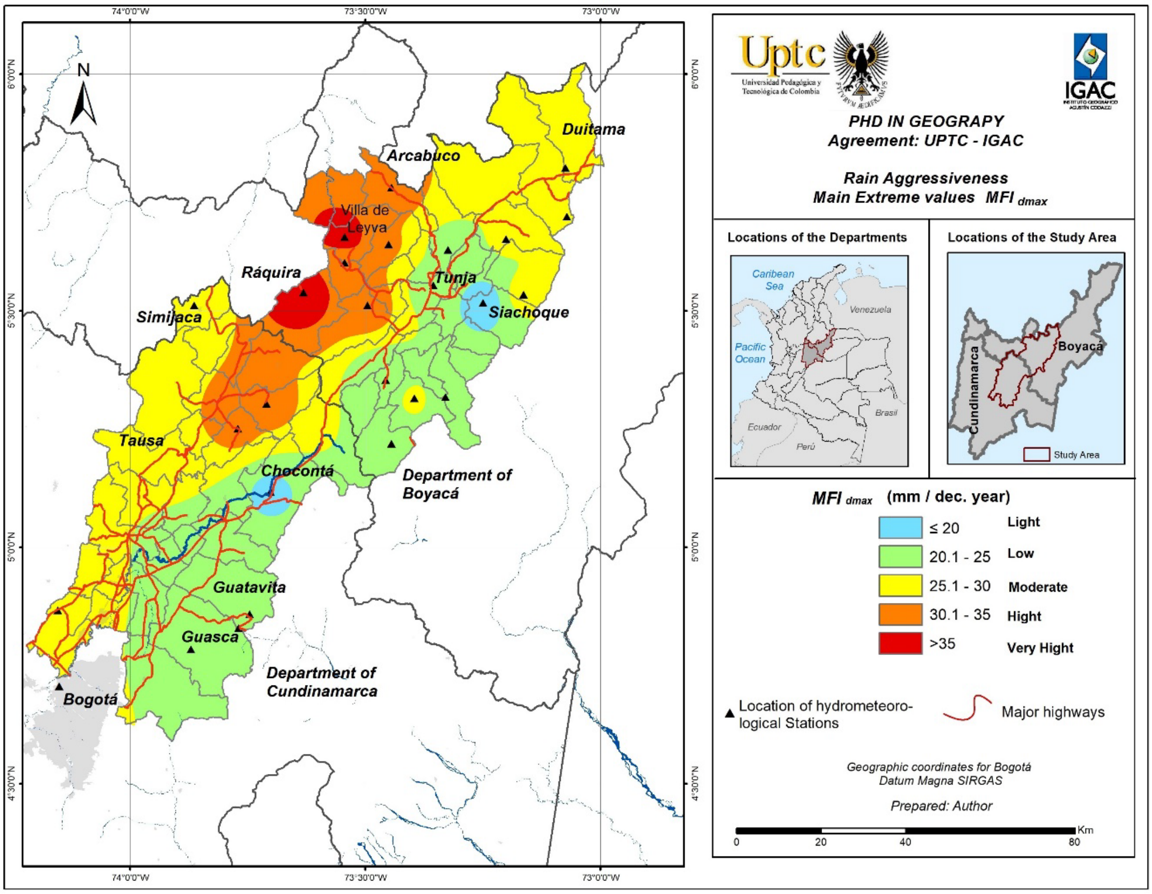

Figure 4. MFI average annual maximum decadal.

Based on the comparison of the map of the average MFI$_{dmax}$ and the map of soil degradation (Instituto de Hidrología *et al.,* 2015), there is a high correspondence with the degrees of severe and very severe erosion in the department of Boyacá in the municipalities of Ráquira, Villa de Leyva, Sáchica, Samacá, Chíquiza, Sora, Santa Sofía and Cucaita; which are located towards the western side of the middle – upper third, of the corridor studied (see polygons in red and fuchsia colours).

In the department of Cundinamarca, the municipalities of Nemocón, Tausa, Suesca and Cucunubá present very severe and severe degrees of erosion, which is consistent in this study with an average IFM_{dmax} greater than 30 mm/decade. In Cundinamarca, possibly due to the lack of rainfall stations in the southeast of the study area, in Guatavita (south of the Tominé reservoir), the aggressive behaviour of the rains was not detected through the MFI_{dmax}. This situation may correspond to a water shadow on the leeward side of the mountain that blocks the path of moist winds from the eastern plains (see Fig. 4).

3.2.1. Trends of annual maximum decadal Modified Fournier indices MFI_{dmax}

After obtaining the decadal Modified Fournier indices (MFI_d), the maximum values of each year (MFI_{dmax}) were selected, to do so, the M–K and Sen tests were employed to evaluate the existence or absence of the trend of the aggressiveness of the rain. The results of the trends of the maximum decadal Modified Fournier Indices of each year by the station are shown in Table 6.

Table 6 includes the "Erosion Level" column, which corresponds to a weighted average of the areas found within a radius of 1 kilometre from each station, based on the degree of erosion in Figure 1 (Instituto de Hidrología *et al.,* 2015). Table 6 is ordered by the level of erosion. Additionally, the following aspects are highlighted.

Table 6. M-K and Sen tests for averages of the decadal annual maximum values of the Modified Fournier Indices (MFI_{dmax}) and multiannual Precipitation mean (Pp)

Station	**Median (Sen)** (mm $year^{-1}$)	**CL MFI_{dmax}** (%)	**CL_l Slope MFI_{dmax}** (mm $year^{-1}$)	**CL_u Slope MFI_{dmax}** (mm $year^{-1}$)	**Mean MFI_{dmax}** (mm dec $year^{-1}$)	**Erosion level** (weighted average)	**Pp** (mm $year^{-1}$)
El Amoladero	-0.054		-0.155	0.126	21.72	0.73	1.769
Arcabuco	-0.099		-0.363	0.105	32.00	0.93	1.813
Turmequé	0.088		-0.125	0.282	23.34	1.00	826
Tibaná	**0.353**	**95.0**	**0.068**	**0.748**	**25.38**	**1.00**	**1.234**
Surbatá Bonza	**0.353**	**90.0**	**0.041**	**0.609**	**25.80**	**1.00**	**904**
Casa Amarilla	0.140		-0.154	0.388	25.90	1.00	790
El Dorado	**0.330**	**90.0**	**0.008**	**0.637**	**27.33**	**1.00**	**860**
Úmbita	**0.268**	**99.5**	**0.003**	**0.697**	**23.86**	**1.04**	**1.077**
San Pedro de Iguaque	**-0.462**	**97.5**	**-1.018**	**-0.018**	**30.20**	**1.49**	**890**
Potreritos	-0.086		-0.264	0.090	23.35	1.56	1.717
Santa Cruz de Siecha	-0.105		-0.360	0.104	22.17	1.60	1.157
El Hato	0.206		-0.189	0.680	28.01	1.74	759
Simijaca	-0.003		-0.293	0.306	27.97	1.84	869
Nuevo Colón	0.036		-0.323	0.410	20.85	1.91	930
Cómbita	**-0.344**	**95.0**	**-0.742**	**-0.047**	**23.96**	**1.98**	**896**
Siachoque	0.020		-0.161	0.166	17.82	2.00	759
Silos	0.034		-0.169	0.248	19.64	2.00	976
El Cerezo	0.144		-0.197	0.471	27.76	2.00	915
Azulejos	-0.087		-0.294	0.194	25.22	2.00	826
Leticia	0.184		-0.068	0.512	30.92	**2.00**	793
UPTC	0.109		-0.081	0.285	22.47	2.00	660
Villa Carmen	0.294		-0.044	0.646	31.98	2.45	717
Cucunubá	0.663		-0.901	2.206	30.45	2.63	717
Villa de Leiva	0.128		-0.208	0.567	36.97	4.50	1.017
El Emporio	0.230		-0.027	0.496	31.51	4.70	665
Ráquira	0.319		-0.167	0.926	38.20	4.92	994

Notes: **CL**: Confidence level of the trend; **CL_l**: lower confidence limit; **CL_u**: upper confidence limit.
The color of the cells corresponds to the median values in yellow, green to the lowest value of erosive aggressiveness (MFImax) and greater precipitation, and red where the highest values of MFI_{max} and less precipitation are found.

Although the Cómbita stations (erosion level 1.98; moderate) and San Pedro de Iguaque (erosion level 1.49; moderate) presented a negative trend; The aggressiveness of the rain (MFI_{dmax}, mm dec yr^{-1}) was close to the range of the moderate value (25.1 to 30.0) in the Cómbita (23.96) and San Pedro de Iguaque (30.2) stations.

With a behaviour contrary to the previous situation, positive trends were detected in the IMFdmax of the Tibaná (25.38), Surbatá Bonza (25.80), El Dorado (27.33) and Úmbita (23.86) stations. However, these values of pluvial aggressiveness were located in low (20.1 to 25.0) to moderate (25.1 to 30.0) ranges, in addition to showing slight levels of light erosion (≤1.04).

The previous results allow us to establish that despite the fact that the aggressiveness of the rain (MFI_{dmax}) showed a positive trend in four rain measurement stations, the level of soil erosion was slight (<1.04) in the period 1980 - 2014. In the opposite sense, the two stations that presented moderate levels of erosion (1.1 to 2.0) showed negative trends in the MFI_{dmax}.

Additionally, the previous results do not show changes in the areas that, until 2014, had severe to very severe levels of erosion. On the one hand, no trends were found and there are averages of high rainfall aggressiveness (30.1 to 35.0) or higher in most of the terrains with degrees of severe (2.10 to 4.50) to very severe (4.51 to 5.00) erosion. Therefore, their degradation conditions due to trends in the aggressiveness of the rains remained in the same adverse conditions.

3.2.2. Relationship between erosion and the mean maximum of MFI_{dmax}

The best regression model between the erosion level (Y) and the MFI_{dmax} was obtained by squaring the values of this index, shown in equation 9.

$$\text{Level of Erosion } (Y) = -\,0{,}0070 + 0{,}0027\,(MFI_{dmax})^2 \qquad \text{(Equation 9)}$$

By including the multiannual mean precipitation (Pp) in a multiple regression model, it was possible to increase the explanatory power with equation 10.

$$\text{Level of Erosion } (Y) = 1{,}0105 - 0{,}0010\,(Pp) + 0{,}0026\,(MFI_{dmax})^2 \qquad \text{(Equation 10)}$$

Using Analysis of Variance and the F test, the existence of a relationship between at least one of the independent variables with the level of erosion at 95% confidence in the two previous models was verified. The coefficients of determination (R^2) and determination ($\overline{R}^2$) adjusted to explain the level of erosion were: 0.445 and 0.421 for equation 9; and 0.519 and 0.478 for equation 10.

The explanation of the levels of soil erosion in more than 50%, based on rainfall, leaves for the inherent conditions of the soil, and agricultural management measures that facilitate the retention of moisture in the land, the key to avoiding erosion.

3.3. Other aspects of rainfall aggressiveness indices and annual precipitation

Based on Table 6, it could be expected that severe or greater erosion occurs in 50% of the cases, where the multiannual average precipitation is less than 720 mm/year, and there are no factors that allow water retention in the land. This annual rainfall threshold is close to the value reported by Hudson (1982) regarding the relationship between precipitation and soil erosion (about 750 mm/year), who adds that the factor that most influences soil erosion by water is the average annual rainfall. In regions with little precipitation, water erosion may be small. However, when little precipitation falls, the water is retained by the water-hungry vegetation, with runoff it is almost nil. At the opposite extreme, rainfall greater than 1,000 mm per year often results in dense forest vegetation that protects the soil.

The approach by Hudson (1982) is oriented in a similar direction to the one exposed by (Várallyay, 2010). The latter author expects that, with greater precipitation, especially heavy rains and electrical storms, an increased rate of erosion will result from greater runoff. However, the increase in moisture could be offset by the increasing soil conservation effect of denser and more permanent vegetation due to increased water supply.

Regarding the non-concordance of the threshold of 720 mm year^{-1} and the higher degrees of erosion in the south of the Tominé reservoir (Guatavita), it could be explained by the effect of the rain shadow (leeward), which despite the high humidity (with more than 1,700 mm/year) in the upper part (2,960 m a.s.l.) of Guatavita, presents severe erosion in the lower part of the mountain (2630 m a.s.l. without rain gauges). Additionally, it should be noted that there is no clear association of the erosive phenomenon with respect to the increase in precipitation, even more so when the spatial variations of the climatic characteristics can be found in mountain areas (di Lena *et al.,* 2021; Valdés-Pineda *et al.,* 2016).

4. Conclusions

Climate changes between 1980 and 2014 with a statistical confidence level greater than 90% using the Mann-Kendall test, and the trends of the median slope with the Sen statistic, were detected. Increases in annual precipitation at El Dorado Airport (Bogotá), Silos (Chocontá), Surbatá Bonza (Duitama) and Tibaná, and decreases in Potreritos (Guatavita), were observed. Similarly, increases in the aggressiveness of rain (decadal annual maximum Modified Fournier Index -MFI_{dmax}) in Úmbita, Tibaná, Surbatá Bonza (Duitama) and El Dorado (Bogotá), with decreases in said index were detected in San Pedro de Iguaque (Chíquiza) and Cómbita.

With the application of methods for calculating the median slope and the detection of trends in rainfall aggressiveness through MFI_{dmax}, a new and useful methodology is presented for the planning and monitoring of territorial ordering against soil degradation processes due to rain erosion.

Although changes with statistical confidence levels (>90%) were found in annual precipitation and in pluvial aggressiveness (MFI_{dmax}) that can cause soil erosion, it cannot be established that greater soil degradation can be explained solely by the change climate of the above variables.

Finally, the level of soil erosion can be explained (R^2 0.519 and $\overline{R}^2$ adjusted 0.478) through a regression model based on the square of the average of the maximum annual values of the decadal Modified Fournier Indices, and the negative value of the average annual precipitation.

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