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ANALYSIS OF AGGRESSIVENESS RAINFALL IN THE FAR NORTH OF CHILE

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ABSTRACT

The far north of Chile presents characteristics of arid zones, where the rainfall it is mainly a convective origin, which leads to high intensities in a limited space and reduced time. This pattern in associated with term aggressiveness, which has been quantified through the use of indices. In the extreme north of Chile, called Norte Grande, aggressiveness has been studied small extent, but its consequences, such as mudflows, are widely know for the multiple human deaths and economic losses. The aim of this research was to evaluate the rainfall aggressiveness in Norte Grande of Chile through the use of indices, for this it was necessary to analyze the spatial behavior of aggressiveness indices and also to apply a trend analysis to examine the temporal variability of the indices. 66 gauge stations distributed in four administrative regions of Chile were used to average seven aggressiveness indices in 30 years of study. The punctual information serves to carry out a spatial interpolation by kriging for different indices. In addition, the Mann-Kendall´s test was realized to the series of annual rainfall and on two aggressiveness indices to find a tendency. The results of the research indicated that aggressiveness has an evident spatial pattern; increase in the indices from littoral zone towards the east, where the maximums were located in the Altiplano in the extreme north of the study area. Regarding the trend analysis, only signs were observed of a decrease in aggressiveness indices in the extreme north attributable to decrease in the concentration and amount of rainfall.

Keywords: Arid zones; convective rainfall; Chile; rainfall aggressiveness; concentration of rainfall

1 INTRODUCTION

Rainfall is one of the important elements of climate and directly affects the availability of water resources. In recent times, global warming has modified the pattern of rainfall on a global scale, as indicated in the report which was prepared by the Intergovernmental Panel on Climate Change (De Luis et al., 2011; Caloiero, 2014). The rainfall has been studied in depth on an annual scale but not so it´s aggressiveness; which refers to the concentration in rainfall over short periods of time (Vega y Febles, 2008). This aggressiveness of rainfall causes environmental impacts related to various natural hazards, therefore it´s important to know it´s spatial and temporal variability in order to adopt prevention and mitigation measures (García-Barrón et al., 2015).

In arid and semi-arid zones rainfall is erratic with high temporal and spatial variability (Salas, 2000). On a daily basis, the registers present a particular distribution; most days these registers do not show rainfall, while a few shows the annual amount (Sen, 2008).

In recent times the scientific community has been interested in the hydrological processes that are generated in the arid zones since that these are characterized as being fragile and also sensitive to the degradation of plants and soils (Lobo et al., 2005). To differentiate them from the processes that occur in humid areas, An Arabic word Wadi has been adopted which means ephemeral water courses. Wadis are usually caused by convective storms that develop flash floods which threaten many communities and are considered the largest source of groundwater recharge (Sen, 2008).

Convective storms in arid areas generate erosive processes, which turn out to be slow, recurrent, progressive and irreversible. Erosive processes can be grouped into energy and resistance factors, where the first is associated with the aggressiveness of the rainfall (Castelán et al., 2014). To quantify the aggressiveness, the modified Fournier index was enunciated by Arnoldus in 1977 (Angulo-Martínez y Beguería, 2009), which has been altered over the years with the aim of creating correlations with sediment transport and/or with the erosion capacity of the rainfall.

The North of Chile due to its climatic conditions of radiation, temperature and rainfall is classified as arid. In this part of the country there is a history of wadis phenomena that left trails of disaster such as loss of life and multiple economic losses, as was the case in the Atacama region in March 2015.

The objective of this study is to evaluate the aggressiveness of the rainfall in the North of Chile through the application of indexes. For this, it is necessary to produce maps that show the quantification of the indexes in order to analyze the spatial behavior. Furthermore, a trend analysis is required to examine the temporal variability of aggressiveness indexes with annual rainfall and their linkage.

2 RAINFALL AGGRESSIVENESS INDICES

The aggressiveness indexes are classified into two types: concentration indexes, which have a dimensionless output value, which moves in a limited range of values, and concentration and quantity indexes, which result in depth of rainfall (mm).
To study the transport of sediments and the erosivity of rainfall, which correspond to two important attributes in the Wadi phenomenon, the concentration and the quantity indexes have been used.

2.1 Concentration and amount indices

The concentration and the quantity indexes have their origin in the Fournier Index (IF) defined in 1960 (De Luis et al., 1997) and which shows a high correlation with the amount of sediment transported by the runoff. Subsequently the modified Fournier index was proposed which corresponds to a modification made to the IF by Arnoldus in 1977 cited by De Luis et al. (1977) It is the index most utilized in the water erosion evaluation and its relationship with the R factor of the Universal Soil Loss Equation (ULSE) has been studied.
Later other indexes with different configurations, such as the F index (Ferro, 1991, cited by Ferro and Porto, 1999), Modified Fournier- Maule Index (Cornejo, 2006, cited by Olivares, 2009), Total Erosivity Index (Vega y Febles, 2008), Annual Fournier Index (Gómez, 1991, cited by Castelán et al., 2014) and the variant of the annual Fournier index (Rey, 1996, cited by Castelán et al., 2014).
The aggressiveness indexes studied, require different input data; monthly rainfall or daily rainfall (Table 1)

Table 1. Classification of aggressiveness indeces

Daily rainfall	Monthly rainfall
Annual Fournier Index	Fournier Index
Annual Fournier Index 2	Modified Fournier Index
	Index F
	Modified Fournier-Maule Index
	Total Erosivity Index

In Table 2 shows the expressions that follow every one of the indexes.

Table 2. Equations for the quantification of aggressiveness indices

Index	Equation
Fournier index	$\mathrm{FI_j} = \frac{\mathrm{Pmax_j}^2}{\mathrm{P_j}}$
Modified Fournier Index	$\mathrm{MFI_j} = \frac{\sum_{i=1}^{12} \mathrm{P_{ij}}^2}{\mathrm{P_j}}$
Index F	$\mathrm{F} = \frac{\mathrm{Pm}}{12}\left[\frac{\sum_{j=1}^{N} \mathrm{P_j}(1+\mathrm{CV}^2(\mathrm{p_{i,j}}))}{\sum_{j=1}^{N} \mathrm{P_j}}\right]$
Modified Fournier-Maule Index	$\mathrm{MFMI_j} = \frac{(\sum_{i=1}^{12} \mathrm{P_{ij}})^2}{\mathrm{Pm}}$
Total Erosivity Index	$\mathrm{TEI_j} = \mathrm{IMFj} \cdot \mathrm{ICPj}$
Annual Fournier Index	$\mathrm{IdF} = \frac{\mathrm{Pm_{pd}}^2}{\mathrm{PT_{pd}}} \qquad \mathrm{AFI} = \sum_{i=1}^{i=36} \mathrm{IdF_i}$
Annual Fournier Index 2	$\mathrm{IdF'} = \frac{\sum_{i=1}^{n} \mathrm{Pm_i}^2}{\sum_{i=1}^{n} \mathrm{Pm_i}} \qquad \mathrm{AFI2} = \sum_{i=1}^{i=36} \mathrm{IdF'_i}$

Where $\mathrm{Pmax_j}$ is the monthly rainfall within a year, j in mm, P_j is the annual rainfall j in mm, P_{ij} corresponds to the monthly rainfall i in the year j(mm) Pm is the average annual rainfall(mm) In the N years of study, $CV(p_{i,j})$ refers to the coefficient of variation of monthly rainfall, Pm_{pd} is the maximum daily rainfall within the decadal period in mm and Pm_i refers to the average daily rainfall of the day i within the decadal period.

For some of these indexes; FI, MFI, TEI and IFA, classification ranks are defined where a level of aggression is associated with the value obtained. (Castelán et al., 2014; Lobo et al., 2005; Vega and Febles, 2008). (Table 3)

Table 3. Classes of aggressiveness indices

FI	MFI	Classification	TEI	Class description	AFI	Degree of aggressiveness
<15	<60	Very low	<1500	Low	<140	Mild
15-30	60-90	Low	1500-2500	Moderate	140-210	Low
30-50	90-120	Moderate	2500-5000	High	210-280	Medium
50-65	120-160	High	>5000	Very high	280-350	High
>65	>160	Very high			>350	Very high

3 METHODS

3.1 Study area and database

The study area corresponds to the so-called Norte Grande of Chile which includes the regions of Arica and Parinacota, Tarapaca, Antofagasta and Atacama which are located from 17.5 to 29.3 south latitude.
The atmospheric circulation develops a high pressure area in a large part of the study area (up to 26 south latitude) which causes slow displacement of the west winds of medium and high latitudes. The above is reflected in the almost immobility of the system in general, which has the effect of acting like a block to the approach of the frontal systems, which are forced to divert their trajectory (DMC, 2010).
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Rainfall information was obtained from two sources, which correspond to that provided by the General Water Directorate (DGA) and the Chilean Meteorological Directorate (DMC). Both sources presented daily rainfall records which makes it possible to build and/or have the monthly and annual records too.
Then a pre-process of rainfall information was carried out, where a 30 year analysis period was considered, since MOP-DGA (1987) indicates that it turns out to be a period that´s sufficiently representative of the average hydrological conditions.
Lobo et al (2005) point out that the first analysis that must be carried out is to verify that the observations are consistent, that is, that the station remained in the same conditions without changing instrumental or conditions of the property. Once the consistency is verified, the filling of missing information is done either because the data was not observed or because it is known to be erroneous. In the study area, characterized by being a climatic zone of the arid type, rainfall is erratic and very variable in time and space. (Salas, 2000). In addition, climatic patterns are forced by low-scale orographic effect and the occurrence of convective rainfall in time intervals and limited spaces (Sen, 2008). Considering the above, it was decided to omit the consistency and filling analysis procedures, since the assumptions that follow the methodologies are not met, so that it is prone to obtain rainfall over a wide range of values.
The procedure followed was to pre-process the rainfall data to establish the number of stations that will be considered in the study. Since the filling was omitted the rainfall series were mostly incomplete. To determine the years that were entered the study, a minimum time of nine months with all information was required and the remaining three months were accepted according to a statistical procedure, which accepts the records if it is more than 20 days measured or if the measured rainfall is not less than the historical average minus the standard deviation of the month analyzed.
Finally, a total of 66 rain gauge stations were obtained, whose distribution by region is presented in Table 4.

Table 4. Distribution of rain gauge stations

Region	DGA stations	DMC stations	Total
Arica y Parinacota	16	1	17
Tarapacá	10	1	11
Antofagasta	19	2	21
Atacama	17	0	17

In Figure 1 it shows the study area, its location and digital elevation, and in blue points the spatial distribution of the stations studied is presented.

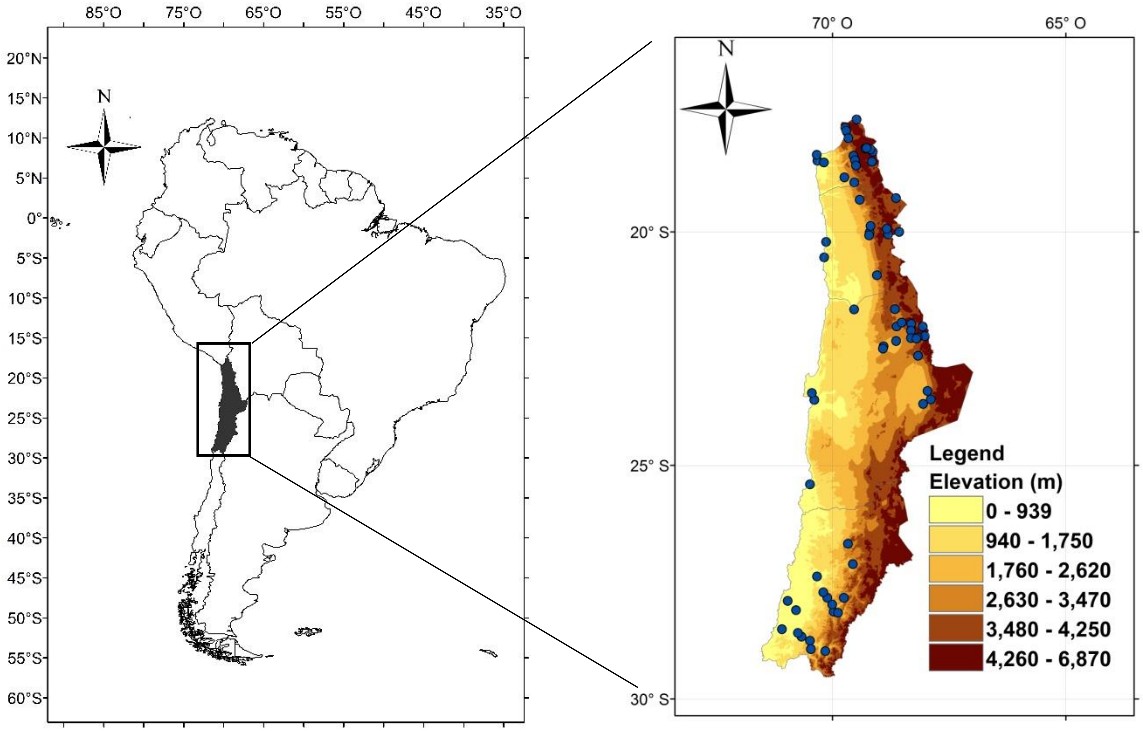


Figure 1. Study area and spatial distribution of rain gauge stations

3.2 Application of aggressiveness indices

At the 66 stations that were selected, the seven aggressiveness indexes studied were then applied. It was noted that there are indexes where only 1 value was obtained for the study period as it is for the F index and the Fournier index (variant) while for the rest of the indexes a value was extracted for each year where it was considered complete information.

3.3 Mapping

The spatial interpolation of the kriging type was performed for the seven indexes under study. Two types of maps were generated; the first consisted in classifying in colour scale according to the ranges proposed in bibliography. The second type of map was made for the seven indexes of aggression and consisted of classifying the data into five ranges using the natural breaks method (Jenks) which according to ESRI (2010) creates class cuts that are characterized by better grouping similar values and maximize differences between classes.

3.4 Linkage between aggressiveness indices and annual rainfall

For the development of the linking analysis, the modified Fournier index and the annual Fournier index were selected. The Mann-Kendall (MK) test, which corresponds to a nonparametric statistical test based on ranges, was used for the annual rainfall series and for the two defined indexes and is used by several researchers to detect trends in rainfall data (Chatterjee et al, 2016)
From the results of the application of the M-K test, the main focus was to identify the opposite tendency between aggressiveness and annual rainfall, that is, positive trends in some indexes and negative tendency in annual rainfall amount or vice versa.

4 RESULTS AND DISCUSSION

4.1 Aggressiveness indices

In Table 5 it shows the maximum and minimum values obtained for each index under study and the respective rainfall stations where they were obtained.
It was observed that the maximums were located in two stations in the Altiplano of the Arica and Parinacota region in the vicinity of Chungará Lake while the minimums in two stations in the coastal zone.

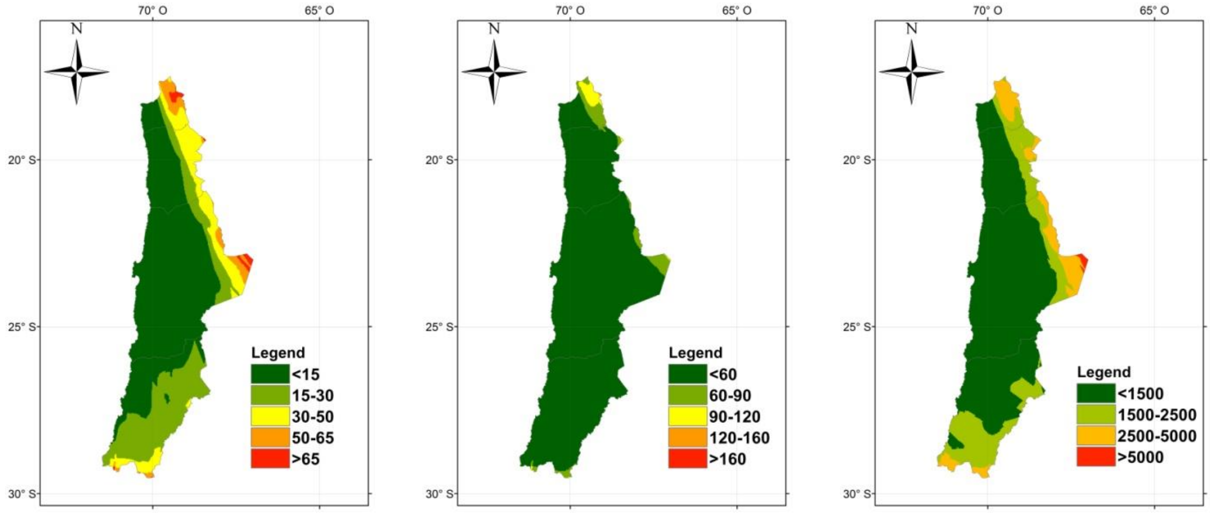
Table 5. Extreme values of the aggressiveness indeces

Index	Maximum	Minimum

	Value	Station	Value	Station
FI	68.0	Chucuyo Retén	0.3	Quillagua
MFI	110.3	Chucuyo Retén	0.3	Quillagua
Index F	120.9	Chucuyo Retén	2.7	Arica Oficina
MFMI	405.7	Chungara Ajata	2.9	Quillagua
TEI	3834.4	Chucuyo Retén	145.2	Quillagua
AFI	68.7	Chungara Ajata	0.2	Quillagua
AFI2	44.5	Chucuyo Retén	0.2	Quillagua

4.2 Maps of categorized aggressiveness indices

For the indexes that were classified according to categories, corresponding to the IF, IMF, EIT and the two variants of the annual Fournier index, maps were generated, which are shown in Figure 2.



a) FI b) MFI c) TEI

Figure 2. Spatial distribution categorized indeces

From what was obtained from the application of the indexes and the generation of maps it was possible to construct Table 6, which shows the percentage of stations and percentage of the study area that was classified according to the different categories defined in the bibliography.

Table 6. Percentage distribution according to classification ranges

Classification	FI		MFI		Classification	TEI	
	% S	% A	% S	% A		% S	% A
Very low	33.3	60.0	81.8	94.8	Low	47.0	70.5
Low	34.8	25.0	12.1	3.9	Moderate	28.8	20.7
Moderate	18.2	11.0	6.1	1.3	High	24.2	8.4
High	10.6	3.2	0.0	0.0	Very high	0.0	0.4
Very high	3.0	0.9	0.0	0.0			

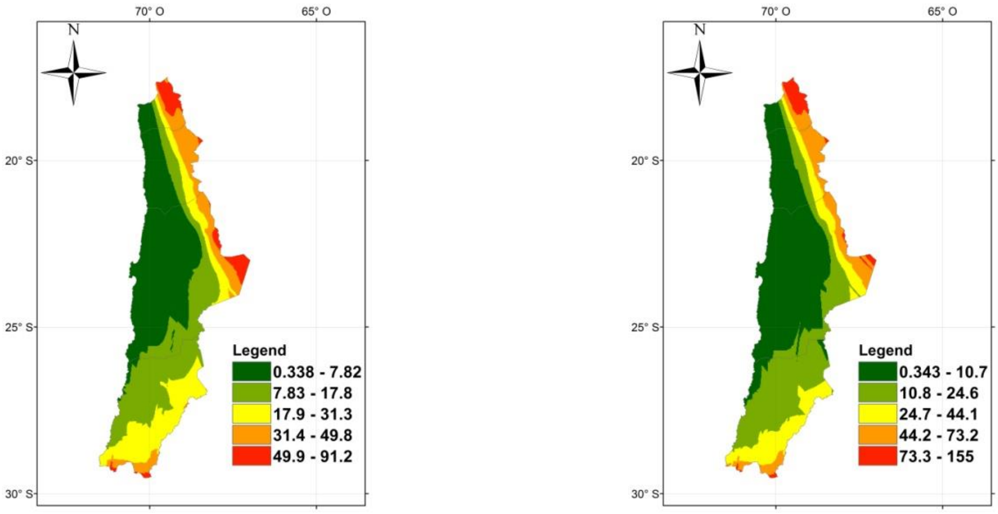
Where the %S refers to the percentage in stations and %A refers to the percentage in surface.

When paying attention to the values, similar situations were presented in terms of stations and interpolated area; a large part of the area was classified in low levels of aggressiveness and small portions showed comparable values with high aggressiveness, which corresponds to the Altiplano of the Arica and Parinacota region.

It was not necessary to include annual Fournier indexes in the analysis, since it was observed that the entire surface was classified with low aggressiveness. Here we can conclude that the aggressiveness is slight in the whole study area, which would suggest that rainfall on a daily time scale is not aggressive, which turned out to be a wrong conclusion considering the convective origin of the rain and what was shown by the other indexes (IF, IMF and EIT). It is possible then that the classification used for the annual Fournier indexes is not applicable to the Norte Grande.

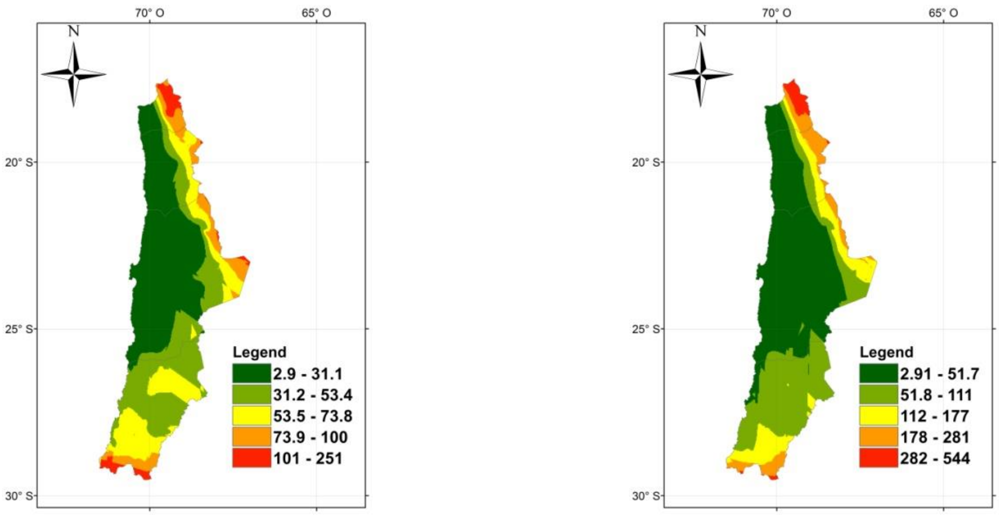
4.3 Maps of aggressiveness indices by class

From Figure 3 to Figure 4 the maps are shown of the seven indexes of aggressiveness under study, which were classified according to the method of natural raptures. In the colour scale, the aggressiveness increases from green to red.

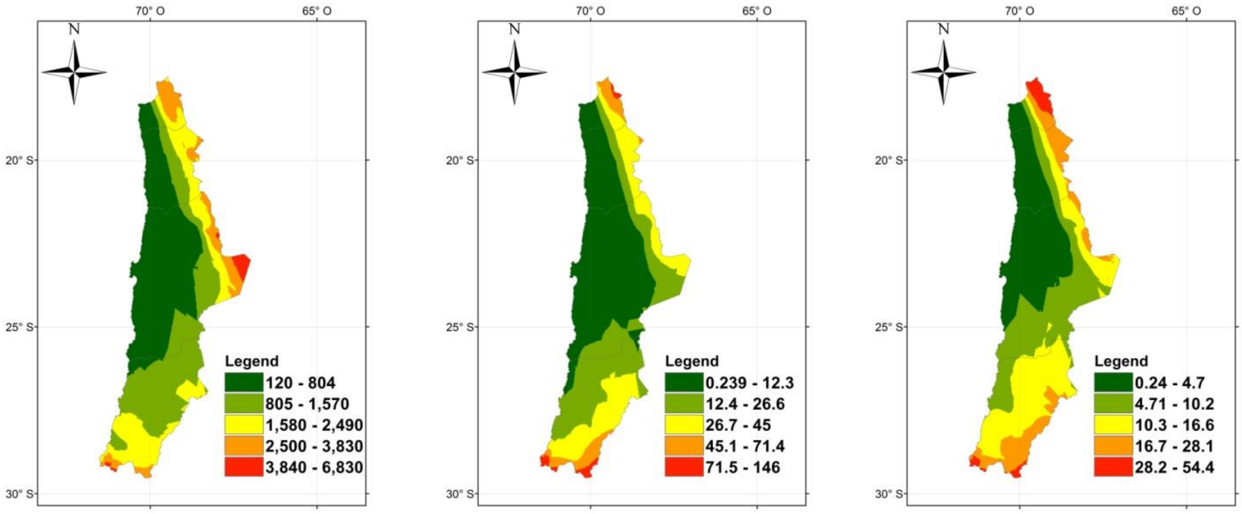


a) FI b)MFI

Figure 3. Spatial distribution of aggressiveness indices



a) F b) MFMI



c) TEI d) AFI e) AFI2

Figure 4. Spatial distribution of aggressiveness indices

When comparing the maps made, a quite similar behavior was observed, where a strip of the fir-green appeared, which covered the northern end of the study area until near the border between the regions of Antofagasta and Atacama and which extended from the coast area to places well inside the continent, the maximum amplitude being south of the city of Calama. Then there are stripes of leaf green and yellow, in the first three regions they were located closer to the area of the highland and had less spatial amplitude than the green fir while in the Atacama region, they were presented from the coastal zone and encompassed almost the entire surface, with different proportions for each of the indexes.
The orange and the red stripes appeared in the Altiplano with much smaller areas compared to the other three mentioned. In six of the seven indexes compared, the range characterized by greater aggressiveness was located in the high zone of the Arica and Parinacota region while in the total erosivity index it was obtained in the extreme east of the Antofagasta region. The other area that also presented orange and red surfaces is the southern end of the study area, where an increase in aggressiveness was observed due to the influence of the frontal origin rainfall.

4.4 Trend analysis

Table 7 shows the seasons in which the indexes and the series of annual rainfall present a tendency with a level of significance of 0.05.

Table 7. Series with tendency according to Mann Kendall test

Serie	Trend	Station	Region
MFI	Increasing	Villa Industrial (Tacora)	Arica y Parinacota
AFI	Decreasing	Chungara Retén	Arica y Parinacota
AFI	Decreasing	Chungara Ajata	Arica y Parinacota
AFI	Decreasing	Guallatire	Arica y Parinacota
AFI	Decreasing	Central Chapiquiña	Arica y Parinacota
AFI	Decreasing	Huaytani	Tarapacá
AFI	Decreasing	Ojos San Pedro	Antofagasta
Anuual rainfall	Increasing	Villa Industrial (Tacora)	Arica y Parinacota

It was decided to generate Figure 5, which shows the locations where the series presented a trend.

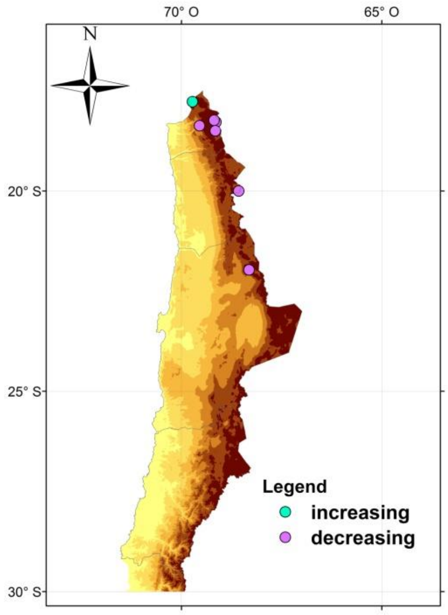


Figure 5. Spatial distribution of stations with series showing trends

The series of aggressiveness presented only a downward trend and were preferably located in the high zones of the study area, concluding that the aggressiveness is decreasing in the stations where the highest values were obtained. This trend is not clear given that there are only two indexes of a limited number of stations.
The other relevant aspect that was observed is that only in a season of the 66 under study showed a tendency in the annual rainfall, thus it was concluded that there is no opposite tendency between the annual amount of rainfall and aggressiveness. It is possible to conclude that the tendency to decrease aggressiveness is due to a synergistic effect of the decrease in concentration and annual amount of rainfall.

5 CONCLUSIONS

In the application of aggressiveness indexes in the Norte Grande of Chile, it was observed that the indexes covered the different categories proposed in the bibliography. The vast majority of the stations, from 47.3% to 93.9% according to the different indexes and a large portion of the study area (over 90%) were classified as low aggressive. The fraction of the study area that was classified with high aggressiveness is due to the higher magnitude of the indexes in the stations that are located in the vicinity of the Chungará Lake, which is explained by the convective origin of the rainfall that affects important amounts of rain on the high plateau in the months of January and February.
On the other hand, in the index maps, according to the natural raptures, the aggressiveness pattern was observed, where the greatest changes were located in the West-East direction. The indexes showed a wide homogenous zone of low aggressiveness in the coastal zone, which is increasing towards the east where the class ruptures, denoted a rapid growth of aggression at its maximum and relatively homogenous in the Altiplano of Arica and Parinacota region. This spatial pattern is quite similar to the rainfall pattern that is present in the study area, ranging from zero values in the coastal zone to more than 300mm per year in the highland zone. This suggests that the quantification of aggressiveness is mostly influenced by the amount of rainfall, above the concentration.
The link between aggressiveness and the annual rainfall that was made through the application of the Mann-Kendall test showed that there is no temporal trend between the two. Only a small decrease in aggressiveness indexes was exhibited in the highland zone, where it was concluded that it is due to a synergistic effect of the decrease in concentration and the amount of rainfall.
It is concluded that aggressiveness rainfall occurs with certain frequency and there are no clear indications about a possible tendency in their behavior. Therefore, the incipient preoccupation with the Wadis phenomena must consider all the historical information in order to try to correlate natural catastrophes with important registered rainfall.

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