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Adaptation of the Thornthwaite Humidity Index for The Characterization of Annual Water Situations

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Abstract:- Dry and humid periods constitute one of the climatic phenomena with the greatest impact on hydrology and agricultural activity in the Pampas region of Argentina.

In this work, a characterization of drought and wet events for annual periods was made in Azul, Buenos Aires, applying the Moisture Index to the Serial Hydric Balance (BHS).

The analysis of the series (1988-2017) confirms a definite trend with consistent results in the three applied methods, which shows a sustained increase in the presence of dry years (negative humidity index). However, when working with decadic periods, the last decade shows a trend break (8 dry years), which was statistically significant between the humidity index (HI) and the two contrasting variables.

Finally, the application of the IH was an appropriate tool when analyzing the complexity of droughts and water excess for annual periods, arising from the BHS.

Keywords:- *Humidity Index, Series Water Balance, Annual Water Situations.*

I. INTRODUCTION

Climate change is already affecting agricultural systems in several regions of the world. The reports of the Intergovernmental Panel on Climate Change (2014) include a list of agroecosystems with sufficient scientific evidence of such effect (Confalone et al. 2017).

Since 1980, there has been a marked variation in the behavior of some meteorological phenomena in the central-south area of the Province of Buenos Aires, translated into an increase in the frequency and intensity of rainfall, droughts, severe storms, etc. (Vilatte et al. 2017). These changes are not only observed at a local level, but they are progressively modifying the spatial pattern that characterized such phenomena covering all continents, which means that it is seriously considered as a climate modification at a global scale. In accordance with this, Mishra and Singh (2010), consider that in recent years, floods and droughts have experienced higher peaks and higher levels of severity. Among these changes, droughts are of great concern, they represent a climatic adversity of regional characteristics, originated by an abnormal decrease of rainfalls, it is a complex and recurrent phenomenon that manifests slowly and affects people, economic activities, the environment, and can even interfere in the social and economic development of towns. According to the World Meteorological Organization (WMO) and the World Water Association (2016) there may not be another danger that lends itself so much to being followed up, since its slow appearance makes it possible to observe the changes in the precipitation, the temperature and the general situation of surface water and groundwater reserves in a region. Indicators or drought indices are used on many occasions to facilitate the monitoring of droughts, and vary according to the region and the season.

Drought is a transient anomaly and in this differs from aridity, which is a permanent feature of climate. Therefore, could be defined as a gradual phenomenon, which can last many years and have devastating socioeconomic, agricultural, livestock and environmental effects, which can be the result of one or more of the factors of water scarcity, such as insufficient rainfall, high evapotranspiration and overexploitation of water resources (Al-Qinna,*et al.*, 2010).

As already mentioned, dry and humid periods are an aspect of climatic variability and constitute one of the climatic phenomena with the greatest impact on hydrology and agricultural activity in the Argentine Pampean region (Bohn *et al*., 2011), and due to the characteristic that the Buenos Aires province territory presents: more than 90% of its surface corresponds to flat environments, which gives it a particular hydrological condition such as the predominance of vertical movements of water (evapotranspiration - infiltration) over horizontal (runoff) (Kruse y Laurencena, 2005). This process is accentuated in the Depressed Pampa, generating floods due to the difficulty in the evacuation of excess water.

In agronomic engineering, it is important to minimize risks in the production processes for the zoning of crops, characterization of droughts, determination of sowing seasons, irrigation scheduling and identification of drainage needs. One of the best ways to know the water regime is by means of a Climatic Hydric Balance (BHC), established by Thornthwaite & Mather (1955), being applied at present by diverse authors (McCabe & Markstrom, 2007; Sharma et al. 2010; Ruiz Alvarez et al. 2012). However, it is known that this procedure does not consider the interannual variability of the climate, specifically of precipitation, so the occurrence of eventual deficits in humid or excessive regions in arid or semi-arid regions, as well as the variation in their magnitude in very wet or very dry years, they would not be identified by this type of balance (Lozada and

Sentelhas, 2003). In that sense, Pascale and Damario (1977) indicate that the climatic hydrological balance is insufficient when it is required to know the probabilities of occurrences of deficits or excesses of a given region, suggesting as a solution the use of the serial hydrological balance.

Thornthwaite (1948) is a great advance over other classifications since it departs from the climate that affects the soil and the plant, *i.e.*, evaporation, transpiration and water available in the soil; instead of monthly averages of classical meteorological parameters. This classification considers an agricultural application by incorporating soil variables and hydrological cycle flows represented mainly by evapotranspiration of crops (Rolim et al. 2007), with which the water supply (precipitation) and the climatic demand of water for a relative area (evapotranspiration) are the main factors that control the appearance and persistence of drought conditions. This methodology makes it possible for climates to be ordered according to the degree of soil moisture, taking into account the water needs of crops (evapotranspiration); and the results of the BHC, such as excess and deficit, and thus determine the water or moisture index (Ih) (Olivares et al. 2018). In this way, the Ih is defined by the climatic elements that influence the inputs (precipitation) and the water outlets of the system such as evapotranspiration and excess (surface runoff and percolation), allowing to know the availability of moisture for vegetation. The positive values of the Ih indicate humid climate with excess water, while negative values indicate arid climate with a deficit of humidity. A value of zero is proof that there is a balance between annual precipitation and the demand for humidity in the environment (McCabe & Wolock, 1991, Ruiz-Alvarez et al. 2012).

The drought indices were developed to reduce the number of variables that intervene in a drought to a simple number with the purpose of defining and comparing their characteristics (Castillo-Castillo et al. 2017), in this work we tried to adapt an index to an agricultural application, for this reason, we analyze the possibility that the humidity index (Ih), which begins the analysis to Thornthwaite (1948), performs its climatic characterization, can be used in in annual terms when applied to the BHS results, and in this way analyze the annual variation of the different possible water situations.

The objective of this work is the characterization of drought and humidity events for annual periods, and to analyze water trends in the city of Azul, located in the south-central part of the Province of Buenos Aires, Argentina, applying the index of humidity to the series water balance (BHS).

II. MATERIALS AND METHODS

For the analysis, rainfall series of two rainfall stations were used in Azul (lat.: 36º45'S, long.: 59º 50'W), covering a period of 30 years, from 1988 to 2017. The series of precipitations mentioned, corresponding to the town of Azul, was generated by the National Meteorological Service (1988-1991) and the Regional Center for Agrometeorology (CRAGM) (1992-2017) under Facultad de Agronomia – Universidad Nacional del Centro de la Provincia de Buenos Aires (UNCPBA). Hellmann pluviometers were used under the standards issued by the WMO. The homogeneity of the two series (1988-1991 of the SMN and 1992-2017 of the CRAGM), with a distance between the two points of 3 km, was based on the particular characteristics of the Salado River basin, with the presence of a flat topography , with very little slope, placing it among the regions of the world with minimal morphogenetic potential (Tricart, 1973); and that the two stations were installed in said area, on natural, undisturbed soil, already referenced in another work (Vilatte et al. 2008).

➢ *Study Zone*

The relief of the district of Azul (36° 13' to 37° 26' of Lat. S and between 59° 09' and 60° 13' Long. O) is of a contrasting nature, varying from the flat-concave relief of the Depressed Pampa (PD) to the north, to the positive relief defined by the hills and piedmont of Tandilia in the southern sector. However, in its greater area it responds to the physiography of the PD, where it is common to find waterlogging (temporary saturation of the subsoil) and, less frequently, extended floods. It presents a humid temperate climate without dry season with oceanic influence of the Cfb type (Köppen, 1931) characteristic of the central-eastern region of the province of Buenos Aires. The average annual temperature for the center of the district is 14.3 °C, with the average record of the warmest month as 21 °C, and 7.6 °C being the coldest month.

The region is part of a regime of Isohigro type rainfall, with a historical average for this place of 858.2 mm per year and a standard deviation of 189 mm, with extreme values that present a minimum annual record of 487.8 mm and a maximum of 1470.2 mm.

➢ *Hydric Balance*

To estimate the reference evapotranspiration (Doorembos & Pruit, 1977), the procedure proposed by Penman-FAO (1948) was used.

In the determination of the water balance the Thornthwaite & Mather (1955) methodology was followed. This method is based on the fact that the loss of water by the evapotranspiration process is directly proportional to the water content in the soil, assuming that evapotranspiration varies linearly with the storage of water in the soil, therefore, for the calculation of storage (ALM) the mathematical expression proposed by Mendonça (1958) was used. In which:

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$NA = CAD \,.\, \ln (ALM / CAD)$
$ALM = CAD \,.\, e^{(NA / CAD)}$

This equation replaces the tables presented by Thornthwaite and Mather (1957), allowing the calculation of the ALM for any value of available water capacity (CAD) (Pereyra et al. 1997).

The available water capacity (CAD, mm), which represents the maximum storage of useful water for the reference crop, was estimated at 140 mm for a typical Argiudol soil, present in the agricultural zone of the district of Azul (Center Agrometeorological Bulletin of center-south of the Province of Bs. As.) (CRAGM).

Water deficiency (DH) is defined as the difference between the reference evapotranspiration and the actual evapotranspiration.

➤ *Calculation of Serial Monthly Hydric Balance*

Originally the calculation was made from the rainfall and potential evapotranspiration (EP) estimated by the Thornthwaite method. However, as the Thornthwaite method underestimates the reference avapotranspiration value (ET_0) with respect to that calculated with Penman-FAO (1948), for the different seasons of the year in the center of the Province of Buenos Aires (towns of Azul and Olavarría) (Navarro, et. al. 1996). This is because Thornthwaite only considers the monthly average temperature of the air, and as it is demonstrated that there are other variables that contribute actively in ET_0 (global radiation, wind and air saturation deficit), for this reason in this study it was replaced by the Penman-FAO method (1948). This is consistent with that expressed by Pascale and Damario (1977), when they formulated the basics of the monthly BHS, where they advise that all BHS applications reach their maximum utility when computing estimates are considered tighter EP estimates and real capacity values of storage for each particular case.

There are different methods for calculating BHS (Palmer 1965, Pascale & Damario 1977), which differ from each other according to whether some are divided into several layers in the soil and others take the soil as a continuous profile. In this work the last case was considered, consisting of a simplification and adaptation of the monthly balance system proposed by Thornthwaite and Mather (1957), accompanied by an analytical methodology for the interpretation of the results and their adequate expression for agroclimatic purposes (Pascale & Damario, 1983). The operational details of the BHS are found in the reference publication, so it is considered necessary to specify here only those aspects considered for this particular application and the way they were included in the electronic computing system prepared for this purpose (Sierra, 1979).

In the BHS, balances are calculated with all years of data for each year, so that as many meteorological balances as years of information available are obtained.

Although the rainfall regime of the study area is Isohigro, the balance began in the winter months of 1987, where maximum records of useful or available water were achieved, because this balance must start from a period in which the storage is full, this is ALM = CAD (Pereyra et al. 1997).

➤ *Humidity Index*

The humidity index (IH) relates the excess and deficit with the evapotranspirative demand of the environment, which provides a clear description of the climate (Thornthwaite 1948). The equation that describes this relationship (Ruiz-Alvarez *et al.* 2012) is:

$$IH = 100\ (EXC\text{-}DEF) / ET_0$$

Where: IH = humidity index (%); EXC = excess water (mm $year^{-1}$); DEF = water deficit (mm $year^{-1}$); ET_0= reference evapotranspiration (mm $year^{-1}$). In this work, the climate classification scale used by Thornthwaite was modified (Table 1), which allowed to characterize the climates, in order to be applied to annual periods (Table 2), in order to be able to analyze water situations for this last period (deficit and excess) using the outputs of BHS in the town of Azul (36° 45' 59" S, 59° 52' 54" W, 137 masl).

Water situation	*Humidity index (%)*
A Perhumid	> 100
B4 Humid	80 a 100
B3 Humid	60 a 80
B2 Humid	40 a 60
B1 Humid	20 a 40
C2 Humid subhumid	0 a 20
C1 Dry subhumid	-20 a 0
D Semiarid	-40 a -20
E Arid	-60 a -40

Table 1:- Climate Classification

Water situation	*Humidity index (%)*
A Perhumid	> 100
Very humid	80 a 100
Humid	60 a 80
Humid Mod	40 a 60
Levem Humid	20 a 40
Humid subhumid	0 a 20
Dry subhumid	-20 a 0
Dry	-40 a -20
Very dry	-60 a -40

Table 2:- Characterization of Droughts and Annual Water Excess.

There are several methods for analyzing trends in climate data series. For the analysis of the IH, which is not normally distributed, we opted for the non-parametric estimation method, such as Spearman's Rho test, which calculates the correlation coefficient of the ranges. To achieve an adequate methodological approach, the simultaneous use of different methods, such as linear correlation or the Sen method (Martínez– Austria, et al. 2014) and the application of the regression analysis to the order number of the ranges of the Rho test of Spearman is pertinent. The method of Sekai Sen (Sen, 2012), although it can not quantitatively estimate the magnitude of the trend, allows to determine with certainty its existence. It has the advantage of not being statistical and allows to observe graphically the existence of some trend in the series studied. The foundation lies in the fact that if two time series are identical, the graph of one with respect to the other will show a specific distribution of points on a line of 45° in a plane of Cartesian coordinates, and this trend will be more marked the more the data pairs of the 45° line are separated. The original data series is taken and subdivided into two portions with respect to time, and ordered in descending order. The first half of the series is selected as the axis of the ordinates and the second as the abscissa axis and a scatter diagram is drawn. The graph will show an upward trend if the points of the graph are located in the upper quadrant of the line; otherwise, if these points are located in the lower quadrant, there is an upward trend.

For climate data series, the statistic (ρ_S) of the Spearman Rho test (Z_{SR}) is expressed in the following equation:

$$\rho_S = 1 - \frac{6\sum d_i^2}{n(n^2-1)}$$

Where d_i is the difference between the ranges of X and Y of the ith observation and n is the number of data in the sample.

The standardized statistic Z_{SR} is given by the equation:

$$Z_{SR} = \rho_S \sqrt{\frac{n-2}{1-\rho_{S^2}}}$$

The null hypothesis indicates that there is no trend in the series. If the observed data $Z_{SR} > t_{(n\text{-}2,1\text{-}\alpha/2)}$, then the null hypothesis is rejected and there is a tendency in this series.

In this equation, $t_{(n\text{-}2,1\text{-}\alpha/2)}$ is the value of the t statistic in the table of the student's t distribution for an α level of significance.

III. RESULTS AND DISCUSSION

Natural temporal variability in the climate contributes to the uncertainty in the detectability of the effects of climate change in wet conditions. Therefore, according to McCabe & Wolock (1991), any potential trend in wet conditions resulting from climate warming will be inferred in a "noisy" time series due to the random variability in both variables (precipitation and temperature). The HI has a strong component of these variables, and is affected above all by the lack of normality of rainfall, which is why we had to resort to non-parametric methods to analyze its trend. The graph obtained by applying the Sen method allows to observe that the points are located above the 45° line, both for the negative values as well for the positive values of the IH, which indicates a clear upward trend in terms of succession of dry years for the series analyzed (figure 1).

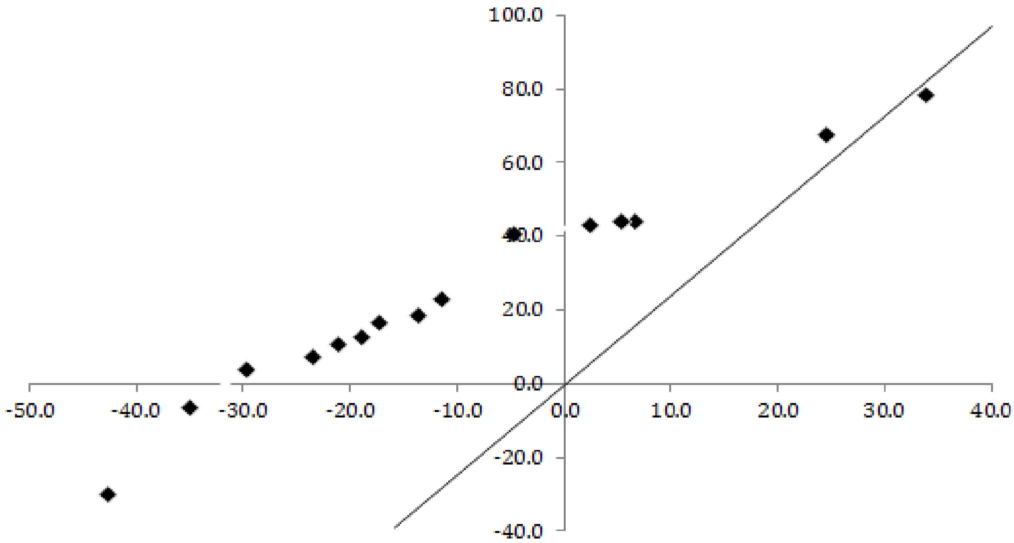

Fig 1:- Trend using the dispersion diagram, Sekai Sen method (Sen, 2012) for the period 1988-2017.

Application of Spearman's Rho method (RS), confirms the result obtained by the Sen method, therefore, indicates the existence of a statistically significant trend in the series for the three decades analyzed (Table 3), when considering the pairing of the variables IH and annual precipitation (Pa), and IH and annual water deficit (Dh), because the observed values are greater than those of the t statistic of the student's t distribution for α levels of 0,05 of significance ($Z_{SR} > t_{(n\text{-}2,1\text{-}\alpha/2)}$).

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Variable	ρ_S	Z_{SR}	t(n-2.1-(α/2))	Trend
Dh	-0.828	6.478	2.048	yes
Pa	0.839	6.842	2.048	yes

Table 3:- Values obtained by Spearman's Rho method for the period 1988-2017.

In agreement with what was found in the application of the RS test, when a linear regression was applied to the ranges of IH vs. Pa and IH vs. Dh, it resulted in both tendencies being favorable with significant and identical p-values (0.0000) (figures 2 and 3).

When applying the median (Mna) to the IH ordered for that series, it rendered a value of 6, which corresponds to a humid subhumid hydric situation.

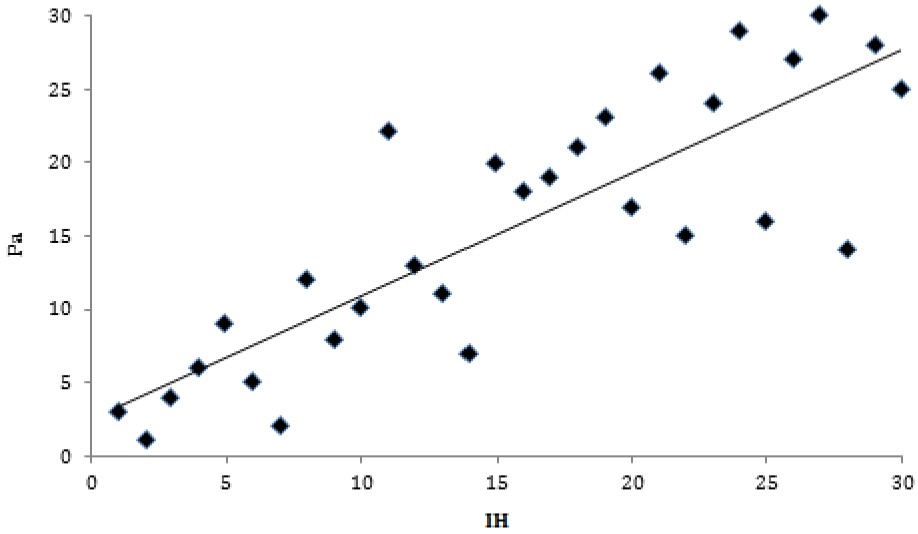

Fig 2:- Linear trend of the ranges of IH vs. Pa for the 1988-2017 series.

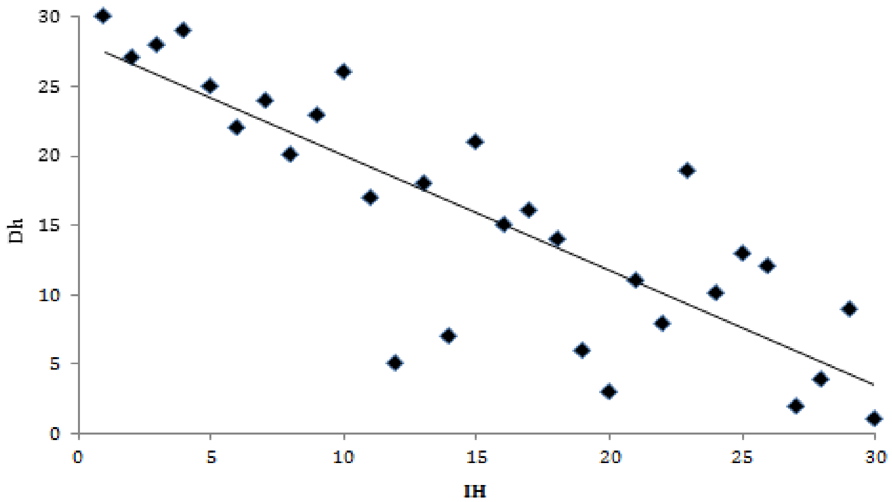

Fig 3:- Linear trend of the ranges of IH vs. Dh for the 1988-2017 series.

However, climatic trends may be masked by the occurrence of some shorter climate phenomenon (Martínez-Austria, et al. 2014), so the RS test and linear regression analysis (ARL) were applied simultaneously to each of the decades (1988-1997, 1998-2007 and 2008-2017).

Variable	ρ_S	Z_{SR}	t(n-2,1-(α/2))	Trend
Dh	-0.757	2.486	2.306	yes
Pa	0.466	0.696	2.306	No

Table 4:- Values obtained by the RS method for the period 1988-1997.

The values in table 4 show a lack of significance in the trend of the HI with respect to Pa, for the first decade. This is due to the fact that in this period there is a greater variability in rainfall records, despite being the decade with the highest rainfall, where the HI was positive in 8 of the 10 years. This lack of tendency can be verified in figure 4, when the ARL was applied to the ranges of HI vs. Precipitation, resulting in a p-value of 0.1739 greater than α (0.05).

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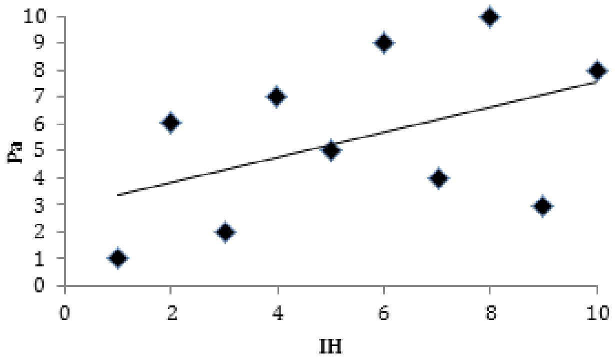

Fig 4:- Linear trend of the IH vs. Pa ranges for the 1st decade.

On the other hand, in terms of Dh it appears positive with an α of 5% (table 5), showing a significative tendency. In the same sense, the ARL showed a p-value (0.0111) confirming its significance (figure 5).

The Mna of the IH ordered for the first decade gave a value of 17.4; which corresponds to a humid subhumid hydric situation.

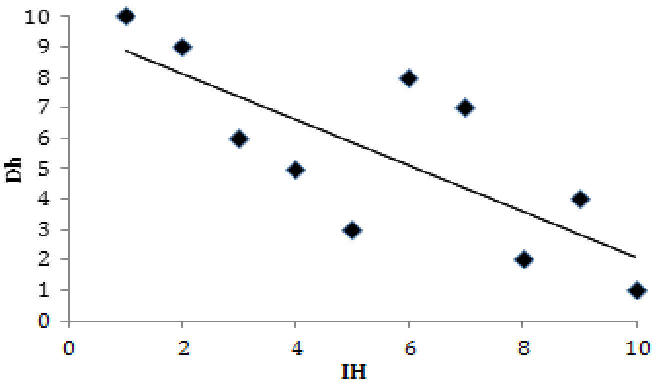

Fig 5:- Linear trend of the ranges of IH vs. Dh for the 1st decade (1988-1997).

Variable	ρ_S	Z_{SR}	$t(n\text{-}2,1\text{-}(\alpha/2))$	Trend
Dh	-0.648	1.562	2.306	No
Pa	0.915	5.876	2.306	yes

Table 5:- Values obtained by the RS method for the period 1998-2007.

The period 1998-2007 (table 5), was also a period with a predominance of wet years (7 out of 10), with a significant trend between the variables Pa and IH, with a value of Z_{SR} that is higher than that of t, which is corroborated with the ARL, which showed a p-value of 0.0005 (Figure 6).

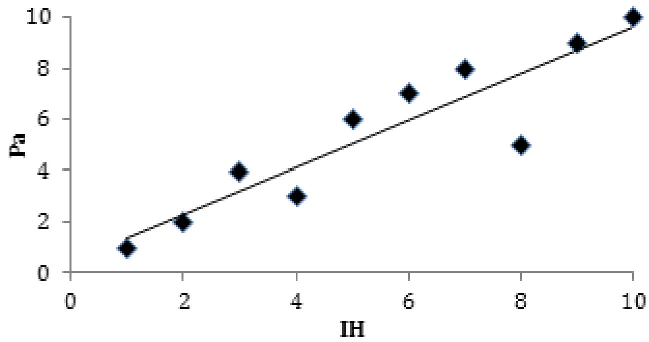

Fig 6:- Linear trend of the IH vs. Pa ranges for the 2nd decade (1998-2007).

However, in contrast to what was previously found between the variables Pa and IH, for this same decade, a lack of significance was observed in the association of the variable Dh, with respect to the IH, where in the RS test the value of Z_{SR} is lower than t (table 5). This is associated with the presence of an anomalous value (year 2006) very infrequent for the area analyzed (figure 7), where there was a strong winter drought in July, August and September, not being reflected in the total of the annual precipitation (825 mm) with respect to the median (840.1 mm) and the annual average (850.4 mm) of the series analyzed (1988-2017), due to the fact that it is the least rainy period of the year, and contrary to the months of January and February which were well above the median. The above gave rise to a very low value of the range of Dh with respect to that of the IH, which has to be opposite for that variable. In contrast to the latter, in the result of ARL of the ranges, the trend reaches to be significant with a p-value of 0.0425.

The Mna of the IH ordered for this decadic period granted a value of 7, which corresponds to a humid subhumid hydric situation, however it shows a downward trend with respect to the previous decade (17.4).

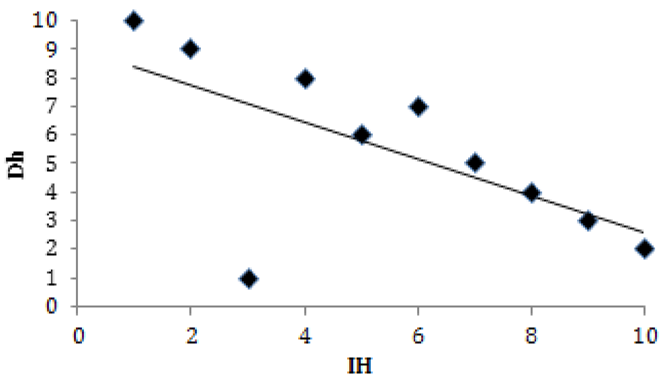

Fig 7:- Linear trend of the ranges of IH vs. Dh for the 2nd decade (1998-2007).

As for the last decade (2008-2017), there is a strong break in the values of the HI, yielding 8 years with negative values. In this period a definite trend is observed in both variables (Pa and Dh) with respect to the IH (table 6), which agrees with the trend lines (figures 8 and 9) with p-values of 0.0001 and 0.0005, respectively, for the paired variables (Pa vs. IH and Dh vs. HI).

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The Mna of the IH ordered for the last decade gave a value of -19.2; which corresponds to a subhumid dry hydric situation, showing a notable decrease, corroborating the downward trend.

Variable	ρ_S	Z_{SR}	$t(n$-2.1-$(\alpha/2))$	Trend
Dh	-0.8909	4.942	2.306	yes
Pa	0.939	7.280	2.306	yes

Table 6:- Values obtained by the RS method for the period 2008-2017.

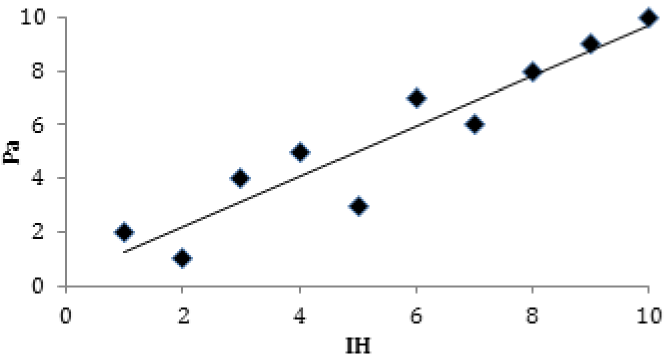

Fig 8:- Linear trend of the IH vs. Pa ranges for the 3rd decade (2008-2017).

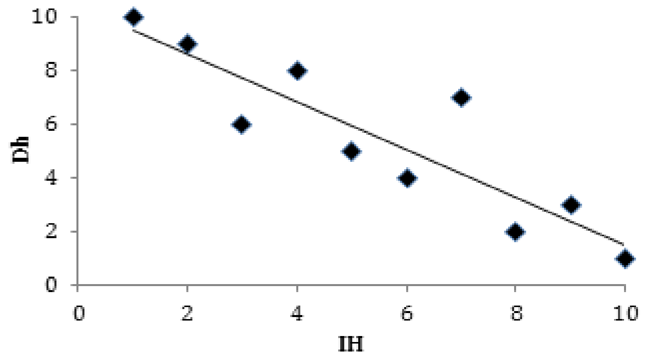

Fig 9:- Linear trend of the ranges of IH vs. Dh for the 3rd decade (2008-2017).

Given the limitations of the various methods for the analysis of trends in climate data series, the simultaneous application of several methods, Spearman's Rho, Sen, and linear regression analysis on the ranges to analyze nonparametric series, such as the IH, the Pa and the Dh, allowed to discern with reasonable certainty the existence of tendencies. In the analysis of the complete series (1988-2017) it is possible to confirm a definite trend with consistent results in the three applied methods, where a sustained increase in the presence of dry years (negative IH) is noted. However, when working with decadics periods, there is a lack of trend between the IH and Pa for the first period (1988-1997), while in the second decade (1998-2007) there was a significant trend between the variables IH and Pa, while in the variables IH and Dh, for that same period, a discordance was found between the RS test, which was not significant, and the p-value delivered in the linear regression analysis, which proves the existence of a trend. The existence of a downward trend is evident in the medians of the IH ordered for the three decades analyzed, with eloquent values (17.4, 7.0 and -19.2), moving from a humid subhumid situation for both first, to dry subhumid for the last. Finally, in the last decadic period, a trend break occurs, with 8 years with negative IH values, which gives rise to a definite trend between the IH and the two contrasting variables.

IV. CONCLUSIONS

The application of the IH, initially generated by Thornthwaite for the determination of the various climates present at a global level, can be an appropriate tool when analyzing the complexity of droughts and water excess for annual periods, because this index encompasses a agricultural application, especially with the incorporation of a formula for the calculation of ET_0 such as Penman-FAO, which contains other variables that actively contribute to ET_0, such as global radiation, temperature, wind and saturation deficit of the air.

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