SPATIOTEMPORAL FEATURES OF DROUGHT CONDITIONS: A CASE STUDY IN AN EQUATORIAL ANDEAN BASIN USING THE SPEI INDEX (1982-2015)

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Darío Zhiña
Grupo de Evaluación de Riesgos Ambientales en Sistemas de Producción y Servicios (RISKEN), Departamento de Química Aplicada y Sistemas de Producción, Eco Campus Balzay, Universidad de Cuenca, Cuenca 010207
https://orcid.org/0000-0001-9556-4025

Alex Avilés
Grupo de Evaluación de Riesgos Ambientales en Sistemas de Producción y Servicios (RISKEN), Departamento de Química Aplicada y Sistemas de Producción, Eco Campus Balzay, Universidad de Cuenca, Cuenca 010207
https://orcid.org/0000-0001-9278-5738

Jheimy Pacheco
Instituto de Estudios de Régimen Seccional del Ecuador (IERSE), Universidad del Azuay, Av. 24 de mayo 7-77 y Hernán Malo, Cuenca 010204, Ecuador
https://orcid.org/0000-0001-7708-0094

Daniel Mendoza
Departamento de Ingeniería Civil, Facultad de Ingeniería. Universidad de Cuenca, Campus Central, Av. 12 de Abril s/n y Loja, 010203 Cuenca, Ecuador
https://orcid.org/0000-0002-2117-2587

ABSTRACT: Drought is one of the extreme phenomena facing the world, which can harm the socioeconomic activities of the population and ecological balance. This study aims to perform a spatiotemporal analysis of droughts within the Machángara sub-basin (Ecuadorian Southern Andes) by the drought index SPEI, using meteorological records in the period 1982-2015. Results indicate that the sub-basin has experienced moderate and severe droughts and less frequent extreme droughts, being the month of August the most frequent period of this phenomenon. The spatial and temporal analysis determined that the study area experiences a more significant number of droughts while increasing the decades, with an extension in the whole territory of the sub-basin. These results could be a source of information for the decision-making of water managers regarding the formulation of measures of preparation and mitigation to fewer impacts of droughts on the population.
KEYWORDS: Drought, spatiotemporal climatic extreme, Equatorial Andean Basin.

1 I INTRODUCTION

Droughts are extreme hydrologic events that we can find naturally. These are caused mainly by precipitation below normal (LENG; TANG; RAYBURG, 2015). Moreover, in the context of climate change, droughts have become a global problem (LABUDOVÁ; LABUDA; TAKÁČ, 2017) because they occur in almost all regions of the world, varying their frequency, severity, and duration (SHATANAWI; RAHBEH; SHATANAWI, 2013).

There are different types of droughts depending on which part of the hydrologic cycle is the most affected. In this way, the lack of prolonged precipitation can manifest as a meteorological drought. When meteorological drought is extended, it can cause a hydrological drought characterized by the reduction of river flows. An additional consequence of prolonged meteorological drought is the occurrence of agricultural droughts, described when soil moisture decreases over time due to the constant lack of precipitation. Finally, when there are not enough resources to satisfy water demand, a socioeconomic drought occurs that relates drought to the supply and demand of an economic resource.(MISHRA; SINGH, 2010; SHATANAWI; RAHBEH; SHATANAWI, 2013; WILHITE; GLANTZ, 1985).

Droughts are characterized by indices, which are indicators of environmental and hydrometeorological variables related to the phenomenon (rainfall, flow, frost, among others) (BRITO et al., 2018). Several drought indices have originated in the last decades to quantify droughts (MISHRA; SINGH, 2010), among these we have: Palmer Drought Index (PDSI) (PALMER, 1965), Crop Moisture Index (CMI) (PALMER, 1968), Rainfall Anomaly Index (RAI) (VAN ROOY, 1965), Standardized Precipitation Index (SPI), Standardized Streamflow Index (SSI) (SERRANO et al., 2012), Standardized Precipitation-Evapotranspiration Index (SPEI) (VICENTE-SERRANO; BEGUERÍA; LÓPEZ-MORENO, 2010), DI index developed for the Andean region (AVILÉS et al., 2015), each one with its strengths and weaknesses.

These indices have been used in different parts of the world to characterize historical droughts, as well as to predict and project droughts in the future at different spatial and temporal scales. For example, SPI (MERESA; OSUCH; ROMANOWICZ, 2016; STAGGE et al., 2015), SSI (BARKER et al., 2016; TURCO et al., 2017), SPEI (GAO et al., 2017; ZHANG; ZHANG, 2016), CMI (PABLOS et al., 2017), PDSI (GE et al., 2016; GONG; ZHAO; GU, 2017). In the Andean region, performed studies that use SPI, SSI, and SPEI appear more frequently (IVITS et al., 2014; PENALBA; RIVERA, 2016; VICENTE-SERRANO et al., 2015).

The reduction of precipitation in the Andes causes droughts that result in an alteration of ecosystem services (including the natural regulation of water, which is very important in these zones) (BUYTAERT et al., 2006; BUYTAERT; CUESTA-CAMACHO; TOBÓN, 2011). Therefore, it is relevant to understand this phenomenon to establish future policies in the face of climate change.

In this research, the SPEI index was used for the spatial-temporal characterization of droughts within of Machángara River sub-basin. It is a more robust index than the previous ones described and takes into account the changes in atmospheric water evaporated by using the monthly water balance (Precipitation [P] - Evapotranspiration reference [ETo]). The study area is of great importance due to the Machángara Hydroelectric complex that uses the water stored in the reservoirs of El Labrado (Chulco river) and Chanlud (Machángara Alto river). These reservoirs also supply half of the demand for human consumption in the city of Cuenca and to meet agricultural and industrial needs. Also, this basin has biological importance since it has a high biodiversity of flora and fauna in the middle and upper watershed (ETAPA EP, 2014). Therefore, the present study intends to provide new knowledge in the region regarding the understanding of droughts and their temporal and spatial characterization that could help water managers to formulate timely and equitable prevention and mitigation measures and, in this way, to reduce the impacts of droughts on the population.

2 | MATERIALS AND METHODS

2.1 STUDY AREA

The Machángara River sub-basin (Figure 1) belongs to the Paute basin, it is located in the southern Ecuadorian Andes (with an altitude between 2440 - 4300 m.a.s.l), and it has an area of 355 km2 divided by three micro-basins (Chulco, Machángara Alto and Machángara Bajo). According to its altitudinal location, the basin corresponds to the low montane dry forest classification (bs-MB) with patches of Polylepis forests; besides, it presents a typical tropical high mountain climate (BUYTAERT et al., 2006).

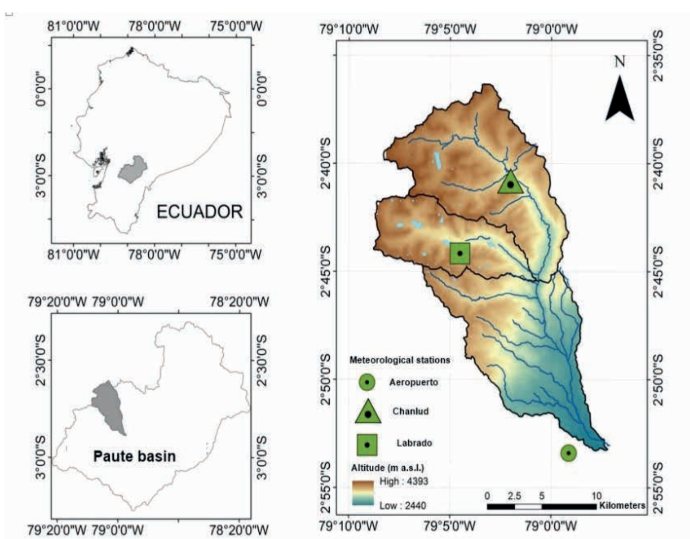

Figure 1. Location of Machángara sub-basin

2.2 METEOROLOGICAL DATA

Monthly time series of precipitation, temperature, relative humidity, and wind velocity (1982-2015) were used in this study to calculate the SPEI index. This information was provided by the National Institute of Hydrology and Meteorology (INAMHI); it corresponds to the meteorological stations of Labrado, Chanlud, and Aeropuerto (Table 1).

Code	Name	Latitude	Longitude	Altitude (msnm)
M141	Labrado	-2.732	-79.073	3335
MA41	Chanlud	-2.676	-79.031	3336
M067	Aeropuerto	-2.886	-78.983	2516

Table 1. Meteorological stations in the Machángara sub-basin

2.3 Standardized Precipitation-Evapotranspiration Index (SPEI)

The calculation of SPEI is based on three steps: a) calculation of reference evapotranspiration (ETo), b) calculation of the water balance (Precipitation - ETo), and c) adjustment of the water balance to Log-logistic probabilistic function, and normalization of it.

a. Calculation of reference evapotranspiration (ETo). According to (CHATTOPADHYAY; HULME, 1997), the reference evapotranspiration under a specific climate is the maximum amount of water that can be lost as water vapor in an extensive vegetative cover. There are different methods to estimate the reference evapotranspiration; these vary according to the available data. In this study, the Penman-Monteith method was used to calculate the ETo.

b. Calculation of water balance. The next step is obtaining the water balance for a month i, which was obtained using Equation 1.

$$D_i = precipitation_I - ET_{0i} \quad (1)$$

c. Calculation of SPEI. The times series of monthly water balance is adjusted to Log-Logistic probability distribution due to the distribution adapts very well to the different climatic regions independent of the time scale used (VICENTE-SERRANO; BEGUERÍA; LÓPEZ-MORENO, 2010), which is given by Equation 2.

$$F(D) = \left[1 + \left(\frac{\alpha}{D - \gamma}\right)^{\beta}\right]^{-1} \quad (2)$$

Where, α, β and γ are the scale, shape and location parameters, respectively, and D is the sample (Water balance). The value of F (D) is normalized following the approximation of (ABRAMOWITZ; STEGUN, 1965). The SPEI can be calculated for different time scales (1, 3, 6, 12 or more months) (BEGUERÍA et al., 2014; POTOP; MOŽNÝ, 2011). In this study, a quarterly analysis (SPEI3) was performed, i.e., we worked with the sum of the water balance for three consecutive months. The classification of the drought categories based on the SPEI index is shown in Table 2.

SPEI values	Type of drought
> 2	Extremely moist
1.99 – 1.50	Very moist
1.49 – 1.00	Moderately moist
0.99 – -0.99	Normal
-1.00 – -1.49	Moderate rought
-1.50 – -1.99	Severe drought
< -2.00	Extreme drought

2.4 STANDARDIZED PRECIPITATION-EVAPOTRANSPIRATION INDEX (SPEI)

Three aspects were considered to characterize droughts: duration, magnitude and severity. The approach used in this study was the threshold level method presented by (YEVJEVICH, 1969); it defines droughts as periods in which the variable under investigation is below a certain threshold level. The method is based on the statistical theory of runs to analyze a sequential time series. This theory indicates that the duration of the drought is expressed in years, months, and weeks or in any other period of time during which a drought parameter is maintained below a critical level (LEE et al., 2017). The duration of the drought is considered as the period between the beginning and end of a drought. The magnitude is defined as the cumulative deficiency of the drought variable below the threshold level, and the severity of the drought is obtained by the ratio between the volume of the drought deficit (magnitude) and the duration (Figure 2). Besides, the frequency of occurrence of the different types of droughts was calculated by adjusting an empirical probability distribution.

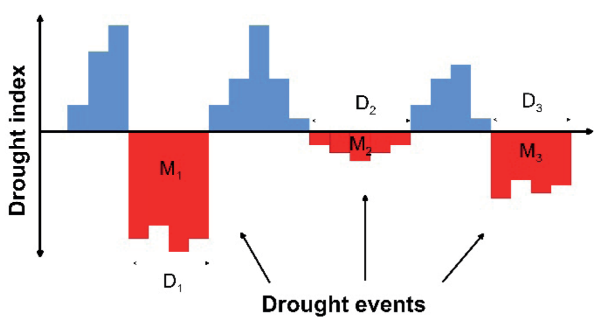

Figure 2. Characterization of droughts. D = Duration, M = Magnitude, S = Severity (M / D)

2.5 STANDARDIZED PRECIPITATION-EVAPOTRANSPIRATION INDEX (SPEI) SPATIAL-TEMPORAL ANALYSIS OF DROUGHTS

The results obtained were analyzed temporarily (full period and by decades), showing both the frequency of each drought event and the months with a higher incidence of each drought type. Also, drought events were analyzed spatially through performed analysis of monthly average drought maps for each decade.

3 I RESULTS AND DISCUSSION

Figure 3 shows the SPEI3 of Labrado, Chanlud, and Aeropuerto meteorological stations. A frequency analysis of the three-time series of SPEI3 indicates that moderate droughts are those that occur most often, followed by severe droughts, and finally extreme droughts are those that happen to a lesser extent (Table 3). Also, it can be observed that since 2000, droughts have occurred with greater regularity and higher intensity.

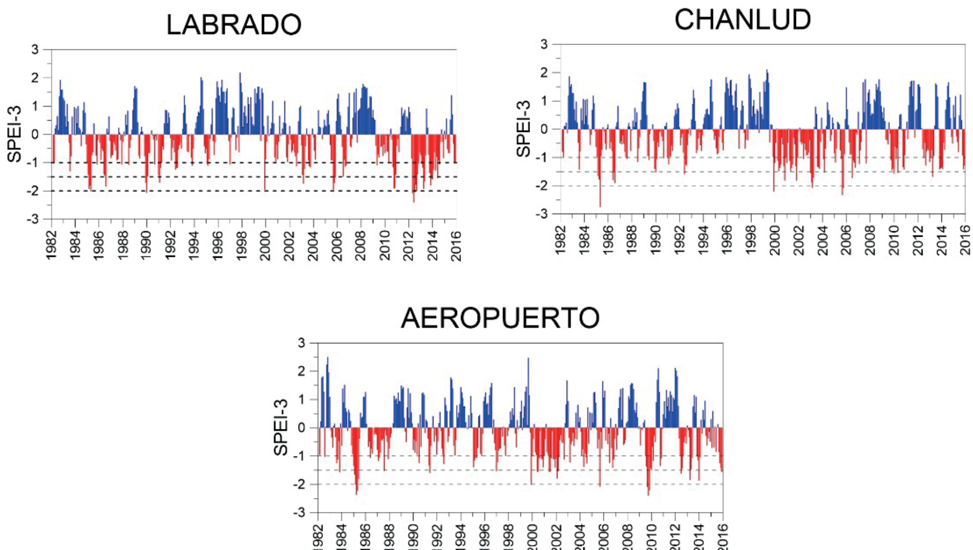

Figure 3.Time series of SPEI3 for the stations located within the Machángara River sub-basin.

Station	Moderate Drought	Severe Drought	Extreme Drought	Total
Labrado	39	20	6	65
Chanlud	54	16	5	75
Aeropuerto	52	18	7	77

Table 3. Monthly frequency of droughts in the Machángara sub-basin (1982-2015)

3.1 TEMPORAL ANALYSIS

The meteorological stations time series show that the months in which moderate droughts occur most frequently are July, August and October (Labrado); February, July, August and October (Chanlud); and August, October, November and December (Aeropuerto). In the case of severe droughts are November (Labrado); January and April (Chanlud); and

June and July (Aeropuerto). While for extreme droughts are May (Labrado); March, May, September, October and December (Chanlud); and September (Aeropuerto) (Figure 4).

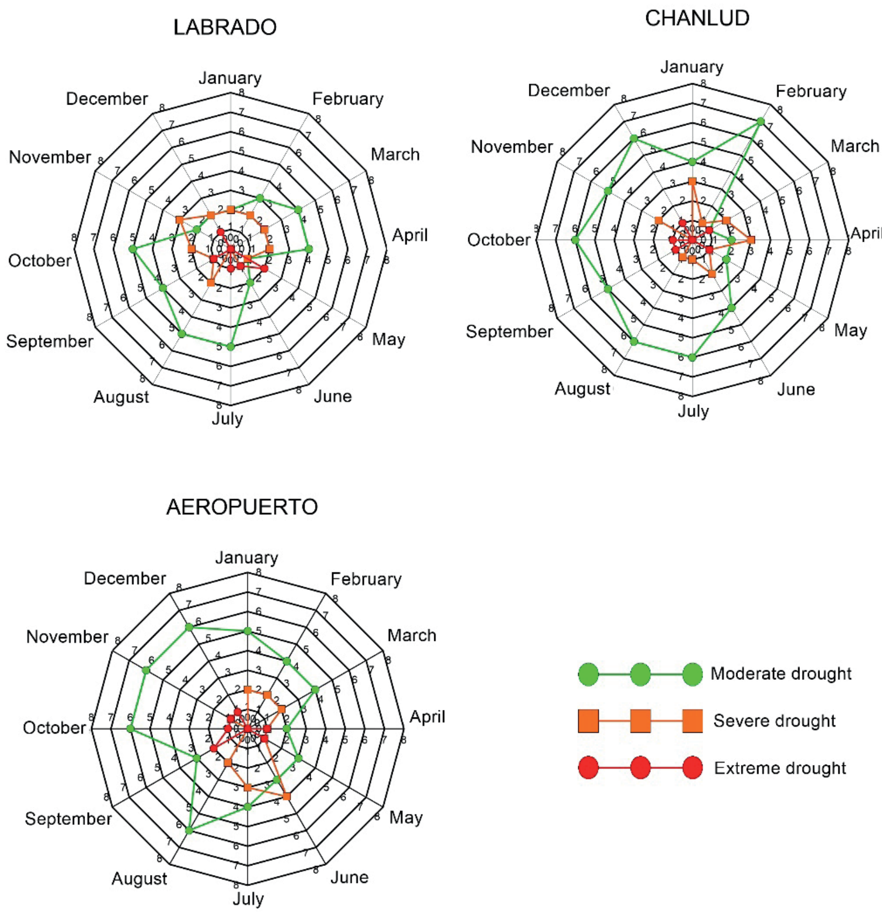

Figure 4. Number of droughts registered in each of the month's stations.

Based on the total period (1982-2015) of SPEI3, the monthly average for each decade was analyzed (the 1980s, 1990s, 2000s, and 2010s), which is shown in Figure 5. For the 1980s, it can be seen that for the three stations, all monthly values of SPEI3 are in a normal range (-1 to 1). July and August for Labrado and Chanlud stations have the lowest values, but even so, these are within the normal range.

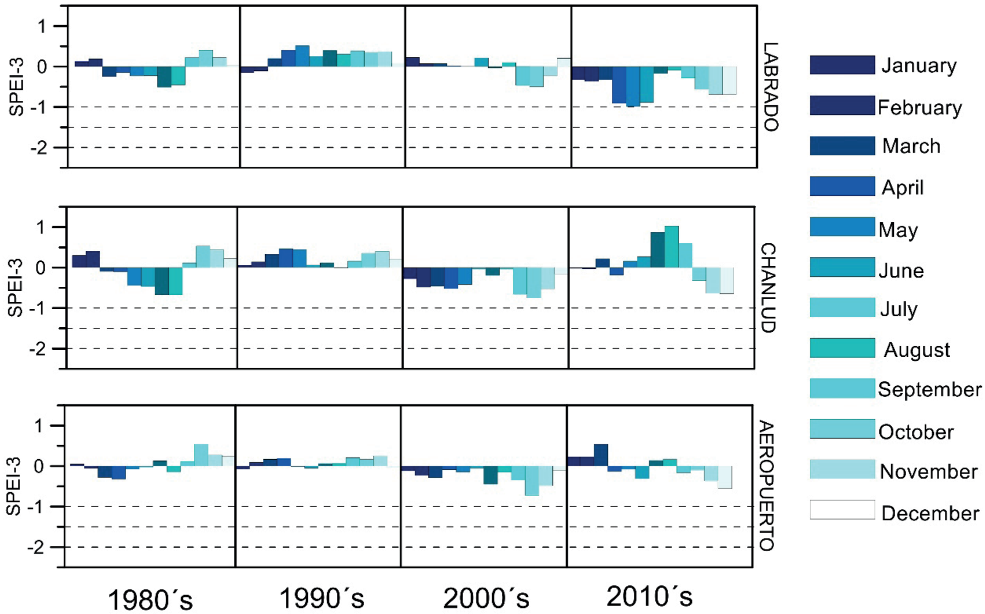

Figure 5. Monthly average for each decade.

For the 1990s, in the three stations, the values of the SPEI3 are almost entirely higher than zero; however, they are still in the normal category. For the 2000s, the values are less than zero, but they are still within a normal range. For the 2010s, there are values less than zero in the Labrado station, and in some months, the values reach a moderate drought. In this same decade, specific values of the Chanlud station are higher than zero, and in certain months the quantities are within a moderately humid range. Instead, at the Aeropuerto station, the values are still within a normal range. Figure 5 shows that in the first decade, most of the values are less than zero. In the second decade, most of the values are greater than zero. In the third decade, most values are less than zero, which would suggest that a wet decade follows a dry decade and vice versa. However, the last decade does not follow this pattern; it could be due to that we do not have full years of the decade.

3.2 SPATIAL ANALYSIS

The monthly average drought maps for each decade were obtained using the SPEI3 distributed throughout the study area. For the 1980s (Figure 6a), it is observed that the values of SPEI3 are within a normal range (-1 to 1); however, it is observed that during July and August, the upper part of the sub-basin experiences moderate droughts. In the 1990s (Figure 6b), it is observed that throughout the year, the SPEI3 of the sub-basin is in a normal category; however, in the month of April in the upper part of the sub-basin, it is very close to a moderate drought category.

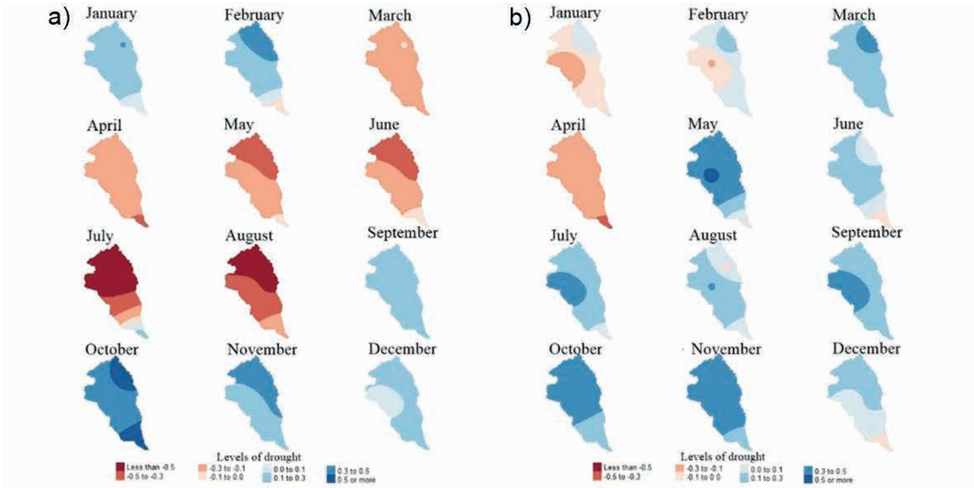

Figure 6. Map of average monthly droughts for the a) 1980s and b)1990s.

In the 2000s (Figure 7a), for nine months, the basin experienced a normal range according to the SPEI3; however, in the remaining three months (July, September, and October), the upper and lower parts of the sub-basin experienced moderate droughts. In the decade of 2010 (Figure 7b), the situation was entirely different from the previous three decades; the upper part of the sub-basin experienced a moderately humid category during the months of July and August, moderate drought in the months of April, May and June (middle part of the sub-basin), and the same category in the months October, November and December (upper and central part of the sub-basin and a portion of the lower part). In the remaining months, there were normal conditions.

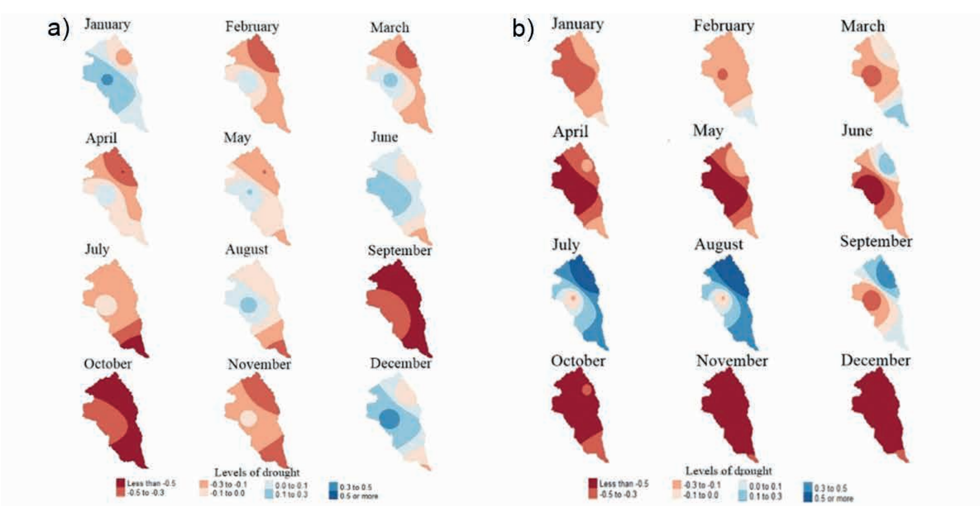

Figure 7.Map of average monthly droughts for the a) 2000s and b)2010s.

When comparing the four decades, it is observed that as time progresses, the number of months and the extension of moderate droughts increase. However, in the decade of 2010, it is possible that this trend changes because the available data used in this study were obtained until 2015.

3.3 MAGNITUDE, DURATION, SEVERITY AND FREQUENCY

For the magnitude, duration and severity, two aspects were taken into account: the first related to the maximum magnitude, its duration and severity of the maximum drought event and the second associated with the total magnitude, its total duration and severity during the entire period of study (Table 4-5).

Station	Maximum magnitude	Duration (months)	Severity	Type of drought
Labrado	-11.42	6	-1.90	Severe
Chanlud	-7.21	4	-1.80	Severe
Aeropuerto	-12.41	7	-1.77	Severe

Table 4. Maximum magnitude, duration and severity of the maximum drought event.

Station	Maximum magnitude	Duration (months)	Severity	Type of drought
Labrado	-94.52	65	-1.45	Moderate
Chanlud	-105.7	75	-1.41	Moderate
Aeropuerto	-107.1	77	-1.39	Moderate

Table 5. Total magnitude, duration and severity during the entire period of study.

As can be seen in Table 3, the Aeropuerto station presents the maximum magnitude of drought with seven months of duration. It is followed by Labrado with six months and Chanlud with four months. In the three stations, it was found that the category corresponds to a severe drought. Table 3 shows that the total duration (in months) of the droughts in the three stations are 65, 75 and 77 months respectively, and the category reveals that all stations have experienced moderate droughts. The probability of empirical occurrence (Figure 8) shows that extreme droughts have a very low probability of occurrence in Labrado, Chanlud and Aeropuerto stations (1.47%, 1.23% and 2% respectively), severe droughts (4.43%, 3.69% and 3.69% respectively) and moderate droughts (9.35%, 12.8% and 12.56% respectively), this last type of drought being the most likely to happen within the study area.

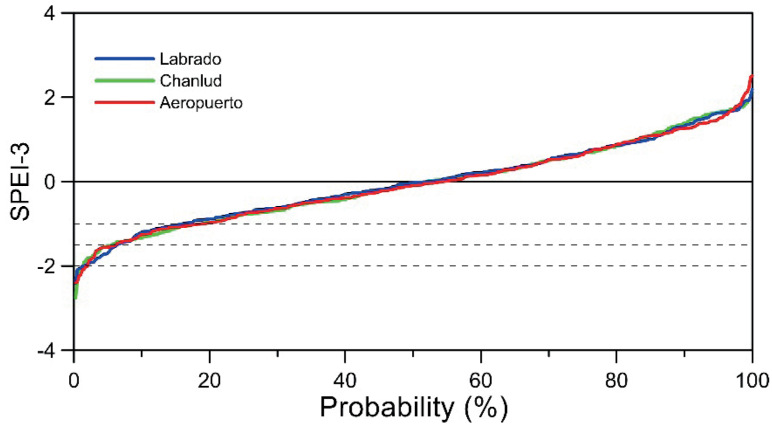

Figure 8. Probability of occurrence of droughts.

4 I CONCLUSIONS

The study focused on characterizing droughts employing the SPEI index in the Machángara River sub-basin. Three stations distributed in the sub-basin (Labrado, Chanlud, and Aeropuerto) were analyzed, and by using time series (1982-2015), it was determined that the study area had been affected by moderate, severe, and to a lesser extent, extreme droughts. It was found that August is when droughts occur most frequently for the three study stations.

A spatial-temporal analysis of droughts was carried out for four decades (the 1980s, 1990s, 2000s, and 2010s). When the decades increase, the number of months in the year in which moderate droughts develop increases as well. This also increases its extension; at the beginning, moderate droughts developed only in the upper sub-basin; however, in the last decade, these have developed in almost the entire extension of the sub-basin. In addition, in most stations, there are changes between wet and dry periods that are repeated every decade.

Through a probabilistic analysis, it was found that the probability of occurrence of extreme droughts is low (around 2%), while severe and moderate droughts are more likely to occur, around 4% and 12%, respectively. It should be noted that the results of the present study could be a source of information for the decision-making of water managers in the basin regarding the formulation of measures to diminish the impacts of droughts on the population of the sub-basins of the Machángara River.

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