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Articles

Comparative analysis of annual and monthly peak flow tendencies, considering two periods in north-central Chile

Análisis comparativo de la tendencia de los caudales punta anuales y mensuales, para dos periodos en Chile centro-norte

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Abstract

It is essential to understand long-term trends associated with water resources in arid climates such as Chili's to prepare and predict potential adverse implications of climate change in these already water-stressed regions. Trends in annual peak flows (instantaneous maximum flows) of the Coquimbo Region were studied through the Mann-Kendall statistical test (5 % error), considering the 1984-2014 period and, in a second analysis, extending the series to at least 29 % more (1976-2014). Results indicate that for the annual peak flows, in both periods, all analyzed series showed a tendency to decrease (80 % of them significantly in the 1984-2014 period and 29 % in the 1976-2014 period). In contrast, analysis of monthly peak flows revealed a more nuanced shift where 99 % of the series tended to decrease in the 1984-2014 period, with 46 % being significant. However, in the 1976-2014 period, 74 % of series tended to decrease, but only 12 % were significant. This decline in negative and significant trends after incorporating years before 1984 suggests that these situations have occurred previously. Finally, this variation in the significance level when considering different time lengths would evidence a cyclic process that influences the behavior of peak flows.

Keywords: Peak flows trends, Mann-Kendall, climate variability.

Resumen

El recurso agua es limitado en la zona norte de Chile por tratarse de una zona árida, de ahí la importancia de estudiar si en ellas se están verificando cambios hidrológicos que pudiesen alertar sobre un incremento de tal situación. Para ello, se estudiaron las tendencias de los caudales punta (caudal máximo instantáneo) de la Región de Coquimbo, a través de la prueba estadística de Mann-Kendall (5 % error) en el periodo 1984-2014 (periodo reciente) y en un segundo periodo extendido (1976-2014). Los resultados indican que para los caudales punta anuales en ambos periodos todas las series presentan tendencia a disminuir, pero un 80 % lo hace significativamente en el periodo 1984-2014, y un 29 % en el periodo extendido. En tanto, para los caudales punta mensuales, en el periodo 1984-2014, un 99.2 % de las series manifiesta una tendencia a disminuir, donde 45.8 % lo hace de forma significativa. Sin embargo, en el periodo extendido, un 73.8 % de series presenta tendencia a disminuir, pero sólo 11.9 % lo hace de manera significativa. Este fenómeno de la baja en las tendencias negativas y significativas al incorporar años anteriores a 1984 demostraría que dichas situaciones se han producido anteriormente. Por último, esta variación en el nivel de significancia al considerar diferentes longitudes temporales estaría evidenciando un proceso cíclico que influencia el comportamiento de los caudales punta.

Palabras clave: tendencias de los caudales punta, Mann-Kendall, variabilidad climática.

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Introduction

Chile is located in a region of high climatic variability, which heightens concerns about the impacts of climate change on the availability, reliability, and use of water resources (Ivanova & Corredor, 2006). Hydrological variables such as rainfall and streamflow provide a direct long-term dataset that can be used to understand local impacts from broader temporal and spatial climatic influences (Whitaker, Younes, Beckers, & Toews, 2002; Waylen & Woo, 2008).

Rosenblüth, Fuenzalida, and Aceituno (1997); Carrasco, Casassa, and Quintana (2005), and Carrasco, Osorio, and Casassa (2008) analyzed the behavior of the 0ºC isotherm in Chile, finding that it has risen in elevation due to a significant increase in temperature. As a result, historically snowpack dominated elevations may have shifted upward, resulting in increased surface runoff, flood events downstream, and less snowpack-associated storage in the Andes. To query if this holds true in the arid region of Chile, we would expect to see a negative trend in the production of peak flows due to a minor contribution from melting. As a result, peak flows have presented some trends on an annual and/or monthly scale in recent decades.

An area of hydrological interest to be studied in Chile is its arid portion, which is a sensitive area in terms of climate variability or change due to the fact that it is in a borderline situation for water availability. This is the case in Chile's Coquimbo Region, which presents an average annual rainfall of between 20 and 300 mm (Favier, Falvey, Rabatel, Praderio, & López, 2009), with storms occurring during the winter months and a prolonged dry season of more than eight months (Pizarro-Araya, Cepeda-Pizarro, Barriga, & Bodini, 2009; BCN, n.d.). Like most of Chile's territory, this region shows a very important orographic zone that corresponds to the Andes mountain range, with peaks exceeding 6,000 m.a.s.l. In this zone, transversal valleys connect the area with the Pacific Ocean combined with a decrease in the hydrographic network of more than 5,000 m in less than 100 km of horizontal route. Summer snowmelt in the Andes Mountain range is the main water supply for the region. This area is significant for mining, agricultural, and touristic development (FAO, 2014). In recent years, this region has suffered a severe mega-drought, which has limited its water supply and brought its reservoirs to historically low levels (CR2, 2015).

Pellicciotti, Burlando, and Van Vliet (2007) studied peak flow behavior in five sub-basins belonging to the Aconcagua River basin (semi-arid zone of Chile), finding a significant decrease in water production between the studied years (1972-2002), even though rainfall did not show a significant decrease for the same period. Rubio-Álvarez and McPhee (2010), on the other hand, described the temporal behavior of flows in south-central Chile (semi-arid and humid climate), documenting negative trends. In turn, Boisier *et al*. (2018) analyzed the behavior of flows and precipitation between latitudes 30°S and 48°S. There were negative linear trends for both variables over the period of 1960-2016. While these studies support water scarcity within the country, the analyzes do not consider variations in different length periods that can skew interpretation and results.

According to Valdés-Pineda *et al*. (2014), the average water availability in Chile is 53 953 m^3/hab-year, and the world's availability is only 6 600 m^3/hab-year. The Coquimbo region, however, has a water availability of 1 020 m^3/hab-year. In other words, this is an arid zone in which the availability of water is one-sixth that of the world average. As indicated previously, snow reserves in the high Andes are the dominant source of water (Favier *et al*., 2009); therefore, peak flows are a function of snow accumulation during winter months and subsequent melting. Hence peak flows in the arid zones of Chile provide a mechanism to query how climate variability and change may influence water resources.

The objective of this study was to analyze peak flow trends within the region with a focus on annual and monthly patterns in natural river basins. We can better understand long-term patterns and variability by comparing trends across different periods.

Material and methods

Study area

The study covered the Coquimbo Region of Chile (between 29°20'S and 32°15'S), located in the north-central portion of the country (Figure 1). The territory is divided into three administrative provinces defined by the watersheds which make up the river basins of the region's three main rivers. The river headwaters originate in the Andes and flow into the Pacific Ocean. These basins are the Elqui river (9,826 km^2), Limarí river

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(11,927 km^2), and Choapa river (8,239 km^2). From these basins, ten sub-basins with fluviometric records in natural regimes were selected (Table 1).

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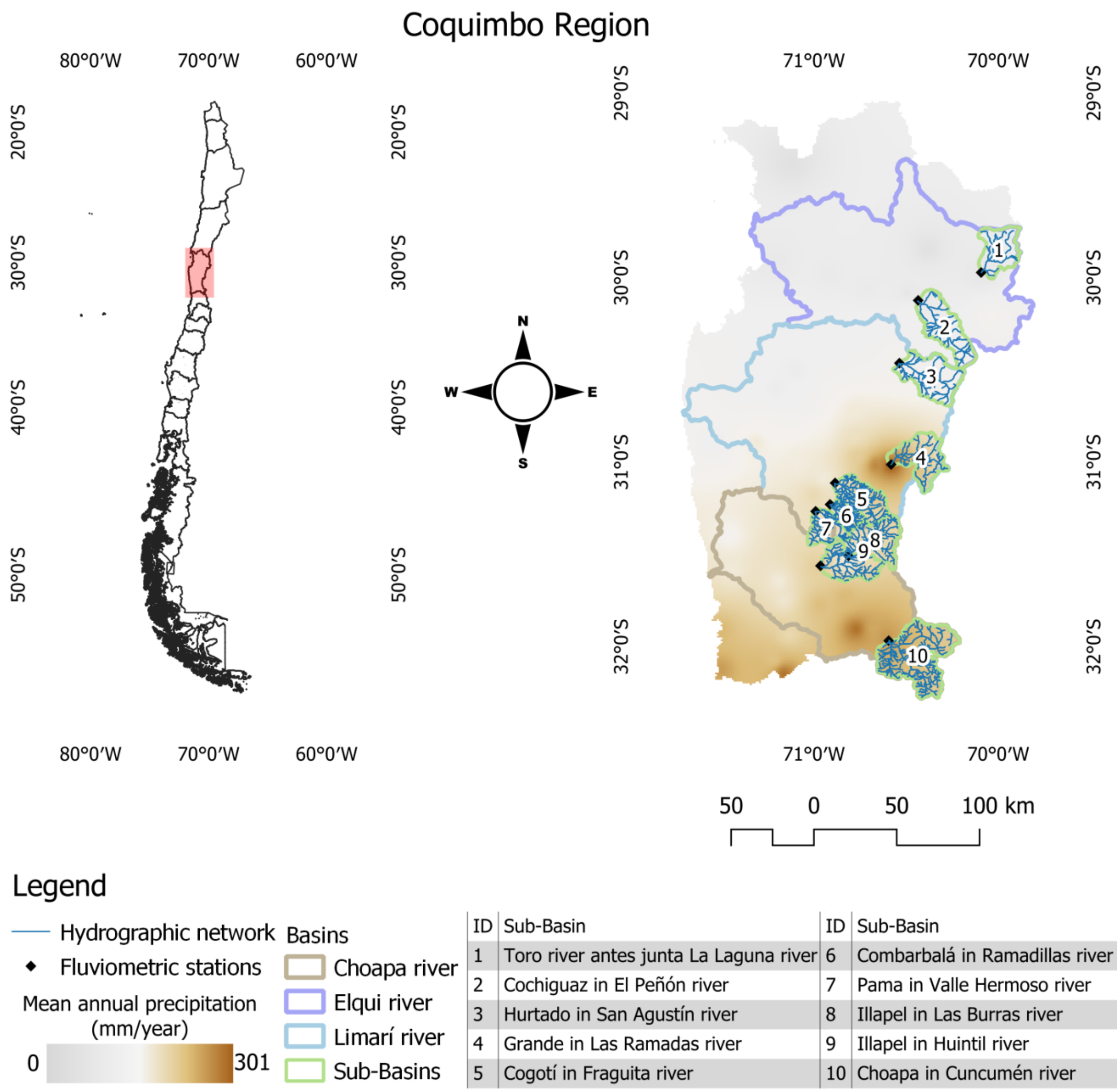

Figure 1. Location and annual precipitation of the study area.

Table 1. Morphometric parameters and analyzed period for each studied watershed.

ID	Area (km^2)	Perimeter (km)	Watershed	*Kc*	*Re*	Available period
1	479	111	Toro river before junta La Laguna river	1.42	4.19	1984-2014
2	659	139	Cochiguaz in El Peñón river	1.52	5.13	1984-2014
3	666	131	Hurtado in San Agustín river	1.42	4.20	1963-2014
4	565	130	Grande in Las Ramadas river	1.53	5.29	1969-2014
5	485	103	Cogotí in Fraguita river	1.31	3.15	1972-2014
6	185	65	Combarbalá in Ramadillas river	1.34	3.42	1976-2014
7	305	80	Pama in Valle Hermoso river	1.28	2.90	1984-2014
8	569	127	Illapel in Las Burras river	1.49	4.88	1962-2014
9	1 035	160	Illapel in Huintil river	1.39	3.93	1968-2014
10	1 115	192	Choapa in Cuncumén river	1.61	6.10	1965-2014

Kc: Gravelius index; *Re*: Equivalent rectangle.

Fluviometric information

The necessary information was provided by the Water General Directorate (DGA), a government institution belonging to the Chilean Ministry of Public Works (MOP). Information from fluviometric stations that presented at least 25 years of data, between the years 1984 and 2014, in watersheds under natural regimes was used, i.e., watersheds that did not have hydraulic works (e.g., dams) that resulted in changes in the natural production of water, a fact that determined a decrease in the possibilities of obtaining valid information for the study.

We used information on monthly peak flows (or instantaneous maximum flows, the highest flow rate recorded in a given month) and maximum annual peak flows. Similarly, it was decided not to complete missing data to avoid biases in the analyzes (Pizarro *et al*., 2009).

Mann-Kendall tendency analysis

The non-parametric Mann-Kendall trend analysis, with a significance level of 5 % (z ± 1.96), was used (Liu *et al*., 2012; Sharif, Archer, Fowler, & Forsythe, 2013). This is one of the most common tests to detect trends and is widely utilized in hydrological sciences (Méndez, Návar, De Jesús, & González, 2008). The main reason for applying this test to other parametric techniques lies in being the one indicated for distributions that do not present statistical normality (Mann, 1945; Kendall, 1975; Hamed, 2008; Song *et al*., 2015).

Fluviometric peak flow data from 10 watersheds were then analyzed at annual and monthly levels. Subsequently, a trend analysis was carried out, extending the series by at least nine years (29 % of the series) and reducing the analysis to seven basins. This extended period begins between 1962 and 1976, depending on the available information from each basin (Table 1).

The Mann-Kendall test validates a possible null hypothesis of no trend (H0) when the *Z* statistic exceeds the defined threshold (± 1.96). On the contrary, if the *Z* statistic does not exceed the threshold, then the null hypothesis H0 is rejected, and the presence of a significant trend is validated.

The analysis was carried out for each station's annual and monthly peak flow series. Additionally, the method considers the calculation of the *S* statistic and its variance (Equation (1)), which are obtained from

Equation (2), where q is the number of related groups and t_p the number of data in the p^{th} group:

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p\left(t_p - 1\right)\left(2t_p + 5\right)\right] \quad (1)$$

$$S = \sum_{k=1}^{n-1}\sum_{j=k+1}^{n} sign(x_j - x_k) \quad (2)$$

Where the function $sign(x_j\text{-}x_k)$ will assume a value of 1 if $x_j\text{-}x_k > 0$; a value of 0 if $x_j\text{-}x_k = 0$; and a value of -1 if $x_j\text{-}x_k < 0$. Besides, x_j and x_k are consecutive values from the studied variable. Finally, values from Equation (1) and Equation (2) are used to calculate the statistical test Z, as shown below (Equation (3)):

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}}\ ;\ if\ S > 0 \\ 0\ ;\ if\ S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}}\ ;\ if\ S < 0 \end{cases} \quad (3)$$

In addition, the magnitude of the exchange rate was calculated through the Sen slope. This technique is not parametric and, therefore, is a reliable test to analyze flow data (Ali, Kuriqi, Abubaker, & Kisi, 2019). This estimator is calculated as follows:

$$Sen\ slope = median\left(\frac{x_j - x_k}{j-k}\right) \tag{4}$$

Where x_j and x_k are the variable values in years j and k, respectively.

The presence of a statistically significant trend is evaluated using the Z value (Equation (3)). A positive or negative value of Z indicates a positive or negative data trend, respectively. The Z statistic has a normal distribution with a level of significance α. $H0$ is rejected if the absolute value of Z is greater than Z1- (α/2), where Z1- (α/2) is obtained from the established tables of the normal accumulated distribution.

Results and discussion

Annual peak-flows

Results from the analysis of annual peak flow trends in the Coquimbo Region (Table 2) indicate that out of 10 stations, all of them show a tendency to decrease (negative z-value). Of these, 8 (80 %) have a significant tendency (z ± 1.96). Additionally, and given that 7 out of the ten stations had longer data series (at least 39 years), the same Mann-Kendall statistical test was performed for the extended period to compare results with the most recent series (1984-2014), visualizing if there are significant differences in the behavior of peak-flows. When visualizing the extended series, only the basins corresponding to Combarbalá and Cogotí rivers maintain a negative and significant tendency in annual peak flows, reducing the number of basins with a significant tendency from 80 to 29 %. Likewise, the Sen slope shows a behavior similar to that of the Mann-Kendall test; that is, the values obtained from 1984 to 2014 show a greater decrease than that of the analysis of the complete series.

Table 2. Statistical values obtained by the Mann-Kendall test (Z-value and *p*-value), Sen slope, and length of the data series (*n*) were analyzed (in years) for the two periods under study.

ID	Station	Regular period				Extended period			
		Z	**Sen slope**	***p*-value**	***n***	***Z***	**Sen slope**	***p*-value**	***n***
1	Toro river befores junta La Laguna river	-1.78	-0.04	0.07	29	---	---	---	---

2	Cochiguaz in El Peñón river	-2.23	-0.18	0.03	29	---	---	---	---
3	Hurtado in San Agustín river	-2.69	-0.23	0.01	31	-1.21	-0.06	0.23	52
4	Grande in Las Ramadas river	-2.65	-0.49	0.01	31	-0.97	-0.12	0.33	46
5	Cogotí in Fraguita river	-2.58	-0.40	0.01	31	-2.24	-0.25	0.03	43
6	Combarbalá in Ramadillas river	-2.52	-0.17	0.01	31	-2.64	-0.13	0.01	39
7	Pama in Valle Hermoso river	-1.96	-0.13	0.05	28	---	---	---	---
8	Illapel in Las Burras river	-3.09	-0.60	0.00	31	-1.40	-0.06	0.16	53
9	Illapel in Huintil river	-2.04	-0.44	0.04	31	-0.68	-0.07	0.5	41
10	Choapa in Cuncumén river	-2.41	-1.70	0.02	31	-1.22	-0.48	0.22	50

Iroumé and Palacios (2013) applied the Mann-Kendall test to annual flows from three basins in south-central Chile (Bío-Bío Region), evaluating two time periods: One for calibration (1962-1992) and the study period (1962-2005), finding that the *Z* values in the calibration period are usually greater than values from the entire period when *Z* value is positive. Likewise, they determined that *Z* values from the calibration period are lower than those from the complete data series when the *Z* value is negative. This research corroborates this situation within the framework of maximum annual flows.

Martínez, Fernández, and Rubio (2012) analyzed the trends of monthly average flows from eight sub-basins feeding the Aconcagua River (Valparaíso Region, central Chile) for the 1960-2000 period, finding parity between positive and negative trends. Furthermore, this research found that the maximum and minimum flows of the Aconcagua basin vary depending on the ENSO phenomenon, increasing in the warm phase, and decreasing in the cold phase. Although this study did not correlate the flows with the phases of the ENSO phenomenon, Masiokas *et al*. (2019) found that the flows in this area are explained by up to 45 % of ENSO. Based on the above, it is expected that they respond in a similar way to those of Aconcagua.

Monthly peak flows

About the series of monthly peak flows for the 1984-2014 period, in general, there is a negative tendency in the maximum flows (Table 3), given that of the 120 series (combination of 10 stations for 12 months) analyzed, 119 (99.2 %) have negative trends and, of these, approximately half denote statistical significance (45.8 %, equivalent to 55 series). On the other hand, only one series is positive, but not significantly.

Table 3. Several stations with positive and negative peak flow trends (monthly analysis), for the regular period (column a) and the extended period (column b), after the application of the Mann-Kendall test.

Month	Total positive		Total negative		Total positive and significant		Total negative and significant	
	a	b	a	b	a	b	a	b
January	0 (0 %)	2 (2.4 %)	10 (8.3 %)	4 (4.8 %)	0 (0 %)	0 (0 %)	4 (3.3 %)	1 (1.2 %)
February	0 (0 %)	1 (1.2 %)	10 (8.3 %)	6 (7.1 %)	0 (0 %)	0 (0 %)	6 (5.0 %)	1 (1.2 %)
March	0 (0 %)	3 (3.6 %)	10 (8.3 %)	4 (4.8 %)	0 (0 %)	0 (0 %)	7 (5.8 %)	1 (1.2 %)
April	0 (0 %)	3 (3.6 %)	10 (8.3 %)	4 (4.8 %)	0 (0 %)	0 (0 %)	6 (5.0 %)	1 (1.2 %)
May	0 (0 %)	2 (2.4 %)	10 (8.3 %)	5 (6.0 %)	0 (0 %)	0 (0 %)	5 (4.2 %)	1 (1.2 %)
June	0 (0 %)	3 (3.6 %)	10 (8.3 %)	4 (4.8 %)	0 (0 %)	0 (0 %)	1 (0.8 %)	0 (0 %)
July	0 (0 %)	1 (1.2 %)	10 (8.3 %)	6 (7.1 %)	0 (0 %)	0 (0 %)	6 (5.0 %)	1 (1.2 %)
August	0 (0 %)	2 (2.4 %)	10 (8.3 %)	5 (6.0 %)	0 (0 %)	0 (0 %)	5 (4.2 %)	1 (1.2 %)
September	0 (0 %)	1 (1.2 %)	10 (8.3 %)	6 (7.1 %)	0 (0 %)	0 (0 %)	4 (3.3 %)	0 (0 %)
October	1 (0.8 %)	1 (1.2 %)	9 (7.5 %)	6 (7.1 %)	0 (0 %)	0 (0 %)	3 (2.8 %)	1 (1.2 %)
November	0 (0 %)	1 (1.2 %)	10 (8.3 %)	6 (7.1 %)	0 (0 %)	0 (0 %)	3 (2.8 %)	0 (0 %)

December	0 (0 %)	1 (1.2 %)	10 (8.3 %)	6 (7.1 %)	0 (0 %)	0 (0 %)	5 (4.2 %)	2 (2.4 %)
Total	**1 (0.8 %)**	**21 (25%)**	**119 (99.2 %)**	**62 (73.8 %)**	**0 (0 %)**	**0 (0 %)**	**55 (45.8 %)**	**10 (11.9 %)**

Considering the above, it is possible to appreciate that February, March, April, and July are the ones with the largest number of negative and significant series, reaching seven significant series in March, followed by February, April, and July with six significant series (Table 3).

In terms of the monthly peak flows series in the extended period (Table 3), negative trends are generally observed (although in smaller numbers than in the 1984-2014 period), given that out of the 84 series (combination of 7 stations and 12 months) analyzed with Mann-Kendall, 62 (73.8 %) presented negative trends. It is important to note that the negative and significant trends decreased from 45.8 % in 1984-2014 to 11.9 % in the extended period. This variation in the significance level when considering different time lengths would evidence a cyclic process that would alter peak flow behaviors. This cyclic pattern could be explained by the Pacific Decadal Oscillation (Núñez, Rovera, Oyarzún, & Arumí, 2013; Valdés-Pineda, Cañón, & Valdés, 2017), which would manifestly influence the hydrological behavior of the rivers in this portion of the country.

These results differ from those obtained by Pizarro, Cabrera, Morales, and Flores (2011), who compared the amounts of monthly average flows associated with a return period of 50 years in two basins from the Metropolitan Region (central Chile) for the 1963-1976, 1963-1986, 1963-1996, and 1963-2006 periods, finding a positive relationship between the temporal length and the amount associated with a 50-year return period. This discordance in the results can be explained on the basis that the number of adjustments (4) made in the comparison done by Pizarro *et al*. (2011) does not allow for verifying the dispersion of the data.

The results achieved in this study, and those observed in similar studies, define the presence of different results depending on the lengths of the data series that are counted and worked on. This fact is quite important when using this information to prepare and apply public policies or when trying to infer the behavior of certain watersheds in climatic terms because the differences obtained can be substantial, and it is always necessary to have the greatest amount of available information.

Conclusions

The trends found are mostly negative, both on an annual and monthly basis, although most are not significant.

Most of the basins (80 %) showed a significant negative trend at the annual level from 1984-2014. However, these are reduced to 29 % when incorporating the extended period.

At the monthly level, and considering the 1984-2014 period, it is observed that 99.2 % of the series shows a negative trend; of these, 45.8% are significant. However, when incorporating the extended period, a situation similar to that from the annual series occurs, given that the significant negative trends decrease from 45.8 to 11.9 %. When information prior to 1984 is incorporated into the trend analysis, a reduction in significant negative trends is observed, which denotes that these events have occurred previously.

Finally, it is concluded that the oscillation of the *Z* values from the studied basins, when segmenting the time series, makes it relevant to continue doing this research.

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