

Hydrological alterations in semi-arid river systems: an exploratory approach to natural and anthropogenic drivers

Alteraciones hidrológicas en sistemas fluviales semiáridos: un enfoque exploratorio sobre factores naturales y antropogénicos

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Resumen. Siendo el Atuel un río con doble jurisdicción provincial, los conflictos hídricos en la árida región que recorre han generado controversia por años. Dentro del análisis hidrográfico y las complejidades del paisaje, la geografía cobra importancia como enlace entre los hechos fluviales, sociales y sus interacciones sobre el territorio. De esta forma, el objetivo de la investigación se centró en obtener un análisis exploratorio de los caudales, con el fin de facilitar la comprensión que los efectos naturales y antrópicos tienen sobre este dentro de la jurisdicción mendocina. La metodología se centró en utilizar pruebas convencionales del análisis exploratorio de datos (normalidad, aleatoriedad, independencia y homogeneidad), a cuyos resultados se dio una connotación física y relacionada al ámbito fluvial. Mediante los resultados, se pudo constatar que existen afectaciones antrópicas que contribuyen a la alteración hidrográfica del Atuel. Esto se manifiesta por las diferencias entre los resultados de las estaciones aguas arriba y aguas abajo de las actividades humanas sobre el río. De este modo, se puede inferir que los usos consuntivos del agua, sumados a los almacenamientos en las represas existentes,

alteran el régimen fluvial y, por ende, el paisaje hacia el final del sistema hídrico en tierras pampeanas.

Palabras clave: análisis exploratorio de datos; conflictos hídricos; impactos antrópicos; zonas áridas; alteración del uso del agua.

Abstract. Given that the Atuel river falls under the jurisdiction of two provinces, water conflicts in this arid region have generated controversy for several years. Within the context of hydrographic analysis and the complexities of landscapes, geography becomes crucial as it links the fluvial and social dynamics and their interactions within the territory. This study aims to provide an exploratory approach to the river flows as they pass through the province of Mendoza, facilitating an understanding of the natural and anthropic effects on the river. Conventional exploratory data analysis tests (normality, randomness, independence, and homogeneity) were employed to analyze hydrological measurements, with the results being physically interpreted and related to the

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fluvial environment. The results confirmed the anthropic impacts contributing to the hydrographic alteration of the Atuel river, as evidenced by differences between the upstream and downstream stations affected by human activities. Thus, it can be inferred that the river regime and the landscapes towards the end of the water system in Pampean lands have

been altered by consumptive water uses, in addition to storage in existing dams.

Keywords: exploratory data analysis; water conflicts; anthropic impacts; arid zones; river regime alteration.

INTRODUCTION

Hydrological alterations in rivers have been widely studied due to their impact on aquatic ecosystems and the availability of water resources for various human uses. It has been demonstrated that maintaining natural flow regimes is essential for preserving biodiversity and ensuring the functionality of river systems (Poff et al., 1997; Richter et al., 2003). Globally, several studies have analyzed the combined effects of natural and anthropogenic factors on river hydrology, including changes in flow regimes due to reservoir regulation, water diversion for irrigation, and the impacts of climate change (Nilsson et al., 2005; Döll & Zhang, 2010).

Several examples include the Colorado river in the United States, where dam construction has drastically reduced downstream flows, altering riparian ecosystems and affecting water-dependent communities (Christensen et al., 2004). Similarly, the Yangtze river in China has experienced significant changes in its flow regime due to the operation of the Three Gorges Dam, impacting aquatic biodiversity and sediment dynamics (Zhang et al., 2016). In South America, the Paraná river system has been affected by multiple hydroelectric dams, leading to disruptions in river connectivity and alterations in natural flooding patterns (Agostinho et al., 2008).

In Argentina, a relevant case is the Ramsar site *Lagunas de Guanacache, Desaguadero y del Bebedero*, located in Mendoza and primarily fed by flows from the Mendoza and San Juan rivers. Since the colonial period, and especially after the construction of dams on both rivers, their flows have diminished, contributing to the economic development of irrigated oases at the expense of downstream riverine and wetland ecosystems (Ramsar site), resulting in evident anthropogenic hydrological alterations (Bastidas, 2023; Bastidas et al., 2024).

Within the arid South American diagonal and the dry central-western region of Argentina, the Atuel river represents the third-largest flow in the region by discharge volume (Lauro et al., 2016). Its springs, located in the Andean foothills, allow it to be fed by melting snow and glaciers, providing perennial flows throughout the year under natural conditions (Sarafian, 2006; Cazevane, 2015).

Downstream from the mountain range, the river irrigates vast areas of cultivated land, passes through dry forests, marshlands (low wetlands of high ecological value), and salt flats before naturally flowing into the Colorado river, a tributary of the Atlantic Ocean (Cazevane, 2015). Politically and administratively, the Atuel crosses (in the direction of flow) the Argentine provinces of Mendoza and La Pampa.

The river's interprovincial nature and the conflicting interests between these provinces led to a decades-long legal dispute, culminating in a ruling by the National Supreme Court of Justice in July 2020 (CSJN, 2020). The court mandated that Mendoza must deliver a continuous flow of 3.2 m³/s (9.2 % of the mean annual daily flow) to La Pampa, requiring a cooperation agreement among the involved stakeholders. This ruling implies that the province of Mendoza must regulate its activities (such as irrigation and hydroelectricity) to allow the stipulated flow to reach La Pampa.

Although the issue extends beyond the stipulated flow and its adequacy, it underscores the importance of hydrological analysis and its connection with geography as a means of understanding and explaining natural phenomena, social dynamics, and their implications for the territory.

In this context, the aim is to provide an exploratory interpretation of the Atuel river flows as they pass through the province of Mendoza, to better understand its characteristics and their relationship with the surrounding environment. Although this study is exploratory, it is driven by several hypoth-

eses that shaped the analytical approach. First, it is hypothesized that variations in the Atuel river's flow regime are significantly influenced by both natural factors (such as seasonal meltwater and precipitation patterns) and anthropogenic interventions (including water extraction for irrigation and the operation of hydroelectric plants). Second, it is expected that these alterations in flow dynamics have led to measurable ecological impacts on the surrounding areas.

Lastly, the study hypothesizes that the ongoing legal and political conflict between the provinces of Mendoza and La Pampa is, at least in part, a result of these hydrological changes, which affect water availability and riverine health. These hypotheses will be examined by exploratory-statistical methods that allow for a detailed analysis of the river's flow characteristics and their broader implications.

METHODOLOGY

Regarding the study area, the Atuel river basin is part of the Colorado river hydrographic system. The basin, located to the east of the Andes mountain range, allows water to flow from west to east, thereby influencing the orientation of agricultural activities and urban settlements along the river's axis, which extends approximately 417 km on the Mendoza side and 220 km on the Pampean side.

The study area (Figure 1) is situated in the central-western region of Argentina, specifically between southern Mendoza province and north-western La Pampa province, within the coordinates 34°27'42" S to 37°00'02" S and 70°04'26" W to 66°45'04" W.

The basin was delineated to encompass the entire watershed, extending to the Atuel wetlands

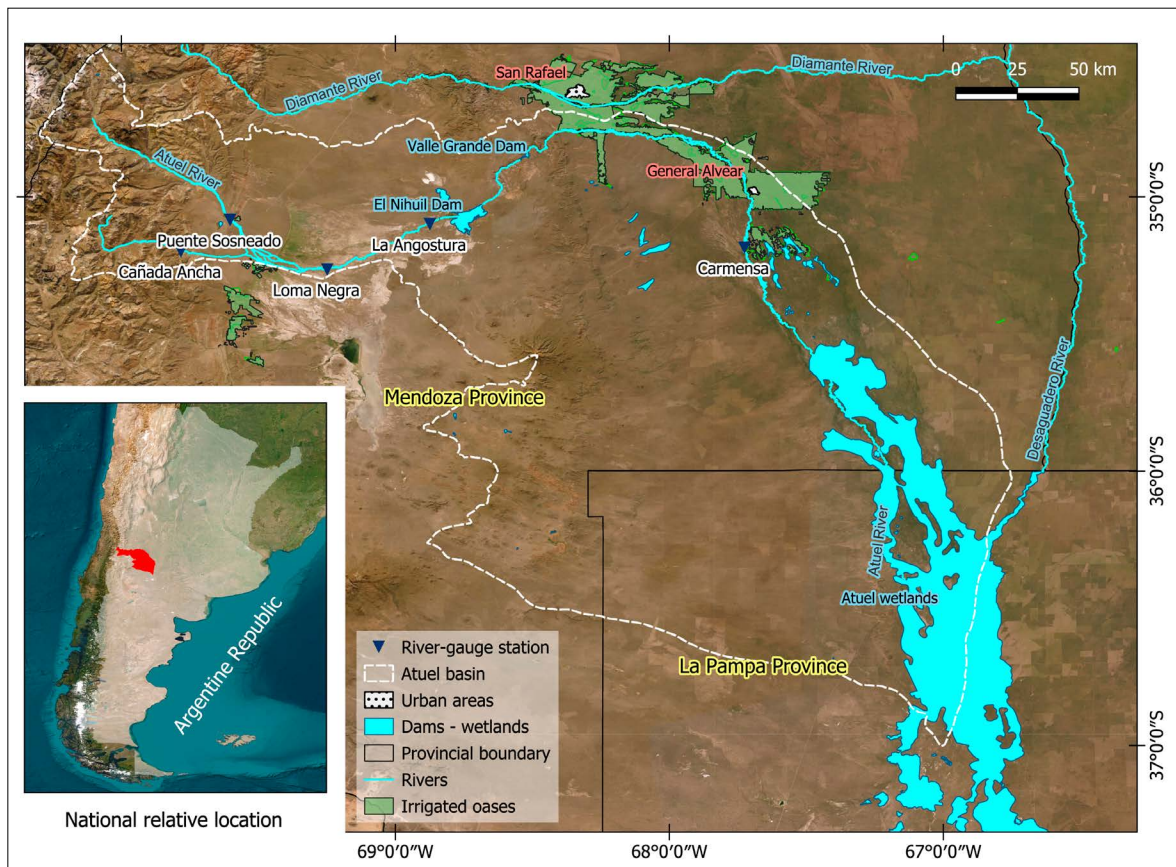


Figure 1. Hydrometric stations and hydrography. Atuel river basin. Source of data: SIPHN (2019). Source: Elaborated by the authors.

in La Pampa, without subdivision into sub-basins for each gauge station (Figure 1).

Four gauge stations were considered along the Atuel river: La Angostura (LAN), Puente El Sosneado (ESO), Loma Negra (LNE), and Carmensa (CAR), with the last one located downstream of the irrigated oasis. Additionally, the Cañada Ancha (CAN) gauge station, located on the Salado river (a tributary of the Atuel river), was also included. Average daily flows (Figure 1) were analyzed over a 34-year period, from 1985 to 2019 (except for the Carmensa station, which has 23 years of data, from 1996 to 2019). These daily measurement stations are part of the Integrated Hydrological Database managed by the Secretariat of Infrastructure and Water Policy of Argentina (SIPHN, 2019). The selected analysis period aims to maximize the length of data shared among the stations with the lowest percentage of missing data.

Additionally, an Exploratory Data Analysis (EDA) was conducted, with the purpose of examining the data prior to applying any advanced statistical techniques (Hirsch et al., 1982). This process, in addition to verifying the properties and basic characteristics of the series used, allows the results to be linked with processes that may be associated with the nature of the data.

Initially, daily missing data was estimated using different procedures depending on the length of the information gap. For gaps of up to three missing days, a third-degree Lagrange interpolating polynomial was employed (Gyau-Boakye and Schultz, 1994). If the gap extended between 4 and 20 days, a first-order autoregressive model with correction was applied (Gyau-Boakye, 1993). Finally, for gaps longer than 20 days, the MOVE (Maintenance of Variance Extension) method was used (Hirsch et al., 1982).

After filling in the missing data for each daily average flow series, average flow values were calculated for the 12 months of the year. Additionally, the four climatic seasons (winter [JJA], spring [SON], summer [DJF], and fall [MAM]), an annual runoff value, six percentiles of the flow duration curve (Q10, Q30, Q90, Q180, Q270, Q355), and two extreme values (minimum and maximum) were also considered. In total, 25 measurements were analyzed.

The tests were based on fundamental statistical assumptions, including the verification of normality, randomness, and independence, as well as homogeneity, which indicates the regularity of data around the mean, the fluctuations of the variable, and the statistical dependency ratio, respectively. Additionally, tests were conducted to detect outliers. These tests, applied in the hydrographic context, can reveal characteristics that may influence the intrinsic nature of the watercourse.

Normality, Randomness and Independence

To verify whether a data series is linked to a standard normal population distribution, the skewness and kurtosis tests were applied (Snedecor and Cochran, 1962, cited in Salas, 1992). Regarding randomness, the non-parametric Runs and Kendall tests were used (McGhee, 1985, cited in Adeloye and Montaseri, 2002), while for independence, the Bartlett (parametric) and Von Neumann (non-parametric) tests were applied (Kundzewicz and Robson, 2000). A significance level of 5 % was used for all tests. If either of the two tests rejects the null hypothesis, it is considered sufficient to accept the alternative hypothesis for each condition.

Homogeneity analysis

For trend detection, both parametric and non-parametric tests were applied, considering the series conditions and the underlying assumptions of the tests. The tests used were the Student's Parametric t-test (Remington & Schork, 1974), Spearman Rank Order Correlation (Kundzewicz and Robson, 2000), and Mann-Kendall (Hirsch et al., 1982; Westmacott & Burn, 1997). In all tests, a significance level of $\alpha = 0.05$ was used.

To detect the presence of abrupt changes in the flow series, the Student's t parametric test and several non-parametric tests were applied, such as the Rank Sum or Mann-Whitney (1947), Pettitt (1979), Buishand (1982), and Worsley (1979). These tests detect a single point of change, and in some cases, the trend must be eliminated previously. The significance level for these tests was 5 %.

Finally, regarding outliers, the Grubbs (EPA, 2000), Interagency Advisory Committee on Water Data (1982) (formerly WCR), Rosner (EPA, 2000),

and MAD-score (median absolute deviation) tests (Leys et al., 2013; Bae and Ji, 2019) were used for the annual mean values of the measurements considered (except for the percentiles of the flow duration curve).

The MAD-score method, which uses the median instead of the mean, offers advantages in handling the sensitivity to outliers. Miller (1991) and Leys et al. (2013) establish three decision criteria, ranging from “low” to “very” conservative, providing greater robustness to the method.

Given the advantages described for the MAD-score method, the other tests were applied to verify their results, corroborating the presence or absence of a value as an outlier.

RESULTS

Normality

The Puente El Sosneado, Loma Negra, and La Angostura stations exhibit significant normality in 70 % of the daily measurements considered. This percentage decreases to 40 % for the Cañada Ancha

station (Salado river) and to 24 % at the Carmensa station (at the exit of the irrigation oasis) (Table 1). In the case of the Carmensa station, the lack of normality in most measurements may be attributed to the high level of water use in the Atuel river, which is at its maximum at the station's gauging point (the end of the irrigated oasis).

Additionally, this station shows an irregular flow pattern, different from that of upstream stations on the same river, possibly due to anthropogenic activities. On the other hand, the situation at Cañada Ancha may be associated with the torrential regimes typical of a mountain river, such as the Salado river, and the hydrological variability it entails.

Randomness

According to the World Meteorological Organization (WMO, 2011), from a hydrological perspective, randomness implies that fluctuations in the variable are due to natural causes rather than anthropogenic effects. However, it is notable that the station with the greatest randomness in its measurements (68 %) is Carmensa. Although this

Table 1. Percentage of daily measurements with and without the presence of Normality, Randomness and Independence. Green color expresses the acceptance of H_0 , while red means its rejection.

	Normality		Randomness		Independence	
Gauge Station	%	%	%	%	%	%
ESO	76	24	16	84	20	80
LNE	68	32	44	56	0	100
LAN	80	20	20	80	4	96
CAN	36	64	44	56	28	72
CAR	24	76	68	32	92	8
Gauge Station	%	%	%	%	%	%
ESO	76	24	16	84	20	80
LNE	68	32	44	56	0	100
LAN	80	20	20	80	4	96
CAN	36	64	44	56	28	72
CAR	24	76	68	32	92	8

Source: Elaborated by the authors.

station records the drainage from irrigated areas as well as the remaining flows released from upstream dams, the observed randomness may be attributed to the statistical inconsistency caused by this situation (Table 1).

On the one hand, the other Atuel river stations (upstream) exhibit more than 60 % lack of randomness in their measurements, particularly pronounced during the months with higher water demand in the irrigated oases (summer and spring). On the other hand, it is notable that all stations show an absence of randomness in the winter and annual measurements, highlighting the anthropogenic impact of water use in the area (reservoirs and irrigation).

Independence

The Puente El Sosneado, Loma Negra, and La Angostura stations reject the null hypothesis (presence of independence) in more than 80 % of the 25 measurements considered (Table 1). This situation may occur because these stations monitor the same river, which also has an upper basin with significant glacial reservoirs (Falaschi et al., 2018). In contrast, the Carmensa station exhibits independence in 92 % of the measurements.

Although Carmensa is located on the Atuel river, being at the exit of the irrigated oasis means that the flow of water (altered by anthropogenic activities) does not statistically depend on natural runoff, as observed at the upstream stations of the Atuel river. A notable aspect of Carmensa is the absence of independence in winter, likely due to it being the season with the lowest agricultural production, minimal water use, and thus the highest reliance on natural flows from the Atuel.

Additionally, the Cañada Ancha station shows 44 % independence in its measurements. Although this station is located upstream of the irrigation system, its basin is nearly three times smaller than the Atuel's basin at Puente El Sosneado, resulting in a lower dependence on flows compared to the first three Atuel stations.

A summary of the relative values for each station, based on the normality, randomness, and independence tests applied, is presented in tabular form (Tables 1 and 2).

Homogeneity analysis

Trend tests indicate negative values for Puente El Sosneado, Loma Negra, and La Angostura in more than 96 % of their measurements. For Carmensa, there is an absence of trend in up to 72 % of its measurements, while Cañada Ancha shows a significant absence of trend in 48 % of its measurements.

It is important to emphasize the similarities among the stations, with maximum negative trends observed in summer (a period of higher evaporative and consumptive water demand from both natural processes and agricultural production) and minimum negative trends in the winter months (Figure 2). In any case, no significant positive trends were recorded for any variable or season.

On the other hand, it is expected that the Carmensa station would exhibit a similar trend pattern to its upstream neighboring stations; however, it shows an absence of trends where the other stations register negative values (winter). This discrepancy may be due to the characteristics of the Atuel river at Carmensa, with drainage runoff from irrigated areas and remnants of upstream flows, indicating a higher level of anthropogenic impact in the basin.

As shown in Figure 3, the annual differences range between 24 % and 74 %, remaining relatively constant across most of the stations except for Cañada Ancha and Carmensa. The latter exhibits the greatest differences between the two periods, ranging from 37.8 % to 74.6 %. For all seasons, the maximum values occurred in the December, January, and February quarter, while minimum values were observed during the winter months.

Regarding abrupt changes, the sequential Student's t-test highlighted the main steps or abrupt changes in the series considered. Significant changes were found to be negative, indicating decreases in the means between the periods 1985-2008 and 2008-2019. The cutoff point was approximately in 2008; however, the period of change for all seasons and measurements occurred between 2007 and 2009.

Given that no dams were constructed in the area during this period, the observed step changes may be associated with climatic events. According to Mendoza's Provincial Law No. 8318, the provincial

Table 2. Assumptions of normality, randomness and independence for the 25 measurements considered. Green color expresses the acceptance of Ho, while red means its rejection.

Randomness						River	G. Sta- tion	J	A	S	O	N	D	J	F	M	A	M	J	Win	Spr	Sum	Aut	Annual	Q ₁₀	Q ₃₀	Q ₉₀	Q ₁₈₀	Q ₂₇₀	Q ₃₅₅	Q _{min}	Q _{max}	
						Atuel	ESO	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
						Atuel	LNE	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
						Atuel	LAN	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
						Salado	CAN	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
						Atuel	CAR	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red

Independence						River	G. Sta- tion	J	A	S	O	N	D	J	F	M	A	M	J	Win	Spr	Sum	Aut	Annual	Q ₁₀	Q ₃₀	Q ₉₀	Q ₁₈₀	Q ₂₇₀	Q ₃₅₅	Q _{min}	Q _{max}		
						Atuel	ESO	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	
						Atuel	LNE	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
						Atuel	LAN	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
						Salado	CAN	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
						Atuel	CAR	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red

Normality						River	G. Sta- tion	J	A	S	O	N	D	J	F	M	A	M	J	Win	Spr	Sum	Aut	Annual	Q ₁₀	Q ₃₀	Q ₉₀	Q ₁₈₀	Q ₂₇₀	Q ₃₅₅	Q _{min}	Q _{max}		
						Atuel	ESO	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
						Atuel	LNE	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
						Atuel	LAN	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
						Salado	CAN	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red
						Atuel	CAR	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red	Red

Source: Elaborated by the authors.

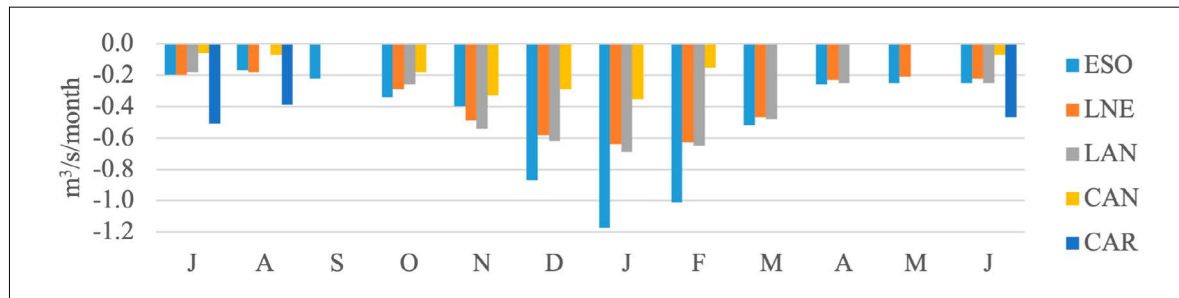


Figure 2. Kendall's significant monthly non-parametric linear trend values. Source: Elaborated by the authors.

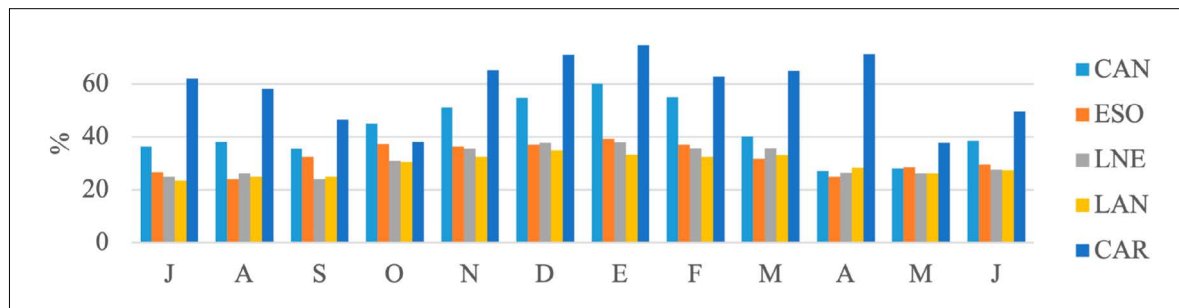


Figure 3. Percentage decrease of the second period with respect to the first one in the years of the step change found (2007, 2008, 2009). Source: Elaborated by the authors.

government declared a water emergency due to expected low runoff for the 2010-2011 hydrological period, resulting from insufficient snowfall during the winter of 2010. This period also coincides with the beginning of the most recent phase of hydrological drought starting in 2009, linked to

a negative El Niño Southern Oscillation (ENSO) event (Rivera, 2018).

Figure 4 shows the percentage difference in step changes between the averages of the most recent block of years (2009-2019) and the previous block (1985-2008). For comparison, the stations

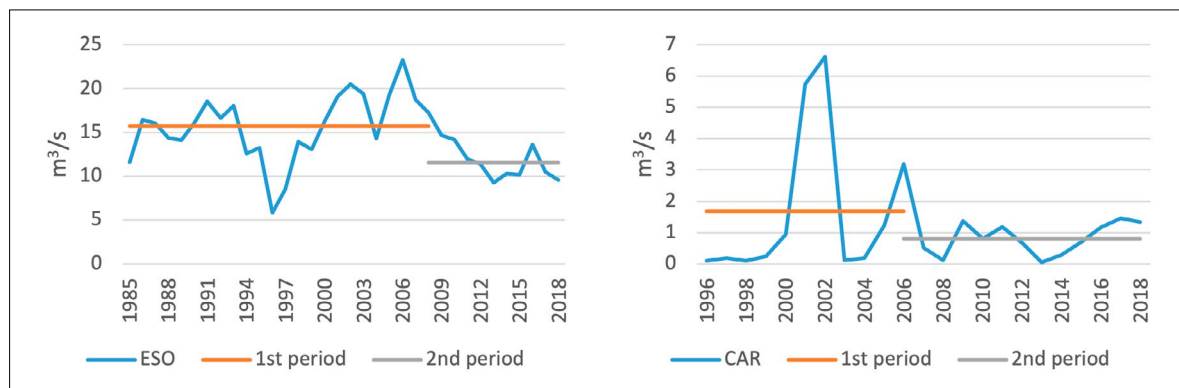


Figure 4. Step changes for annual minimum flows in the gauge stations of the Atuel basin. Source: Elaborated by the authors.

Puente El Sosneado (ESO) and Carmensa were analyzed. The percentage of differences increases downstream, exceeding 70 % at Carmensa. This situation, primarily influenced by the onset of “La Niña” (negative ENSO), may have been exacerbated by anthropogenic activities, leading to reduced flows in the Atuel river as it passes through Carmensa and the irrigated oasis.

Regarding the results related to outliers, it is important to highlight that, since all stations are located within the same basin, the time series theoretically share similar characteristics concerning the magnitude and occurrence of extreme minimum and maximum events.

The atypical data, identified by the MAD-score test and verified by the WRC, Grubbs, and Rosner tests, are presented in Figures 5 and 6, respectively. These figures are linked to the time series of maximum and minimum flows, categorized by months and each climatic season.

It should be noted that the tests used only detected outliers above the mean of the series, which are important for highlighting the hydrological response to external climatic events (such as ENSO). Outliers below the mean were not detected because there were no negative flow values. In this case, the identification of such outliers can be complemented by an analysis of hydrological droughts, where anomalies are more significant in terms of

temporal and spatial references than in magnitude (for stations and values with zero flow records).

Analyzing outliers for ecosystems in the study area can be valuable, as they reveal the presence of periodic flood pulses, which are essential for maintaining healthy riparian and wetland environments. These flood pulses provide extraordinary water inputs that help control the salinization of such environments (Magnani, 2016), among other benefits.

Although all the stations exhibited high outliers, their verification was performed by comparing all stations during the same reference periods. If one station presented an outlier, the others were expected to show either another outlier or, at a minimum, an increase in flows for the same period. Thus, there was no need to consult additional sources for verification or, in other cases, to exclude any data from the series.

Climatic and socio-economic context of the Atuel river basin

To better understand the above results, it is important to present the socio-natural context of the Atuel basin.

Regarding climatic characteristics, the basin's geographical position (intertropical zone and the southern hemisphere) on the slopes of the Andean mountain range and within the arid South Ameri-

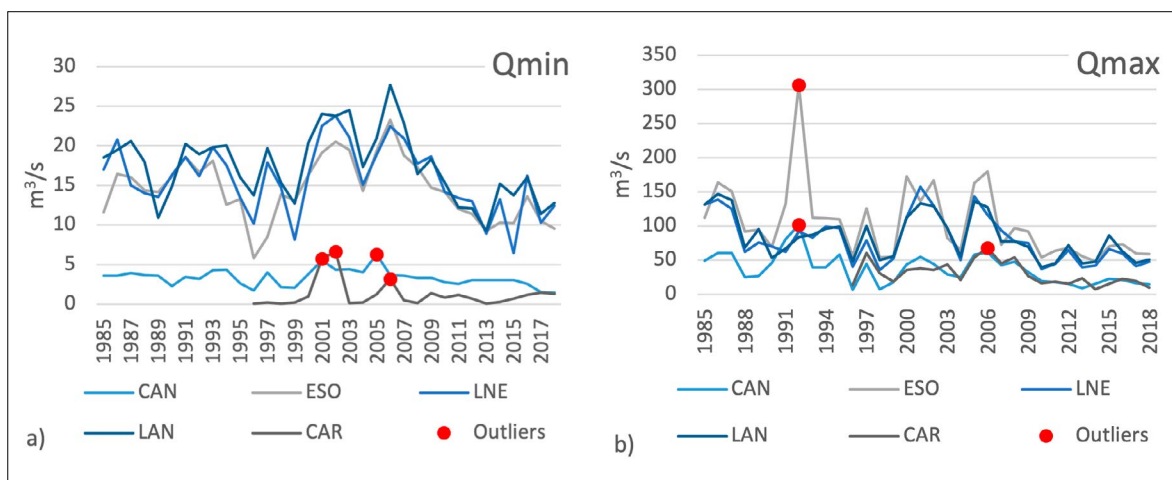


Figure 5. Annual values out of range according to minimum (a) and maximum (b) flows. Source: Elaborated by the authors.

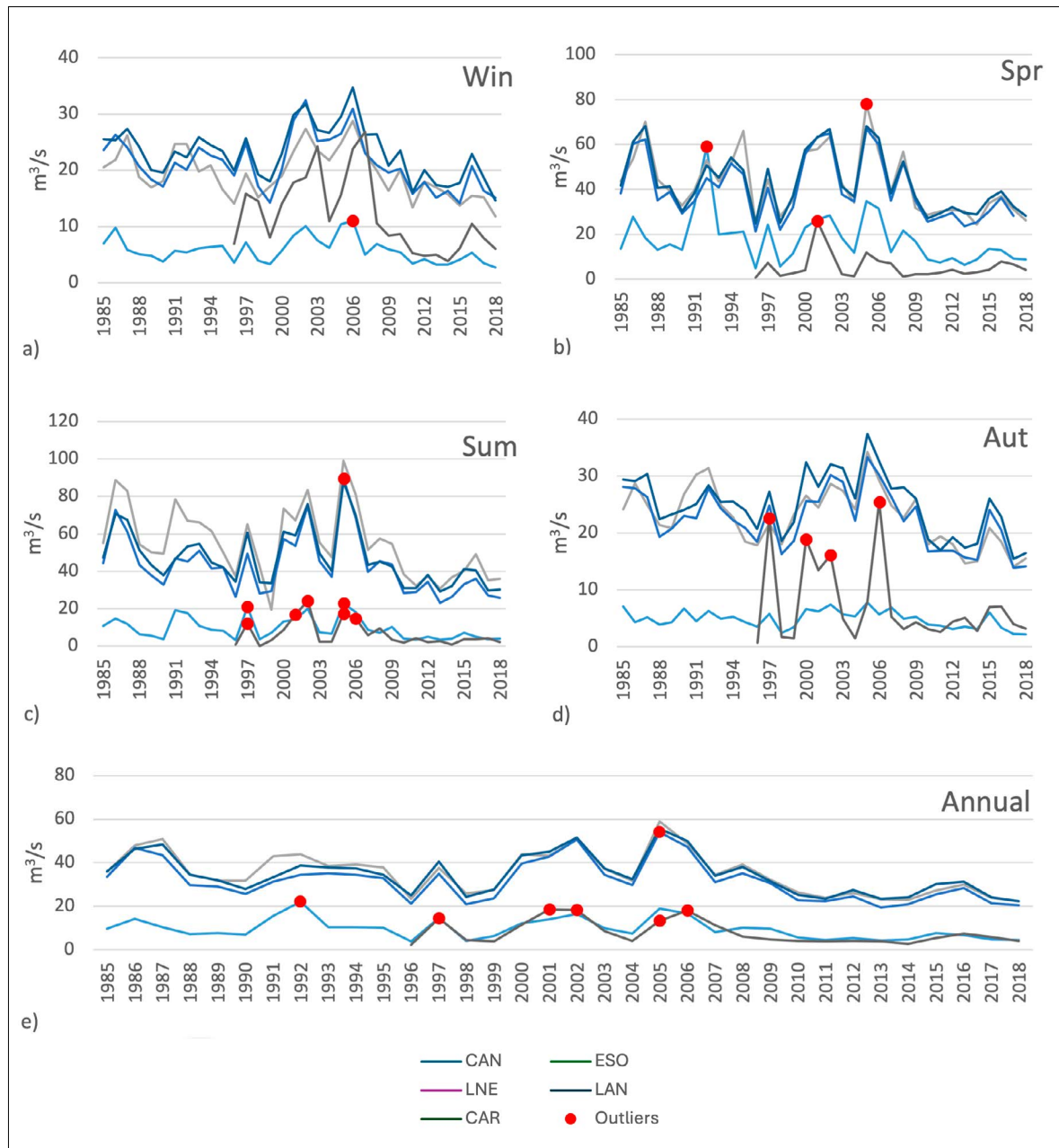


Figure 6. Annual values out of range by climatic stations - annual average and hydrometric station. Source: Elaborated by the authors.

can diagonal, means that the availability of water resources may be influenced by external events. These include the Föhn effect (in the rain shadow of the Andes), anticyclones, and humid winds from the Atlantic and Pacific Oceans (DGI, 2017).

The Andean mountain range, as a natural barrier where Pacific winds deposit rain on the windward side, also acts as a retention and accumulation area for snow during the winter season. This snowmelt feeds the rivers with a permanent

snowfall regime and represents a major source of groundwater recharge (Viale et al., 2019).

As one of the main rivers in the region, the Atuel river's hydroelectric potential was recognized as early as the mid-1940s with the construction of dams. The Los Nihuiles complex, which serves multiple purposes (flood control, flow regulation, hydroelectric generation, and irrigation storage), consists of four dams with a combined storage capacity of nearly 431.7 hm³ (DGI, 2017).

Regarding other anthropogenic factors and given the low rainfall, the economic potential of the basin is concentrated along the river axis, with greater emphasis downstream of the hydroelectric complex. In this area, agricultural activities are prominent (Southern Oasis), which, while shared with the neighboring Diamante river basin, are irrigated by the Atuel river over approximately 137,290 hectares. Table 3 presents the volumes and percentages of water allocated to various uses within the Atuel basin, according to the General Department of Irrigation (DGI, 2020), the provincial entity responsible for organizing and planning the use of water resources for agricultural purposes.

The oases of Mendoza, such as those in the south (dominated by the Atuel and Diamante rivers), exemplify the local people's achievements in overcoming the region's natural desert conditions.

Table 3. Estimated distribution of the surface water of the Atuel river Season 2019/2020.

Activity	Volume (hm ³)	Volume (%)
Total to be distributed	415.4	100
Water population supply	5.3	1.3
Agriculture	406.4	97.8
Industry	0.3	0.1
Mining and oil	0.0	0.0
Fracking	0.0	0.0
Recreational / environmental	2.3	0.6
Public use	1.0	0.3

Source: DGI (2020).

These areas, situated on large alluvial deposits, have fertile soils, although their historical limitation has always been the lack of water for irrigation.

In 2019, the population of the Atuel basin was estimated at approximately 60,000 inhabitants (INDEC, 2020). This includes the populations of General Alvear (50,387 inhabitants, the capital of the homonymous department in the Province of Mendoza), Algarrobo de Águila (1,520 inhabitants, the capital of Chical Co department in the Province of La Pampa), and Santa Isabel (3,616 inhabitants, the capital of the Chalileo department in the Province of La Pampa).

Although the basin also extends into other departments of La Pampa province, such as Limay Mahuida and Puelín, and parts of Mendoza departments like San Rafael and Malargüe, it primarily encompasses the more populated areas of the departments. The rural population is significantly smaller than the urban areas indicated. Additionally, due to the concentration of population around the oases, the basin's population is considerably smaller compared to the contiguous northern basin (Diamante river), which includes San Rafael, the largest and most dynamic city in southern Mendoza, with over 110,000 inhabitants.

In this context and linking the above with the results from the normality, randomness, and independence tests, the basin exhibits a high level of water resource exploitation (evidenced by the absence of normality in 76 % of the measurements at the Carmensa station). This may suggest that most of the drained volume is utilized on the Mendoza side for the described purposes, leaving minimal or no runoff (Figure 7) for La Pampa (a situation resulting from the litigation).

Furthermore, regarding randomness, human impacts on the basin are evident, with significant absences of this statistical characteristic in the months with higher irrigation demands. This is reinforced by the 92 % independence in measurements at Carmensa, indicating a disconnection from the natural river flows and a greater reliance on the remaining flows from upstream irrigated areas.

Figure 7 illustrates the differences in average annual flow between the upstream stations of

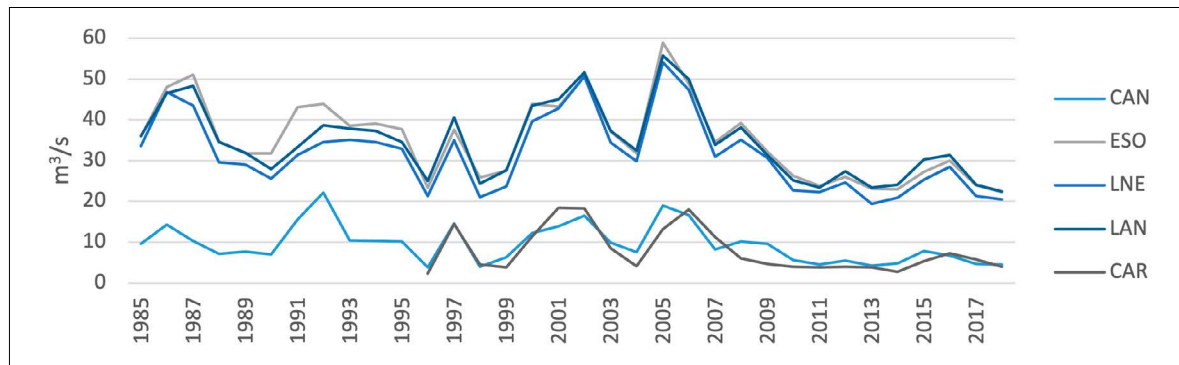


Figure 7. Annual runoff hydrograph for the stations under consideration. Source: Elaborated by the authors.

the hydroelectric complexes (El Sosneado, Loma Negra, and La Angostura) and Carmensa, located downstream and near the end of the oasis.

The differences in runoff illustrate the decrease in flows from Mendoza to La Pampa. When considering additional natural demands such as evaporation and infiltration, these differences highlight the challenging reality faced by societies and ecosystems along the Atuel river in La Pampa territory for decades.

DISCUSSION

Results of Exploratory Data Analysis (EDA) are commonly used as preliminary tests to assess the statistical quality of data and to evaluate assumptions required for subsequent methodologies, such as normality, randomness, or independence (Hirsch et al., 1982). These methods provide a foundational approach to understanding hydrological variability and its drivers, particularly in basins where human intervention plays a significant role.

Unlike previous research in the study area (Vich et al., 2013; Lauro et al., 2016; Lauro et al., 2018), which primarily describes the statistical conditions of the data series analyzed, this research aims to establish physical relationships (causality) based on the results (geographic principle of “relationship”).

The results from normality, randomness, and independence tests indicate anthropic intervention along the Mendoza axis of the Atuel river. While

the river naturally exhibits irregular flow patterns typical of mountain systems, human activities contribute to significant hydrological alterations downstream, leading to increased randomness and independence of flows at the Carmensa station.

Given that the Carmensa station is the final gauge before the Atuel river enters the Pampean territory, the results suggest an altered state of the river upon entering the wetlands area, a situation contested by La Pampa in the lawsuit against Mendoza (Prieto, 1998; Rojas and Prieto, 2018; Barbosa, 2019; Rojas and Wagner, 2019).

The quantitative results are consistent with previous studies in the area (Vich et al., 2013; Lauro et al., 2016; Lauro et al., 2018; López and Vich, 2018), showing significant normality, randomness, and independence in 70 %, 68 %, and 80 % of the measurements, respectively. Trend analysis indicates negative values like those found by the authors, except for the Carmensa station, which was not included in their studies.

In contrast, the findings related to abrupt changes differ from those as Lauro et al. (2016), as their methodologies' position step changes based on the final date of the series considered. This research identifies significant abrupt changes consistent with a negative ENSO event in 2009 (Rivera, 2018).

Finally, in agreement with Lauro et al. (2018), the maximum outliers in 1992 for El Sosneado and Cañada Ancha stations are highlighted (Figure 5b) as the highest peaks in all the time series analyzed.

It is noteworthy that these outliers, along with others detected by the MAD-score, were corroborated among the stations analyzed, although not all peaks were classified as outliers.

Unlike the methodologies used by the authors, MAD-score employs the monthly median measurements for each of the 12 months of the year, offering greater robustness to extreme events. This allows the detection of outliers where methods such as Rosner, WRC, or Grubbs may fail (Lauro et al., 2018). Notably, the atypical values related to summer floods in most seasons, particularly at Carmensa, with outliers in autumn (Figure 6d), reflect runoff from agricultural activities combined with years of water abundance in the region (Rivera, 2018).

These findings contribute to the broader discourse on hydrological alterations in semi-arid and arid regions worldwide, where water scarcity exacerbates conflicts over resource allocation. In the case of the Atuel river, the interplay between water storage, consumption, and interprovincial governance adds another layer of complexity to hydrological and environmental management.

The hydrological alterations observed in the Atuel river are consistent with patterns reported in other semi-arid basins worldwide, like the Mendoza and San Juan rivers, which highlights how water management decisions in Andean basins, particularly through dam construction and irrigation, have led to the desiccation of wetlands and conflicts over resource allocation (Bastidas, 2023; Bastidas et al., 2024). Similar processes have been documented in the Colorado river (Christensen et al., 2004), where extensive damming and water diversion have significantly altered downstream hydrology, and in the Yangtze river, where the Three Gorges Dam has disrupted natural flow regimes and sediment transport (Zhang et al., 2016). In South America, the Paraná river basin has experienced hydrological alterations linked to hydroelectric development, leading to changes in flood dynamics and ecosystem connectivity (Agostinho et al., 2008).

While the methodology applied in this study is not entirely novel, its focus on establishing physical relationships and detecting abrupt changes in

flow variability using a combination of statistical tests provides a more detailed understanding of the extent of human influence in the Atuel basin. This approach contributes to the broader discussion on water governance in semi-arid regions, where competing demands for water resources exacerbate environmental and socio-political tensions.

Future research should incorporate a multi-scalar approach that integrates hydroclimatic modeling with socioeconomic analyses to better understand the long-term implications of these alterations, which could provide valuable insights into mitigating the negative impacts observed in the Atuel river.

CONCLUSION

As the Atuel is one of the primary rivers in the region, both for its ecological importance in the arid zone and for the irrigation of oases, the human impacts on its flows are evident through exploratory approaches such as normality, randomness, and independence tests.

Exploratory analyses and the applied tests have verified the presence of anthropogenic impacts contributing to the river's hydrological alteration. This is evident from the similarities between the results of the upstream stations, located before the dam complex, and the Carmensa station, situated almost at the end of the Southern oasis and downstream of water usage. It can be inferred that water consumption and dam storage negatively affect the river's continuity and flow towards the Pampean territory.

Thus, human activities have a clear negative impact on river flows, facilitating the socioeconomic development of surrounding communities but with repercussions on downstream ecosystems and societies. The methodology used provides preliminary and exploratory evidence of the natural characteristics of the rivers, their hydrological conditions, and the human impacts on them.

The findings demonstrate that the region's aridity, combined with the natural characteristics of the rivers and human impacts on their hydrological regimes, creates a vulnerable situation for the

ecosystems. This vulnerability has been evident for decades due to ongoing degradation.

Human presence in the territory alters the landscape and its resources, impacting both societies and natural spaces based on their location. Additionally, political-administrative differences (such as interprovincial boundaries) can be significant factors contributing to geographic alterations within the same basin.

In response to these differences, geography, as an integrative science of socio-natural elements in the territory, offers a diagnostic, analytical, and action-oriented approach to address problems, events, or phenomena in the regions.

Through its scientific branches (such as hydrography) and auxiliary sciences (such as statistics), exploratory analyses like the one conducted in this study enable the diagnosis of events along a river course such as the Atuel. The scope of current or future studies will depend on their relevance to the societies involved and the natural spaces affected (positively or negatively) in the human appropriation of the territory.

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