Daily streamflow of Argentinian rivers analysis using information theory quantifiers.

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Daily streamflow of Argentinian rivers
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ABSTRACT. This paper analyzes the temporal evolution of the streamflow for different rivers in Argentina, based on information quantifiers such as statistical complexity and permutation entropy. The main objective is to identify essential details of the dynamics of the processes to differentiate the degrees of randomness and chaos. The permutation entropy is used with the probability distribution of Ordinal Patterns and the Jensen-Shannon divergence to calculate the disequilibrium and then the statistical complexity. Daily streamflow series at different river stations were analyzed to classify the different hydrological systems. The Complexity Entropy Causality Plane (CEPC) and the representation of the Shannon Entropy and Fisher Information Measure (FIM) show that the daily discharge series could be represented approximately with Gaussian noise, but the variances highlight the difficulty of modeling a series of natural phenomena. An analysis of stations downstream from the Yacyretá dam shows that the operation affects the randomness of the daily discharge series in hydrometric stations near the dam, but when the station is further downstream this effect is attenuated. The size of the basin plays a relevant role in modulating the process, large catchments have smaller values for entropy and the signal is less noisy due to integration over larger time scales. The small and mountain basins present a rapid response that influences the behavior of daily discharge while presenting a higher entropy and lower complexity. The results obtained characterize the behavior of the daily discharge series in Argentinian rivers and provide key information for hydrological modeling.

Keywords: Permutation entropy, statistical complexity, streamflow series, Argentina rivers

Introduction

Proper water management has always been a key to societies' progress. For this reason, solutions have been developed to modify spatial and temporal availability and adapt them to human needs. Under a global context of climate change that
affects the region, its availability should be assessed now and, in the future, to optimize water resources management and planning.

The hydrological cycle is mainly a coordinated and balanced interaction between the atmosphere, the ocean, and the land that controls the planet’s temperature, it moves a large amount of matter and energy, resulting in a complex system with highly variable processes in space and time, and this variability exists at all scales, from centimeters to the continent scale, from minutes to years [1,2].

Argentina is a large country; the continental area is 2,791,810 km$^2$ and the water resources are not uniformly distributed. A high percentage of the territory is characterized by arid or semi-arid climates, even with water deficits, where water demand exceeds the availability, presenting basins of different sizes with varying characteristics depending on their location.

Hydrological modeling plays a crucial role in capturing the complex hydrology of large basins and informing basin development decisions through comprehensive modeling approaches [3].

Catchment classification can be used in transboundary rivers that face water usage competition across distinct hydrological characteristics, the information can aid stakeholders in irrigation planning, navigation, and flood risk management, among others [4]. Hydrologic system complexity provides a suitable basis for this classification, and nonlinear dynamic concepts offer an appropriate methodology for assessing it [5-7].

To classify basins into different groups based on their hydrological characteristics, a framework is necessary, and nonlinear dynamic concepts offer a suitable methodology. For this purpose, the complexity-entropy causality plane (CECP) has been introduced as a diagnostic diagram that plots statistical complexity versus entropy considering disequilibrium, introduced in nonlinear dynamics analysis to classify signals according to their degrees of randomness and complexity [8,9].

It has several applications in the field of hydrology, almost 500 series of daily discharge rivers from different countries were studied in [10] and found that the data are a mixture of random and deterministic process and proposed a comparison with k-noise series in the CECP, quantifying the differences. In [11] was conducted

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the Complex Entropy Causality Plane (CECP) for the analysis of 80 series of daily flows at different stations in the United States over a period of 75 years and found that both chaotic and stochastic systems can be compatible with the daily streamflow dynamics and the CEPC can discriminate the signals in presence of moderate observational noise.

Another application of the methodology is to analyze the behavior in the series of flows concerning changes in the basin, such as the construction of dams or land uses, as well as the influence of the climate and long-term phenomena. An example of application is presented in [12,13], a study about the influence of the construction of the Sobradinho dam on the series of daily flows of the São Francisco River in Brazil, finding different patterns of complexity and entropy. In addition, the close relationship between the dynamics of the flows and the El Niño Southern Oscillation phenomenon is confirmed.

Statistical complexity was used as a metric of hydrologic alteration at the basin scale [14]. The daily streamflow records for 22 urban watersheds in US cities were studied using urbanization to represent hydrological changes. The results showed that, in urban watersheds, the measure of complexity tends to decrease and entropy increases while hydrological alteration increases.

This paper analyzes the temporal evolution of the flows of different rivers in Argentina, based on information quantifiers to identify the complexity-entropy causality plane and be able to classify the different hydrological systems. This characterization allows knowing the behavior of the daily discharge series, providing relevant information for hydrological modeling. This work is organized with the following sections: Methodology: where the methods and equations used are described, Data: involves the source of information and characteristics of time series used, Results: the outcomes and interpretation analysis are developed, and Conclusions: a summary of the main contributions obtained from this work.

**Methodology**

For a given arbitrary probability distribution $P = \{p_i: i=1, \ldots, N\}$, the Shannon logarithmic information measure is defined by:

$$S[P] = - \sum_{i=1}^{N} p_i \ln(p_i) ,$$  \hspace{1cm} (1)
and it is considered the measure of the uncertainty associated with the physical processes described by $P$. If $S[P] = 0$ means that it is possible to predict with certainty which of the possible scenarios $i$, with associated probabilities given by $p_i$, will actually occur. On the contrary, our ignorance is maximum for a uniform distribution $P_e = \{p_i = 1/N \ i=1,...,N\}$ [15] presented a measure of statistical complexity capable of detecting essential details of the dynamics, this is defined through the product:

$$C_{JS}[P] = Q_j[P,P_e] \cdot H_S[P], \quad (2)$$

and the generalized Shannon entropy is:

$$H_S = \frac{S[P]}{S_{\text{max}}}, \quad (3)$$

with $S_{\text{max}}=S[P_e]=\ln(N)$, $0 \leq H_S \leq 1$ and $P_e=1/N, \ldots,1/N$ the uniform distribution. The disequilibrium is defined in terms of the Jensen-Shannon divergence:

$$Q_j[P,P_e] = Q_0 J[P,P_e], \quad (4)$$

being $Q_0$ a normalization constant equal to the inverse of the maximum possible value of $J[P,P_e]$ and the Jensen-Shannon divergence:

$$J[P,P_e] = \frac{S[P + P_e]}{2} - \frac{S[P]}{2} - \frac{S[P_e]}{2}. \quad (5)$$

Bandt and Pompe (2002) [16] methodology is used for the distribution probability function, it's called Ordinal Patterns and takes into account the temporal causality in the process dynamic. The approach is based on the sequence of the symbols that occurs in the time series, replacing the time series with the corresponding range sequence. Given a time series $\{x_t : t = 1, \ldots, N\}$, and an embedding dimension $D \geq 2$ ($D \in \mathbb{N}$) and the delay time $\tau$ ($\tau \in \mathbb{N}$), the D-ordinal pattern is generated by:

$$s \rightarrow \{X_{s-(D-1)\tau}, X_{s-(D-2)\tau}, \ldots, X_{s-\tau}, X_s\}, \quad (6)$$

For every time instant $s$, a $D$-dimensional vector is assigned, and results from the evaluation for the time series in the $s \cdot (D-1) \tau$, ..., $s-\tau$, $s$ instants. A greater $D$ value means greater information about the pass incorporated in the resultant vector. The
$D$-ordinal patterns related with the instant $s$ is referred to the permutation $\pi = \{r_0, r_1, ..., r_{D-1}\}$ of $\{0, 1, ..., D-1\}$ defined by:

$$x_{s-r_0\tau} \geq x_{s-r_1\tau} \geq \cdots \geq x_{s-r_{D-2}\tau} \geq x_{s-r_{D-1}\tau}, \quad (7)$$

In this way, the vector defined by Equation 6 becomes a unique symbol $\pi$. With the objective of finding a unique result $r_i < r_{i-1}$ if $x_{s-r_i\tau} < x_{s-r_{i-1}\tau}$ is considered. The reason is that if the value of $x_t$ has a continuous distribution, equal consecutives values are unusual. For every possible $D!$ orders (permutations) $\pi_i$ from order $D$, their relative frequencies associated can be computed as the number of times that this sequence appears in the series and divided by the total of sequences. In this way the ordinal patterns distribution probability for the time series given is obtained.

It is shown that the complexity remains within the bounds of minimum and maximum complexity. A maximum and minimum envelope complexity as a function of the entropy can be calculated [17]. The Complexity-Entropy Causality Plane (CEPC) is the representation of plotting the permutation statistical complexity $C_{JS}$ versus the generalized Shannon entropy $H_S$ and the bounds for an admissible region that only depend on $D$ [8-9].

Another graphic representation is the Fisher-Shannon plane, evaluated using the Bandt and Pompe [16] recipe to evaluate the probability distribution to a time series. This method can uncover the informational properties of the planar location [18]. The Fischer-Shannon casualty plane $H_s \times F$ was calculated, where $H_s$ is the generalized Shannon entropy in equation (3), and $F$ is the Fisher’s Information Measure (FIM) [19] as a measure of the gradient content of the distribution $f(x)$, as follows:

$$F[f] = \int_{\Delta} \frac{1}{f(x)} \left(\frac{df(x)}{dx}\right)^2 dx = 4 \int_{\Delta} \left(\frac{d\Psi(x)}{dx}\right)^2. \quad (8)$$

FIM could be interpreted as a measure of the ability to estimate the amount of information that can be extracted from a set of measurements [20]. For a discrete environment the best-behaved expression to use [21] is the discrete normalized FIM given by:

$$F[P] = F_0 \sum_{i=1}^{N-1} \left(\frac{1}{(p_{i+1})^2} - \left(\frac{1}{p_i}\right)^2\right)^2, \quad (9)$$

and the normalization constant $F_0$ is given by:
\[ F_0 = \begin{cases} 1 & \text{if } p_{i^*} = 1 \text{ for } i^* = 1 \text{ or } i^* = N \text{ and } p_i = 0 \forall i \neq i^* \\ 0 & \text{otherwise} \end{cases} \]  

(10)

The algorithms are obtained from the Python library ordpy: A Python Package for Data Analysis with Permutation Entropy and Ordinal Network Methods [22]. The color noise series was generated with the library colorednoise\(^3\) that generates Gaussian distributed noise with a power law spectrum based on the algorithm in [23]. Plots are made using matplotlib [24], seaborn [25] and geopandas [26] Python libraries.

Data

The methodology was applied to the daily discharge series in different stations across Argentina. The data was obtained from the National Hydrological Network of the National Water Information System of the Secretariat of Infrastructure and Water Policy\(^4\). The main information of the stations is shown in Table 1 and their geographical locations in the map in Figure 1.

Table 1. Basic information of the hydrometric stations studied.

<table>
<thead>
<tr>
<th>River</th>
<th>Station</th>
<th>Basin area (km(^2))</th>
<th>Record (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colorado</td>
<td>Buta Ranquil</td>
<td>15,300</td>
<td>1990-2019</td>
</tr>
<tr>
<td>Pilcomayo</td>
<td>La Paz</td>
<td>96,000</td>
<td>1960-2019</td>
</tr>
<tr>
<td>Paraguay</td>
<td>Puerto Pilcomayo</td>
<td>800,000</td>
<td>1910-2017</td>
</tr>
<tr>
<td>Paraná</td>
<td>Corrientes</td>
<td>1,950,000</td>
<td>1904-2019</td>
</tr>
<tr>
<td>Bermejo</td>
<td>Pozo Sarmiento</td>
<td>25,000</td>
<td>1940-2019</td>
</tr>
<tr>
<td>Mendoza</td>
<td>Guido</td>
<td>8,180</td>
<td>1956-2019</td>
</tr>
<tr>
<td>Carrenleufú</td>
<td>La Elena</td>
<td>1,500</td>
<td>1954-2019</td>
</tr>
<tr>
<td>Uruguay</td>
<td>Paso de los Libres</td>
<td>189,000</td>
<td>1908-2019</td>
</tr>
<tr>
<td>Atuel</td>
<td>La Angostura</td>
<td>3,800</td>
<td>1931-2019</td>
</tr>
<tr>
<td>Bermejo</td>
<td>El Colorado</td>
<td>65,736</td>
<td>1968-2019</td>
</tr>
<tr>
<td>Paraná</td>
<td>Itatí</td>
<td>1,600,000</td>
<td>1910-2019</td>
</tr>
<tr>
<td>Bermejo</td>
<td>Aguas Blancas</td>
<td>4,850</td>
<td>1944-2019</td>
</tr>
<tr>
<td>Paraná</td>
<td>Túnel Subfluvial</td>
<td>2,302,000</td>
<td>1904-2019</td>
</tr>
<tr>
<td>Bermejo</td>
<td>Balapuca</td>
<td>4,420</td>
<td>1971-2019</td>
</tr>
</tbody>
</table>

\(^3\) colorednoise by Felix Patzel on github

\(^4\) Sistema Nacional de Información Hídrica
The daily deseasonalized discharge series were obtained from the equation:

$$Q_{d_{i,j,k}} = \frac{Q_{i,j,k} - \bar{Q}_{i,j}}{\sigma_{i,j}}, \quad (11)$$

where $Q_{d_{i,j,k}}$ is the discharge deseasonalized for the $i$-th day, $j$-th month and $k$-th year, $Q_{i,j,k}$ is the daily discharge for the $i$-th day, $j$-th month and $k$-th year, $\bar{Q}_{i,j}$ is the average of all the $i$ days and $j$ month and $\sigma_{i,j}$ is the standard deviation of all $i$ days and $j$ month for every year of the record [27].
An example of daily discharge and deseasonalized discharge series is shown at Figure 2, for the Bermejo River at Balapuca station. The same procedure was made for all the series at stations mentioned at Table 1.

![Figure 2](image)

**Fig. 2** Daily discharge (above) and deseasonalized discharge (bottom) series for the Bermejo River at Balapuca hydrometric station.

**Results**

The results obtained from applying the methodology to the daily discharge and deseasonalized discharge series are shown. The entropy and complexity were calculated for $\tau=1$ and varying $D$ from 3 to 7 (Figure 3 to 6).
Fig. 3 Permutation entropy for daily deseasonalized discharge series varying parameter $D$.

Fig. 4 Complexity for daily deseasonalized discharge series varying parameter $D$. 
The comparison analysis for the daily discharge and deseasonalized discharge series shows that the permutation entropy decreases with increasing the parameter $D$ (Figures 3 and 5). For the complexity measure a different behavior is observed in Figures 4 and 6. The variation of the complexity increasing the parameter $D$ is
not similar between the time series studied. A possible explanation could be related to the fact that the record for the different series is not the same for every station. For further analysis in this study $D = 5$ will be considered, following the criteria that the record length of the series $N$ should be $N >> D$.

The same analysis was made for the shuffled series of daily discharge and deseasonalized discharge series, and the results showed that in both cases the entropy approaches 1 and the complexity 0, as shown in Figures 7 and 8 for daily discharge and 9 and 10 for deseasonalized discharge time series. This result indicates that the sorting of the values has an impact in the behavior of the time series in terms of entropy and complexity.

Fig. 7 Entropy for shuffled series of the daily discharges varying parameter $D$. 
Fig. 8 Complexity for shuffled series of the daily discharges varying parameter $D$.

Fig. 9 Entropy for shuffled series of the daily deseasonalized discharge series varying parameter $D$. 
The Complexity Entropy Causality Plane (CECP) of Shannon and Fischer-Shannon for the daily discharge series are shown at Figure 11 and Figure 12, respectively. The same procedures are repeated for the daily deseasonalized discharge series and shown in Figures 13 and 14. The methodology was also applied to dynamic stochastic series of $K$-noises (noise with power spectrum frequency dependence fitted by $f^{(-K)}$ values), with $K$ from 0.00 to 3.50, with intervals of 0.25 and 10 random simulations for every $K$.

Fig. 10 Complexity for shuffled series of the daily deseasonalized discharge series varying parameter $D$.

Fig. 11 Complexity - Entropy causality plane for daily discharges series.
Fig. 12 Fisher Information Measure - Entropy plane for daily discharges series

Fig. 13 Complexity - Entropy plane for daily deseasonalized discharge series.

Fig. 14 Fisher Information Measure- Entropy plane for daily deseasonalized discharge series.
The CEPC shows that the daily streamflow series from different hydrometric stations exhibit similar behavior compared to Gaussian noise in most cases. In particular this occurs for the parameter $k$ between 2 and 3 and this is consistent with the results found in other studies [10, 11]. The approximation to the noise series fits better in the deseasonalized discharge series. The same conclusion arises for the Fisher-Shannon plane, revealing that it is not easy to characterize natural phenomena as stochastic or chaotic. The results obtained from the Fisher-Shannon plane analysis for both the daily river discharge and its deseasonalized series reveal that for the Paraná River at Corrientes station and Uruguay River at Paso de los Libres station the time series cannot be adequately described as Gaussian noise.

In [12,13] the authors investigated the influence of the construction of Sobradinho dam on daily streamflow of São Francisco river. The authors found that there are different complexity and entropy patterns after the construction, in particular a higher entropy permutation, showing that the operation of the reservoir induces a decreased regularity. Following this methodology, a comparison for three selected stations was made. The generalized Shannon Permutation Entropy was calculated for the daily discharge time series at three stations downstream of the location where the Yacyretá hydropower dam is situated, between Argentina and Paraguay in the upper basin of Paraná River. Yacyretá is a run-of-the-river power plant, has 20 Kaplan turbines with a total power of 3200 MW and the area of the lake is 1600 km$^2$. The comparison was made between the data series before the construction of the dam in 1983 and after 1994, when the first turbine was made operational. The results are shown in Table 2.

Table 2. Comparison of the permutation entropy for the daily discharge series at Paraná river in three stations downstream Yacyretá dam, before and after the construction.

<table>
<thead>
<tr>
<th>River</th>
<th>Station</th>
<th>Basin area (km$^2$)</th>
<th>Permutation Entropy</th>
<th>Variation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pre Yacyretá</td>
<td>Post Yacyretá</td>
</tr>
<tr>
<td>Paraná</td>
<td>Itatí</td>
<td>1,600,000</td>
<td>0.48</td>
<td>0.66</td>
</tr>
<tr>
<td>Corrientes</td>
<td>1,950,000</td>
<td>0.51</td>
<td>0.62</td>
<td>18%</td>
</tr>
</tbody>
</table>

5 Entidad Binacional Yacyretá
Consistent with [12,13], in Table 2 the results show that after the construction of Yacyretá the permutation entropy is higher than before, even when the analysis is not made in a hydrometric station immediately downstream from the dam. An interesting conclusion is that the further downstream from the dam a station is, the lesser the influence of the dam operation on entropy. In this analysis the presence of a co-induced climatic effects is not considering and could be another source of change in the dynamic of the discharge series.

However, this result shows that the operation of Yacyretá affects the randomness of the daily discharge series when the hydrometric station is immediately downstream of the dam, but when the station is further downstream this effect is attenuated. An explanation for that behavior is that the size of the basin plays an important role in modulating the process on a daily scale. Large catchments have smaller values for entropy, and the signal is less noisy due to integration over larger time scales [10].

Other studies have also found that the statistical properties of river flow fluctuations of daily data depend on the watershed area, and for this reason, prediction models should not be directly transferred across watersheds of varying sizes without taking into account the effects of basin area into consideration [28-29].

To compare the different cases, a geospatial analysis was carried out. The hydrometric stations were geographically located identifying the entropy and complexity indicators with different colors depending on the range of values obtained, in order to identify if there is any pattern in the obtained results. The results are shown in Figures 15 and 16 for the deseasonalized discharge series, and 17 and 18 for daily discharge series.
Fig. 15 Complexity for the deseasonalized discharge series
Fig. 16 Entropy for the deseasonalized discharge series
Fig. 17 Complexity for the daily discharge series
On the one hand, Figure 15 and 17 shows that the values for complexity seem to be similar for the discharges series as for the deseasonalized discharge series, varying approximately between 0.15 and 0.30 and finding a greater complexity in the East than in the West, coinciding with the stations of less entropy.

On the other hand, Figures 16 and 18 show that for the entropy the results are similar for both series, discharge and deseasonalized discharge series. In the first case with variations between 0.45 and 0.85, and in the second case 0.55 and 0.90, finding higher values of entropy in stations which are located to the West and with smaller basins - except for the La Elena station - and decreasing towards the East. The lowest entropy values were obtained for all the stations at the Paraná, Uruguay, and Paraguay rivers, and El Colorado station at the Bermejo river.

**Fig.18** Entropy for the daily discharge series
The stations that present higher entropy are La Angostura, Atuel river; Buta Ranquil, Colorado river; La Elena, Balapuca river; Aguas Blancas and Pozo Sarmiento, Bermejo river; and Misión La Paz, Pilcomayo river. On the contrary, the stations Corrientes and Túnel, Parana river; Paso de los Libres, Uruguay river; El Colorado, Bermejo river; and Puerto Pilcomayo, Paraguay river present a lower value of entropy.

On the one hand, a possible explanation could be that those basins with a small area and the influence of highlands or mountains present a rapid response that affects the behavior of daily discharge. On the other hand, in basins with larger area and flat topography the response is slower. The catchment area plays a role softening the daily variations and decreasing the degree of randomness of the series.

**Conclusions**

This paper analyzes the temporal evolution of the streamflow of different rivers in Argentina, based on information quantifiers such as statistical complexity and permutation entropy. The main objective is to identify essential details of the dynamics of the processes and quantify them in order to differentiate the degrees of randomness and chaos.

The analysis carried out for the shuffled series shows that the sorting of data has an impact on the structure and the measures of information.

The complexity entropy causality plane, and the representation of the entropy and Fisher information measure show that the daily discharge series could be approximately represented with Gaussian noise for a parameter $K$ between 2 and 3, and this approximation fits better for the deseasonalized discharge series. The Fisher-Shannon plane presents an important difference with respect to the Gaussian noise for the Corrientes station at Parana River and Paso de los Libres at Uruguay River, highlighting the difficulty of modeling a series of natural phenomena observed in real life.

Analyzing the daily discharge time series at the stations at Parana River downstream from the location where the Yacyretá hydroelectric dam was situated and comparing the total period of data and a second period after the power plant became operational, the results show that the operation of the dam affects the randomness of the daily discharge series when the hydrometric station is near the
dam, but when the station is further downstream this effect is attenuated. An explanation for that behavior is that the size of the basin area plays an important role in modulating the process on a daily scale. Large catchments have smaller values for entropy, the signal is less noisy due to integration over larger time scales. A geospatial analysis was carried out. On the one hand, those basins with a small area and with the influence of highlands or mountains present a rapid response that influences the behavior of daily discharge and present a higher entropy and lower complexity. On the other hand, in basins with greater area and smooth topography the response is slower, the results show a lower entropy and higher complexity. The catchment area plays a relevant role by softening the daily changes and decreasing the degree of randomness of the discharge series.

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**Statements and Declarations**

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**Competing Interests**

The authors have no relevant financial or non-financial interests to disclose.

**Author Contributions**

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Micaela Suriano, Leonidas Facundo Caram and Osvaldo Anibal Rosso. The first draft of the manuscript was written by Micaela Suriano and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

**Data availability**

The data used to support the findings of this study are included within the article. The processed data are available from the corresponding author upon request.