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Recurrence quantification analysis of São Francisco River flow: hydrological alterations caused by the construction of Sobradinho dam

Análise de quantificação de recorrência da vazão do rio São Francisco: alterações hidrológicas com a construção da barragem de Sobradinho

Análisis de cuantificación recurrente del caudal del río Sao Francisco: alteraciones hidrológicas provocadas por la construcción de la presa Sobradinho

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Abstract

We investigated how the construction of the Sobradinho dam and reservoir affected the daily streamflow of the São Francisco River, using the method of Recurrence plot (RP) and Recurrence quantification analysis (RQA) which serves to visualize and quantify the recurrences of the states in the phase space of the dynamic system. We analyzed daily streamflow time series recorded in the fluviometric station Juazeiro that is located downstream of the Sobradinho dam, for the periods before (1943-1972) and after (1980-2009) the dam

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construction. We observed that in the natural regime, before the dam construction, the streamflow dynamics shows characteristics of periodic and quasi-periodic process, indicated by the checkerboard patterns in RP. After the dam construction, streamflow dynamics exhibit sudden changes indicated by white bands in RP, and become less predictable, less complex, and remain s in certain laminar states for shorter periods, indicated by the decrease of the values of RQA parameters.
Keywords: Streamflow; Dam; Recurrence plot; Recurrence quantification analysis.

Resumo

Investigamos como a construção da barragem e reservatório de Sobradinho afetou a vazão diário do rio São Francisco, utilizando o método de Gráfico de Recorrência (*Recurrence plot* - RP) e Análise de quantificação de recorrência (*Reccurence quantification analysis* –RQA) que serve para visualizar e quantificar as recorrências dos estados no espaço de fase do sistema dinâmico. Analisamos séries temporais de vazões diárias registradas na estação fluviométrica de Juazeiro que está localizada a jusante da barragem de Sobradinho, para os períodos antes (1943-1972) e depois (1980-2009) à construção da barragem. Observamos que no regime natural, antes da construção da barragem, a dinâmica da vazão apresenta características de processo periódico e quase periódico, indicadas pelos padrões de xadrez em RP. Após a construção da barragem a dinâmica da vazão passa a apresentar mudanças repentinas indicadas por bandas brancas no RP, tornando-se menos previsível, menos complexa, e permanece durante os períodos mais curtos em certos estados laminares, indicados pela diminuição dos valores dos parâmetros RQA.
Palavras-chave: Vazão; Barragem; Gráfico de recorrência; Análise de quantificação de recorrência.

Resumen

Investigamos cómo la construcción de la presa y embalse de Sobradinho afectó el caudal diario del río São Francisco, utilizando el método Gráfico de recurrencia (*Recurrence plot* - RP) y Análisis de cuantificación de recurrencia (*Reccurence quantification analysis* –RQA) que sirve para visualizar y cuantificar las recurrencias de los estados en el espacio de fase del sistema dinámico. Analizamos series temporales de caudales diarios registrados en la estación fluviométrica Juazeiro que se ubica aguas abajo de la presa Sobradinho, para los períodos antes (1943-1972) y posteriores (1980-2009) a la construcción de la presa. Observamos que en el régimen natural, antes de la construcción de la presa, la dinámica de los caudales presenta

características de proceso periódico y cuasiperiódico, indicado por los patrones de ajedrez en RP. Después de la construcción de la presa, la dinámica de los caudales presenta cambios repentinos indicados por bandas blancas en RP, y se vuelven menos predecibles, menos complejos y permanecen por los períodos más cortos en ciertos estados laminares, indicado por la disminución en los valores de los parámetros RQA.
Palabras clave: Caudal; Presa; Gráfico de recurrencia; Análisis de cuantificación de recurrencia.

1. Introduction

Rivers are the principal source of renewable water supply for humans and freshwater ecosystems, and are heavily influenced by the various natural and anthropogenic factors such as climate change (Christensen, Wood, Voisin, Lettenmaier, & Palmer, 2004), land use changes (Y. K. Zhang & Schilling, 2006) and dam construction (Magilligan & Nislow, 2005). Dam construction and reservoir operation have major impact on ecology and biological diversity of aquatic and riparian zone (Poff, Olden, Merritt, & Pepin, 2007).

Traditionally hydrological alterations were evaluated by classical statistical methods (Q. Zhang, Gu, Singh, & Xiao, 2014) and methods that use the set of ecologically relevant hydrological indicators (Richter, Baumgartner, Powell, & Braun, 1996). However, other streamflow characteristics that emerge as result of complexity of hydrological systems could also be relevant components of hydrologic alterations.

In this work we use Recurrence plot (RP), and the Recurrence quantification analysis (RQA) to evaluate hydrological alterations caused by the construction of Sobradinho dam located in Sub Middle section of São Francisco River in Brazil, which is highly affected by diverse water use practices (Roman, 2017). These methods were developed for nonlinear analysis of time series by visualizing the recurrences of dynamical systems and calculating different complexity measures (Marwan, Carmen Romano, Thiel, & Kurths, 2007). They were widely used in in physiology (Afsar, Tirnakli, & Marwan, 2018), geophysics (Zou, Donner, Marwan, Donges, & Kurths, 2019), climatology (Ogunjo, Adediji, & Dada, 2017; de Santana, da Silva, Menezes, & Stosic, 2020) and finances (Bastos & Caiado, 2011).

2. Methods

2.1 Data

The data used in this work are daily streamflow series recorded in Juazeiro station (code: 48020000, coordinates: 09^0 24' 23" S, 40^0 30' 13" W, drainage area: 516000km^2) which is located about 40km downstream of Sobradinho dam and it is influenced by reservoir operation. The data were recorded during the period 1929-2009, and are provided by the National Water Agency (Agência Nacional de Águas-ANA) (http://hidroweb.ana.gov.br, last access September 2020). The location of study area (sub-middle region of São Francisco River basin) with Juazeiro station and Sobradinho dam which is constructed between 1973 and 1979 is shown on Figure 1. The original streamflow data are shown on Figure 2.

Figure 1. Sub-middle region of San Francisco River basin, with location of Sobradinho dam and Juazeiro fluviometric station.

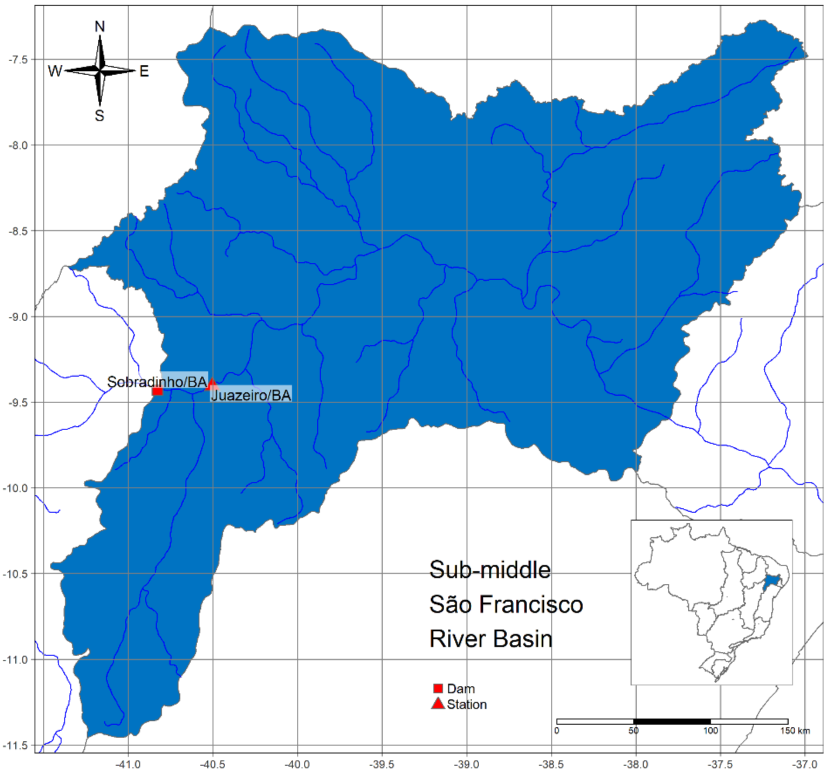


Figure 1 shows the map of Sub-middle São Francisco River Basin. Triangle represents the fluviometric station of Juazeiro/BA and square represents Sobradinho dam. Source: Authors.

Figure 2. Daily streamflow data from Juazeiro station.

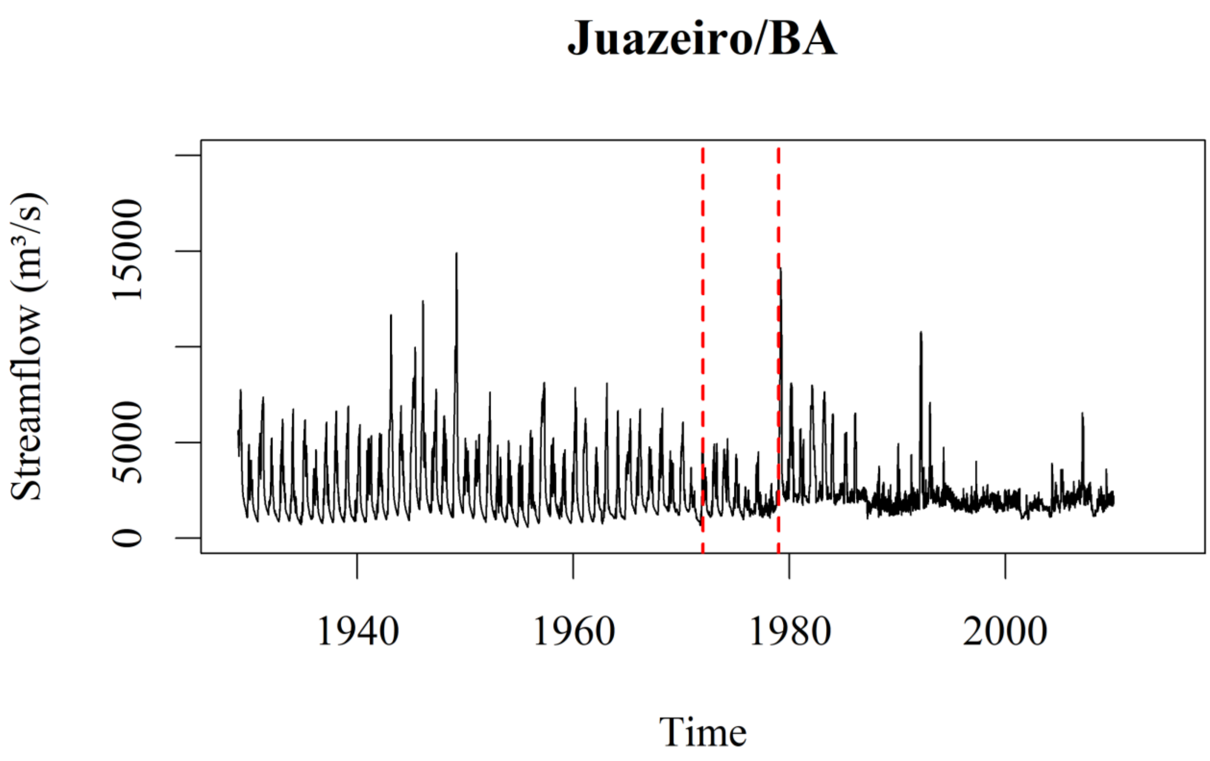


Figure 2 describes the streamflow (m³/s) from the period of 1929 to 2009 in Juazeiro/BA. The vertical lines indicate the beginning of construction and the beginning of operation of the Sobradinho dam. Source: Authors.

2.2 Recurrence plot (RP)

Recurrence plot (RP) was introduced by by Eckmann et al. (Eckmann, Kamphorst, & Ruelle, 1995) in order to visualize the time dependent behavior of the dynamics of systems. RP is represented by NxN matrix

$$R_{ij} = \Theta\left(\varepsilon - \| \vec{x_i} - \vec{x_j} \|\right) \; i,j = 1, \ldots, N (1)$$

where ε is a cut-off distance, $\|.\|$ is a norm (e. g. the Euclidean norm), $\Theta(x)$ the Heaviside function. Phase space vectors$\vec{x_i}$ and $\vec{x_j}$for one-dimensional time series $\{u_i\}$ can be reconstructed according to Takens' embedding theorem (Takens, 1981) by using an embedding dimension m and a time delay τ :$\vec{x_i}$ =$(u_i, u_{i+\tau}, \ldots, u_{i+(m-1)\tau})$.Parameters$m$ and τcan be obtained using themethod of false nearest neighbors (for m)and mutual information (for τ) (Kantz & Schreiber, 2004). The values in R_{ij} can be visualized by a matrix plot with the colors black ($R_{ij} = 1$) and white ($R_{ij} = 0$). As $R_{ii} = 1,$ RP contains the main diagonal line, called the line of identity – LOI.

The patterns in RPs are linked to a specific behavior of the dynamic system. Large scale patterns (typology) can be classified in homogeneous which are typical for stationary systems, diagonal lines and checkerboard structures which indicate periodic and quasi-periodic systems, RP's that fade away from main diagonal, indicating systems characterized by slowly varying parameters and white areas or bands for systems with abrupt changes in the dynamics (Marwan et al., 2007).

RPs also exhibit small-scale structures (texture) which can be classified in single dots (occur if states are rare, if they persist only for a very short time, or fluctuate strongly), diagonal lines (occur when segments of the trajectory visit the same region of the phase space at distinct times and the duration of these visits are determined by the length of these lines) and vertical (horizontal) lines that occur when the system is in a state that does not change or changes very slowly (Marwan et al., 2007). Diagonal and vertical lines are the base for a quantitative analysis of RPs.

2.3 Recurrence quantification analysis

A quantification of recurrence plots, Recurrence quantification analysis (RQA) developed by Zbilut and Weber (Zbilut & Webber Jr, 1992) and extended by Marwan et al. (Marwan, Wessel, Meyerfeldt, Schirdewan, & Kurths, 2002) provides a set of measures of complexity which quantify the small scale structures in RPs.

REC (Recurrence rate) is the fraction of recurrence points in the recurrence plot. It estimates the probability that a certain state recurs. DET (Determinism) is the fraction of recurrence points forming diagonal lines. This measure provides an indication of determinism (predictability) in the system. L (Average diagonal line length) measures the time phase space trajectories visit the same phase space regions (time of predictability of system). LMAX is the length of the longest diagonal line, excluding the line of identity - LOI.

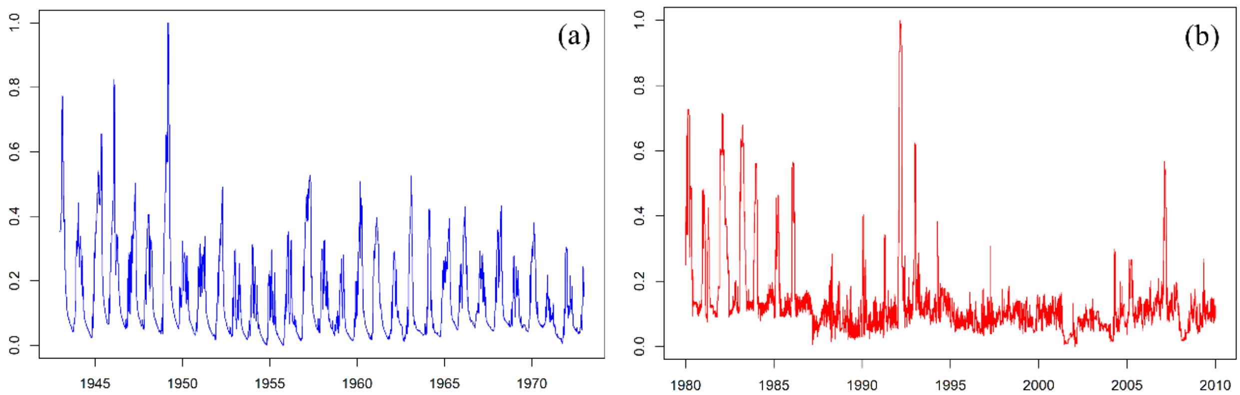
The inverse of this measure (DIV-divergence) is related to the exponential divergence of the phase–space trajectory. The faster the trajectory segments diverge, the shorter are the diagonal lines and the higher is DIV. ENTR (Shannon entropy of the distribution of lengths of diagonal lines) provides information about the complexity of the RP with respect of the diagonal lines. For uncorrelated noise the value of ENTR is rather small, indicating its low complexity.

LAM (Laminarity) is the fraction of recurrence points forming vertical lines. This measure is related to the occurrence of laminar states in the system (intermittency). TT (Average length of vertical lines) estimates the mean time that the system remains at a specific state ("trapping time").

3 Results and Discussion

Following Bastos et al. (Bastos & Caiado, 2011) the streamflow series Q were normalized between 0 and 1, according to $\tilde{Q} = \frac{Q - \min(Q)}{\max(Q) - \min(Q)}$ where $\min(Q)$ and $\max(Q)$ are the minimum and maximum values of the series in the analyzed period, respectively. The normalized series for the periods before and after the construction of Sobradinho dam are shown in Fig. 3.

Figure 3. Normalized streamflow data for Juazeiro station for periods (a) before (1943-1972) and (b) after (1980-2009) the construction of Sobradinho dam.



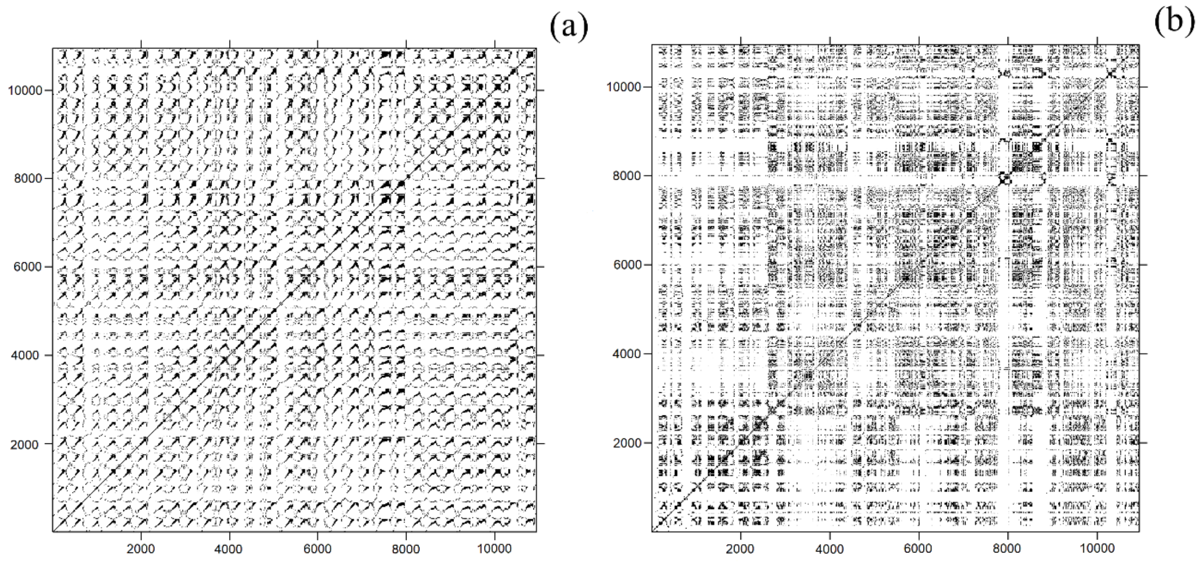
Source: Authors.

The construction of RP requires the determination of the values for the embedding dimension m, time delay τ and threshold ε. The embedding dimension $m = 4$was obtained using the false nearest neighbors method and time delay $\tau = 1$ using mutual information method (Kantz & Schreiber, 2004). The threshold ε was determined to produce the value of REC between 1% and 5% (Webber Jr & Zbilut, 2005) which gives $\varepsilon = 0.009$. The calculation of RP and RQA was performed using software R Core Team (Team, 2020).

The graphs of RP's for periods before and after the construction of Sobradinho dam, obtained using these parameters are shown on Fig. 4 where it is seen that streamflow fluctuations are not random, since RP's do not display only isolated points. Pre-construction period shows checkerboard structures, indicating periodic and quasi-periodic process (Fig. 4a), which can also be observed on Fig 2a.

The RP for post-construction period (Fig 4b) shows white bands in 1986 (~ 2600 days), 1994 (~ 5500 days) and 2002 (~7800 days) indicating sudden changes in the streamflow dynamics in these years, as can be seen in Fig. 3b. It also presents vertical and horizontal lines indicating a typical laminar state behavior (intermittency), where several states of the system do not change or change slowly.

Figure 4. Recurrent plot for streamflow series for Juazeiro station for periods (a) before (1943-1972) and (b) after (1980-2009) the construction of Sobradinho dam.



Source: Authors.

The results of RQA for streamflow series for pre-construction and pos-construction periods are shown on Table 1. It is seen from Table 1 that after the construction of Sobradinho dam the values of all RQA parameters decrease indicating that dam construction induced the changes in streamflow regime that can be described as less predictable (lower REC and DET), less complex (lower ENTR), with trajectories that diverge faster in phase space (lower LMAX) and remain in certain laminar state for shorter time periods (lower LAM and TT).

Table 1. Recurrence quantification analysis (RQA) for streamflow series for Juazeiro station for periods before (1943-1972) and after (1980-2009) the construction of Sobradinho dam.

Period	REC	DET	L	L_{max}	ENTR	LAM	TT
1943-1972	0,048	0,980	12,085	284	3,189	0,982	14,284
1980-2009	0,012	0,795	3,654	166	1,706	0,698	4,038

Source: Authors.

The shift towards less predictable (less regular) streamflow regime after the construction of Sobradinho dam, was also identified by Barreto et al (Barreto et al., 2020), with Sample entropy method and by Stosic et al (Stosic, Telesca, de Souza Ferreira, & Stosic, 2016), based on permutation entropy and statistical complexity analysis:

4 Conclusion

We analyzed the changes in the streamflow of Sao Francisco river induced by the construction of Sobradinho dam by using Recurrence plot (RP) and Recurrence quantification analysis (RQA). The texture of RP's indicate that the dam construction induced sudden changes in the streamflow dynamics in 1986, 1994 and 2002.The results of RQA indicate that after the construction of Sobradinho dam, the streamflow series become less predictable, less complex, and remain shorter in certain laminar state. Future work could include data analysis of fluviometric stations at various locations along the São Francisco River in order to investigate the relationship between flow dynamics and other natural and human factors such as drainage area, climate change and land use.

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