Revista Brasileira de Meteorologia, **v. 34, n. 2,** 293−300, 2019
DOI: http://dx.doi.org/10.1590/0102-77863340242
rbmet.org.br

Article

Long-Term Correlations in São Francisco River Flow: The Influence of Sobradinho Dam

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Received: 20 April 2018 - Accepted: 22 April 2019

Abstract

In this work we study the influence of the Sobradinho dam construction on daily streamflow of São Francisco River, Brasil, by analyzing long-range correlations in magnitude and sign time series obtained from streamflow anomalies, using the Detrended Fluctuation Analysis (DFA) method. The magnitude series relates to the nonlinear properties of the original time series, while the sign series relates to the linear properties. The streamflow data recorded during the period 1929-2009, were divided in the periods pre-construction (1929 to 1972) and post-construction (1980 to 2009) of Sobradinho dam and analyzed for small scales (less than 1 year) and for large scales (more than 1 year). In post-construction of Sobradinho dam, DFA-exponents of magnitude series increased at small scales (0.895 to 1.013) and at large scales (0.371 to 0.619) indicating that the memory associated with nonlinear components becames stronger. For sign series, the DFA-exponent increased at small scales (0.596 to 0.692) indicating stronger persistence of flow increments direction, and decreased at large scales (0.381 to 0.259) indicating stronger anti-persistence (positive increments are more likely to be followed by negative increments and vice versa). These results provide new evidence on the hydrological changes in the São Francisco River caused by human activities.

Keywords: streamflow, dam, correlations, magnitude, sign.

Correlações de Longo Alcance na Vazão do Rio São Francisco: A Influência da Barragem de Sobradinho

Resumo

Neste trabalho estudamos a influência da construção da barragem de Sobradinho na vazão diária do rio São Francisco, Brasil, analisando correlações de longo alcance em séries temporais de magnitude e sinal obtidas a partir da anomalia das vazões utilizando o método Detrended Fluctuation Analysis. A série de magnitude está relacionada com as propriedades não lineares da série original enquanto que a série de sinal está relacionada as propriedades lineares. Foram analisados os dados de vazão registrados durante o período 1929-2009, divididos nos períodos anterior a construção (1929 a 1972) e após a construção da barragem de Sobradinho (1980 a 2009) em pequenas escalas (menos de 365 dias) e em grandes escalas (mais de 365 dias). Após a construção da barragem de Sobradinho os expoentes-DFA para a série de magnitude aumentaram tanto em pequenas escalas (0,895 para 1,013) quanto para grandes escalas (0,371 para 0,619) indicando que a memória associada a componentes não lineares se tornou mais forte. Para a série de sinais, os expoentes-DFA aumentaram em pequenas escalas (0,596 para 0,692) indicando maior persistência na direção dos incrementos da vazão e diminuíram em grandes escalas (0,381 para 0,259) indicando maior anti-persistência (incrementos positivos são mais propensos a serem suscedidos por incrementos negativos e vice versa). Estes resultados trazem novas evidências quanto as alterações hidrológicas no rio São Francisco causadas pela atividade humana.

Palavras chave: vazão, barragem, correlações, magnitude, sinal.

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1. Introduction

It is well known that climate is strongly influenced by solar radiation. In particular, seasonal variations of solar radiation cause periodic changes in temperature and precipitation which can affect other components of the hydrological cycle, such as the seasonal periodicity of river flow (Livina *et al*. 2003a).

Labat *et al*. (2004) showed the influence of global warming on global runoff: the increase of runoff by approximately 4% per °C. The relationship between rainfall and streamflow variability was found in many parts of the world (Langat *et al*. 2017; Groisman *et al*. 2001; Dettinger & Diaz, 2000). Among natural resources rivers are one of the most vulnerable to human activities, such as the construction of reservoirs and irrigation systems, which can largely affect natural flow fluctuations and consequently various components of freshwater ecosystems (Vörösmarty *et al*. 2010).

Healthy, free-flowing rivers possess natural ability to absorb disturbances trough flow adjustments that buffer against impacts, but this ability is already severely limited in many world's river basins (Poff *et al*. 2007; Palmer *et al*. 2008). Analyzing underlying stochastic processes that govern this ability may improve our understanding of the relationships between alteration of natural flow and ecological responses, and thus enable the development of environmental flow standards to be incorporated in water resources management practices (Stosic *et al*. 2016a).

Over the last decades, various studies have shown that hydrological systems display fluctuations that may be characterized by long-term power-law correlations (memory) which indicates fractal and multifractal nature of the underlying process dynamics (Vogel *et al*. 1998; Sivacumar, 2000; Kantelhardt *et al*. 2006). Long term correlations of stream flow can be affected by both natural and anthropogenic factors which is indicated by changes in scaling laws (Zhou *et al*. 2014; de Souto Araújo *et al* 2014).

The memory of temporal series is commonly evaluated by techniques such as Hurst exponent (Hurst, 1951) and Detrended fluctuation analysis-DFA (Peng *et al*. 1994). However, Ashkenazy *et al*. (2001) showed that signals with identical long-term correlations can exhibit different temporal organization for the magnitude (volatility) and sign series of signal increments.

They found that the magnitude series relates to the nonlinear properties of the original time series, while the sign series relates to the linear properties. The existence of long-term correlations in magnitude series indicate multifractality of underlying process if scale exponent are different from 0,5 (Ashkenazy *et al*. 2001) and the decrease in DFA exponent indicates the loss of non-linearity and weakening of correlations (memory) (Kalisky *et al*. 2007).

Livina *et al*. (2003a) studied magnitudes of river flux increments and found that volatility series exhibits strong seasonal periodicity and strong power-law correlations for time scales less than one year, which can be reproduced by a simple nonlinear stochastic model (Livina *et al*. 2003b).

In this paper we evaluate the applicability of magnitude/sign DFA method to detect hydrological alterations caused by human activities, in this case the construction of Sobradinho dam, on São Francisco River, Brazil. It is located on its Sub-Middle section, which since 1948 has been the preferential area for irrigation projects, interbasin water transport and hydropower generation (Ioris, 2001; Maneta *et al*. 2009; Roman 2017).

The São Francisco River presents a strong alteration of its hydrological regime due to human activity such as the construction of several hydroelectric plants (Gurjão *et al*. 2012; Pereira *et al*. 2007; Santos *et al*. 2017), among which the Sobradinho plant has the largest reservoir and plays the greatest role in the downstream flow control.

2. Data and Methodology

2.1. Study area

The São Francisco River basin is the third largest in Brasil, after Amazon River basin and Paraná River basin. It is the longest river that runs entirely in Brazilian territory. With the area of 630000 km^2 it covers about 8% of national territory and extends through seven Brazilian states: Pernambuco, Alagoas, Sergipe, Bahia, Minas Gerais, Goiás and the Federal District. Its headwaters are in Serra da Canastra, Minas Gerais, the mouth is in Piaçabuçu, Alagoas and Brejo Grande, Sergipe. The vegetation cover includes fragments of several biomes: Atlantic forest in its headwaters, the Cerrado (Upper and Middle São Francisco) and the Caatinga (Middle and Sub-Middle São Francisco).

There are also transitional areas between the Cerrado and the Caatinga, deciduous and semi-deciduous seasonal forests, mangrove and coastal vegetation, the latter in Lower São Francisco. The climate is diversified such that the high and medium São Francisco have a humid tropical climate, the Sub-Middle a semi-arid climate and the low one has a hot and humid climate. The annual average natural flow of the São Francisco River is 2,846 m^3/s, but throughout the year, it can vary between 1,077m^3/s and 5,290m^3/s. (ANA, 2013).

Among the uses of the water resources of the São Francisco river, one of the activities that stands out is irrigation, whose withdrawal is 213.7 m^3/s, representing 77% of the total demand of the region with total irrigated area of 626 thousand hectares (ANA, 2013). Although there is evidence that agricultural activities affect the health and sustainability of watersheds mainly in the lower regions

(Atapattu & Kodituwakku, 2009), the São Francisco River is less affected by this activity (Maneta *et al*. 2009).

The Brazilian semi-arid region occupies 57% of the area of the São Francisco river basin and situations of water scarcity are common in the region. Sub-Middle and Low São Francisco show higher frequency of critical events of drought (ANA, 2013).

The greatest potential of the river is through hydroelectric power, which has an installed capacity of 10,708 MW, among which come from 28 small plants and 12 large plants (ANA, 2013). The proper operation of the large plants allows accumulating water in the rainy season to meet the water demands in the dry period, besides reducing the risks of upstream flooding (Gurjão *et al*. 2012). According to Andrade *et al*. (2012) CHESF (2015) (São Francisco Hydroelectric Company) does not implement an adequate policy to prevent floods and droughts due to extreme weather events and consequently an adequate energy security policy.

Along 3200 km of river, there are several large dams: Três Marias, Sobradinho, Itaparica, Moxotó, Paulo Afonso I, II, III and IV, and Xingó, which were constructed between 1962 (Três Marias) and 1994 (Xingó). Sobradinho dam (coordinates: 09^0 25' 54" S, 40^0 49' 40" W; construction: 1973-1978) is located 742km from the mouth at the border between middle and lower portion of São Francisco river, in the Bahia state, about 40 km upstream of cities Juazeiro (Bahia state) and Petrolina (Pernambuco state).

Its height is 41 m, length 12.5 km, the reservoir (considered one of the largest artificial lakes in the world) has 320 km of extension, surface area of 4214 km^2 and storage capacity of $34.1 \bullet 10^6$ m^3. It serves for electricity generation, and represents a principal instrument of hydrological resource control in the region (CHESF, 2015).The climate is semiarid, the average annual precipitation is 514 mm and the wet season is from April to July (Santos *et al*. 2012).

2.2. Data

Figure 1 shows the data used in this work are daily streamflow series recorded in São Francisco River basin, at the location near Juazeiro, about 40km downstream of Sobradinho reservoir. The data are provided by the National Water Agency (Agência Nacional de Águas-ANA) (HIDROWEB, 2010), for station Juazeiro, code 48020000, coordinates: 09^0 24' 23" S, 40^0 30' 13" W and drainage area 516000 km^2, for the period 1929 to 2009. This station was affected only by the Sobradinho dam, the reservoir of Três Marias, the largest reservoir upstream of Sobradinho is very distant (about 1087 km) and the buffering effect mitigates any influence (Zhang *et al*. 2012).

2.3. Detrended fluctuation analysis

Detrended Fluctuation Analysis (DFA) was introduced by Peng *et al*, (1994) as a modified root-mean-square analysis of a random walk, and serves to detect long-term correlations in non-stationary time series (Kantelhardt, 2001). The DFA method was successfully applied in physiology (Goldberger *et al*. 2002; Kirchner *et al*. 2014), geophysics (Zheng *et al*. 2012), ecology (Stosic *et al*. 2016b), climatology (Jiang *et al*. 2016), and finance (Li *et al*. 2011]).

The implementation of DFA algorithm is described as follows:

a. First the original temporal series $x(i), i = 1, \ldots, N$ is integrated to produce

$$X(k) = \sum_{i=1}^{k} [x(i) - \langle x \rangle]\,,\; k = 1, \ldots, N$$

where $\langle x \rangle = \frac{1}{N}\sum_{i=1}^{N} x(i)$ is the average.

b. Next, the integrated series $X(k)$ is divided $N_n = \text{int}(N/n)$ into non-overlapping segments of length n and in each segment $s = 1, \ldots N_n$ the local trend $X_{n,s}(k)$ is estimated as a linear or higher order polynomial least square fit, and subtracted from $X(k)$.

c. The detrended variance is then calculated as

$$F^2(n) = \frac{1}{nN_n}\sum_{s=1}^{N_n}\sum_{k=(s-1)n+1}^{sn}\left[X(k) - X_{n,s}(k)\right]^2$$

d. Repeating this calculation for different window sizes provides the relationship between the fluctuation function $F(n)$ and window size n. If long-term correlations are present in original series, $F(n)$ increases with n according to a power law

$$F(n) \approx n^{\alpha}$$

The scaling exponent is obtained as the slope of the linear regression of $\log F(n)$ versus $\log n$. For $0 < \alpha < 1$, DFA exponent is equal to Hurst exponent H and describes correlations in original series: the value $\alpha = 0.5$ indicates the absence of correlations (white noise), $\alpha > 0.5$ indicates persistent long-term correlations meaning that large (small) values are more likely to be followed by large (small) values, $\alpha < 0.5$ indicates anti-persistent long-term correlations, meaning that large values are more likely to be followed by small values and vice versa. The value $1 < \alpha < 2$ indicates fractional Brownian motion with increments described by Hurst exponent $H = \alpha - 1$. The values $\alpha = 1$ and $\alpha = 1.5$ correspond to $1/f$ noise and a Brownian noise (integration of white noise) respectively (Peng, 1994; Kantelhardt, 2001; Løvsletten, 2017).

3. Results

We analyze deseasonalized series (anomalies) of daily streamflow $x(t)$

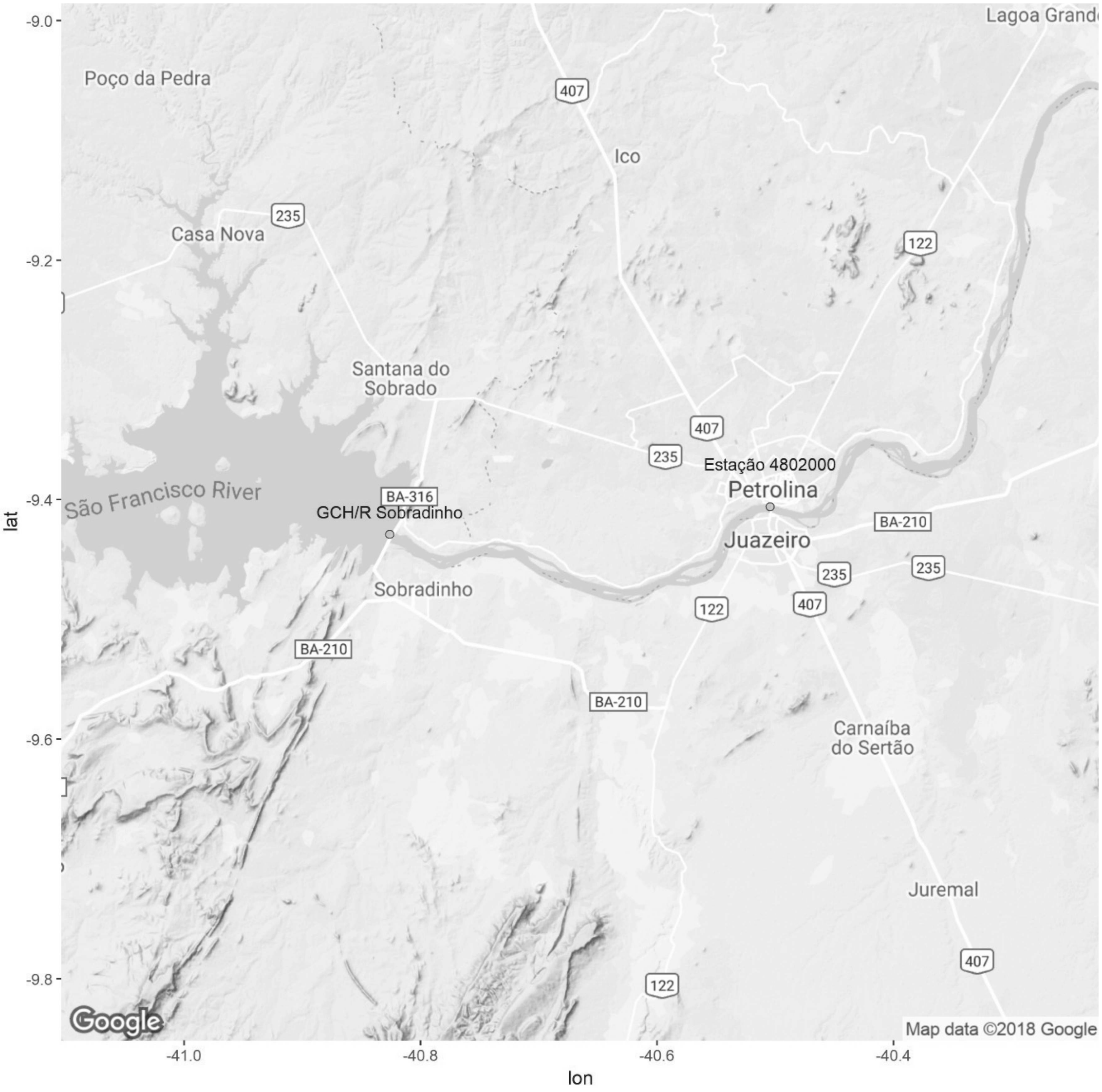

Figure 1 - Geographic location of study area, with Juazeiro station and Sobradinho reservoir.

$$X(t) = \frac{x(t) - \mu_t}{\sigma_t},$$

where μ_t is the mean daily streamflow calculated for each calendar date by averaging over all years in the record, and σ_t is the standard deviation of $x(t)$, also calculated for each calendar date (Kantelhardt, 2006). We apply DFA method on daily anomaly series and two sub series: magnitude $M(t) = |\Delta X(t)|$ and sign $S(t) = sign[\Delta X(t)]$. Figure 2 shows these series where we can see the change of streamflow dynamics after the construction of Sobradinho reservoir: lower magnitude and less periodicity.

This modification of flow regime is associated with the reservoir operation (Gurjão *et al.* 2012). Magnitude series shows different behavior: for post-construction period, the magnitude of anomaly increments increases but similarly to original series exhibits less periodicity.

We calculate DFA exponents for entire series (1929-2009) and for pre-construction (1929-1972) and post-construction period (1980-2009). Figure 3 shows the DFA graphs. In all cases two scaling regimes can be observed: short term memory regime for scales up to 1 year, and long-term memory regime for scales greater than 1 year. Similar behavior was observed for Karst springs (Labat, 2011), and for the Yangtze River (Zhang, 2012), and it can be contributed to synchronization between hydrological and solar cycle (Livina *et al.* 2003a, Labat *et al.* 2011).

The values of DFA exponents (calculated as slopes of linear regressions from Fig. 3) are presented on Table 1. For anomaly series, for all analyzed periods for scales less than 1 year (short memory) the value of the DFA exponent is found to be between 1.0 and 1.5, indicating anti-

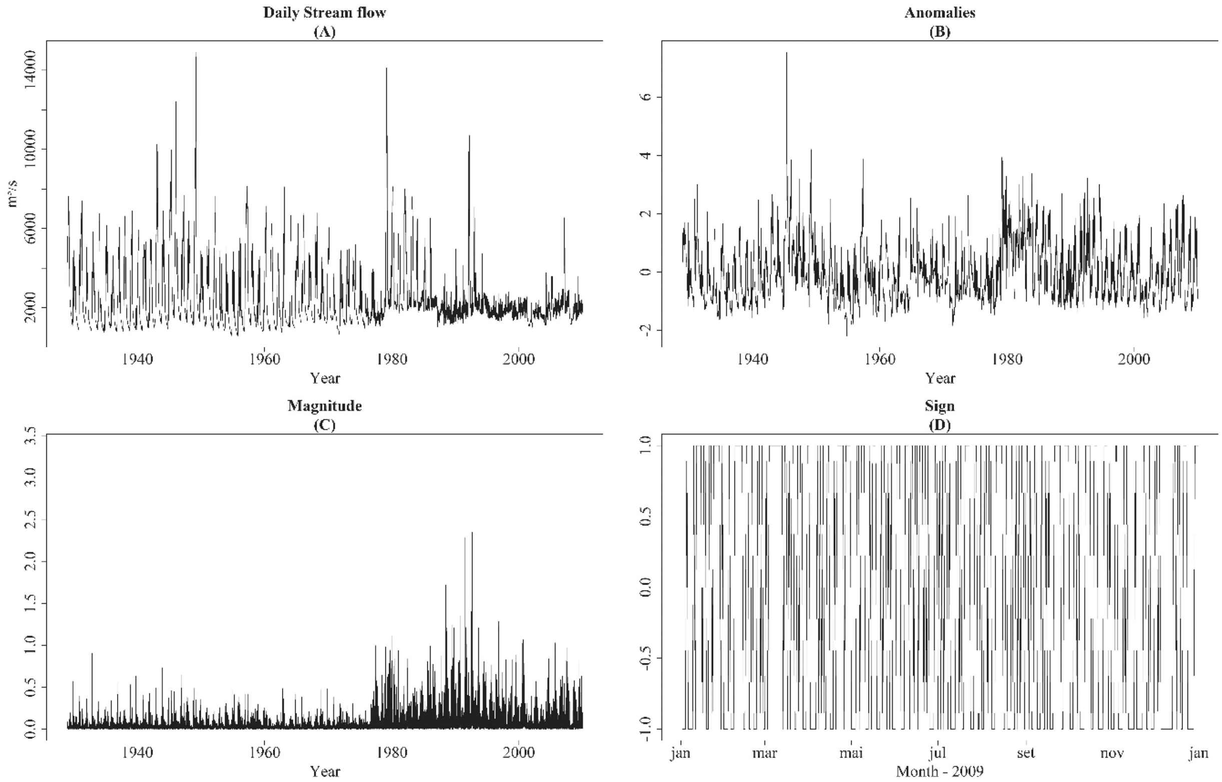

Figure 2 - Daily streamflow series (A), anomaly series (B), magnitude series (C) and sign series (D) for Juazeiro hydrological station for the period 1929-2009.

Table 1 - DFA exponents for anomaly series, magnitude series, and sign series, for total (1929-2009), pre-construction (1020-1972) and post-construction (1980-2009) period for Juazeiro hydrological station.

	α_{DFA}	
	n < 365	n > 365
Anomalies		
1929-2009	1,316	0,803
1929-1972	1,275	0,757
1980-2009	1,410	0,750
Magnitude		
1929-2009	0,989	0,593
1929-1972	0,895	0,371
1980-2009	1,013	0,619
Sign		
1929-2009	0,602	0,353
1929-1972	0,586	0,381
1980-2009	0,692	0,259

persistent fractional Brownian motion ($H = \alpha - 1$): the small increments are more likely to be followed by large increments and vice versa.

The long memory (scales larger than 1 year) is characterized by persistency in anomaly series ($0.5 < \alpha < 1$). After the construction of Sobradinho reservoir the process, for short memory regime, shifts toward Brownian motion indicating that reservoir operation induces more randomness in streamflow increments. There is no difference in values of DFA exponents for scales larger than 1 year indicting that reservoir operation doesn't affect long memory of stream flow dynamics.

The behavior of magnitude series reveals nonlinear properties of stream flow. For short scales, the values of DFA exponents are for all periods close to 1 indicating strong nonlinear properties of stream flow. After the reservoir construction magnitude series exhibits the strongest persistence ($\alpha_{DFA} \approx 1$) indicating that the reservoir operation changes streamflow dynamics toward more nonlinear regime. The persistence of magnitude series indicates that the original series has multifractal properties (there are clusters of high magnitude and clusters of low magnitude), which become stronger after the reservoir construction.

The multifractality of river flow and its alteration due to human activities is found for rivers in different parts of the world and seems to be a good indicator of river health (Araujo *et al*. 2014; Zhou *et al*. 2014). For large scales, nonlinear properties also become stronger (increase in DFA exponent) after the construction of reservoir but non-linearity is weaker than for short scales. Linear properties of stream flow dynamics were also affected by reservoir operation.

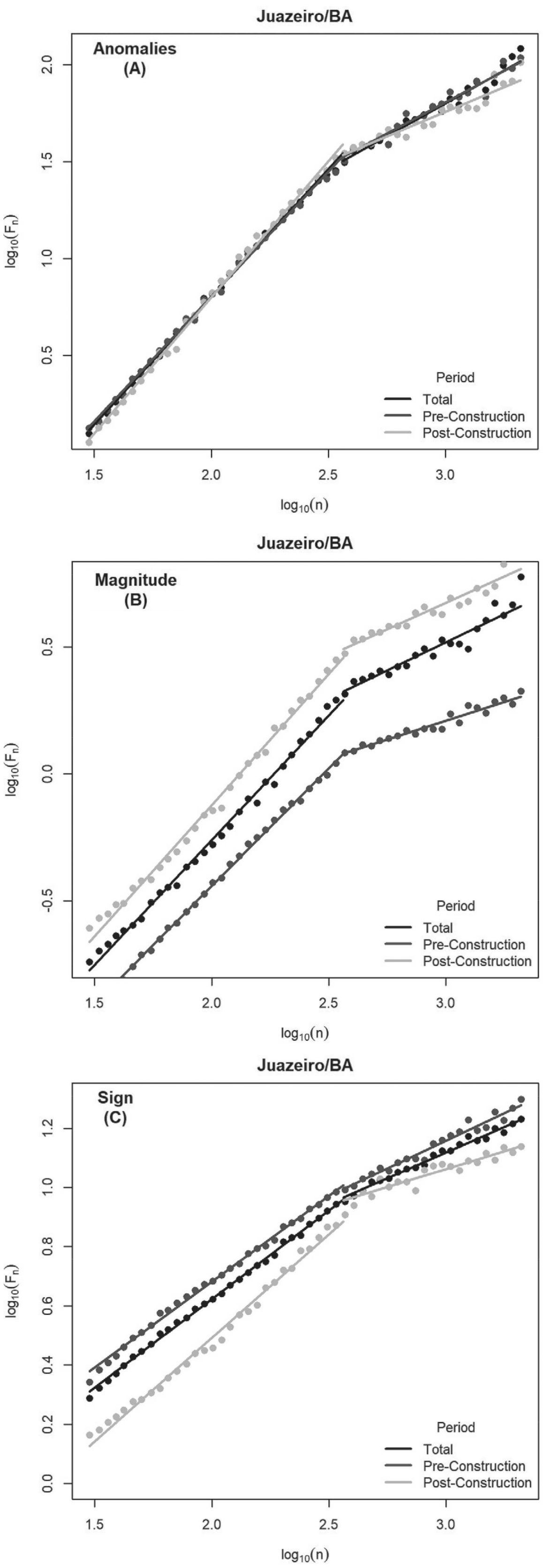

Figure 3 - DFA graphs for anomaly series (A), magnitude series (B) and sign series (C) for Juazeiro hydrological station.

For all periods sign series exhibits similar behavior: week persistency at short scales (positive/negative increments are more likely to be followed by positive/negative increments) and week anti persistency at long scales (positive increments are more likely to be followed by negative increments and vice versa). After the reservoir construction, the value of DFA exponent increases for short scales and decreases for long scales indicating correlations (both persistent and anti-persistent) become stronger.

4. Conclusion

In this work we investigate the changes in memory properties of São Francisco river streamflow caused by the human activities, in particular the operation of the Sobradinho reservoir. By applying Detrended fluctuation analysis (DFA) on magnitude and sign of streamflow anomaly increments, we analyze nonlinear and linear properties of underlying stochastic process for pre and post construction periods. We find that the reservoir operation induces changes in the stream flow temporal organization.

For both short scales (less than 1 year) and long scales (larger than 1 year), the stream flow dynamics exhibits nonlinear behavior as indicated by the values of DFA exponents ($\alpha_{DFA} > 0.5$) for magnitude series. After the reservoir construction short memory regime shifts toward stronger non-linearity ($\alpha_{DFA} \approx 1$). Long memory regime (for scales larger than 1 year) also exhibits nonlinear properties (although weaker than for short scales) that become stronger after the reservoir construction as indicated by the increase of DFA exponent.

The evidence of persistent properties of magnitude series also indicates that stream flow dynamics can be modeled as a multifractal process whose parameters could be used as indicators of human caused alterations. Linear properties of stream flow dynamics were also affected by reservoir operation: weak persistency at short scales and weak anti persistency at long scales of increment sign series become stronger after the reservoir construction.

The long memory analysis of original anomaly series did not show sensitivity to reservoir operation, and in that case, magnitude/sign DFA could be used as an alternative method to quantify alterations in linear and nonlinear components of hydrological processes, caused by natural and anthropogenic factors.

Traditionally river flow fluctuations were studied by classical statistical methods (Richter *et al*. 1996; Doll & Zhang, 2010; Magilligan & Nislow, 2005), however there is an increasing interest of hydrologists in applying concepts developed in complex system science, such as chaos (Sivakumar, 2009), fractals (Zhang, 2012), multifractals (Zhou, 2014) and methods based on information theory (Mihailovic *et al*. 2014; Stosic *et al*. 2016a) to reveal some hidden properties of stream flow dynamics such as scaling and complexity, especially in the presence of natural and/or anthropogenic stress.

In this context, our work represents one more step toward the incorporation of these emergent methods in evaluation of river health, which should be considered when planning of sustainable use of freshwater resources.

For São Francisco River (Velho Chico, as called by riverside communities whose economic and cultural development for centuries has been strongly tied to river conditions) this work contributes to better understanding of human-nature interaction and provides new knowledge that can be used as a scientific base when developing new water management practices to maximize ecologically sustainable freshwater use, and preserve hydrological resources of São Francisco River basin for future generations.

Acknowledgements

The authors are grateful to the CAPES and PPGBEA for funding Ikaro Daniel de Carvalho Barreto during his PhD course.

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