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POSSIBLE CAUSES OF TEMPORAL CYCLES AND SCALE OF RUNOFF IN THE SÃO FRANCISO RIVER, BRAZIL

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Understanding the mechanisms generating rainfall and runoff, its space-time variability, and its impacts, improves planning of agricultural activities and provides benefits to society at large. The objective of this paper is to use wavelet analysis to study the runoff in the Alto São Francisco sub-basin, examining the characteristics of inter-annual and seasonal variability, as well as determining the dominant temporal scales. Variability is dominated by a decadal scale, which is associated with other temporal scales. These include seasonal, inter-annual short, and inter-annual linked to the El Niño southern oscillation, which cause peaks of the runoff in the time series. Peak runoff cycles average 12 years, approximately coinciding with sunspot cycles.

INTRODUCTION

Studies investigating temporal scales in hydrology and their causes have been performed for some time. The understanding of the mechanisms generating rainfall (and consequently runoff), its space-time variability and its effects, can provide gains to agricultural activities and society, in the sense of planning its activities and reducing losses. Today, previous studies using wavelet analysis (WA) have been shown to give useful results.

In relation to hydroclimatic studies, Abreu Sá et al. (1998) used the Morlet wavelet, in order to study the scales in which the level of Paraguai river in Ladário (Mato Grosso do Sul) shows greater variability. A dominating variability at the annual scale and important variability at the scales in a period between to two and five years, were verified, which was not persistent.

Trigo et al. (1999) applying the wavelets to the study of the daily discharge variability at the Portuguese and Brazilian basins, determined for the Mondego river, peaks of the power spectrum of about 64 of 128 days, corresponding to the semiannual period, and the interval of 2 to 16 days, coinciding with synoptic scale weather phenomena. For several years, the Piancó river (Paraíba) presented (irregularly) a strong variability between 256 and 1024 days, associated with the irregular frequency of the El Niño (ENSO) episodes.

Moura et al. (2010) showed, using wavelet, that the Salgado river presents its variability dominated by decadal scale, which is combined with other temporal scales (seasonal, inter-annual and inter-annual linked to ENSO). The cycle or period of the occurrence of runoff peaks occurred on average each five years. This information reveals important facts for agricultural planning, local infrastructure development, and supporting civil defense.

Other studies relate to the weather and climatic fluctuations and to the signs found in the temporal series, using WA. Among these is a study by Kerr (1996), which related the 11 year temporal scale to the sunspot cycle.

The objective of this paper is to use WA to study the runoff variability of the Alto São Francisco sub-basin, examining aspects of inter-annual and seasonal variability, as well as to determine the dominant temporal scales.

MATERIALS AND METHODS

Study area

The São Francisco river is one of the most extensive Brazilian rivers. It is located in the areas of Minas Gerais, Bahia, Goiás, Distrito Federal, Pernambuco, Sergipe and Alagoas states. The basin is divided at the four physiographic regions: Alto, Médio, Submédio and Baixo São Francisco (PBHSF, 2004).

Alto São Francisco (ASF) (Figure 1) originates at São Roque de Minas municipality through Pirapora city (Minas Gerais). It has an area of 100,076 km^2, or 16% of the area of the São Francisco basin and is 702 km in length.

Data

This study used the data of 11 runoff stations from the Water National Agency - Brazil of ASF: Pirapora, Porto Sabino, Vargem Bonita, Barra Paraopeba, Iguatama, Jusante Barra Paraopeba, Olegário Maciel, Pirapora Barreiro, Ponte de Chumbo, Sabará, and Três Marias. The data were collected between 1968-2008.

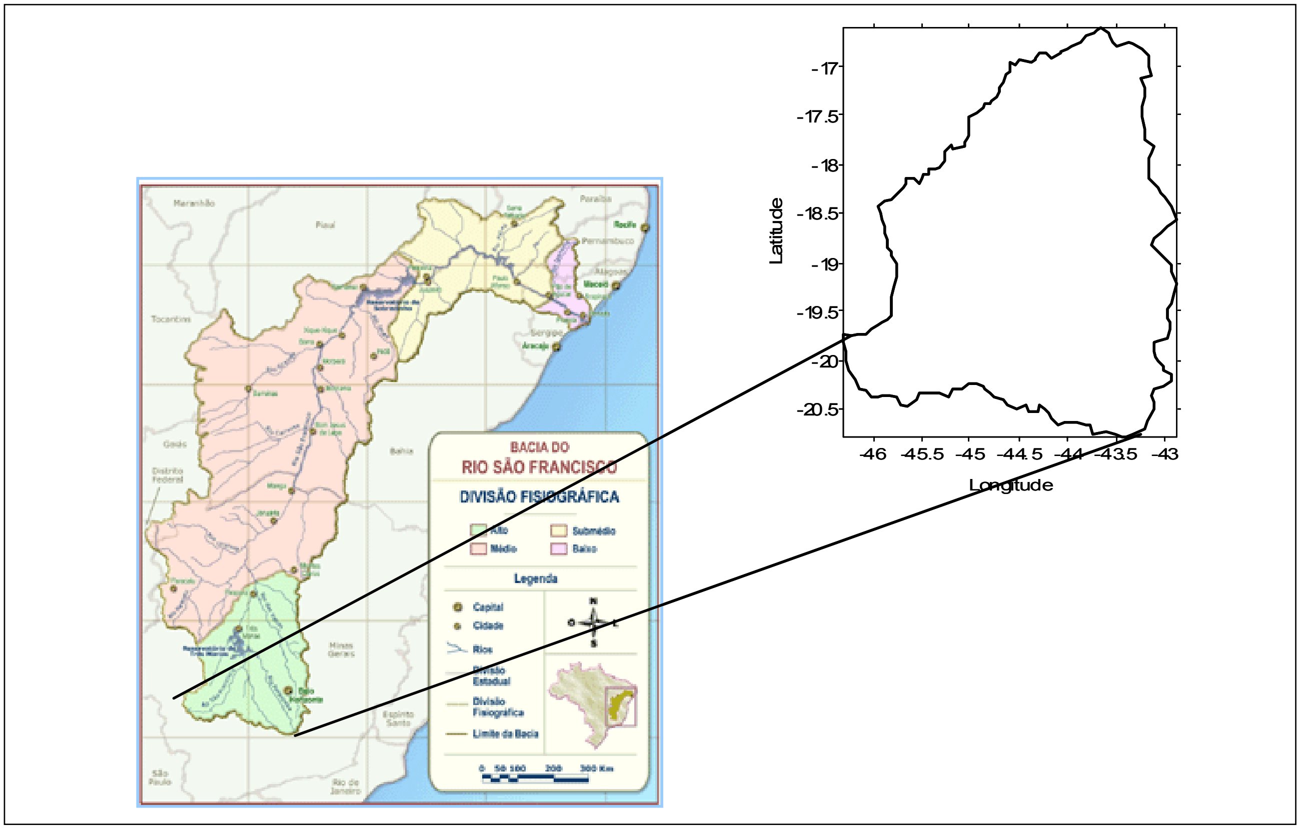


Figure 1. São Francisco river basin showing the Alto São Francisco subbasin.

River Discharge Index (RDI)

Runoff data were transformed to river discharge index (RDI), (Da Silva, 2003; Andreoli et al. 2004; Da Silva, 2009; and Da Silva et al., 2010) as follows:

$$RDI_{I,J} = (D_{I,J} - Dmean_I) / \sigma i \qquad (1)$$

where:

$RDI_{I,J}$ - is the monthly river discharge index (I) years (J);

$D_{I,J}$ - is the monthly runoff (I) years (J);

$D\ mean_I$ - is the monthly mean runoff (I);

σi - is the monthly standard deviation.

Wavelet Analysis (WA)

This technique is useful to detect, analyze and characterize the time scales which affect the weather systems over South America and adjacent oceans. This tool shows the temporal structure of non-stationary time series (Repelli et al., 1998; Schneider et al., 2005).

Other papers have utilized the analyses of wavelet for meteorological or hydrological studies: Gu and Philander (1995), Robock and Mao (1995), Robock and Free (1995), Andreoli and Kayano (2004), Abreu Sá et al. (1998), Torrence and Compo (1998), Torrence and Webster (1999), Schneider et al. (2005), Labat et al. (2005), and Da Silva et al. (2010).

The Morlet wavelet is used in this study (Torrence and Compo, 1998). This wavelet is a complex exponential modulated by a Gaussian, $e^{i\omega_o\eta}e^{-\eta^2/2}$, $\eta = t/s$, where t is time, s is the wavelet scale and

w_0 is non-dimensional frequency. The computational procedure WA used here is the one described by Torrence and Compo (1998). Importantly, the function of wavelet in each s scale is normalized by $s^{-1/2}$ to obtain unit energy. The Morlet wavelet is complex and its has similar characteristics to meteorological signs, such as symmetry or asymmetry, and abrupt or smooth temporal variation. According to the literature, this is a criterion for choosing the wavelet function (Weng and Lau, 1994; Morettin, 1999).

RESULTS

The RDI temporal distribution (Figure 2) shows rotation periods of high and low runoffs at the ASF sub-basin. Years with minimal runoff as in 1971 (La Niña year) and years with maximal runoff as in 1983 (El Niño to normal year), were observed. From 1968 to 1987 the runoff was either high or low. From the half of the series on, it was observed that the variability between events was higher. The periods from 1978 to 1987 deserve special attention, which will be better explained by WA.

The signs of local wavelet spectrum 1983-1984 and 2006-2007 are shown in Figure 3, as RDI or runoff peaks. In these cases, the association of events occurs in different temporal scales (Figure 4), allowing increased runoff.

It is then suggested that the decadal scale has dominance on runoff variability at the São Francisco river, highlighting at the same time both the seasonal and inter-annual variability. The joining of temporal scales plays role of high importance to river flood events, which present an average interval of 12 years.

The period from 1968 to 1971 should receive special attention because runoff above the average was not observed (Figure 3) due to the simultaneous occurrence of decadal temporal scale events and inter-annual events linked to ENSO, but without inter-annual short forcing, and possibly in phases which do not promote the increase of rainfall/runoff at the São Francisco river (Table 1).

We can verify that the decadal scale was present throughout the series (Figure 4a) and was statistically significant (Figure 4b). The dominant peak is found by wavelet from 20.2 to 22 years. The peaks of 11 and 7 years linked to ENSO also have their signs in the local wavelet spectrum.

Thus, the runoff riverbed of São Francisco river reflects the union of several events of different temporal scales, which together, promote increase the values of runoff observed in some events (decadal, ENSO, inter-annual, etc.) that are visualized in the Table 1.

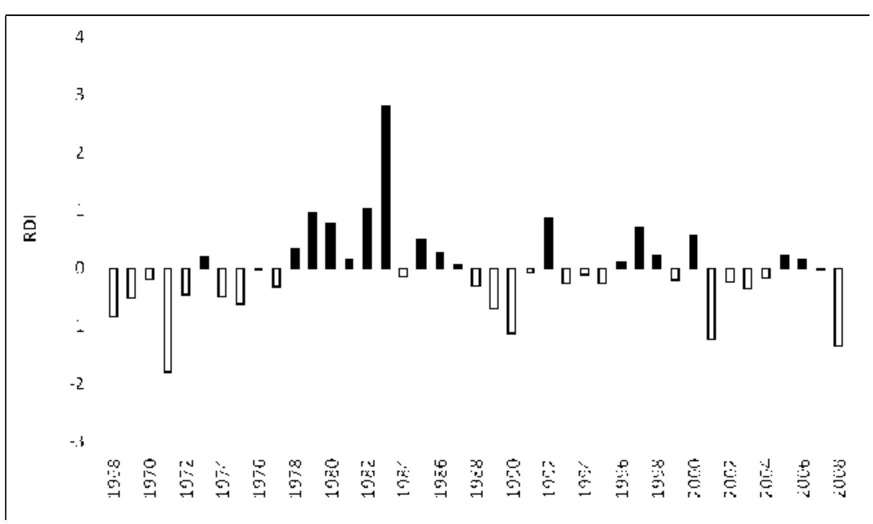


Figure 2. Annual RDI of ASF.

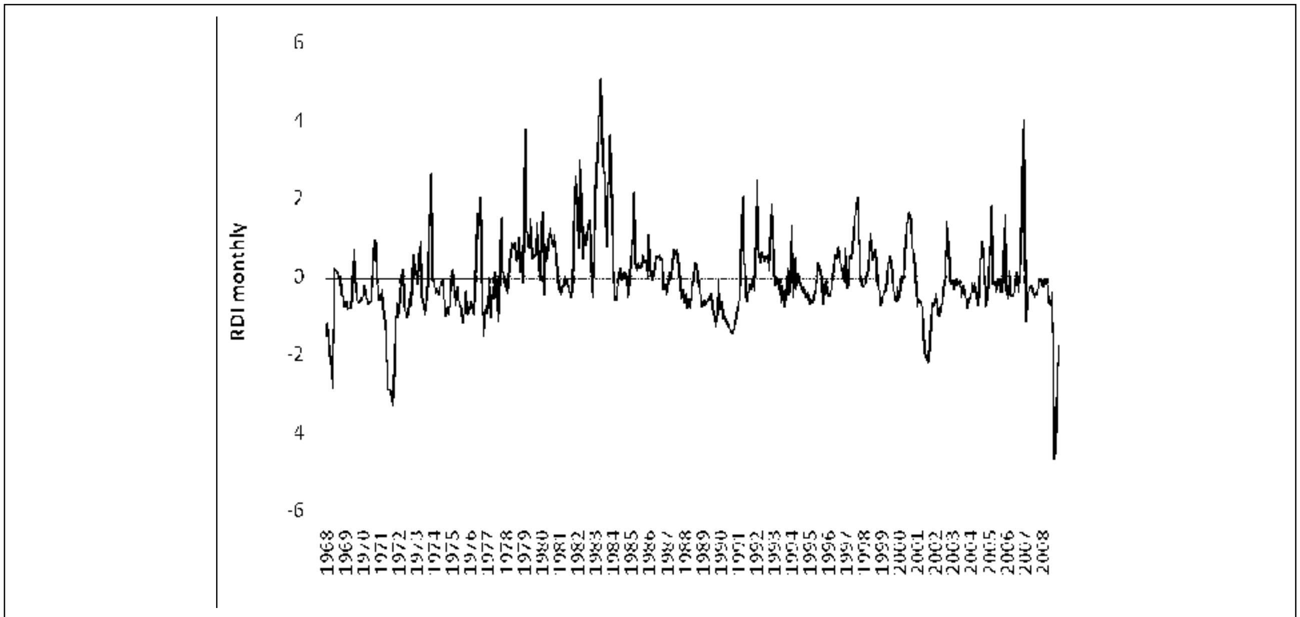
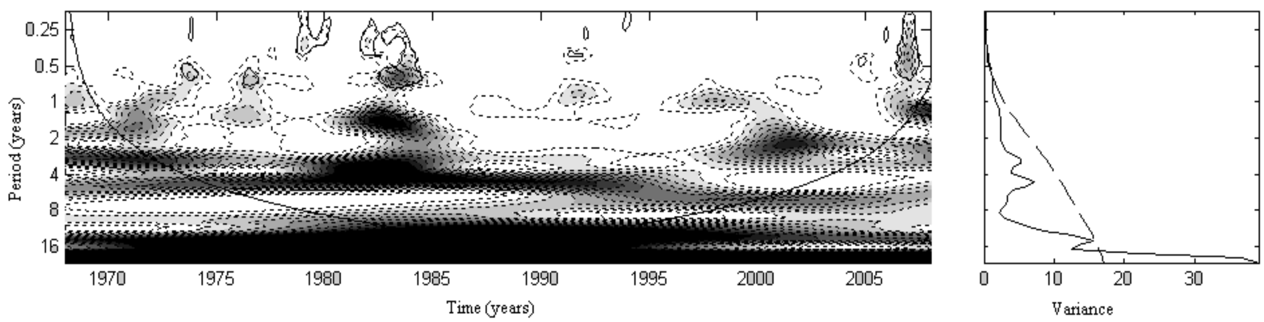


Figure 3. Monthly RDI of ASF.



(a) Energy Spectrum (EPW) (b) Global Spectrum (EPG)

Figure 4. Local and Global spectrum anomalies of runoff. Shaded contours corresponds values of standardized variance. The dashed outline indicates that the global wavelet spectrum is significant at a confidence level of 95%.

Table 1. Peak runoff events of the Alto São Francisco and time scales of phenomena of climate variability.

YEARS / EVENT	TEMPORAL SCALES PARTICIPANTS IN THE INCREASE OF THE RUNOFF			
1968-1971	DECADAL	ENSO	-	-
1979-1984	DECADAL	ENSO	INTER-ANNUAL and INTER-ANNUAL SHORT	SEASONAL
1992-1994	DECADAL	ENSO	INTER-ANNUAL	SEASONAL
2005-2008	DECADAL	ENSO	INTER-ANNUAL and INTER-ANNUAL SHORT	SEASONAL

DISCUSSION

Huang and Marimoto (2009) using the wavelet analysis observed with certain periods, show that El Niño is sensitive to noise whereas in other periods, it is not. The roles of noise for ENSO are significant but not yet clear. When can it start or end an El Niño? How does it start an El Niño? Are there certain general modes or conditions for noise to trigger an El Niño? Noise has an effect on ENSO through a stochastic resonance mechanism. These are some questions raise by Huang and Marimoto (2009) that may also have affected the results of this study.

According to Popinski et al. (2011) the wavelet analysis and time lag functions show frequency dependent time lags corresponding to maxima of the modules of cross-covariance functions between the polar motion and atmospheric excitation functions. The study investigated the time-frequency relationships between complex-valued polar motion and its atmospheric excitation using the wavelet coherence and cross-covariance functions. The wavelet transform with Morlet wavelet transform (MWT) (Chui, 1992) and harmonic wavelet transform (HWT) (Newland, 1998) techniques were applied. Both wavelet techniques enable changing the frequency resolution in the coherence and cross-covariance functions. The computed coherence and cross-covariance functions allow the comparison of polar motion and atmospheric excitation function data in the chosen frequency band from several to about 250 days. In this study the wavelet analysis showed results better than other methods tested. Other study using WA including Popinski and Kosek 1994, Schmidt and Schuh 2000b, and Alves et al., 2007, also show its efficiency in identifying the atmospheric excitation.

According to Da Silva (2009) the monitoring of rainfall variability in certain localities can be affected using climatic indices. This tool is particularly essential in the northeast region of Brazil . Analyzing temporal variation of rainfall in the Mundaú river basin over a period from 1974 to 1983, a change in rainfall standards was verified with an "inflection point" in 1974. Before this, in Medio Mundaú and Alto Mundaú, the years had been drier and after 1974 had been more humid. The opposite occurred in the Baixo Mundaú.

This methodology has been widely used in northeastern Brazil river basins to assess indices of rainfall anomalies and obtained significant results. In this study, wavelet analysis was used to assess runoff anomaly indices. As the rain is one of the main forces of occurrence of runoff, and due to lack of studies using wavelet methods for evaluating runoff anomalies, using results of the papers mentioned above, wavelet analysis of rainfall is valid and can be conducted.

In this study, the runoff of the São Francisco river reflects the union of several events of different temporal scales, which together, increase the values of runoff observed in some events (decadal, ENSO, inter-annual, 30-60 days oscillation, etc.). According to Kayano and Kousky (1992) the 30-60 day oscillation propagates relatively uniformly across the equatorial Indian and Pacific Oceans to the west. In the remaining tropical regions, its spread is not uniform and anomalies are less pronounced, but detectable.

The results of this study use the understanding of the hydrologic processes and create scenarios of the climatic change impacts on surface runoff. Galvincio and Moura (2010), using modeling of the sub-medium São Francisco Valley to simulate the climate changes impacts, conclude there is no trend of increase or reduction of the surface runoff between 1963 and 1988.

Information obtained in this paper turns out to be important for agricultural planning. Using this information, the farmers could plan their agricultural activities and reduce losses due to flooding of crops on banks of the river. Every 12 years the local population could prepare for maximum runoff or even floods, thereby assisting in civil defense.

CONCLUSION

The runoff at the São Francisco river shows that it is dominated by variability on a decadal scale, which associated with other temporal scales (seasonal, inter-annual, and short inter-annual linked to ENSO) promotes maximum runoff along the series.

The cycle or period of occurrence of maximum runoff rate has an average 12 years, approaching the sunspot cycle.

The WA methodology has been shown to be efficient in detecting signs, abnormalities, and variability of natural runoff and can be applied in hydrologic studies of other areas of world.

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