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Effects of small hydropower plants in cascade arrangement on the discharge cyclic patterns

Efeitos da operação de pequenas centrais hidrelétricas em cascata nos padrões dos ciclos de vazão

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ABSTRACT

Because it is assumed that the impacts in the natural streamflow regime promoted by Small Hydropower Plants (SHP) are negligible, environmental licensing for such facilities is usually easier. Nonetheless, recent studies have shown that the operation of SHPs may disturb the natural flow conditions, mainly when the plants are placed in a cascade arrangement. In this context, the main objective of this study is investigating the alterations in flows periodic behavior in a system of six hydropower plants, being five of them SHPs. Daily discharge time series were extracted from eight streamflow gauging stations located in the Jauru River catchment, Brazil, whose period-of-record spans from May/2016 to Aug/2017. By using the wavelet transform, dominant cycles along the time series were identified and their coherence in nearby stations was compared. Among the results, one may observe that, from upstream to downstream, the high frequency cycles became more important whereas the low frequency ones have weakened. Additional analyses indicate that such alterations are not directly related to meteorological factors or to the gradual increasing in the catchment's drainage area in the downstream direction, which suggests that the operation of SHPs may affect the streamflow natural cycles.

Keywords: Streamflow periodicity; Wavelet transform; Small dam impacts; Run-of-river power plant; Time series analysis.

RESUMO

Por assumir que os impactos nos regimes naturais de vazão de Pequenas Centrais Hidrelétricas (PCHs) são desprezíveis, os licenciamentos ambientais para esses empreendimentos são relativamente fáceis de serem obtidos. Contudo, estudos recentes têm mostrado que a operação de PCHs pode afetar as condições naturais de escoamento especialmente quando os aproveitamentos hidrelétricos são alocados em cascata. Nesse contexto, o principal objetivo deste trabalho é investigar a alteração do comportamento das periodicidades de vazões em um sistema com seis aproveitamentos hidrelétricos, sendo cinco PCHs. Foram utilizadas séries de vazões diárias extraídas de estações localizadas na bacia do rio Jauru, na região hidrográfica do Alto Paraguai, Brasil, entre maio de 2016 e agosto de 2017. Por meio da transformada *wavelet*, foi possível identificar ciclos dominantes ao longo do tempo e comparar a coerência de séries de vazões entre estações adjacentes. Entre os resultados, observou-se que, no sentido de montante para jusante, os ciclos de alta frequência se tornam mais evidentes enquanto aqueles de baixa frequência ficam enfraquecidos. Análises adicionais indicaram que tais alterações não estão diretamente relacionadas a fatores meteorológicos ou ao aumento gradual da área de drenagem da bacia na direção a jusante, o que sugere que a operação das PCHs pode afetar o ciclo natural de vazões.

Palavras-chave: Periodicidade de vazão; Transformada wavelet; Impacto de pequenas barragens; Usina a fio d'água; Análise de séries temporais.

INTRODUCTION

Brazil has a large territory and watersheds with considerable amounts of water, which suggests a natural tendency towards producing power by hydroelectricity. The development of this technology and the concerns for favoring renewable energies propelled this power source during the 20th century, when hundreds of hydropower plants were built across the country, many of them with large reservoirs for water storage.

In recent years, however, the requirements for energy production have evolved to minimize the times of construction and for financial return, along with environmental and social impacts. These concerns have led to a rapid increase in the number of licensed small hydropower plants (SHPs) in Brazilian territory. According to the national legal standards, among other restrictions, SHPs are those that: (i) produce between 3MW and 30MW; (ii) have reservoir surface area lesser than 13km^2; and (iii) in cases where larger surface areas are required, have reservoir residence time of, at most, one week.

Most SHPs consist of low head dams, commonly used for run-of-river operations, with no mechanism for inhibiting water discharge over the dam, and whose heights, in general, do not exceed the elevation of the upstream reach in bankfull channel conditions. As the hydraulic heads upstream and downstream of SHPs are generally small, and the residence times of stored water in the upstream channel reach are short, the operation of SHPs should not, at least in theory, significantly affect the streamflow distributional properties downstream of the dams. On the basis of this argument, environmental licensing has been made considerably easier for such a class of facilities in many Brazilian states.

In opposition to this assumption, recent studies have suggested that the natural streamflow regimes may be disturbed even by small reservoirs. These alterations are usually related to shifts in the marginal distributions of peaks and recessions of inflow hydrographs (HAAS et al., 2014), which increase the streamflow variation and may affect the dynamics of both sediment and nutrient transport and the conditions for aquatic fauna and flora development in a river reach. They may also entail the reduction of river-floodplain connectivity and induce losses of the associated ecosystem services (ANDERSON et al., 2015; FANTIN-CRUZ et al., 2015; FANTIN-CRUZ et al., 2016; KUMAR; KATOCH, 2015; and references therein). In fact, Haas et al. (2014) point that, in run-of-river operations, flow rates released from the reservoir are set to be similar to the inflow counterparts, but usually do not account for the time lag due to storage effects. Therefore, these operations generally do not produce similar flow conditions as compared to those in pre-dam conditions. Moreover, according to Poff and Schmidt (2016), the transformation from lotic to lentic water systems conditions, as promoted by artificial lakes, may lead to fragmentation of river corridors and reduction of ecosystem services. These aspects highlight the need for strategic plans for decision-making processes related to dam operations, in order to minimize environmental and social damages.

Several analysis techniques have been proposed for investigating the effects of SHPs in the streamflow regimes. They encompass flood frequency analysis (AYALEW et al., 2017), flow duration curves (FANTIN-CRUZ et al.; 2015) and statistical evaluation of changes in daily, seasonal or annual hydrological indexes (RICHTER et al., 1996; ALONSO et al., 2017). Notwithstanding, these methods usually rely on specific (and often coarse) time resolutions for the analyses and do not provide meaningful insights on the potential alterations of streamflow-related cyclic phenomena (WHITE et al., 2005; TONGAL et al., 2017).

In fact, natural streamflow signals may be thought of as the superimposition of multiple wave-like patterns, associated to distinct frequencies, which aggregate periodic or quasi-periodic characteristics of the phenomena that drive the water cycle in a catchment. These overlapping waves provide a comprehensive account on the physical processes underlying the streamflow regimes and play an important role in many human activities, as, for instance, in agricultural production (LIU et al., 2014), and in the maintenance of ecological balance (CUNHA; JUNK, 2015; KUMAR; KATOCH, 2015; FANTIN-CRUZ et al., 2015). From such a perspective and given the acknowledged sensitiveness of natural systems even for small to moderate departures from their natural conditions, it appears that, for developing more coherent decision-making strategies concerning the licensing and operation of SHPs, the previously mentioned statistical analysis techniques regarding post-dam streamflow conditions should be complemented with formal spectral analysis procedures.

The effects of large reservoirs in natural cycles are relatively well known. In general, regularization is associated with strong impacts in low-frequency cycles, such as the annual or larger ones (WHITE et al., 2005). Similarly, small storage structures are expected to alter periodic characteristics and disrupt some of the natural frequency spectral components (e.g., HAAS et al., 2014; TONGAL et al., 2017). However, as opposed to large facilities, small dams are more likely to affect the high frequency signal components.

As a matter of fact, many characteristics of the annual cycle (e.g., the annual block-maxima and annual mean streamflow distributions) are approximately preserved in the operation of run-of-river power plants. Nonetheless, the storage effects of small reservoirs and their operation have been linked to the arise of artificial short term cycles, with potentially deep impacts in the skewness of the short duration low flows distributions (HAAS et al., 2014). This may entail non-compliances to the ecological flows and sediment and/or nutrient loads downstream of the dams, for both daily and sub-daily time scales (LIU et al., 2014; FANTIN-CRUZ et al., 2016), the loss and fragmentation of habitats, the loss of the connectivity between the main channel and floodplains, invasion of exotic species, barriers to dispersal of river biota and desynchronization of life cycles, resulting in the loss of biodiversity and ecosystem services (RICHTER et al., 1996; CUNHA; JUNK, 2015; FANTIN-CRUZ et al., 2015).

An additional aspect of the outlined problem is that most low head dam studies comprise a single facility, hence ignoring potential cumulative disturbances when a set of small hydropower plants are placed in a cascade (FENCL et al., 2015; KIBLER; ALIPOUR, 2014). Nonetheless, for taking utmost advantage of the hydropower generation potential of a river, SHPs are frequently allocated in such an arrangement. In this regard, Ayalew et al. (2017) and Kibler and Alipour (2014) argue that, even though the impacts of individual small dams are often limited, the combined river regularization effect is likely to be significant.

Moreover, in general, there are no rules for establishing adequate distances between two hydroelectric plants, which should ensure the conditions for the natural flow patterns to be restored due to the potentially dominant effects of incremental lateral flow contribution (FENCL et al., 2015; KUMAR; KATOCH, 2015).

In view of the foregoing, this paper addresses two main issues. First, wavelet analysis is utilized for investigating the existence of significant intra-annual cycles in streamflow signals, along with their potential relationships with exogenous forcing mechanisms, in the Jauru river catchment, which is located at a fluvial transition system between the high plateau and the Pantanal great floodplain in the Brazilian state of Mato Grosso. Such high frequency components are usually not explored in depth in streamflow spectral studies, but are acknowledged relevant in the referred study area. Once the main cycles are identified, the effects exerted by a cascade of dams on the natural periodic patterns of the time series are formally assessed by means of the level of correlation between the signals recorded in successive streamflow gauging stations, expressed through the computation of the wavelet coherence. This is, to the best of our knowledge, a novel approach for dealing with changes in streamflow regime due to the operation of multiple power plants and, at least to some extent, may constitute a useful tool for properly locating the dams along the cascade.

The remainder of the paper is organized as follows. In section 2, a brief description of the study area and the utilized dataset is presented, along with theoretical considerations regarding the wavelet transform, the wavelet power spectrum and the wavelet coherence. Section 3 provides a case study. Finally, the conclusions and potential research developments are presented in Section 4.

MATERIAL AND METHODS

Study area and dataset

Justified by the agribusiness expansion, Brazilian midwest states have experienced a great increase in the number of licensed and constructed hydropower plants, many of them concentrated in the Upper Paraguay Hydrographic Region (UPHR), whose drainage area is 362,376km^2. The Brazilian National Council for Water Resources defines the UPHR as the Brazilian territory of the Paraguay River Basin, which also covers Bolivia, Paraguay and Argentina, and evocates the status of international basin (GAP, 2015). An interesting feature of UPHR is that it encompasses one of the largest wetlands in the world, Pantanal.

The small slopes submit Pantanal to annual cycles of overflows from rivers or lakes towards the floodplain, with pronounced aquatic and terrestrial parts. This flood pulse concept explains the lateral exchange of water, sediments, nutrients and organisms between rivers (or lakes) and their adjacent wetlands. For these reasons, the interchanged pattern imposes the Pantanal wetland to a strong dependence of natural cycles, which sets the main conditions for the existence, productivity and interactions of the biota between river and floodplain. The flood pulse coincides with the rainy season in the northern part of the region and has a lag of approximately three months in the southern counterpart (CUNHA; JUNK, 2015; FANTIN-CRUZ et al., 2015).

Among the catchments in the UPHR, that of the Jauru River, located in the southwest region of the Brazilian state of Mato Grosso, has proved interesting to this study as it comprises six operating hydropower plants and eight streamgauging stations (STs). In addition, the portion of catchment in which the referred facilities and STs are located is strongly elongated and, therefore, the incremental areas between streamgauges are relatively small. This should attenuate, at least to some extent, the potential restoration of the natural cycles due to lateral flow contribution.

Although the Jauru River catchment encompasses a drainage area of 15,800km^2, where the river has 390km in length, this study is limited to the outlet defined by ST8 (Figueirópolis Jusante power plant), with a drainage area of 3,093 km^2. The altitudes in Jauru river catchment range of from 700m in the north, in the Chapada dos Parecis region, and 116m at the confluence with the right bank of the Paraguay River, near the Pantanal floodplain.

As for rainfall characteristics, the mean annual precipitation is around 1250mm, with the rainy season spanning from October to March (REBOITA et al., 2010; PERTUSSATTI et al., 2013). A particular feature during the rainy season in this region is the occurrence of dry spells, the so-called *veranicos*, along well-marked periods of approximately 33 days, as observed by Pertussatti et al. (2013). A *veranico* can be defined as a sequence of dry days during the wet season and it is reported to occur in a quasi-periodic basis (ÖZGER et al., 2010). Such patterns, therefore, can respond for some cycles observed in the rivers of the study region during the rainy season.

Veranicos are often ascribed to the large-scale anticyclonic circulation of High Bolivia and to a low-pressure system near the coast of Brazilian northeast. These are the most conspicuous features that drive the wet season upper-level circulation in the Brazilian midwestern region (REBOITA et al., 2010; VERA et al., 2006). Over the synoptic focus, the dry spells are caused by a large-scale pattern in the atmospheric pressure, which effectively blocks the atmospheric flow (VERA et al., 2006). The dry spells are commonly described by their durations and magnitudes and constitute an influent factor for agricultural production in the Brazilian midwestern states. This fact has motivated a number of research efforts regarding dry spells in this region (CARVALHO et al., 2013; PERTUSSATTI et al., 2013).

The Electric Sector Georeferenced Information System database (SIGEL/ANEEL) indicates that there are five operating SHPs and one hydropower plant in the Jauru River (Table 1). Six additional hydropower plants are in licensing stage, being four of them in the Jauru River (upstream of the currently operating facilities) and the remaining two in the Sangue River, Jauru's main tributary, whose confluence is located between ST7 and ST8, 5 km downstream of the Salto SHP. Figure 1 presents the UPHR (mid-right panel) and the Jauru River catchment (left panel). The figure depicts the licensing status of hydropower plants, along with the eight streamgauging stations described with details in Table 2.

In the present analyses, daily streamflow samples, as associated to the eight stations, were obtained in the data collection platform powered by the Brazilian National Water Agency (ANA, 2017). The period-of-record of the time series spans from May 07, 2016 to August 10, 2017 (462 days), encompassing wet and

Table 1. Hydropower plants in operation in the Jauru river catchment.

Characteristics	Antônio Brennand	Ombreiras	Jauru	Indiavaí	Salto	Figueirópolis
Operator	Brennand Energia	Brennand Energia	Queiroz Galvão	Brennand Energia	Brookfield Power	Desa Dobrevè
Operation start	Jul, 2003	Jul, 2005	Jun, 2003	Aug, 2003	Feb, 2008	Oct, 2010
Installed capacity (MW)	22	26	121	28	19	19
Cachment area (Km^2)	2062	2352	2470	2493	2523	3087
Reservoir surface area (km^2)	0.03	1.21	1.93	0.27	0.79	7.26
Distance from the upstream plant (km)	-	14.2	14.8	2.8	4.2	16.3
Hydraulic residence time (h)	1.4	132	96	11	11	163

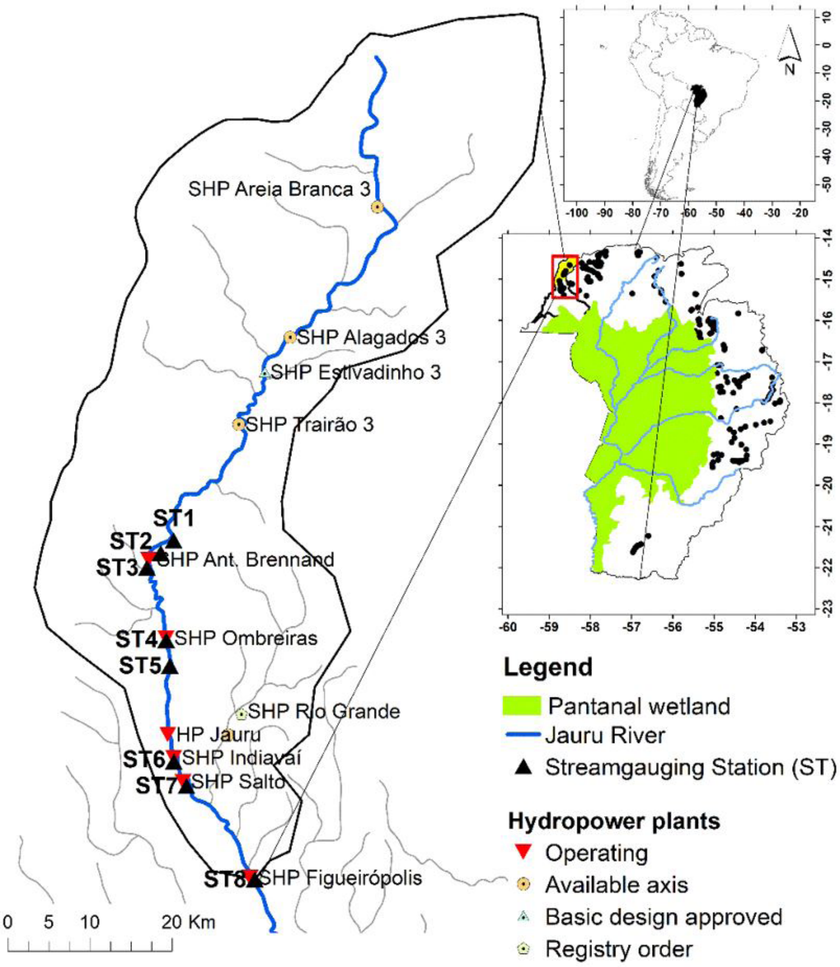

Figure 1. Jauru River catchment, their hydropower plants according to the stage operation and the streamgauging stations.

Table 2. Streamgauging stations in the Jauru River catchment.

Code	Symbol	Station	Operation start	Catchment area	Tc*	Altitude
(ANA)				(km^2)	(h)	(m)
66071353	ST1	PCH Antônio Brennand Montante2	Apr, 30 2012	2046	47.6	452
66071355	ST2	PCH Antônio Brennand Montante1	Dec, 7 2012	2054	48.9	449
66071363	ST3	PCH Antônio Brennand Jusante	Dec, 7 2012	2139	49.2	413
66071380	ST4	PCH Ombreiras Jusante	Apr, 23 2015	2355	51.4	375
66071382	ST5	UHE Jauru Montante	Jun, 21 2014	2405	51.9	362
66071392	ST6	PCH Indiavaí Jusante	Dec, 10 2012	2495	54.2	224
66071397	ST7	PCH Salto Jusante	Apr, 26 2012	2528	54.9	204
66071470	ST8	PCH Figueirópolis Jusante	Mar, 26 2012	3093	60.4	187

*Time of concentration.

dry periods. Filling of missing data was performed according to the following criteria: (i) fitting of rating curves, in situations of water stage measurements and a set of gaugings were available; (ii) linear interpolation of the hourly discharge, when the missing data were limited to three hours; or (iii) by linear regression between ST1 and ST2, after verifying that the coefficient of determination between the discharge data of these two stations is larger than 0.94. Besides, some values considered spurious were excluded from the samples.

It is worth mentioning that two streamgauging stations (ST1 and ST2) are located upstream of the first hydropower plant and, hence, there is no dam effect acting on their time series. As there is no intermediate streamgauging station between the Jauru power plant and the Indiavaí SHP, the analysis in this river stretch is done directly by means of the outflow data of the former, hereafter termed “Outflow JHP”. This data was obtained by the Reservoir Monitoring System (SAR, in Portuguese), also operated by ANA.

Pre-processing of data was concluded with the transformation of streamflow data to the logarithmic space, in order to approximate their distribution to the Gaussian model. Such an expedient is necessary for performing significance tests on power spectra in the subsequent steps of the study.

Wavelet transform

Time series of hydrologic random variables are often related to processes which exhibit quasi-periodic characteristics, but whose statistical properties are not exactly regular, making it difficult to extract periodicities by means of the Fourier transform. The wavelet transform has been recognized as an improvement in the processing of signals with time-varying characteristics, as it allows their decomposition in terms of localized time functions with no fixed scale. Therefore, the wavelet transform provides the identification of periodicities in non-stationary signals, since it captures their frequency components and allows visualizing them at different scales of time (SHOAIB et al., 2016; MISITI et al., 2018).

The wavelet transform estimates the correlations between a background signal and a given wavelet function. As streamflow data usually present wave-like characteristics, the Morlet function is frequently applied to such time series (WHITE et al., 2005). The complex Morlet wavelet function $\psi_0(\eta)$, formalized by Equation (1), consists of a Gaussian curve (the third multiplier in Equation 1 right-hand side) that multiplies a complex sine wave (the second multiplier) (TORRENCE; COMPO, 1998; SANTOS et al., 2013). The Morlet function, utilized in the current analysis, is expressed as

$$\psi_0(\eta) = \pi^{-1/4}.e^{i.\omega_0.\eta}.e^{-\eta^2/2} \tag{1}$$

in which η is a dimensionless time parameter; and ω_0 is a dimensionless wave number related to frequency, usually assumed $\omega_0 = 6$, as it provides a suitable balance between time and frequency localization and satisfies the zero mean admissibility condition of the wavelet function (GRINSTED et al. 2004).

Mathematically, the Continuous Wavelet Transform of a time series is defined as the product of a scaled and translated version of a wavelet function ψ by the signal x(t), integrated along the data domain, characterizing the convolution of a time series (TORRENCE; COMPO, 1998; SHOAIB et al., 2016). Formally

$$W_t(s) = |s|^{-1/2}\int_{-\infty}^{+\infty} x(t)\,\psi^*\left(\frac{t-b}{s}\right)dt \tag{2}$$

where “*” denotes the complex conjugate of the function. The output of the Continuous Wavelet Transform are coefficients, which are functions of two parameters: “s”, the scale factor, interpreted as a dilation (s>1) or a contraction (s<1) factor of the wavelet function; and “b”, the shifting factor, which is responsible for the translation of the wavelet function over the time.

Because the wavelet function $\psi_0(\eta)$ has a complex value, the wavelet transform $W_t(s)$ is also complex. Therefore, the $W_t(s)$ can then be divided into real and imaginary parts, i.e., amplitude $|W_t(s)|$ and phase $\tan^{-1}[\mathrm{Im}\{Wt(s)\}/\mathrm{Re}\{Wt(s)\}]$. Hence, the wavelet power spectrum for a given time series x(t) is expressed as (TORRENCE; COMPO, 1998):

$$WPS_t^x(s) = \left|W_t^x(s)\right|^2 \tag{3}$$

The $WPS_t(s)$ describes the power of the signal x(t) at a certain time t, on a scale “s”. The analysis of the WPS allows examining the oscillatory pattern of the signal at various time scales in a single time series, indicating the power estimation of the signal for each scale.

The wavelet transform has attracted significant attention to application in the large field of Earth Sciences since the pioneer work of Grossmann and Morlet (1984). In recent years, the multi-scale resolution features of continuous wavelet approach have been applied in hydrological time series to identify, for example, relationships between El Niño Southern Oscillation (ENSO) and Southern Oscillation index (TORRENCE; COMPO, 1998); precipitation and streamflow (LABAT, et al. 2000; TONGAL, et al. 2017); Artic Oscillation index and sea ice extents (GRINSTED et al. 2004); ENSO and North Atlantic Oscillation (MARAUN; KURTHS, 2004); pre and post dam regularization streamflow (WHITE et al. 2005); extreme hydrological events (SCHAEFLI et al. 2007); relative humidity and the shortwave radiation (VELEDA et al., 2012); precipitation series (SANTOS et al., 2013); and streamflow discontinuities (ADAMOWSKI; PROKOPH, 2014). Additionally, Sang (2013) and Nourani et al. (2014) published reviews on the applications of wavelet transform in hydrological time series analysis. However, despite of the diversity of research, no studies were found in our literature review that focused the effects of small dams or in cascade arrangements.

From a bivariate perspective, the joint analysis of signals, such as those provided by the Wavelet Cross Spectrum (WCS) and the Wavelet Coherence (WCO), may be used for investigating similarity and correlation between two time series x(t) and y(t). The wavelet cross spectrum WCS_t (s) is the product of the corresponding wavelet transforms, $W_t^x(s)$ and $W_t^y(s)$. Formally

$$WCS_t^{XY}(s) = W_t^x(s)\,W_t^y(s)^* \tag{4}$$

A wavelet cross spectrum is a complex number that can be decomposed into real and imaginary parts. The real part $\left|WCS_t^{XY}(s)\right|$, or amplitude, is the cross wavelet power, which reveals areas with high common power. This is expressed as:

$$\mathrm{WCS}_t(s) = \left|\mathrm{WCS}_t^{XY}(s)\right| . e^{t.\Phi_t.(s)} \tag{5}$$

The interpretation of the cross spectra is done in conjunction with appropriate confidence intervals. As they are non-normalized measures of the time and scale, significant peaks will occur not only in case of covarying power between two signals, but also if one (or both) of the single spectra exhibits strong power. Thereby, Maraun and Kurths (2004) and Schaefli et al. (2007) suggest calculating, instead, the wavelet coherence, which is a normalized measure of time and scale for the relationship between two time series x(t) and y(t). The wavelet squared coherency is defined as the absolute value squared of the smoothed cross-wavelet spectrum, normalized by the smoothed wavelet power (TORRENCE; WEBSTER, 1999).

$$\mathrm{WCO}_t{}^2(s) = \frac{\left|S.\left[s^{-1}\mathrm{WCS}_t^{XY}(s)\right]\right|^2}{S\left[s^{-1}\left|W_t^x(s)\right|^2\right].S\left[s^{-1}\left|W_t^y(s)\right|^2\right]} \tag{6}$$

The factor "s^{-1}" is used to convert to an energy density and "S" is a smoothing operator related to wavelet scale axis and time separately (TORRENCE; WEBSTER, 1999; GRINSTED et al., 2004). Thus, $0 \leq \mathrm{WCO}^2 \leq 1$, where a value of 1 indicates a perfect linear relationship between x(t) and y(t) around time "t" on a scale "s", while a zero value means no correlation. Since the wavelet transform does not affect the variance of the underlying stochastic processes, the wavelet coherence constitutes an appropriate measure of the linear correlation between two time series (TORRENCE; WEBSTER, 1999). The WCO can find significant coherence even though the common power is low. Therefore, it is expected that the comparisons between pairs of adjacent series allow recognizing cyclic patterns with the same possibilities of those observed at the upstream pairs, which includes the possibilities of restoration of a natural periodicity due to the incremental area.

Two physically related series tend to present an almost fixed phase lag (or lead). Hence, the phase expresses the delay between the two signals at time "t" focusing on a specific scale "s". Details on phase relationship interpretations are explained in Torrence and Webster (1999) and Misiti et al. (2018). In this paper, x(t) represents the discharge time series from the streamgauging station immediately upstream and y(t) the data from the downstream counterpart of a pair to be compared.

RESULTS AND DISCUSSION

The main aspect of the results is to observe whether or not the discharge cyclic patterns are preserved along the river in post-dam operation conditions, by evaluating the WPS of the set of the streamgauges. In a second moment, the degree of linear relationship between two series in the time-frequency domain will be assessed by means of wavelet coherence analysis. The main consideration is that, even outside the WPS significant regions, a time series may be visually, or qualitatively, compared to an adjacent one by using the wavelet coherence for the examination of compatibilities and changes in the discharge behavior. A change indicates some disturbance between the signals of two streamgauging stations, possibly due to dam operations, or to the existence of an important tributary.

The hydrographs and the WPSs of ST1 and ST2 are shown in Figures 2 and 3, in which areas with confidence level of 95%, delimited by a black thick contour, delineate those times and frequencies with the dominant oscillatory pattern. The gradation between warm colors (red) and cold colors (blue) represents the power of this periodicity.

By comparing the power spectra of ST1 and ST2, the aspect of the significant periodicities is remarkably similar. The longest resemblance is in cycles around 16 days between September 2016 and April 2017, with a slight interruption in November 2016 in ST1. The strongest power (dark red) in both signals is around 35 days, between mid-December 2016 and late March 2017. However, other less durable cycles with significant power are present in both ST1 and ST2 as, for example, the cycles of 8 days between February and March 2017; and those of 12 days between mid-November 2016 and mid-March 2017, with some interruptions.

The discharge values and the continuous wavelet power spectrum of ST3 are depicted in Figure 4. There is a strong power pointing out a cycle of approximately 35 days between early February and mid-May 2017, centered in the same time-frequency region as the strongest powers exhibited in the scalograms of ST1 and ST2. In addition, there is a significant period from late October to early November 2016, with higher frequency cycles of around 16 days. Despite significant areas being highlighted in smaller scales, in some short periods in the dry season, mainly those smaller than 16 days, one may easily note that these are intermittent cycles. Therefore, it is visible that some similarity between the WPS of ST3 and ST2, or ST1, persists, although many frequencies are no longer significant, and have weakened in the ST3 power spectrum.

In order to establish potential physical relationships with the oscillatory patterns observed in the three upstream STs, one may remind that the existence of dry spells in the Brazilian Midwest region (PERTUSSATTI et al., 2013; CARVALHO et al., 2013) provides a plausible explanation for the occurrence of significant power spectra in these streamgauging stations. In addition, it was expected that the smaller scales with significant power would be related to the time of concentration of the sub-basins, as responding for precipitation events. However, this was not verified by the analysis of daily discharges, possibly due the temporal discretization. Moreover, an analysis between October 2016 and March 2017 in five rain gauges in the Jauru River catchment pointed the longest period of dry spells (28 days) starting in October; and the majority of occurrences starting in early and mid-March, ranging from 10 to 16 days.

The hydrographs and the continuous wavelet power spectra of ST5, Outflow Jauru, ST6, ST7 and ST8 are shown in Figures 5 to 9. As opposed to the other time series, that of ST5 starts on Nov, 16 2016 and that of ST7 series is limited to May, 07 2017, both due to missing data that could not be filled by the previously outlined procedures.

Focusing on the larger periodic scales in the scalograms, the significant cycles seem to disappear from ST2 onwards. At the

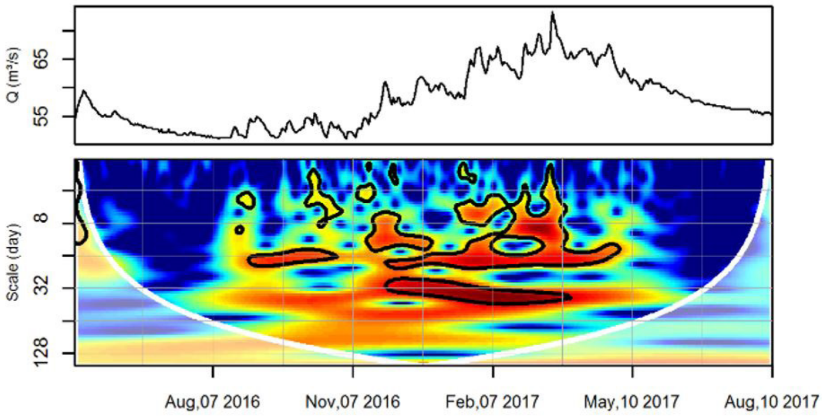

Figure 2. Discharge and wavelet power spectrum – ST1.

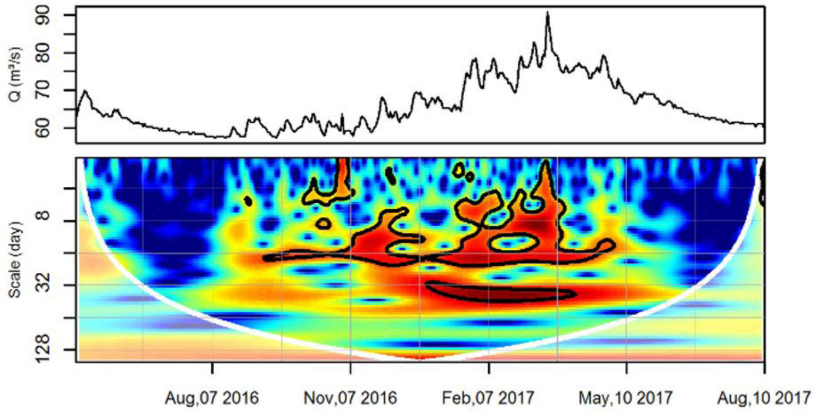

Figure 3. Discharge and wavelet power spectrum – ST2.

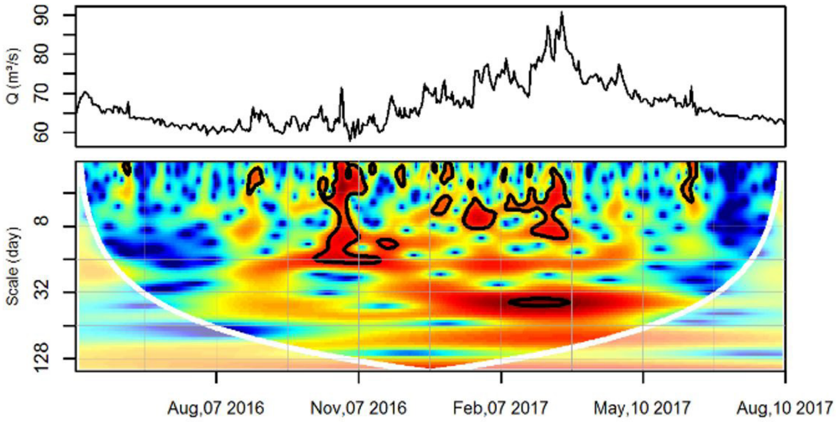

Figure 4. Discharge and wavelet power spectrum – ST3.

same time, the power spectra at the smaller periodic scales became stronger, revealing the increasing importance of the short time oscillations. The weakening of the WPS at the lower frequency cycles and the increasing WPS at the higher frequency ones support the initial assumption of alterations in the streamflow distribution due to the operation of the reservoirs. This may indicate some regularization effect, which is often ignored in small reservoirs, and may lead to environmental damage, even in such a class of dams.

A major conclusion with the analysis of wavelet power spectra of the flow signals is that the cyclic patterns observed in the firsts streamgauges are not observed with similarity in time and periodicity aspects in post-dam conditions. Most of the WPS downstream of the streamgauging stations have no dominant frequency. One may state that this stems from the regularization of the small reservoirs and the increased variability that their operation may promote in discharges, which possibly includes effects in the time series variance.

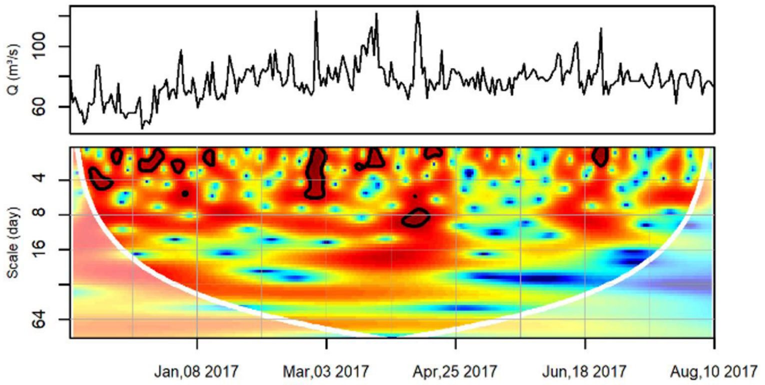

Figure 5. Discharge and wavelet power spectrum – ST5.

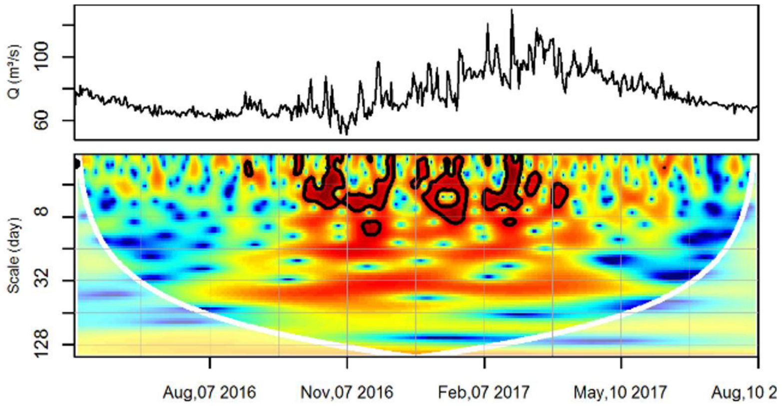

Figure 6. Discharge and WPS – Outflow JHP.

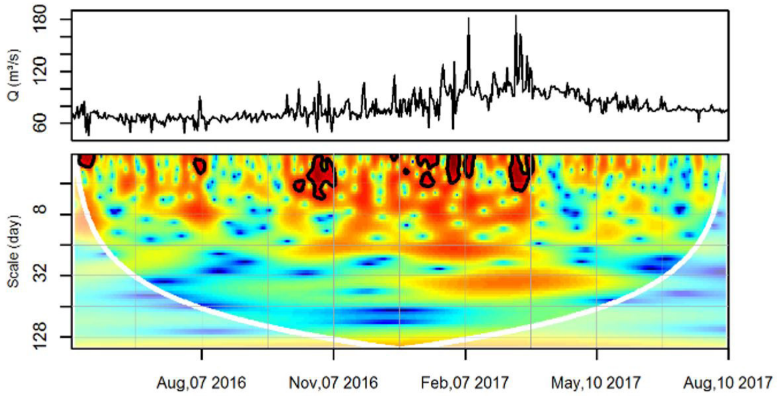

Figure 7. Discharge and wavelet power spectrum – ST6.

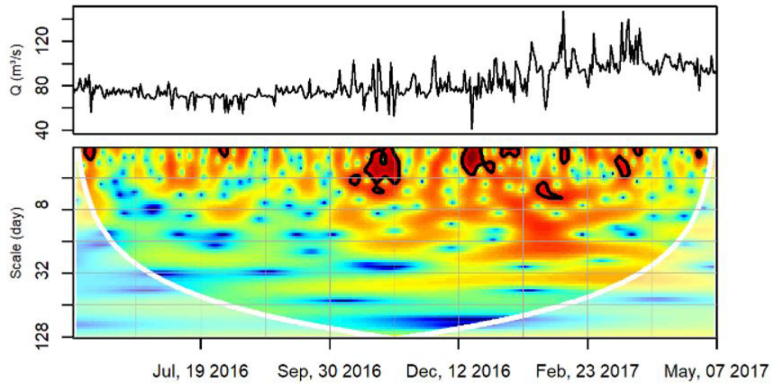

Figure 8. Discharge and wavelet power spectrum – ST7.

As explained before, the WPS is believed to reveal aspects of the time series data such as periodicities, trends, breakpoints and discontinuities in the patterns that other signal analysis techniques might not. However, it is generally agreed that an analysis of the connection between two signal patterns by means of WPS is difficult to perform (GRINSTED et al., 2004; MARAUN; KURTHS, 2004; SCHAEFLI et al., 2007; VELEDA et al., 2012). Therefore, the bivariate analysis, such as wavelet cross spectrum (WCS) and wavelet coherence (WCO), may be useful for such a purpose.

Discussing some drawbacks related to wavelet analysis, Maraun and Kurths (2004) explain that since the WCS describes the common power of two processes without a normalization, some significant peaks arising from the random co-oscillation can appear even when the two series are independent. On the basis of their arguments, the comparison between two subsequent signals by means of bivariate analysis was performed only with the WCO technique. The coherence analysis of the wavelet transform allows visualizing the degree of linear relationship between two series in the time-frequency domain. The main question in this analysis is that, even without a dominant periodicity for a specific flow signal, the comparison between contiguous flow series allows identifying the compatibilities and changes in the behavior of the hydrographs. Nevertheless, Schaefli et al. (2007) point out that, even for the WCO, a short and spurious contour of coherence is not necessarily indicative of a physical relationship.

Figure 10 presents the squared WCO power contrasting the times series from ST1 and ST2. The normalization of the WCO restrains its values to the interval 0 (cold colors in scalogram) to 1 (warm colors). The highest values are those with highest correspondences between the series. Regions beyond the significant areas of the 95% confidence level, delimited by a thick black contour, represent time and frequencies with no dependence in the series.

From Figure 10, one may observe an extremely large covariance of ST1 and ST2 time series between the scales around 8 and 96 days, excluding areas outside the edge effects. Moreover, in most part of the period-of-record, mainly from early November 2016 to mid-May 2017, i.e., during almost all the wet season, the minor scales of coherence extend from 4 days or less. This similarity had already been identified by comparing WPS ST1 and WPS ST2, and it was expected since there is not a dam or a large incremental contribution between ST1 and ST2.

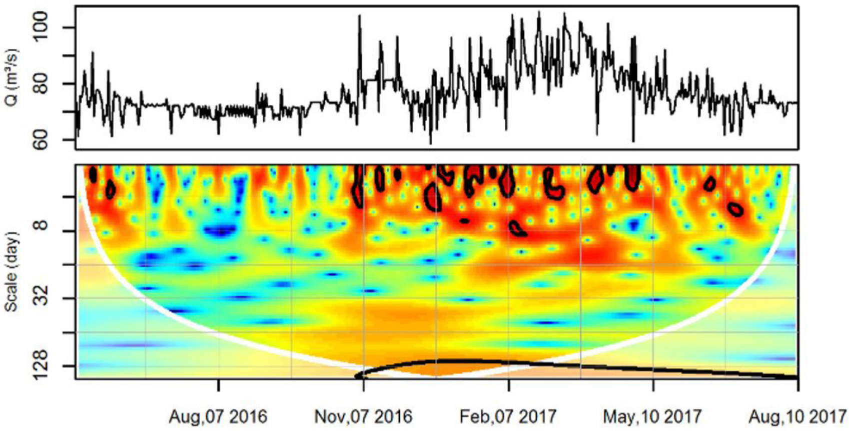

Figure 9. Discharge and wavelet power spectrum – ST8.

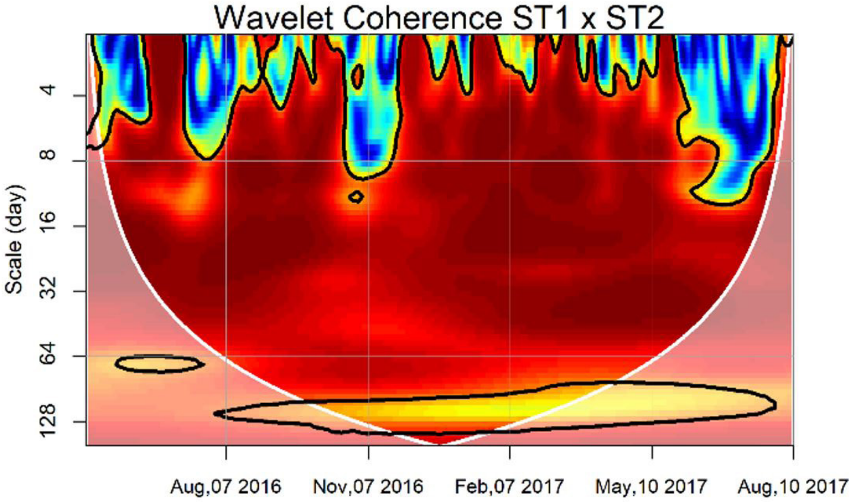

Figure 10. Squared wavelet coherence between ST1×ST2.

Figures 11 to 16 show the squared wavelet coherence between contiguous streamgauging stations in the catchment. Analysing the Figure 11, the oscillations in ST2 are coherent with those in ST3 on scales varying from around 24 days to approximately 64 days during all the period-of-record. As compared to the WCO ST1xST2, besides the reduced correlation (dark red), the scale range of correspondences is also narrower. The region with no significant coherence around 128 days expanded up to 64 days, and the smallest scales appear to become more random. Nevertheless, it seems that most part of spectrum remains in agreement with the previous discharge behavior. The low degree of disturbance in the streamflow patterns between ST2 and ST3 suggests a slight regularization in this river reach. However, it is worth reminding that its reservoir is the smallest among those in the Jauru River catchment, which is probably the main reason for the low disturbance.

The comparison of the ST3xST5 WCO does not allow a similar conjecture. Unlike the two previous analyses, there is not a permanent periodicity between discharges, although a significant correlation is present from January to June 2017, between 32 and around 48 days, and another significant correlation appears in shorter intervals in smallest scales. Focusing on the cycles between 4 and 8 days, the pattern discharges were not strongly affected along the wet season, however, the correspondences between these series disappear during the dry season. The ST3XST5 WCO indicates a moderate to strong disruption in the periodicity of the signals, which is probably related to the Ombreiras SHP operation and the incremental catchment contribution (266km^2).

The WCO analysis between ST5 (supposed to be reservoir inflow in the Jauru hydropower plant) and Jauru Outflow also indicates an alteration in periodicities, in similar scales and periods of the last analysis. However, in general, the correspondences

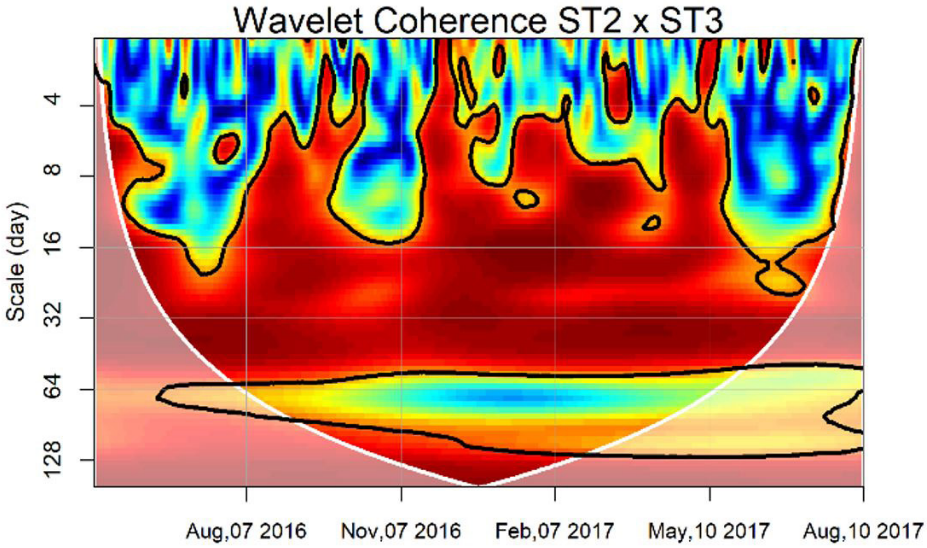

Figure 11. Squared wavelet coherence between ST2×ST3.

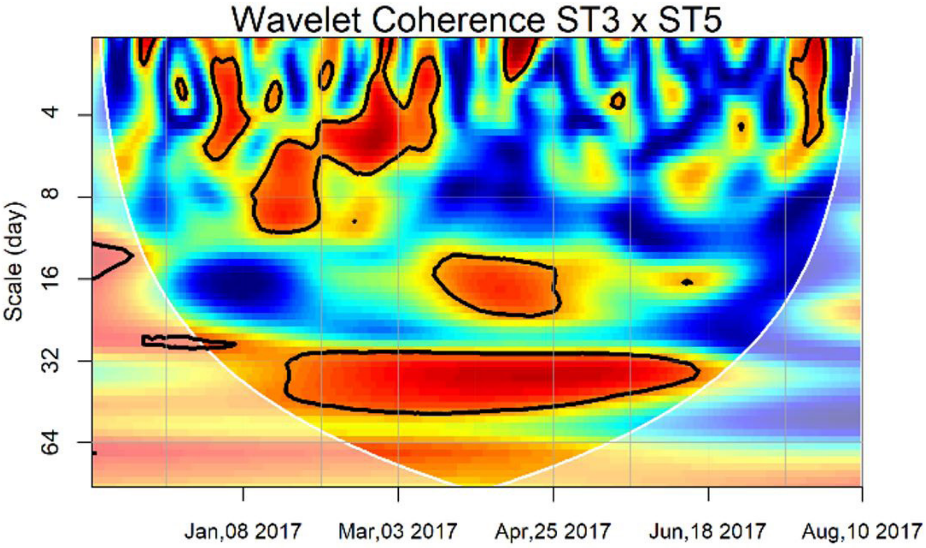

Figure 12. Squared wavelet coherence between ST3×ST5.

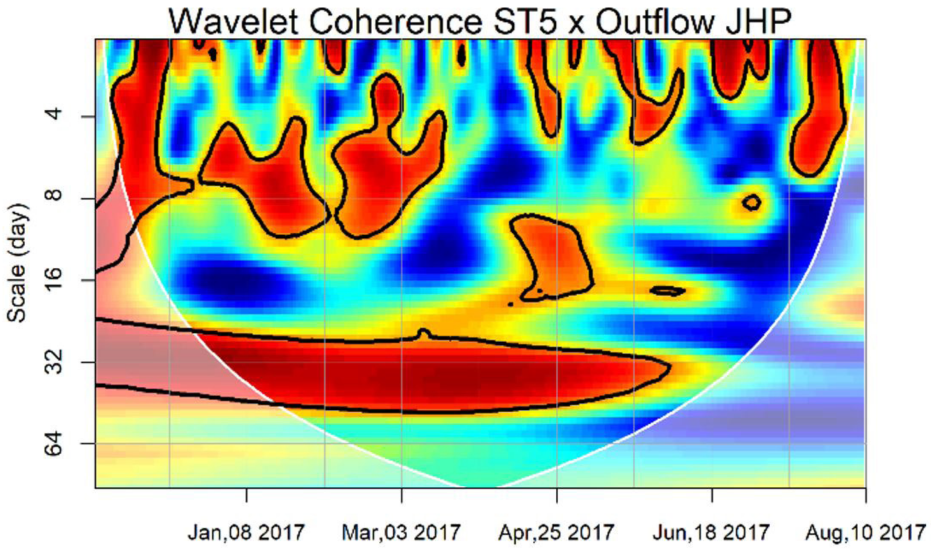

Figure 13. Squared wavelet coherence between ST5×Outflow JHP.

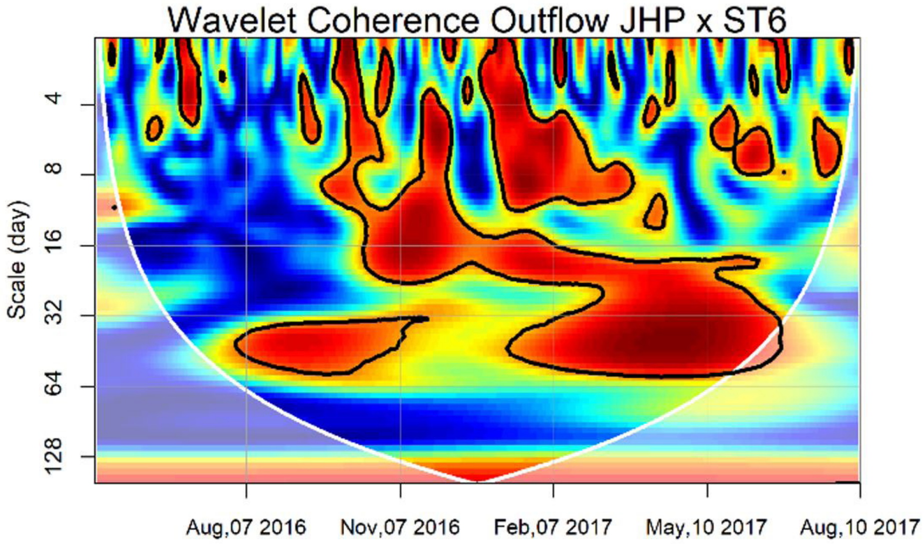

Figure 14. Squared WCO between Outflow JHP×ST6.

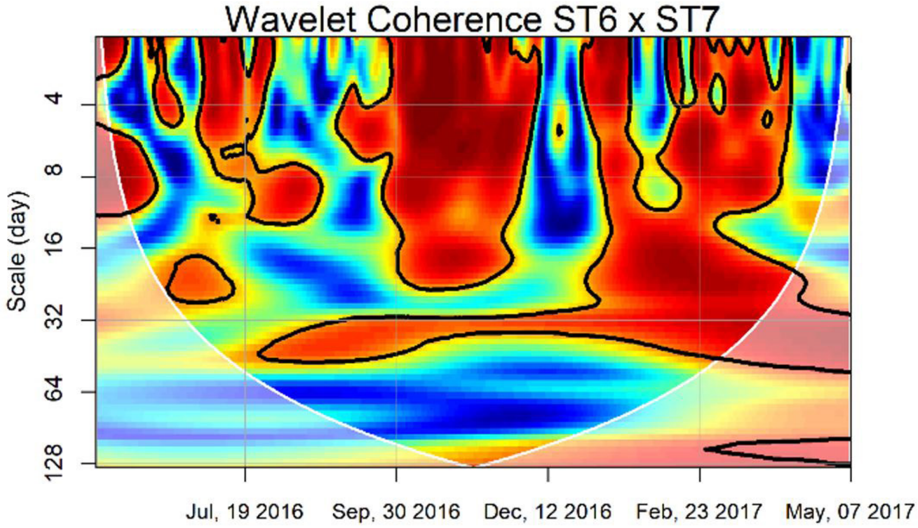

Figure 15. Squared wavelet coherence between ST6×ST7.

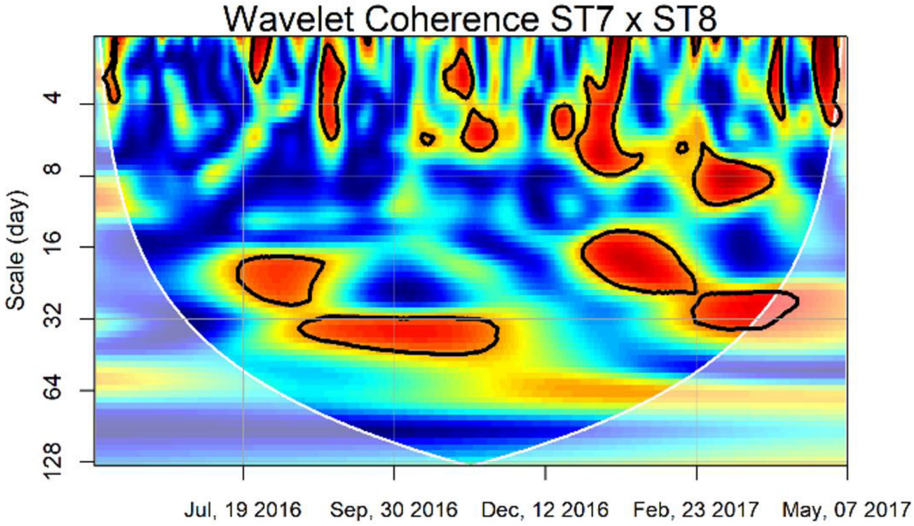

Figure 16. Squared wavelet coherence between ST7×ST8.

have larger widths in time and in wavebands. Even though the referred power plant has the greatest installed capacity in the study catchment, its reservoir surface area and hydraulic residence time have an intermediate magnitude, being even smaller than the Ombreiras SHP allocated upstream.

The comparison between signals before and after the Indiavaí SHP (Figure 14) also demonstrates some changes at periodicities, assuming a different conformation from the last analyses. One can observe a lower level of coherence in periods before late October in all scales. The correlations were more common in bandwidths of 16 days and around 48 days from November 2016 to May 2017. Following the previous arguments, this suggests that Indiavaí SHP promotes a moderate to strong disturbance, despite its small incremental catchment contribution.

In the ST6xST7 WCO, there is some increase in the areas with significant power between late September and late March, excluding a very weak area from early December to mid-January. Despite verifying these correlations, it can be assumed that a moderate degree of disturbance in discharge periodicity due to the operating of Salto SHP and the incremental area of 33km^2 occurs.

Finally, the ST7xST8 WCO presented the smallest common area, with no permanent correlation along time and scale, since, from Figure 16, it appears that the upstream and downstream discharges series are weakly correlated. As there are fewer areas with significant coherence, there is a chance that only spurious peaks remain, which is discussed by Maraun and Kurths (2004). Thus, the disturbance in the periodicity of the signals can be classified as strong. It should be reminded that a relatively large tributary (the Sangue River) flows between these streamgauging stations, which could have led to this change in the flow pattern (the incremental catchment area is 565km^2). Furthermore, in addition to the larger lateral area among the pairs of streamgauging stations under analysis, this river reach has the smallest slope in the whole stream and the reservoir of this last hydropower plant is the largest in the Jauru River catchment, which could also explain, at least to some extent, the strength of the disruption on the upstream streamflow signals.

As there is no available data from a streamgauging station in Sangue River tributary, it was not possible to examine its discharge patterns and demonstrate its straightforward influence in the Jauru River. However, as this incremental area should present periodicity patterns similar to those observed in the upstream regions of the catchment, such as ST1 and ST2, an assessment of whether this contribution is substantial to the restoration of natural cyclic phenomena was performed.

Figure 17 depicts ST2xST8 WCO, i.e., those located in the upstream and downstream extremes in the system under study. A hypothetical restitution of the natural conditions in the Jauru River would present a scalogram with some relationship between ST2 and ST8 data. However, this investigation reveals only spurious peaks. This aspect denotes no correspondences between upstream and downstream discharge patterns, which may suggest that the influence of this tributary is not strong enough to enable the restoration of the natural cycles of the Jauru River.

It is worth mentioning that other aspects besides reservoir operation could be linked to changes in the discharge cyclic patterns in different stations. In effect, it is acknowledged that factors such as the catchment size, the spatial distribution of precipitation, soil and lithology may affect the streamflow natural regimes. In order to evaluate the "catchment area" component and to identify possible disturbances due to its variation, WPS and WCO analyzes were conducted with area-scaled streamflow series. Results (not shown here) indicate that the WPS and WCO patterns were repeated. This suggests that, at least for this study, the disturbances are somewhat insensitive to the catchment size. Besides this, other possible factors, such as the distribution of the precipitations in the catchment and the pedological and geological components, could not be deeply analyzed. However, in view of the small area of the study region, some degree of homogeneity in these climatological and physiographic characteristics is expected, which reduces the possibility that the disturbances on the hydrographs arise from these factors.

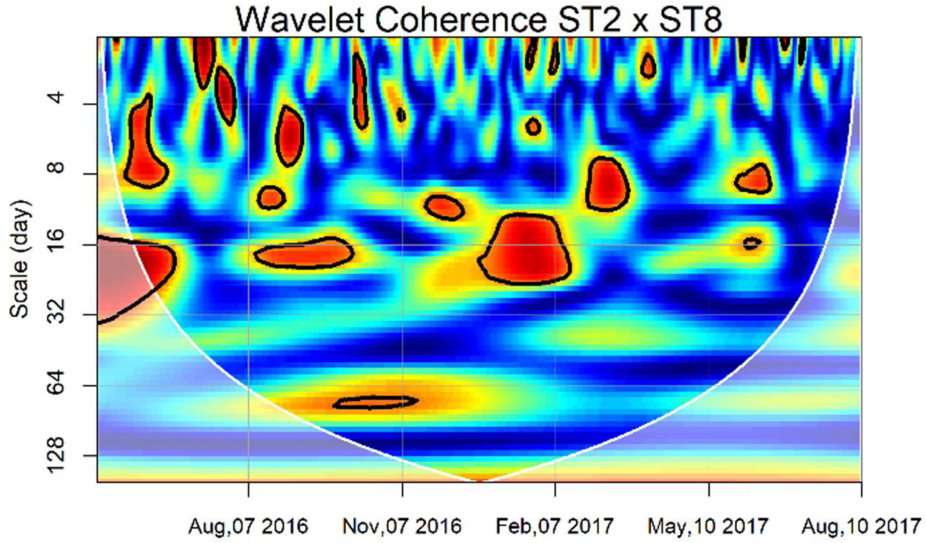

Figure 17. Squared wavelet coherence between ST2×ST8.

CONCLUSIONS

This paper aimed at contributing for reducing the non-scientific conjecture about the construction of dozens of dams without an integrated study in a catchment. Because most of them have characteristics of low impact, as, for instance, run-of-river operations, this subject has been extensively discussed, specifically in the Upper Paraguay Hydrographic Region. This fact has encouraged more research in this matter.

The wavelet transform approach substantially contributed to the understanding of the hydrological behavior of Jauru river catchment, allowing one to analyze the hydrologic effects between discharge data series on river systems. This method seemed to be useful, since it does not require a previous specification of relevant events or cycles. Although no conclusions can be stated with respect to the change of cyclic patterns, since the incremental catchment contribution could not be isolated, there is strong evidence that turbine operations and even small reservoirs modify the cyclic patterns of discharge. Additionally, in a system with no modifications in the fluvial behavior, it is reasonable to expect, as the river flows, the intensification of the natural cycles, supposed to be similar to those presented in ST1 and ST2.

By using the wavelet coherence analysis between the different series, it was possible to observe the gradual decrease in the correspondences of the discharges towards downstream. An exception can be made for the ST6xST7 WCO analysis, where the Salto SHP operates in the intermediate section, presenting a small increase in the correlation of WCO series. After this, the ST7XST8 WCO analysis shows the lowest correlation between series in this study.

In summary, the overall comparisons of WCO present the following degree of disturbance, from the most coherent to the least one: ST1xST2, ST2xST3, ST6xST7, ST5xOutflow JHP, Outflow JHPxST6, ST3xST5 and ST7xST8. The graduation involving the Outflow JHP is more uncertain due to the short period of available data, with missing values in most part of the discharge records in 2016. It was also possible to evaluate the relationship between the degrees of disturbance of streamflow signals with respect to the characteristics of the hydropower plants at the Jauru River catchment. Thus, the properties that were most compatible with the scaling of the disturbances were the residence time, the surface area of the reservoir and the ratio between installed power and surface area (MW/Km^2). Additionally, it does not seem that the installed capacity of the power generating facility acts straightforward in the degree of the disruption of the periodicities, since the Jauru power plant is not the one that most affect the cyclic patterns, and Salto SHP and Figueirópolis SHP are not those with less influence. These observations are still to be corroborated by subsequent studies. However, they may provide useful insights for the design of future constructions and for other environmental licensing.

The researchers are aware that the changes arising from run-of-river operations have their modifications limited to the proportions of the reservoir and water channels, which reduces the possibility of long-term effects on periodicities. However, there is evidence that such effects exist, and, as a result, further studies are required for appreciating whether or not they are harmful to the environment and to what extent. The scale of this work does not allow to identify the consequences of the operation of all planned power generating facilities in the Upper Paraguay Hydrographic Region. Since there are basins in a similar situation as Jauru River Catchment, and others in perspective, for this understanding, there is a vast field of work ahead. The applications of wavelet spectral analysis provide the opportunity to evaluate changes in the dominant cycles. Yet, more research efforts into the interpretation of hydrological processes and the characteristics of the physical and ecological attributes are required. In addition, it is recommended that this kind of study should be developed in collaboration with different analysts, with an interdisciplinary scope. White et al. (2005) and Schaefli et al. (2007) share this idea.

Finally, by presenting results pointing out situations with smaller and larger impacts, this work may be useful for understanding the conditions of installation and operation of power plants with similar characteristics, in an attempt to coordinate uses for electric energy production and for ecosystem services.

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Wilson dos Santos Fernandes: Conceptualization, data analysis, review.