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Nonstationarity in determining flow-duration curves aiming water resources permits

Não Estacionariedade na Construção de Curvas de Permanência com Vistas à Outorga de Recursos Hídricos

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ABSTRACT

Anthropogenic activities in the watersheds are responsible for land use changes, thus interfering in its rivers flows regimes. Consequently, changes occur in the hydrological series statistical moments, a condition known as nonstationarity. The use of a nonstationary time series can cause relevant errors, misleading and biasing the ongoing analyses. In this manner, this paper evaluates the possible effects of nonstationarity over water availability for water resources permits in six Brazilian gauges, considering the $Q_{95\%}$ as reference. Median and seasonal flow-duration curves are employed in two distinct periods, before and after 1969, for all the series. Results suggested that $Q_{95\%}$ increased in four gauges and reduced in the remainder two. Moreover, important changes were observed in intermediate flow-durations, suggesting that the variations are not limited to the series extreme values.

Keywords: *Statistical stationarity. Flow-duration curve. Water resources permits*

RESUMO

Atividades antrópicas nas bacias hidrográficas são responsáveis por causar mudanças no uso do solo, de modo a ocasionar reflexos nas vazões afluentes de seus rios. Dentre essas consequências está a alteração dos primeiros momentos estatísticos das séries hidrológicas, condição conhecida por não estacionariedade. O emprego de uma série não estacionária pode repercutir em erros relevantes e conclusões tendenciosas nas análises propostas. Dessa maneira, o presente trabalho avalia os possíveis efeitos dessa condição na disponibilidade hídrica para outorga de uso dos recursos hídricos em seis postos hidrométricos brasileiros, considerando como referência a $Q_{95\%}$. Opta-se pelo uso da curva de permanência mediana anual e de curvas de permanência sazonais, determinadas em dois momentos distintos das séries históricas, antes e depois do ano de 1969. Os resultados sugerem aumento da $Q_{95\%}$ em quatro postos e redução nos outros dois. Além disso, alterações importantes foram também identificadas em permanências intermediárias, sugerindo que as variações nas séries não estão limitadas a valores extremos.

Palavras-chave: *Estacionariedade estatística. Curva de permanência. Outorga de recursos hídricos*

INTRODUCTION

Time series are valuable sources of information that can be consulted for the characterization of variables in several areas of knowledge. In hydrology, such series are employed in water systems management as tools for the hydrological cycle understanding.

Traditionally, stochastic models use time series to reproduce the behavior of a given phenomenon. Models for synthetic rainfall series generation (RASMUSSEN, 2013; DETZEL; MINE, 2011) and streamflow (NIU; SIVAKUMAR, 2013; DETZEL et al., 2014) are examples. Alternatively, reservoir storage capacity determination (SILVA; PORTELA, 2013), water demand related analysis (ADAMOWSKI et al., 2012) and assessment of water availability in rivers (CRUZ; TUCCI, 2008) may also consider time series.

In most studies, hydrological time series application requires the knowledge of its basic properties. Evidently, one may expect these properties to undergo changes over time since they derive from natural phenomena. However, these fluctuations should be low enough as to preserve the series' first statistical moments. Otherwise, one may classify the series as nonstationary.

In streamflow time series, studies point anthropogenic activities in watersheds as potential sources of nonstationarity (TUCCI; BRAGA, 2003; TUCCI, 2007). Other authors mention climate change as another cause, although this still is an ongoing discussion (SALAS et al., 2012). Nevertheless, nonstationarity detection in streamflow series is a recurrent topic in the literature (FLEMING; WEBER, 2012; BORMANN et al., 2011; SÁFADI, 2004; MÜLLER et al., 1998; GENTA et al., 1997).

Recently, Detzel et al. (2011) analyzed inflows to 146 Brazilian hydropower plants aiming nonstationarity detection. The authors applied six well-known statistical inferences and concluded that 75 series were second-order nonstationary. Moreover, they identified the beginning of the 1970s as an important period for streamflow regime alteration in Southern Brazil. In some rivers, the average streamflow increased 25% in the periods prior and after 1969.

The present paper proposes advancing the analysis towards understanding the possible effects caused by these nonstationarities. Water availability for water resources permits (or grants) were evaluated under a water resources management context. The granting of water rights is one of the five instruments provided by the Brazilian Federal Law number 9433/97 (BRASIL, 1997), document that regulates the country water resources management. Notably complex for relating water availability with demand, both space and time dependent, Cruz and Tucci (2005) points it as the main instrument of the referred law. The presented results also highlight the need for better understanding the nonstationarity effects over the remainder water resources management instruments provided by the federal legislation.

In agreement with other water availability studies, flow-duration curves constructed with daily mean natural flow data were used as method for the analyzes. After a brief description, the paper shows the flow-duration curves in different historical periods for six gauges located in hydropower plants. In addition, seasonal (monthly) flow-duration curves were obtained. A discussion on the nonstationarity influence over water resources permits is proposed, as well as recommendations when using time series with such condition.

WATER AVAILABILITY VIA FLOW-DURATION CURVES

The flow-duration curve is a widespread tool among hydrologists as it can express the diverse rivers regimes in a single plot. Vogel and Fennessey (1995) argue that its use is convenient since it synthesizes complex elements of a river hydrology. Hence, it is suitable for stakeholders or managers with limited knowledge in the area. Although not the only method in determining water availability in a river (e.g. 7-day low-flow with a 10-years return period, $Q_{7,10}$, see WOLFF et al., 2014), it certainty is the most common.

The flow-duration curve relates the streamflow magnitude (vertical axis) with the temporal exceedance frequency (horizontal axis). Typically, one may use daily data in constructing such curve. However, it can also be obtained using data in any available time scale. Given a streamflow sample, the flow-duration curve estimates the exceedance frequency of the observed magnitudes. In other words, it expresses the frequency that a historical flow was equaled or exceeded within the sample period. With water resources grants purposes, one may employ the 95% percentile ($Q_{95\%}$, MÜLLER, 2009) as the target streamflow. Alternatively, this value may be determined relating the watershed topology with consensus measurements established by local committees, as in many Brazilian states.

In determining flow-duration curves, one may employ two methods: (i) fitting probabilistic functions or (ii) empirically. In method (i) one may consider skewed distributions, in agreement with many rivers streamflow behavior. For example, LeBoutillier and Waylen (1993) compared log-normal, gamma and generalized extreme value distributions for estimating flow-duration curves. Log-normal distribution provided the best results, however underestimated the sample variance.

In method (ii) one may sort the streamflow time series in decreasing order and rank the results. Mathematically, let q_i be a set of n streamflow observations, with $i = 1,...,n$. One may sort it in such way that q_i and q_n assume the highest and lowest elements, respectively. Equation (1) represents each observation exceedance probability:

$$p = 1 - F_Q(q) \qquad (1)$$

where $F_Q(q)$ is the streamflow probability density function. To each element q_i one associates an exceedance probability p_i. The latter can be estimated using Weibull plotting positions [equation (2)]. Vogel and Fennessey (1994) state that this method provides unbiased estimators regardless the streamflow theoretical distribution.

$$p_i = \frac{i}{n+1} \qquad (2)$$

Still concerning the empirical technique, one may identify distinct approaches in selecting the series historical reference period. The classical method (BEARD, 1943) employs the entire series available to build a single curve. Vogel and Fennessey (1994) criticize this format for its susceptibility to extreme events. Alternatively, the authors propose to estimate a median flow-duration curve based on yearly curves calculated from the observed series. This method also allows determining confidence intervals for the percentiles.

Cruz and Tucci (2005) defend a third approach based on seasonal flow-duration curves specifically calculated for water granting purposes. According to the authors, water demand follows seasonal variations, justifying the need to estimate water availability in distinct periods over the year.

Apart of the method used for the flow-duration curve estimation, nonstationarity may influence the water availability determination. In the present paper, this issue is firstly addressed with curves determined for periods prior and after 1969 in all gauges. Vogel and Fennessey (1994) concepts are employed in calculating median annual flow-duration curves. In addition, seasonal curves are also obtained, based on a monthly time scale. In all cases, the 95% percentile is considered for water granting purposes.

STUDY AREA AND DATASET

The study area and dataset selection allied the presence of nonstationarity (according to DETZEL et al., 2011) with long and consisted records of streamflow. Six gauges installed in Brazilian hydropower plants were selected, each one representing distinct hydrological regimes. At first, this number may be considered limited, however it is sufficient for the proposed analyses. Table 1 lists the selected gauges and Figure 1 exhibits their location.

Naturalized daily mean flow data were collected from the National Electrical System Operator database (www.ons.org.br). All the records are consisted and have no missing values. The time series consider the consumptive water uses (for irrigation, livestock and urban, rural and industrial activities) and discount the reservoir evaporation losses (BRAGA et al., 2009). The historic period varies from 1931 to 2010 in all gauges, except Mascarenhas and Salto Osório with periods spanning from 1938 to 2010 and from 1940 to 2010, respectively.

Table 1 last column shows the long-term mean (LTM) variation for the periods prior and after 1969 as calculated by DETZEL et al. (2011). One may note distinct situations of increase and decrease rates between periods. A stationary time series was also included for comparison purposes. It is important to mention that these variations are merely indicators of the average behaviors before and after 1969; the approach adopted in this paper is independent of these numbers.

Figure 1 also shows monthly LTM histograms, plotted to characterize the seasonal variations among gauges. Southern gauges (Rosana e Salto Osório) have undefined seasonality across the year. In addition, the same series exhibit higher variation rates prior and after 1969 (see Table 1). On the other hand, the remainder gauges present clear seasonal behavior, with high and low averages in summer and winter seasons respectively.

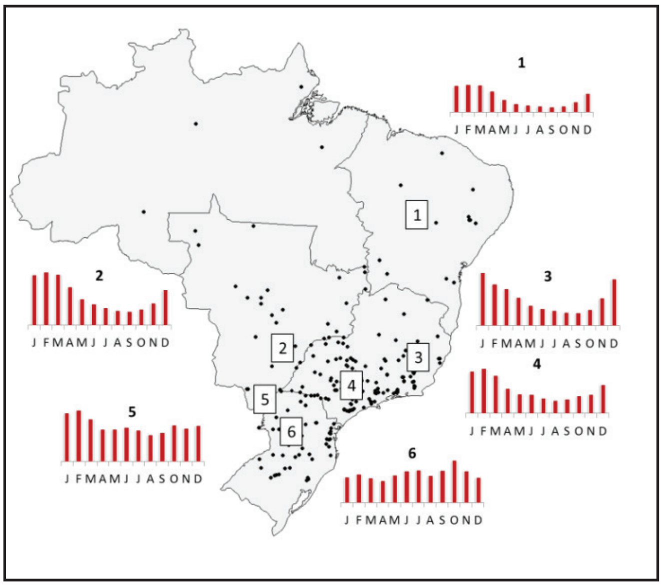

Figure 1 – Hydrological gauges location and histograms for streamflow monthly long-term mean. The numbers refer to the first column of Table 1

Table 1 – Studied hydrological gauges

#	Name	River	LTM (m³/s)	Variation rate	Drainage area (km²)
1	Sobradinho	São Francisco	2,667	Stationary	499,084
2	Ilha Solteira	Paraná	5,322	+10.3%	377,197
3	Mascarenhas	Doce	974	-11.7%	73,487
4	Barra Bonita	Tietê	438	+16.2%	33,156
5	Rosana	Paranapanema	1,286	+28.4%	100,799
6	Salto Osório	Iguaçu	1,045	+26.2%	45,769

*LTM – Long-term mean

RESULTS AND DISCUSSION

Median annual flow-duration curves

Figure 2 shows the median annual flow-duration curves for all considered gauges. Curves for the periods before and after 1969 were plotted, as well as the median curve considering the records full length.

The first notable result was obtained from Sobradinho, which exhibited significantly differences in the 15-55% percentile range. One may recall that Detzel et al. (2011) classified this series as stationary. In their study, the authors applied inferences over annual means, what might have hidden an eventual nonstationarity.

As to the other series, the general behavior proved to be consistent with the magnitudes of the LTM variations showed in Table 1. Rosana and Salto Osório presented the highest discrepancies in the flow-duration curves for the considered periods. In turn, Mascarenhas exhibited an interesting result: the curve prior 1969 was above the curve for the latter period, which is a direct reflex of the negative LTM variation.

An important result can be inferred in the intermediate percentiles (20-50%). The observed differences between curves suggest that the streamflow variations were not limited

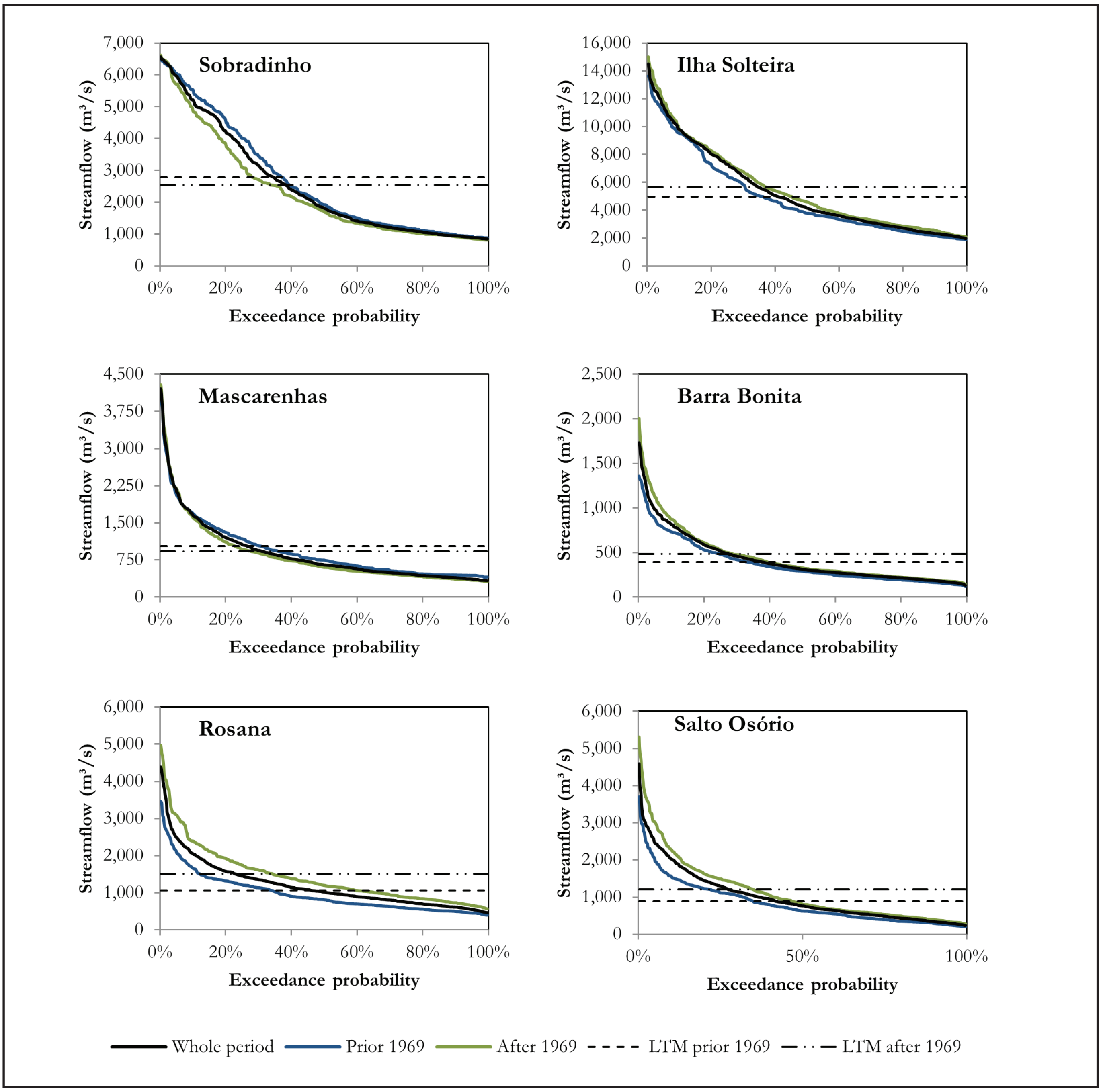

Figure 2 – Flow-duration curves for periods prior and after 1969 and median curve for the whole historical period

to the extreme events. This may imply a change in the overall streamflow regimes for these rivers. This argument is reinforced by the use of median annual flow-duration curves, insensitive to extreme events (VOGEL; FENNESSEY, 1994). Naturally, this conclusion is more evident in Rosana and Salto Osório.

Together with all those curves, LTMs for the periods prior and after 1969 were also plotted. The intention was to investigate a possible variation in the associated percentiles. Barra Bonita presented a reduction from 33.3% to 29.0% percentile. Therefore, even with higher flows in magnitude after 1969, its associated LTM percentile decreased. In other words, the frequency that the flows reached (or surpassed) its LTM was reduced. Another decrease was observed in Sobradinho, from percentiles 37.0% to 33.4%. Nonetheless, in this case the mean flows also reduced between the periods. For the remainder gauges, no changes were observed in this regard.

Table 2 presents a specific analysis over the 95% percentile. Associated flow magnitudes prior and after 1969 are shown, as well as their percentage variation. One may note significant variations on the $Q_{95\%}$ for all series, with positive changes in four gauges. In this sense, Ilha Solteira, Barra Bonita, Rosana and Salto Osório had their $Q_{95\%}$ flows increased in the period after 1969. To provide an in-depth analysis and discuss its consequence for water granting, seasonal flow-duration curves results are shown in the next section.

Table 2 – 95% percentile streamflows (Q95% – m³/s)

Name	Prior 1969	After 1969	Variation
Sobradinho	912	859	-6.2%
Ilha Solteira	2.027	2.287	+11.4%
Mascarenhas	443	343	-29.5%
Barra Bonita	151	179	+15.6%
Rosana	454	653	+30.5%
Salto Osório	249	324	+23.1%

Seasonal flow-duration curves

Monthly flow-duration curves were obtained for all six studied gauges, however only the most important results are presented due space limitation. The choosing criterion was based on the results exhibited in Table 2 and in the histograms showed in Figure 1. At first, Figure 3 presents January and June flow-duration curves for Ilha Solteira and Salto Osório.

Differences are most evident in Ilha Solteira, which has a well-defined seasonality over the year. In January, the associated LTMs percentiles reduced 12.5%, from 50.0% before 1969 to 37.5% in the latter period. This is a similar conclusion drawn for the annual curves in Barra Bonita.

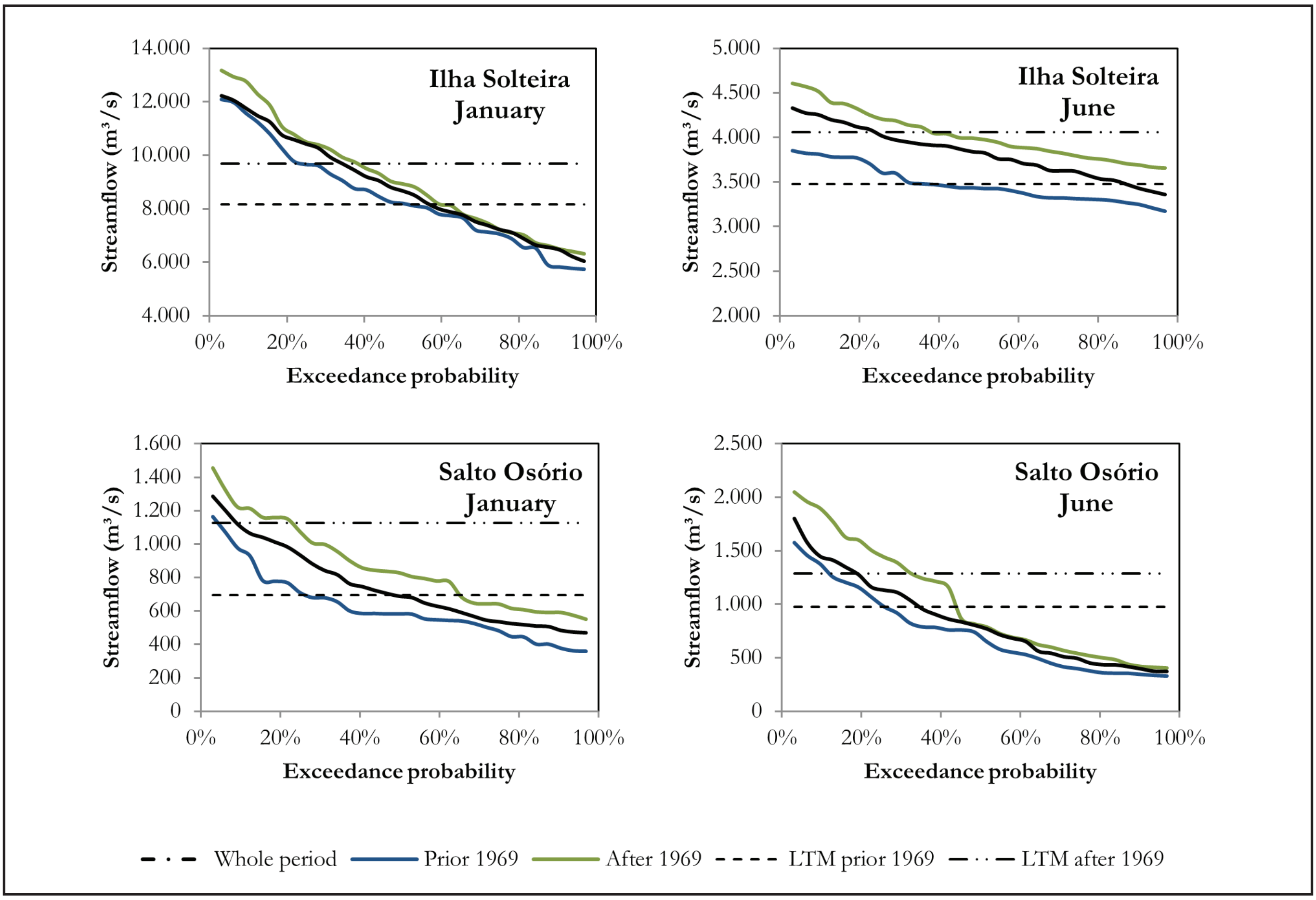

Figure 3 – January and June flow-duration curves for Ilha Solteira and Salto Osório

Yet, the highest distinctions in the $Q_{95\%}$ percentiles were noted in January for Salto Osório gauge. While Ilha Solteira presented 9.4% (January) and 13.1% (June), Salto Osório displayed 35.0% (January) and 19.7% (June) variations. Moreover, the highest increase in Ilha Solteira occurred in January, a month within the wet season (see Figure 1). No similar conclusion can be drawn for Salto Osório, since its wet/dry seasons are not clear.

Figure 4 details the monthly differences in the 95% percentile for Mascarenhas. Reductions in the Q95% flows were observed in all months, being more severe in May, July, September and October. For these months, the variations overcame 30% in reducing the $Q_{95\%}$ (-40.2%, -31.7%, -37.3% e -32.3%, respectively). Recalling the histograms in Figure 1, one may note that July, September and October are in the dry season. Hence, the detected reductions may indicate a concern in Mascarenhas gauging station. The smaller reductions were observed in January and December (-11.6% and -8.6%, respectively).

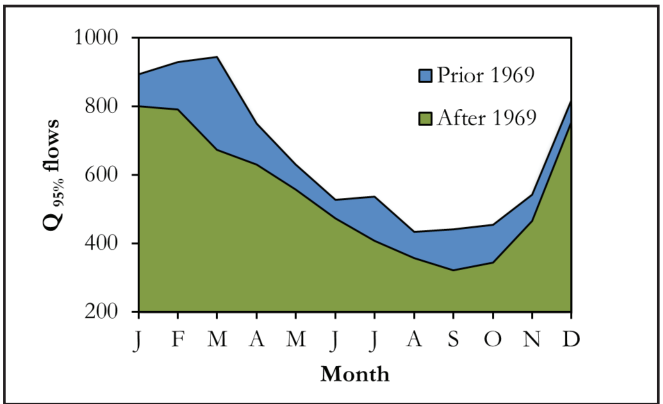

Figura 4 – Monthly variations in the Q95% flows in Mascarenhas

It is important to stress that the presented monthly flow-duration curves should be analyzed with caution. In dealing with monthly scale curves, the considered sample sizes are reduced. While for annual scale one may use samples with 365 elements, in monthly scale these samples are limited to 31 elements. Vogel and Fennessey (1994) explain that small samples may induce bias in the flow-duration curves. Alternatively, they propose an estimator based on the Beta distribution, considerably more complex than the Weibull estimators [equation (2)]. Nevertheless, the results presented in this section confirm that nonstationarity plays a significant role in water resources grants estimation via flow-duration curves.

Further discussion

The search for nonstationarity causes is out of the scope of this paper. However, it is known that they are a consequence of land use changes, climate variability and other anthropogenic activities in the watersheds. Soil sealing and deforestation for crop planting possibly altered the runoff processes and increased the $Q_{95\%}$ in some gauges. On the other hand, two gauges shown reduction in the $Q_{95\%}$. One may point the consumptive uses as a plausible cause, though they were considered in obtaining the naturalized streamflow time series. Thus, one can argue whether the reductions resulted from inaccuracies in the streamflow series reconstitution or are a consequence of climate variability.

Evidently, the choice for 1969 as the reference year for the analysis can be considered a simplification. Although based in other studies (GENTA et al., 1997; MÜLLER et al., 1998; SÁFADI, 2004) it is possible that variations occurred in different moments for each gauge. In contrast, the existence of a database with consisted and long time series is rare and may limit studies like the one presented here. In particular, the considered database resulted of a great effort by National Electrical System Operator in obtaining and validating the naturalized streamflow series (MÜLLER, 2009). Yet, these records carry uncertainties mainly associated with consumptive uses. Braga et al. (2009) explain that estimates for consumptive uses were obtained through other hydrological variables, censuses and documents published by diverse institutions. They also argue that the consumptive uses peaks occur in the dry season. This is important considering the results obtained in the present paper.

It is worth mentioning that Sobradinho, Ilha Solteira and Barra Bonita gauges operate in hydropower plants with reservoirs that are able to regularize the inflows. This may increase the $Q_{95\%}$ percentiles as well as the water availability for granting purposes. On the other hand, run-of-river reservoirs are unable to do so.

Usually, one may need to determine water availability in sites with insufficient or low quality data. Cruz (2001) states that there is great difficulty in obtaining reliable information and thus achieve proper characterization of the watercourse in question. This requires researchers and potential stakeholders interested in water granting to use residual streamflow records (i.e. discounting water uses before the gauge measurement point).

Considering the presented results, it is clear that determining water availability in watersheds affected by anthropogenic activities must be done carefully. It is strongly recommended that nonstationarity condition must be verified. Should the nonstationarity be confirmed, procedures for data correction can be employed (see DETZEL et al., 2011).

CONCLUSION

The analyzes presented in this paper raised important issues. The most important ones are listed below:

- Sobradinho showed notable differences in the flow-duration curves prior and after 1969 even with Detzel et al. (2011) classification as a stationary series.
- Overall, the flow-duration curves variations in the sub-samples were consistent with the respective series LTM variations.
- Changes in the intermediate percentiles (20-50%) were observed. This is an important finding of the paper.
- Barra Bonita and Sobradinho exhibited changes in the associated LTM percentiles prior and after 1969.
- As to the $Q_{95\%}$, variations ranged from -29,5% (Mascarenhas) to +30,5% (Rosana).

- Important changes also occurred in the seasonal flow-duration curves. Salto Osório suffered a 35% increase in Q95% in January.
- Mascarenhas presented significant reductions in $Q9_{5\%}$ reaching -40,2% in May. Other decreases were detected in the driest months of the year for this gauge.

In-depth studies on the nonstationarity condition of hydrological time series have been done almost exclusively for modeling purposes. However, the results here obtained alert that these analyzes should be embedded in water resources management activities as well.

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Authors' contributions:

Detzel, D. H. M.: Literature research, study area selection, data collection, method implementation, results analyzes (statistical approach) and paper organization.

Fernandes, C. V. S.: Analysis scheme organization, results analyzes (water resources management approach) and paper organization.

Mine, M. R. M.: Statistical tools selection, results analyzes (statistical approach) and paper organization.