Hydrological characterization of the Araguaia River through reference flows

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Abstract This study examined the hydrological behavior of the Araguaia River through reference flow, analyzing the capacity of granting the river segments in three different fluviometric stations. The study exposed the comparison of monthly and annual reference flow, considering a hydrological series of 33 years. Consequently, it was proposed seasonal flow comparing to the methodology of annual reference flow for water grants in national rivers. The adoption of the annual reference flow restricts the grants of water use in most of the time, because the proposal of monthly and seasonal $Q_{95\%}$ in the rainy period for grants processes showed much higher values. The proposal of monthly and seasonal reference flows to grant the multiple right of use of water may be the most adequate for power generation, because it presents the inherent characteristics of the flows of each month and per period, respectively. However, the use of seasonality for grants must be analyzed along with the environmental aspect of the river basin concerning to the damage of aquatic life of the Araguaia River.

Keywords Fluviometric station · Reference flow · Grant · Araguaia River

Introduction

Brazil has a privileged situation regarding its water availability compared to other countries, but there are problems of water scarcity in the country, which are fundamentally due to the combination of the exaggerated growth of localized demands and the degradation of water quality (Setti et al. 2001).

The great need for multiple uses of water due to its huge demand in urban areas, industry, agriculture and power generation justifies the necessity to increase the efficiency of water management and, therefore, it requires reforms in the planning of the water resources use (Montaño and Souza 2016).

Law 9.433/97, which establishes the National Water Resources Policy (PNRH) and creates the National Water Resources Management System (SNGRH), seeks to organize planning and management of water resources at a national level. Therefore, the granting of rights to use water resources, which is one of the PNRH instruments, aims to ensure the quantitative and qualitative control of water uses and the effective exercise of water access rights (Brasil 1997).

To obtain more concrete results to meet all usage demands, it is necessary to know the fluvial behavior of watershed, using the reference flow methodology. According to Silva et al. (2006), the reference flow is the establishment of a flow rate that becomes the maximum limit of water use in stream. Therefore, there are different standards for adoption of reference flows in Brazil, and the variability of these standards is related to the individual characteristics of each river basin.

According to Mendes (2007), the minimum flows such as $Q_{7,10}$ and the permanence flow rates $Q_{90\%}$ and $Q_{95\%}$ are generally used as reference flows. Brazil and its federal

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states set their own percentages of the reference flow as the maximum flow for consultative uses.

The fluvial behavior undergoes variations throughout the year, in which they are closely related to the precipitation. In most of Brazil, there is a marked seasonality with rainy seasons and well-defined droughts, so that at the end of the dry period one can observe flow rates far below the average flow rate and even absence of water (ANA 2016).

The Araguaia River forms the natural landmark initially between the states of Mato Grosso (MT) and Goiás (GO), and then between Mato Grosso and Tocantins (TO) and finally between Pará (PA) and Tocantins. According to the Agência Nacional de Águas (ANA), the river is therefore classified as a national river, which divides or passes through two or more states or even crosses the border between Brazil and another country. Therefore, it is incumbent upon ANA to issue the right to use of water resource in the Araguaia River for several types of uses, thus defining the maximum flow rate to be granted.

Therefore, the aim of the study is to evaluate the hydrological behavior of the Araguaia River through temporal variability, analyzing the concession capacity of the river segments, divided into upper, medium and lower Araguaia. Different standards were defined to calculate reference flows through monthly, seasonal and annual analyses.

Materials and methods

Area of study

The Tocantins–Araguaia basin is the fourth largest drainage basin in South America, extending over approximately 800,000 km² and encompassing a part of two large South American biomes: Amazon forest in the north and Brazilian Savanna (Cerrado) in the south. It is formed mainly by two major river systems: Tocantins and Araguaia (Aquino et al. 2005, 2009).

The Araguaia River is a plain river that rises in the foothills of the Serra dos Caiapós at 850 m, traveling almost parallel to the Tocantins for about 2600 km. Four sections are formed in the cascade, with the gradient around 300–200 m in the middle course and below 100 m in the lower course. The upper course is 450 km long on a steep gradient of 120 cm/km, with waterfalls and rapids. The Island of Bananal, considered the largest fluvial island in the world (Mérona et al. 2010), is located in the upper–middle course.

The climatic conditions that predominate at the Araguaia River basin are of continental tropical nature, due to its continental position that does not suffer the direct effect of the intertropical confluence. According to Köppen, this

region is classified into type Aw, hot and humid climate, with annual rainfall of the order of 1700 mm, average monthly temperatures oscillating between 24 and 26 °C and drought in the June–September period (ANA 2009).

According to Latrubesse and Stevaux (2002), the Araguaia River is divided into three segments: upper, middle and lower Araguaia, as shown in Fig. 1. The upper Araguaia (Upper-ARA) drains an area of 36,400 km². In the middle Araguaia (Middle-ARA) that extends for 1600 km from Registro do Araguaia to Conceição do Araguaia, the drainage area increases dramatically, reaching an area greater than 300,000 km². The lower Araguaia (Lower-ARA) constitutes the locality of Conception of the Araguaia until its confluence with the Tocantins River.

The selected fluviometric stations for the study, presented in Table 1, were chosen so that they could relate the flow behavior at three segments along the Araguaia River. Therefore, a station near the downstream of upper, middle and lower Araguaia was selected.

Flow data of fluviometric stations were obtained on ANA's Hidroweb database during the period from 1975 to 2011. In 1985, there were faults at the Araguatins station that were corrected using the simple linear regression method proposed by Tucci (2002). The Conceição do Araguaia station had a good data series, but there were faults in 1980, 1987 and 2008. The Araguatins and Aruanã stations had gaps in 1980, 1987 and 2006 that could not be filled because of having large series with failures in consecutive months. Therefore, the 1980s, 1987s, 2006s and 2008s were discarded in all fluviometric stations to homogenize the historical series of the study. Thus, a historical series of the study had 12,052 daily flow records in 33 years.

Low flow $Q_{7,10}$

According to Oliveira (2008), the low flows are naturally linked to the critical periods of the river; so it is essential to know the flow rate for studies of water availability. The low flow $Q_{7,10}$ method analyses drought flow which occurs for a period of seven consecutive days at a period in 10 years. Therefore, it is examined 365 daily average flows by the database of daily flows, calculating the moving average of seven consecutive days (Q_7), in which it is calculated for seven terms that are moving (average from the 1st to the 7th day, from the 2nd to 8th day, from the 3rd to 9th day), and so on.

Statistical analyses were performed using values of the lowest average of 7 days of each year, which when extrapolated provided the value for different times of return. Therefore, we set out for the frequency analysis and the determination of the flow rate for the desired return period.

Fig. 1 Location of the Araguaia River basin

In the present study, the lognormal distribution function was applied following the methodology presented by Chow et al. (1988) and Von Sperling (2007), which corresponds to the adjustment of a normal distribution to the logarithms

($\log_{10}$) of the flows through Eq. (1) and the calculation of flow Q in m^3/s by converting the value of the logarithm of the flow to the flow itself through Eq. (2) as

Table 1 Selected fluviometric stations at Araguaia River. Source: Adapted Hidroweb-ANA, 2016

Station code	Station	Drainage area (km ²)	Latitude	Longitude
25200000	Aruanã–GO	76,300	−14:54:46	−51:04:53
27500000	Conceição do Araguaia–PA	332,000	−08:16:10	−49:15:34
28850000	Araguatins–TO	388,000	−05:39:05	−48:07:57

$$\log_{10}(Q_{\text{calculated}}) = \text{mean of } \log_{10}(Q) + Z \times \text{standard deviation of } \log_{10}(Q), \quad (1)$$

$$Q_{\text{calculated}} = 10^{\log_{10}(Q_{\text{calculated}})}, \quad (2)$$

where Z is the variable of standardized normal distribution, which returns the standardized normal ordered value associated with a certain cumulative probability. An interpolation was performed to obtain the value of the flow corresponding to the return period of 10 years for each fluviometric station.

Permanence flow $Q_{90\%}$ and $Q_{95\%}$

The permanence flows are obtained by permanence curves that relate the flow with the percentage of the time in which it is equalized or exceeded; Q_{90} and Q_{95} are frequently applied by the Brazilian legislation (Mendes 2007). The Q_{90} is the flow with 90% permanence in time and Q_{95} with 95%, with an extrapolation in the rainy periods in which there is a great increase of the river flow.

The calculation of $Q_{90\%}$ and $Q_{95\%}$ permanence flows was carried out using a historical series of daily values, taking the same years as those used in the calculation of $Q_{7,10}$. The calculations were carried out in a spreadsheet, according to the methodology proposed by Von Sperling (2007).

The permanence curve is usually estimated, considering the entire data period of the historical series. This type of curve does not contemplate the effects of seasonality throughout the year and of the interannual variation. To consider the seasonality, it can determine the curve for each month of the year for all the years of the series. Therefore, this type of result allows to distinguish the monthly conditioning factors of seasonality (Cruz and Tucci 2008).

The studies on granting criteria by Ribeiro (2000, 2003) considered empirical monthly and seasonal empirical flows through simulations, comparing the use of a single annual value. This methodology was also used by Vergara et al. (2013), comparing the reference flow $Q_{90\%}$ monthly, bimonthly and quarterly with $Q_{90\%}$ seasonally, by the environmental agency of the state of Tocantins.

In this way, the calculation of the monthly and seasonal permanence flows was also performed, in which 12 values

of $Q_{90\%}$ and $Q_{95\%}$ permanence flows were obtained for the monthly analysis and a value of $Q_{90\%}$ and $Q_{95\%}$ for the rainy season and for the drought season.

Maximum grant flow

The maximum granted flow ($Q_{\text{max\_granted}}$) is the maximum available flow to be granted for various uses. According to Mendes (2007), Brazil and its federal states express the maximum limit as percentages of a reference flow when establishing the water availability for granting for consultative uses as in Eq. (3):

$$Q_{\text{max\_granted}} = k * Q_{\text{Ref}}, 0 < k < 1, \quad (3)$$

where Q_{Ref} is the determined reference flow (m³/s) and k is the maximum withdrawn percentage for grant, expressed by a determined multiplicative factor.

The determined criterion for granting rivers in the domain of the Federal Government by ANA is that the granting flow must be up to 70% of $Q_{95\%}$ and may vary according to the peculiarities of each region (ANA 2011). Therefore, the value of k will be 0.70 for this situation. Following the methodology of Cruz (2001), it was possible to evaluate the maximum flow rate, by performing seasonal and annual analysis.

Results and discussion

The flow behavior is directly related to the rainfall regime, as well as the use and occupation of the soil and physical properties of the river basin. Discharge changes over time are represented by a hydrograph of each station analyzed and provide an idea of the temporal variability of annual periodicities of dry and rainy seasons, as shown in Fig. 2.

The hydrographs for the fluviometric stations comprised average daily flows, reflecting peaks of maximum and minimum flows and clearly showing the oscillation of the hydrological regime of the system.

It is observed that the three higher maximum flows of the considered period occurred in 1979, 1997 and 2004 for the three fluviometric stations. The 1976s, 1996s, 1998s and 1999s presented lower flows than the double of

Fig. 2 Hydrograph of the average daily discharge of each fluviometric station from 1975 to 2011

historical average flow at Araguatins station. However, these same years and 2001s presented flows close to the historical average in the Conceição do Araguaia station, according to Fig. 2b, c. As can be shown in Fig. 2a, there was a variability in the Aruanã station, in which only the 1975s, 1976s, 1986s, 1996s and 2001s were expressively the driest years.

Another fact that can be noticed in Fig. 2 is the upward trend in flow as the drainage area increases from upstream to downstream of the Araguaia River. The drainage area of Aruanã (76,300 km²) is much lower than those of Araguatins (388,000 km²) and Conceição do Araguaia (332,000 km²).

The discharge peaks of Araguaia River occur predominantly from January to May; however, in the region near higher Araguaia, there are variabilities and additions in the peaks that begin in December. The lowest discharges are from July to October for all selected stations, according to Fig. 3.

Observing Fig. 3b, c, the highest peaks usually occur from January to April at the Conceição do Araguaia and Araguatins stations. The peaks at Aruanã station occur from January to March, according to Fig. 3a, linking directly the hydrologic regime with the climate of upper Araguaia region. This region is already part of the Cerrado

Fig. 3 Hydrograph of the average monthly discharge of each fluvimetric station from 1975 to 2011

Fig. 4 Annual reference flows $Q_{90\%}$, $Q_{95\%}$ and $Q_{7,10}$ for the period from 1975 to 2011

biome, characterized by having two well-defined seasons, rainy season and drought season, while the other stations further downstream are in the Amazon biome.

In Fig. 4, it is observed that the flow $Q_{7,10}$ is more restrictive and has lower values than the annual $Q_{90\%}$ and $Q_{95\%}$ for each fluvimetric station.

According to Castro et al. (2004), when the water demand is high in the watershed, the practice of applying a more restrictive limit may make it impossible to grant an adequate concession for surface water catchment for the existing demands in the region, leading to conflictive situations. The flow rate $Q_{7,10}$ is required when verifying the self-purification capacity of a river to get effluents under more unfavorable conditions.

When it establishes the permanence flows per fluvimetric station, there is a great difference among the $Q_{90\%}$ and $Q_{95\%}$ obtained by annual test compared to the permanence flows in the monthly tests, as can be observed in Fig. 5.

The values of $Q_{90\%}$ and $Q_{95\%}$ per month have shown a greater capacity of granting from December to June, against the annual $Q_{90\%}$ and $Q_{95\%}$. From August to October, the monthly permanence flows are close to the annual $Q_{90\%}$ and $Q_{95\%}$. Therefore, Ribeiro (2000, 2003) and Vergara et al. (2013), recommended the adoption of monthly permanence flows, since it obtains better results than the use of a single annual value.

The socioeconomic options and goals must be considered as well as the multiple uses in addition to purely hydrological criteria, when evaluating the granting flow. Figures 6, 7 and 8 show the seasonal $Q_{95\%}$ for the four wettest months (from January to April) and the four driest months (from July to October).

The $Q_{95\%}$ for the drought season against the annual $Q_{95\%}$ showed similar flow values. The extrapolation of $Q_{95\%}$ for the rainy season becomes more expressive at the stations closest to downstream of the Araguaia River, as can be observed in Figs. 7 and 8.

The use of annual $Q_{95\%}$ restricts the granting of concession to users because it does not consider the rainy and drought period of the region. Therefore, it may be more appropriate to define the percentage to be withdrawn for granting the $Q_{95\%}$ seasonal flow, considering the higher and lower flows, according to Table 2.

Fig. 5 Monthly reference flows Q_{90} % and Q_{95} % for each fluviometric station for the period from 1975 to 2011

It can be observed that the $Q_{\max\_granted}$ for the drought season presented a value close to the single annual $Q_{\max\_granted}$ in three studied stations. However, the difference between the annual and seasonal $Q_{\max\_granted}$ in the rainy season is more significant in Conceição do Araguaia and Araguatins with values greater than 1000 m³/s. Therefore, the maximum granted flow for a single annual $Q_{95\%}$ is more restrictive, since it does not consider the high granting capacities in the rainy season and, consequently, the flow to be granted for each user will be lower.

In fact, the criterion of the seasonality for granting favors the right of use for power generation. However, this criterion

must be analyzed concomitantly with the environmental aspects of the river basin, since the indiscriminate use of the water resource can lead to water stress and damage to aquatic life. Thus, the greater amount of granted flow induces a greater exploration of the aquatic environment.

Conclusion

The hydrological characterization through reference flows is utilized for the process of analysis of the river regime of the Araguaia River, which allows obtaining data of

Fig. 6 Comparison of annual and seasonal permanence flow in Aruanã: **a** permanence curve in the rainy season; **b** permanence curve in the drought season

Fig. 7 Comparison of annual and seasonal permanence flow in Conceição do Araguaia: **a** permanence curve in the rainy season; **b** permanence curve in the drought season

Fig. 8 Comparison of annual and seasonal permanence flow in Araguatins: **a** permanence curve in the rainy season; **b** permanence curve in the drought season

significant importance for the planning of water resources, applying them to the granting of environmental licenses articulately. This articulation allows to evaluate the enterprises in all its phases regarding its environmental aspect and the water availability.

However, when analyzing the reference flows, we observed the variability in the region near upstream and downstream of the Araguaia River. In general, the values of flows increase when there is an increase of the drainage

area and, consequently, makes possible an evaluation for risks of floods in future works.

It was observed that the adoption of the annual reference flow restricted the grants of water use most of the time, since the proposal of monthly and seasonal $Q_{95\%}$ in the rainy period for the granting processes presented values much higher. This significant restriction can influence the regional economy. It was also verified that the river has a greater capacity of granting, mainly from February to April

Table 2 Comparison of annual and seasonal reference flows and their respective maximum grant flow from each fluvimetric station in the period from 1975 to 2011

Fluviometric station	Annual permanence flow (m ³ /s)		Seasonal permanence flow (m ³ /s)			
	Annual $Q_{95\%}$	$Q_{\max\_granted}$	$Q_{95\%}$ (rainy season)	$Q_{\max\_granted}$ (rainy season)	$Q_{95\%}$ (drought season)	$Q_{\max\_granted}$ (drought season)
Aruanã	306.14	214.30	938.59	657.01	275.97	193.18
Conceição do Araguaia	892.78	624.95	4245.24	2971.67	765.28	535.70
Araguatins	965.02	675.51	5238.17	3666.72	823.47	576.43

for Araguatins and Conceição do Araguaia stations, and from January to March for the Aruanã station.

Therefore, the ways of analyzing the reference flows influence the grants: between a state and another one, and from these to the Federal Government. The proposal of monthly and seasonal reference flows to grant the multiple right of water use may be the most adequate for power generation, since it presents the inherent characteristics of the flows of each month and per period, respectively. However, the use of seasonality for grants should be analyzed along with the environmental aspects of the river basin as well as the impact on aquatic life.

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