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Hydrodynamic behaviour of water resources with and without inequency of the tide in the Amazon region

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Abstract: Knowledge of the flow of water resources has become indispensable for the management process due to the granting of the right of use, defined as an instrument of the national water resources policy by Law 9433 of 2000. Thus, understanding hydrodynamic behavior has become essential in order to define the maximum limits for withdrawing water from a body of water that can be granted to users. Therefore, the purpose of this article was to analyze the hydrodynamic behavior of two rivers located in the Amazon region in the state of Pará, one of which is the Arienga River, a tributary of the Pará River which is subject to periodic tidal influence, and the other, the Capim River, which in the stretch analyzed does not experience tidal influence. The speed of water flows is often a factor that influences the different behavior of water dynamics and the results showed that in quantitative terms the speeds of the Capim River had an average speed of 0.57 m/s and that of the Arienga River 0.32 m/s, due to the differences caused by the distinct topographic gradients of each water body analyzed. It is a factor strongly influenced by the presence of sand banks that generate preferred paths causing randomness in the behavior of the speed of the longitudinal flows of the rivers analyzed.

Key words: integration of velocity distribution; flow determination; Amazonian rivers

1 Introduction

The Amazon River basin is the most extensive hydrographic network on the globe, occupying a total area of around 6,110,000 km², from its sources in the Peruvian Andes to its mouth in the Atlantic Ocean (in the northern region of Brazil) (BRASIL, 2017). According to Gurgel (2015), the Amazon region has a large amount of fresh water, but it is influenced by various natural processes, including the tides in several rivers.

There is a large deficit of studies related to the flow of Amazon rivers, leading to the scarcity of information. Costa et al. (2009) state that the period of greatest availability of data in this area was the 80s, but the available data of precipitation and flow decreased from that year on. Bonifácio and Freire (2013) emphasize that the knowledge of parameters or hydrological variables is of great relevance for the planning and management of water resources. In summary, the study of hydrology comprises the collection of basic data such as the amount of precipitated or evaporated water and the flow of rivers (PINTO, et al., 2011).

Knowledge of the flow of water bodies has become fundamental to the management process because the granting of the right of use was defined as an instrument of the national water resources policy, by Law 9433 of 2000 (BRASIL, 1997). As a result, certain methodologies have been adopted to define the maximum limits for withdrawing water from a body of water that can be granted to users (SILVA, et. al, 2006). These reference flow values are established according to the ecological flow based on hydrological criteria, which use historical flow series data from fluviometric stations, with the adoption of Permanence Flows of 90% of the time (Q90) and 95% of the time (Q95) and a minimum flow of seven days for a return period of ten years (Q7.10) (Schvartzman et al., 2002).

Flow estimation has gained in precision, reliability and versatility with the progress and sophistication of electromechanical instrumentation, and is capable of being used in increasingly varied service conditions (CAMAPUM FILHO; DALL'AGLIO, 2014). Although there are sophisticated techniques for measuring river flows, this activity isrestricted to teams and institutions that have equipment and training for this activity, contrasting with the lack of information on the discharge of the main water bodies in the Amazon region with and without tidal influence, a fact reflected by the number of only 9. 926 fluviometric stations installed in Brazil registered in the hydrological information system in 2009 and managed by the National Water Agency (Brazil), taking into account that this number includes all the registered, existing or extinct fluviometric stations operated under the responsibility of the most diverse entities.

Thus, measuring the flow of watercourses in both tidally and non-tidally influenced bodies of water is fundamental to obtaining discharge information for their management, preservation and conservation (TUCCI; MENDES, 2006). In view of the above, determining the flow rate is a fundamental step in characterizing hydrological conditions and assessing the water availability of rivers in the Amazon region, which have well-defined characteristics and differ from other regions due to their climatic, geomorphological and hydrological characteristics. To this end, the "integration of velocity distribution" methodology was adopted by Finotti et al. (2009), which quantifies the variables width, channel depth and fluid velocity (MALDONADO, et al., 2015).

Therefore, the purpose of this article was to analyze the hydrodynamic behavior of two bodies of water located in the Amazon region, one of which is the Arienga River, a tributary of the Pará River subject to the periodic influence of the tide with topographic elevations of less than 6 meters, and the Capim River at an intermediate point in its stretch where it does not experience the influence of the tide, located in an area with topographic elevations of 70 meters.

2 Material and methods

2.1 Characterization of the study area

The research was carried out in two rivers in the municipalities of Ipixuna do Pará and Barcarena, the rivers cover varied conditions, from a river affected by tides (Arienga) to a larger river (Capim), these are located in the State of Pará (Figure 1), which is the second largest state in Brazil with a territorial extension of 1,248,042.515 km², is located in the North Region and is part of the Amazon region (BRASIL, 2017).

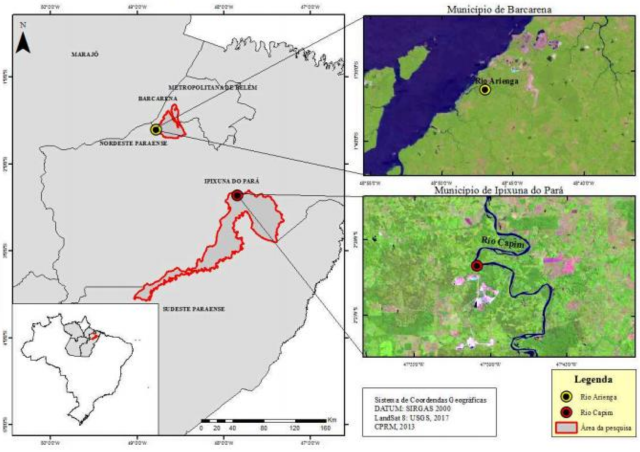

Figure 1. Location of the study area

With regard to the climate of the municipalities, Koppen classified the state of Pará as being in climate group A (rainy tropical climate) and subdivided it into three groups in terms of their additional temperature and rainfall characteristics: f, w and m, where f refers to rainy tropical forest climate, w to summer rainfall and m to tropical monsoon climate, with a brief dry season and heavy rainfall during the rest of the year (MENDONÇA, 2007).

2.2 Municipality of Ipixuna do Pará, PA

According to information from the IBGE (2017), the municipality of Ipixuna do Pará belongs to the Northeast Pará Mesoregion and has an estimated population of 62,237 inhabitants for 2017, with a territorial area of 5,215.555 km². The water body analyzed was the Capim River, which forms the axis of the state's greatest economic circulation along the Belém-Brasília Highway (BR 010), including various projects such as the Guamá-Capim waterway, the implementation of industrial and mining projects and those resulting from the expansion of extractive (logging) and agricultural activities in the region's municipalities (PACA, et. al, 2018), the flow measurement took place at coordinates 2°24'49"S and 47°48' 59"O, on September 30, 2017, and was carried out in a stretch without tidal influence.

2.3 Municipality of Barcarena, PA

The municipality of Barcarena is located in the Metropolitan Mesoregion of Belém, with a population estimated by the IBGE (2017) of 99,859 inhabitants in 2016, its territory comprising 1,310.588 km². The water body analyzed in the municipality was the Arienga River, located in the village of Beja on the border between the municipalities of Abaetetuba and Barcarena, which is constantly influenced by the waste products produced by neighboring companies, and is a source of income for artisanal fishermen (CAETANO, et.al, 2012). The flow measurement took place at coordinates 01º 36'18.53" S and 048°46'56.55" O, on May 9, 2017. The stretch of the Arienga River studied is directly influenced by the tides and is an estuarine zone. It is also a perennial river, so it contains water all year round, just like the Capim River.

2.4 River flow measurement

The flow of a river is the amount of water that passes through a given section of the river for a unit of time and is expressed in L/s or m^3/s (GARCEZ; ALVAREZ,1999).

Indirect measurement is a "manual" way of estimating flow in rivers and streams (CARVALHO, 2008). The method used was the measurement and integration of the distribution of velocities described by Finotti et al. (2009), which consists of measuring and integrating the distribution of velocities in the defined sections, based on the principle of the continuity equation that by identifying the values of velocity and area of the determined sections it is possible to calculate the flow rate.

$Q = A.V$

Where:

Q: Flow rate (m^3/s)

A: Wetted cross-sectional area (m^2)

V: Average speed of the sections (m/s)

According to Pinto et al. (2011), for flow measurements it is necessary to use more favorable locations to obtain better quality data, thus determining the locations with the following requirements.

• Location on a straight stretch of river, with well-defined banks and free of obstacles (rocks, vegetation and others) that could significantly disturb the flow.

• Cross-section as symmetrical as possible and with steep slopes to prevent overflow; and

• Regularly distributed speeds.

2.5 Definition of measurement profiles

Finotti et. al, (2009) also point out that the velocities of watercourses normally vary along the cross-section, so in order to obtain a good estimate of the average velocity of the river, measurements are required at various points and at various depths, thus:

In the selected profile of the Capim River in the municipality of Ipixuna do Pará, velocity and flow measurements were taken over a width of 175 meters. Thus, the width of the river was divided into 10 sections: seven (7) of 20 m (L = 20 m), one (1) section of 15 m (L = 15 m) and two (2) sections of 10 m (L = 10 m), as shown in Figure 2.

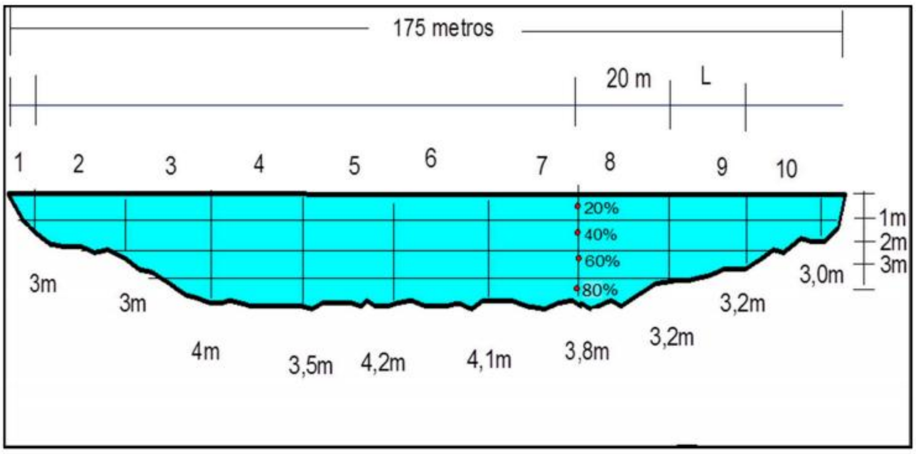

Figure 2. Profile of the measurement sections on the Capim River - Ipixuna Pa

In the selected profile of the Arienga River (Barcarena), velocity and flow measurements were taken over a width of 30 meters. The river section was divided into 06 5m sections to take the measurements (Figure 3).

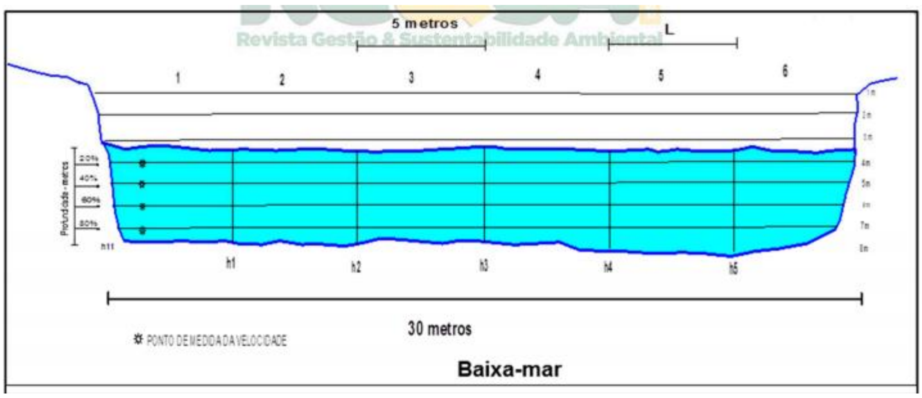

Figure 3. Profile of the measurement sections in the Arienga River at low tide - Barcarena-Pa.

Tidally influenced rivers display their natural characteristics, including their flow at the final stage of the ebb, so the flow was measured at low tide, starting at 6pm, as shown in Figure 4.

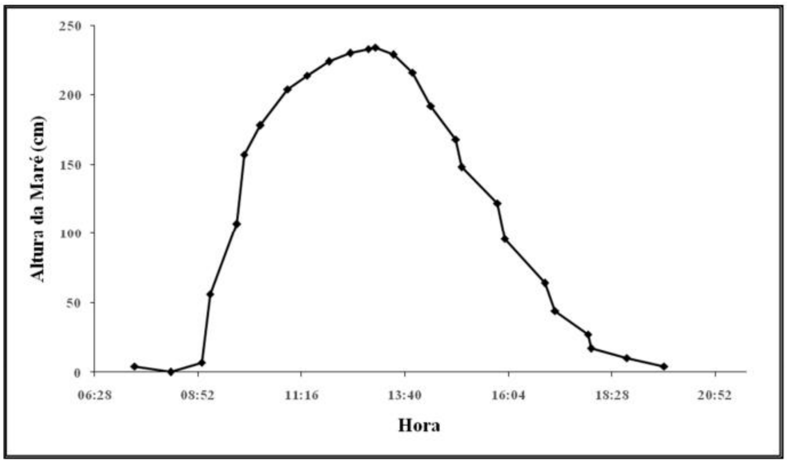

Figure 4. Tidal behavior of the Arienga River - Barcarena on May 9, 2017

Measuring the area of the wet flow section after delimiting the river sections, the depth at each profile (H) was determined using a previously graduated nylon rope. The cross-sectional area (A) was defined by the product of the distance between the profiles (L).

Being: $A = Ln * \sum Hn$

A: Cross-sectional area (m^2)

Ln: Profile width (m)

Hn: height of the water table (m)

2.6 Speed determination

The vertical hydrometric velocity was determined using Mechanical flowmeters model 2030 from Genera Oceanics Inc.

2.6.1 Determination of velocity in the Capim River - Ipixuna, Pa

In sections with depths of less than or equal to 2 m, one measuring point (60%) was used, and in sections where the depth was between 2 and 4 m, the two-point methodology was used (20% and 80% of the depth). In sections with depths greater than 4 m, the 4-point methodology was used (20%, 40%, 60% and 80%), as can be seen in Figure 2.

$Vm = V_{60\%}$ (depth between <2 m)

$Vm = (V_{20\%} + V_{80\%}) / 2$ (depth between 2 and 4 m)

$Vm = (V_{20\%} + 2V_{40\%} + 2V_{60\%} + V_{80\%}) / 6$ (depth >4 m)

$Vmi = Vm1 + Vm2 + ... + Vmn$

V: Speed m/s

Q: Flow m^3 /s

A: Area in m^2

I: Section length in m

2.6.2 Determination of velocity in the Arienga River - Barcarena, PA

In sections where the depth was less than or equal to 2 m, one measuring point (60%) was used, and in sections where the depth was greater than 2 m, the 4-point methodology was used (20%, 40%, 60% and 80% depth), as shown in Figure 3.

$Vm = V_{60\%}$ (depth between <1 m)

$Vm = (V_{20\%} + V_{80\%}) / 2$ (depth between 1 and 2 m)

$Vm = (V_{20\%} + 2 V_{40\%} + 2V_{60\%} + V_{80\%}) / 6$ (depth >2 m)

$Vmi = Vm1 + Vm2 + ... + Vmn$

V: Speed m/s

Q: Flow m^3/s

A: Area in m^2

I: Section length in m

2.7 Specifications of the device used for measurement

The velocities at different depths were determined using the Mechanical flowmeters model 2030 from General Oceanics Inc (Figure 5), following the instructions in its manual and using the following mathematical formulas:

Standard Speed Rotor Constant = 26.873

Distance in meters = (revolutions * Rotor Constant)/999999

Speed in cm/sec = (distance in meters * 100) / time in seconds.

Flow in cubic meters = (speed in meters/sec) * section area in m^2

Figure 5. Mechanical flowmeters used to determine velocity

3 Results and discussion

3.1 Flow estimation

The river flows were calculated according to Pinto et al. (1973), where the flow in a given cross-section of a river (Q), defined as the volume of water passing through that section in a unit of time, can be measured by the product of the area of the section (A) and the average speed of the water passing through it (V), thus following the sequence of the following formulas:

$$Q = \Sigma Q$$

$$\Sigma Q = \Sigma A * Vm = A1\ Vm1 + A2\ Vm2 + .. + Ai\ Vm$$

Where:

V: speed m/s

Q: flow m^3 /s

A: area in m^2

The results of calculating the flow rate using the Mechanical Flowmeters model 2030 and the area of the sections can be seen in Figures 6 for the Capim River and 7 for the Arienga River.

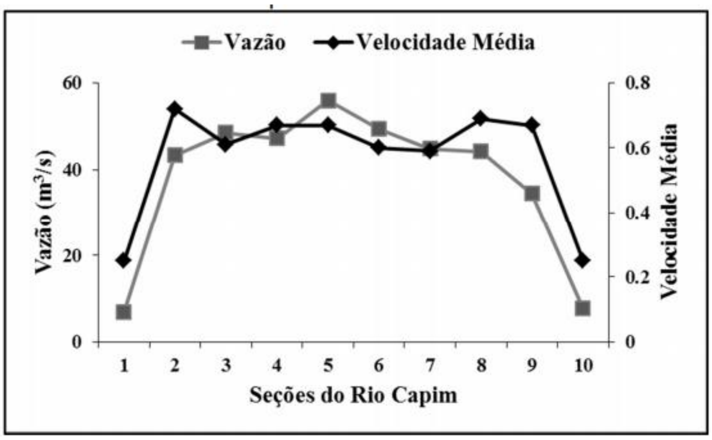

Figure 6. Graph of the results of the velocities and flows of the profiles of the Capim River - Ipixuna do Pará

Analysis of the water flow velocity behavior in the different longitudinal profiles of the Capim River shows lower velocities and flows on the right bank (profile 10) and left bank (profile 1). This behavior, characteristic of water bodies without tidal influence and larger topographic gradients, was defined by Maldonado et al. (2015), where in a flow study they noted that the highest velocities are located at a considerable distance from the bank. It was also noted that the highest flow in the analyzed stretch is in the middle of the horizontal profile in section 5, but the highest velocity was in section 2, where the flow increases significantly compared to section 1. In addition, it was found that where there is lower flow and velocity in the profile there are also lower depths according to Figure 6. The distribution of flow and velocity along the profile of the Capim River shows that water bodies in the Amazon region, in their lower stretches and closer to their mouths, behave similarly to water bodies located at higher topographic elevations with greater topographic gradients where the highest velocities and flows are found in the central profiles, gradually decreasing towards the banks.

The results obtained from the velocity and flow measurements of the Capim River show the existence of preferential paths where the highest velocities and flows are necessarily in the central region of the water body, a fact that is most evident in the results for the flow and velocity of the Arienga River.

The velocity and flow results in the different longitudinal profiles of the Arienga River were random, with higher velocities in profiles 2 and 5, closer to the bank, and lower velocities and flows in the profiles furthest from the river bank (profiles 3 and 4). As can be seen in Figures 6 and 7, there is a significant difference in the flow and velocity behavior of the two water bodies analyzed, with the Capim River showing lower velocities on the banks and higher velocities in the central region. On the other hand, the results for the velocity of water flows in the Arienga River showed random behavior, with higher velocities, sometimes in sections close to the banks and sometimes in the central region of the water body.

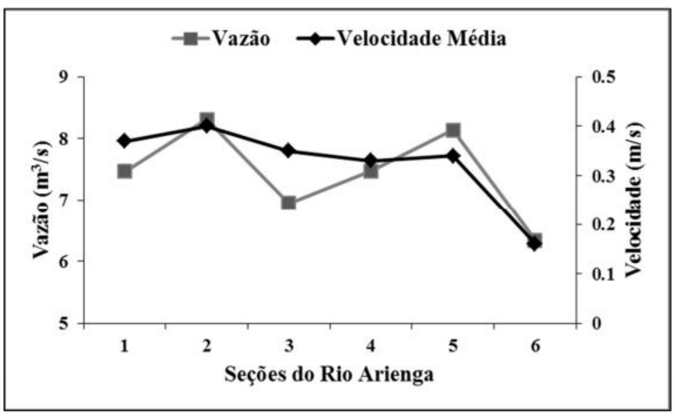

Figure 7. Graph of the results of the velocities and flows of the profiles of the Arienga River - Barcarena

As can be seen, the velocities recorded in the different profiles of the Capim River changed between 0.25 and 0.70 m/sec while the Arienga River showed velocities changing between 0.15 and 0.40 m/sec. The difference in the velocity of water bodies in the Amazon region is strongly influenced by topographic gradients, being greater in the stretches located at the higher topographic elevations when compared to the lower topographic elevations near the mouth. The lower velocities recorded in the Arienga River cause the deposition of sandbanks which end up being deposited randomly and cause presential paths influencing the velocity of flow of water.

Figures 8, 9 and 10 show the results of the water flow velocities along the longitudinal and vertical profile, showing that in the water body with tidal influence, the lowest velocities were on the banks of the water body, also showing areas of lower velocities in the central region, but with a certain randomness. The Capim River, on the other hand, was similar to the classic behavior of rivers without tidal influence, with higher velocities in the central region and lower velocities in the middle, which approaches the banks with a certain randomness.

With regard to velocity at depth, the Arienga River did not show clear evidence of variation, apparently presenting a uniformity in velocity along the vertical profiles, with higher velocities being observed in some cases in the deeper zones, as can be seen in profiles 6 and 3 in Figure 8. This behavior in profiles 6 and 3 contrasts with the distribution of velocity in profiles 1, 2, 4 and 5, which showed homogeneous behavior, showing that depth in these profiles has no influence on velocity.

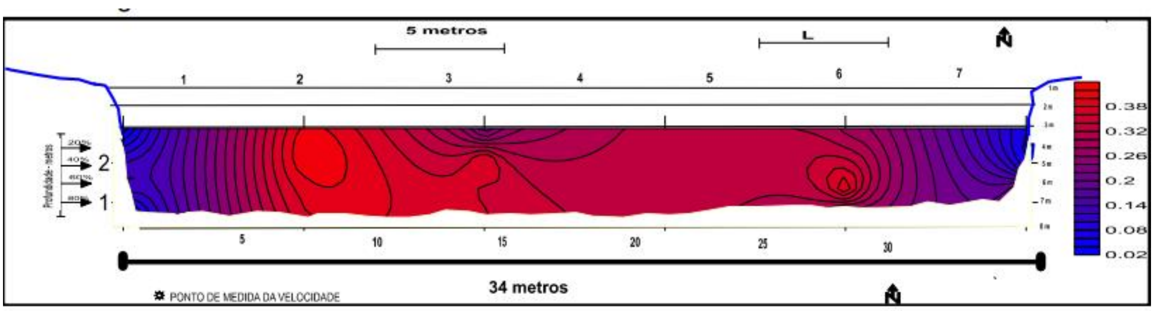

Figure 8. Details of the velocity variation in each profile of the Arienga river fraction at low tide

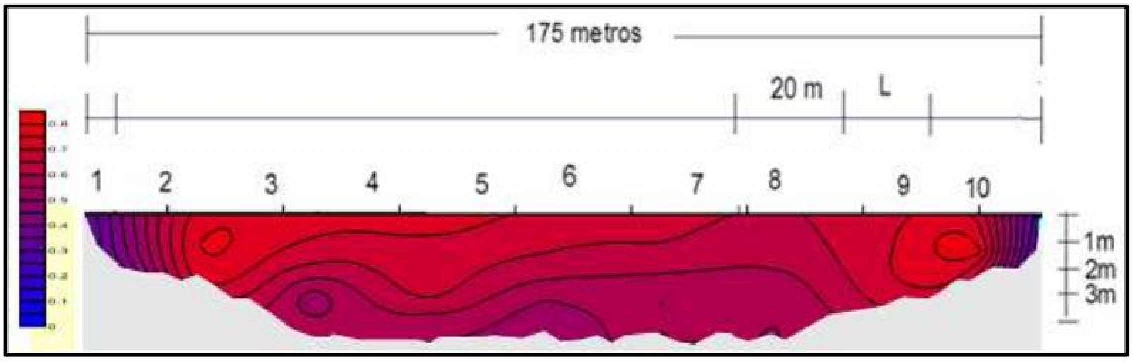

Figure 9. Details of the velocity variation in each profile of the Capim river fraction

Figure 9 shows the results of the water flow velocities along the longitudinal and vertical profiles recorded in the Capim river, which represents water bodies in the Amazon region without tidal influence. Longitudinally, the lowest velocities were found on the banks of the water body (profiles 1 and 10), with the highest velocities recorded in profiles 3 and 9, which are precisely the profiles before the bank profiles. In general, higher velocities were recorded in the centre profiles when compared to the profiles on the banks of the water body.

With regard to velocity at depth, the Capim River showed higher velocities in the zones slightly below the surface, with lower velocities in the deeper zones. It should be noted that this behaviour was not clearly evident in the profiles located on the banks of the water body. The velocity behaviour in the spill profiles of the Capim River, which represents bodies in the Amazon region without the influence of the tide, is similar to the classic behaviour of rivers that do not experience the influence of the tide, with higher velocities in the areas located slightly below the surface with a gradual decrease towards the deeper areas. According to Carvalho (2014), this is due to the morphology of the river, in which the friction of the water on the banks and bed causes a slowing effect on the velocity. The relatively low velocities of the River Capim contribute to the presence of sandbanks and the predominance of wide, shallow beds may be the cause of the differences in the behaviour of the velocity of the longitudinal profile.

Based on the analysis of the information on the water bodies analysed, it was found that there is a notable difference in the hydrodynamic behaviour of the Capim and Arienga rivers, since the Capim River is not influenced by the tide and has a classic longitudinal and vertical profile that is most often cited in the literature, where the velocity and flow values are higher as they move away from the banks and increase with depth (PINTO, et. Al... 2011), 2011), while the Arienga River did not show any similarity, but Carvalho (2008) states that this is due to the river's morphology. In addition, it was found that the Rio Capim has a flow rate of 382.11 m^3/s, which is higher than the Arienga's 44.69 m^3/s. Considering the width of the rivers, this difference was to be expected. With regard to velocities, the Rio Capim had an average velocity of 0.57 m/s and the Arienga 0.32 m/s, differences caused by the different topographical gradients for each water body analysed.

An analysis of Figure 10(b) shows that the velocity in the vertical profiles of the Capim River decreases from the surface to the bottom, corroborating the observations of Pinto and colleagues (2011) who point out that, in general, the velocity of water in a river decreases from the surface to the bottom and from the centre to the banks. On the other hand, the Arienga River (figure 10(b)), which represents water bodies in the Amazon region with tidal influence, did not show an increase in velocity with depth, and some of the profiles even showed the opposite effect where the deeper zones showed higher velocities, as recorded in profiles 4 and 2. This kind of somewhat random behaviour of velocity with depth in tidally influenced water bodies was described by Holdefer and Severo (2015) who observed similar behaviour in tidally influenced water bodies in measurements taken during periods of low flow (low tide), conditions similar to those in the water body being analysed.

The speed of water flows can be a factor that influences the different behavior of the water dynamics of water bodies with and without depth. The Capim River showed maximum depths of 4 meters at the time of the measurements, but can reach depths of up to approximately 12 meters in the rainy season. The Arienga River showed depths of between 4 and 5 meters at low tide and up to 8 meters at high tide. The depths of water bodies influenced by the tide show little variation during the dry season and the rainy season, in contrast to the greater variation in the depths of water bodies in the Amazon region that are not influenced by the tide.

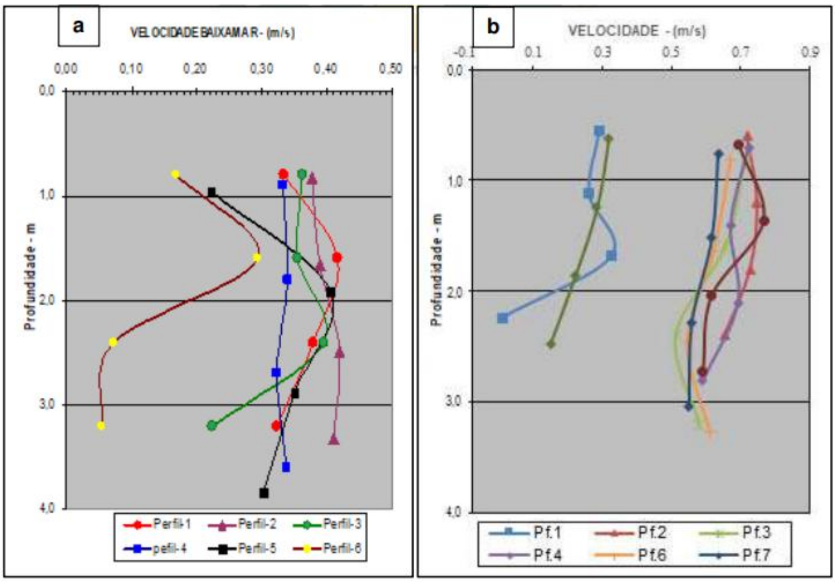

Figure 10. Variation in low-water depth velocity in (a) the Arienga Barcarena River and (b) the Capim Ipixuna River

4 Final considerations

The method of integrating the distribution of velocities proved to be efficient for measuring the flow of rivers with different characteristics from the Amazon region. The method is simple and only requires a theoretical foundation in order to estimate the flow, unlike automatic methods in which the result is immediate and the operator does not need specific advanced knowledge. However, it is a low-cost method and provides reliable data. Although the method has proved to be suitable for measuring flows, it is suggested that a comparison be made with other methods in order to obtain a better measurement for rivers with tidal influence, given that in some sections of the Arienga River there were unusual oscillations in the results of flows and velocities.

The results showed that there are differences in the behavior of the velocity along the longitudinal profiles of water bodies located in the Amazon region, with and without the influence of the tide, translated into different topographic gradients that end up influencing the presence of sandbanks that originate premature water flow paths.

In quantitative terms, the velocities of the Capim River averaged 0.57 m/s and the Arienga 0.32 m/s, showing the random behavior of the longitudinal and vertical profiles characteristic of water bodies in the Amazon region.

Conflicts of interest

The author declares no conflicts of interest regarding the publication of this paper.

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