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Characterization of the hydrological regime of the Rio Negro with altimetric data provided by the Sentinel-3A satellite

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ABSTRACT

The Amazon Basin, the largest in the world, covers an extensive area of about six million km² and extends over seven countries. The Amazon Hydrographic Region, within the Brazilian territory, covers about 45% of the country and includes seven states. One of the main rivers is the Rio Negro, the second largest tributary of the Amazon River, with characteristics of black water and an extensive drainage area. The climate in the region is humid tropical, with average rainfall of 2500 mm/year and average temperatures ranging from 26°C to 33°C. El Niño and La Niña phenomena affect the global climate and cause extreme events in the Amazon basin, such as droughts and floods. El Niño causes droughts and forest fires, while La Niña raises rainfall, resulting in major floods. Droughts and floods are critical phenomena that cause hydrological imbalances and impact inhabited areas and ecosystems.

Keywords: Amazon Basin, Hydrographic Region, Rio Negro.

INTRODUCTION

The Amazon Basin is the largest river basin in the world, covering a vast area of approximately six million km² and extending over seven countries: Brazil, Colombia, Bolivia, Ecuador, Guyana, Peru and Venezuela. The Amazon Hydrographic Region is inserted in the Amazon basin, and is limited to the Brazilian territory, occupying approximately 3,870 thousand km², corresponding to 45% of the national territory and encompassing seven states. It is characterized by the extensive hydrographic network, with great availability of water resources (ANA, 2024).

One of the main rivers in this basin is the Rio Negro, the second largest tributary of the Amazon River, which is a typical blackwater river that flows over an area of up to 600,000 km². The climate in this region is humid tropical, with an average rainfall of 2500 mm/year and an average temperature variation of 26 °C in the austral winter and 33 °C in the austral summer (FILIZOLA, 1999). The Negro River has two distinct flow peaks during the flood season, one with low amplitude, during the first three months of the year, and another, more intense, in the middle of the year. The average water flow of the Rio Negro is approximately 30,000 m³/s and represents about 14% of the total freshwater flow of the Amazon River in the Ocean (FILIZOLA *et al*., 2009).

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The El Niño/La Niña-Southern Oscillation – ENSO phenomena are due to anomalies in the temperature of the Pacific Ocean and have consequences for the climate around the world, although in different ways. The El Niño phenomenon is due to the abnormal warming of the waters of the Pacific Ocean, while the phenomenon with opposite characteristics, called La Niña, is due to the cooling of the waters of the Pacific Ocean. (SANTOS et al., 2011). In the Amazon basin, these phenomena cause extreme events (droughts and floods), El Niño causes drought and forest fires (FEARNSIDE, 2009) and La Niña increases rainfall, which causes major floods.

Droughts are characterized by a sufficiently prolonged period that the absence or poor distribution of precipitation causes serious hydrological imbalance. As for the critical flood phenomena, floods and floods are caused by the rise in the water level of rivers, lakes and dams, above their normal flow, causing overflow in areas that are not usually submerged (ANA, 2015).

The occurrence of extreme events has occurred more frequently in recent decades in the Rio Negro, such as the droughts that occurred in 2005, 2010, 2016 and 2023, in addition to the largest floods ever recorded in 2009, 2012 and 2021. In 2005, the drought was considered the greatest in the last century, being caused by high temperatures in the tropical North Atlantic, which effectively shifts the trade winds, and all the moisture they carry, to the north, far from the Amazon, however, this event would be overcome 5 years later by the drought of 2010, when the quota reached 13.63 m and again exceeded in 2023, when it reached 12.70 m, the lowest level ever recorded in more than 120 years, which emptied important rivers in the Amazon and isolated thousands of people in riverside communities, since rivers are the main transport routes to the interior of the state and, with low levels, vessels could not achieve the minimum navigation conditions, events that would be predicted to occur only every 100 years (MARENGO *et al.*, 2011). In 2009, 2012 and 2021 the Central and Northern regions of the basin experienced floods of great magnitude, registering in Manaus the three largest floods in the last 120 years, whose values reached 29.77, 29.97 and 30.02 m, in 2009, 2012 and 2021 respectively. These record floods were associated with the cooling of the surface waters of the Pacific Ocean, a phenomenon known as La Niña, which caused rainfall above the climatological standard in the Southwest, North, and Central part of the basin (CPRM, 2009, 2012, and 2021). The flood event of the year 2021 represented for the state of Amazonas the largest and most impactful 3-flood event in its entire history of hydrological monitoring. Of its 62 municipalities, 57 had an emergency situation recognized. In the state capital, Manaus, where river level data has been recorded since 1902, the level of the Rio Negro surpassed all previous records, confirming 2021 as the highest flood in the last 122 years in the region. (CPRM, 2021).

Such events cause impacts that influence not only the dynamics of the river and its tributaries, but also the diversity of landscapes and the lives of populations, which are directly affected by changes in river levels, both in periods of prolonged drought and in periods of atypical floods (AGUIAR *et al*., 2013; SANTOS, 2015).

One of the hydrological components routinely considered in the monitoring of extreme hydrological events is the variation of the water level. The monitoring of this variable is carried out through networks of hydrometric stations and requires a series of *in situ* observations for a very long period, with very high installation and maintenance costs (ALSDORF *et al*., 2007). In the Amazon basin, the hydrological information system HidroWeb, maintained by the National Water Agency – ANA, contains data from different hydrological stations in Brazilian territory (ANA, 2024). Although such data provide a dense temporal definition, spatial resolution is limited and updating this system can take 6 to 12 months. Several initiatives have been carried out in search of advances to provide hydrological information in basins without fluviometric monitoring or little monitored, such as the intensification of the use of hydrological data estimated from remote sensors, embedded in satellites. Inserted in this thematic area, spatial altimetry provides data on water levels in rivers and lakes, with acceptable spatial and temporal resolution (SILVA, 2010). The extensive rivers of the Amazon basin allow large ranges of fluviometric data acquisition via remote sensing. The applications of satellite altimetry in this region have a great contribution to the management of water resources and the possibility of acquiring data in regions of difficult access and little monitored (SILVA *et al*., 2014).

OBJECTIVE

This study seeks to apply the spatial altimetry technique, using the Sentinel-3A altimetric satellite in order to characterize and analyze the spatial and seasonal variability of the hydrological regime of the Negro River, based on water level altimetric data, obtained through virtual stations, whose operating period extends from 2016 to 2023, with a revisit time of 27 days and 1338 time cycles.

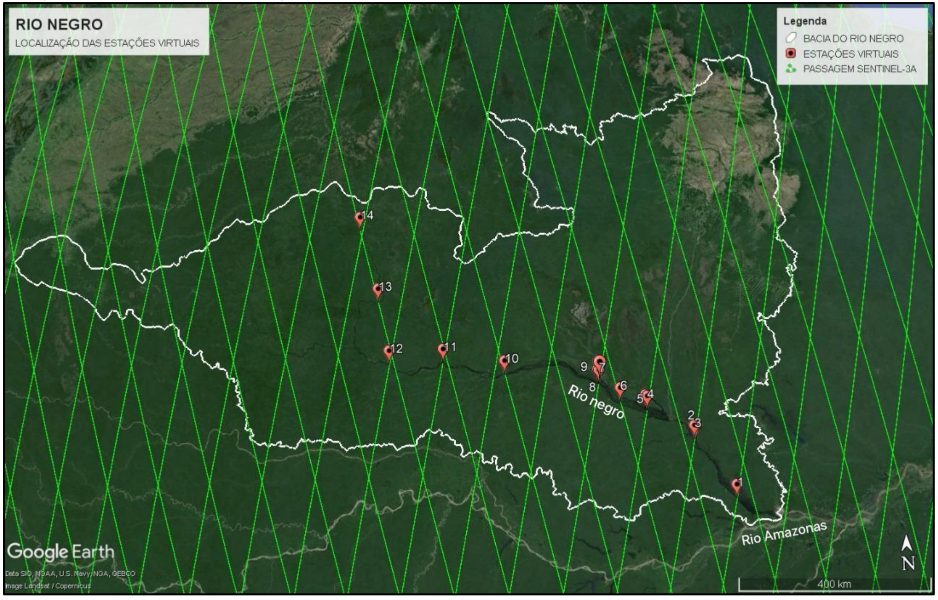
METHODOLOGY

FIELD OF STUDY

The Rio Negro is a river with transboundary waters that extends between the coordinates 73º25'W to 5º4'N and 59º35'W to 3º35'S, crossing Colombia (10%), Venezuela (6%), Guyana (2%) and Brazil (82%) (LATUBRESSE *et al*., 2005; FRAPPART *et al*. 2008). It has its origin in Colombia with the name of Chamusiqueni River, then receives the name of Guainia River, and after the confluence with the Cassiquiare River receives the name of Rio Negro. Its main tributaries are the Branco River and the Vaupés River. It drains the eastern Andes region of Colombia and follows a southeasterly direction until it flows into the Amazon River (Figliuolo *et al*., 2011). According to Liebmann and Marengo (2001), in the

Rio Negro basin the average annual precipitation rate varies by more than 50%, with values between 2000 and 2500 mm/year in the vicinity of Manaus and about 3000 mm/year in the Northwest (Figure 1).

Figure 1 — Location of the Rio Negro basin with the virtual stations in red circles, traces of the Sentinel-3A satellite in green lines. Google Earth image mosaic, in the background.



Source: Prepared by the Author, 2024.

ALTIMETRY DATA

Data from the Sentinel 3A altimetric satellites were used, covering the periods from June 2016 to December 2023, using the standard FO treatment algorithm Ice-1 and the geoidal swell model EGM2008, developed by Pavlis *et al*. (2008).

The altimetry data adopted are part of the Elevation Monitoring Network of the RHASA Laboratory and are available in the Hydroweb database, of the THEIA-CNES platform (https://hydroweb.next.theia-land.fr/).

DOWNLOAD OF ALTIMETRIC DATA FROM THE THEIA-CNES PLATFORM

A Virtual Station (EV) is determined from the crossing between the satellite's orbits over the surface of a body of water, with feasibility for the acquisition of a time series of the height of the water level (SILVA, 2010; CALMANT et al, 2006). In the Hydroweb database it is possible to filter the data and select it by basin, river or lake. 14 stations were extracted, totaling 1338 cycles, referring to the period from 06/2016 to 12/2023.

CHARACTERIZATION OF THE HYDROLOGICAL REGIME

In order to characterize the behavior of the hydrological regime, the hydrological information was graphically represented by means of time series, in the Excel 365 software, which reflected the variations in the height of the water depth. The objective was to analyze the elevation levels over the years, identifying the presence of regular patterns, stability over time and any anomalies that could manifest themselves. Individual cotagrams were elaborated for each time series. This was achieved by calculating the annual monthly averages of the altimetric quotas according to the methodology proposed by Bittencourt and Amadio (2007).

Values of the mean amplitude of the water surface calculated according to Equation 1 were also obtained. These results were obtained based on the data of the cotacgrams, and were used in the evaluation of the variability of the hydrological regime in question.

$$\bar{A} = \overline{\overline{\bar{H}_{máx}} - \bar{H}_{mín}} \quad (1)$$

where is the average amplitude, the maximum dimension of the cotagram and the minimum dimension of the cotagram.$\bar{A}\overline{\bar{H}_{máx}}\bar{H}_{mín}$

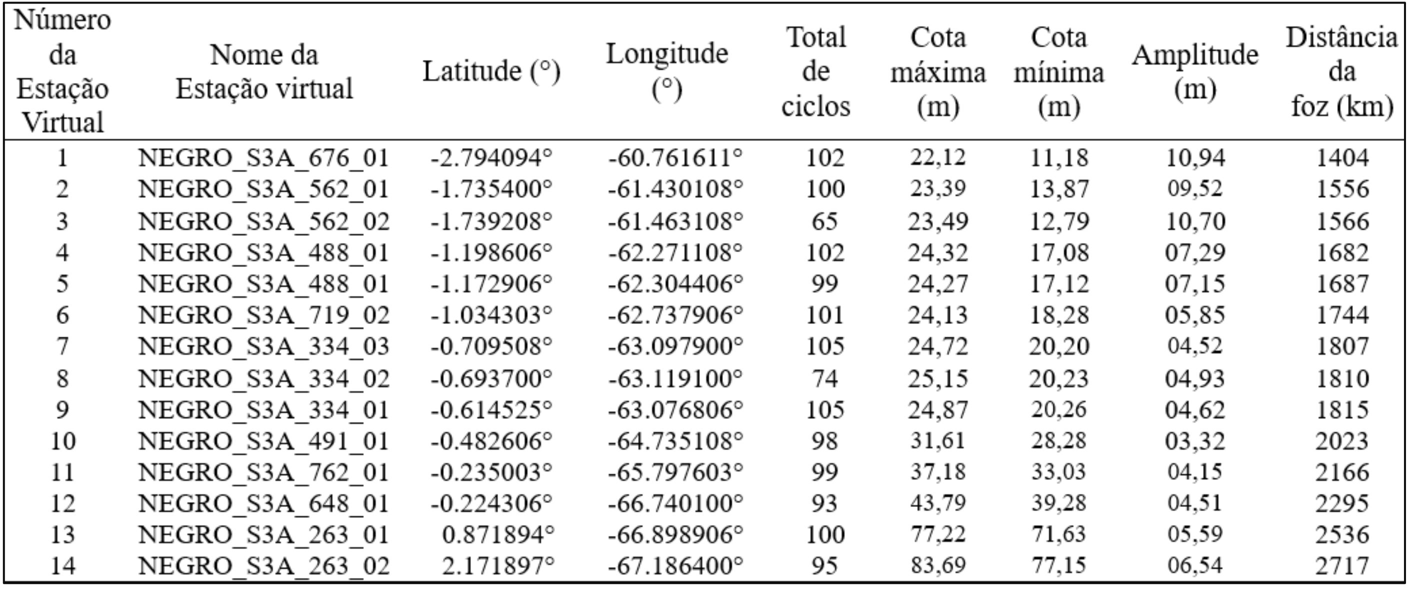
DEVELOPMENT

The altimetric data from the Sentinel-3A satellite resulted from the set of 14 virtual stations (EVs), listed and described in Table 1 together with their respective maximum and minimum elevations and amplitude and illustrated in Figure 1.

It can be seen in Table 1 and Figure 2 that as the course of the river approaches the mouth, there is an increase in the values of the average amplitude, where the virtual station NEGRO_SA32_263_01, distant 2532 km from the mouth, has an amplitude of 5.59 m, while the station, NEGRO_SA32_676_01, distant 1404 km from the mouth, It has a width of 10.94 m.

The cotagrams prepared for each EV are illustrated in Figure 3, they were generated with the intention of analyzing the variability of the water level throughout the year, seeking to evaluate the seasonality in the interval of activity of Sentinel-3A, between the years 20168 and 2023.

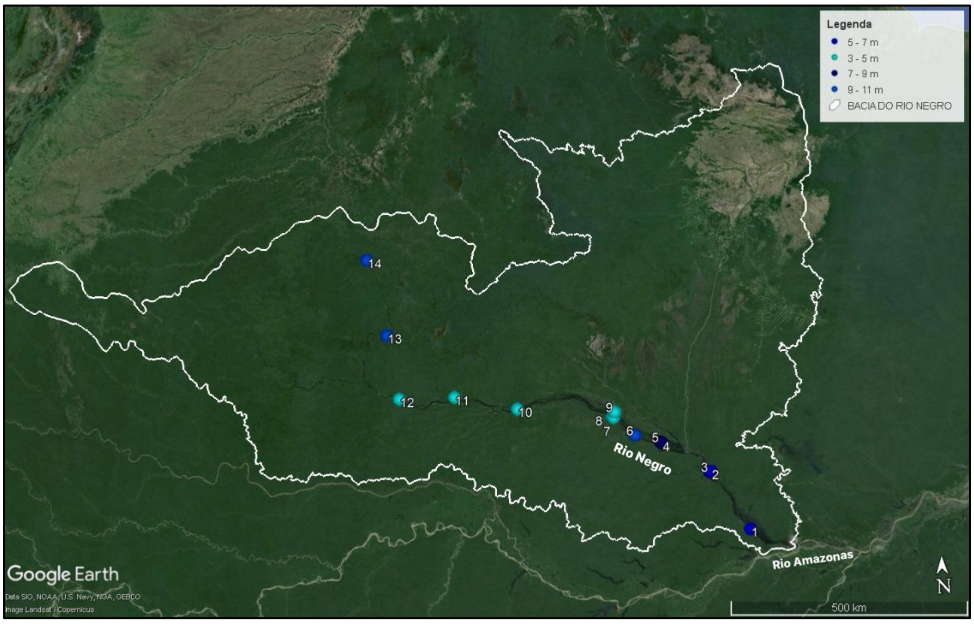
Table 1 – Breakdown of virtual stations, with maximum, minimum and amplitude values.



Número da Estação Virtual	Nome da Estação virtual	Latitude (°)	Longitude (°)	Total de ciclos	Cota máxima (m)	Cota mínima (m)	Amplitude (m)	Distância da foz (km)
1	NEGRO_S3A_676_01	-2.794094°	-60.761611°	102	22,12	11,18	10,94	1404
2	NEGRO_S3A_562_01	-1.735400°	-61.430108°	100	23,39	13,87	09,52	1556
3	NEGRO_S3A_562_02	-1.739208°	-61.463108°	65	23,49	12,79	10,70	1566
4	NEGRO_S3A_488_01	-1.198606°	-62.271108°	102	24,32	17,08	07,29	1682
5	NEGRO_S3A_488_01	-1.172906°	-62.304406°	99	24,27	17,12	07,15	1687
6	NEGRO_S3A_719_02	-1.034303°	-62.737906°	101	24,13	18,28	05,85	1744
7	NEGRO_S3A_334_03	-0.709508°	-63.097900°	105	24,72	20,20	04,52	1807
8	NEGRO_S3A_334_02	-0.693700°	-63.119100°	74	25,15	20,23	04,93	1810
9	NEGRO_S3A_334_01	-0.614525°	-63.076806°	105	24,87	20,26	04,62	1815
10	NEGRO_S3A_491_01	-0.482606°	-64.735108°	98	31,61	28,28	03,32	2023
11	NEGRO_S3A_762_01	-0.235003°	-65.797603°	99	37,18	33,03	04,15	2166
12	NEGRO_S3A_648_01	-0.224306°	-66.740100°	93	43,79	39,28	04,51	2295
13	NEGRO_S3A_263_01	0.871894°	-66.898906°	100	77,22	71,63	05,59	2536
14	NEGRO_S3A_263_02	2.171897°	-67.186400°	95	83,69	77,15	06,54	2717

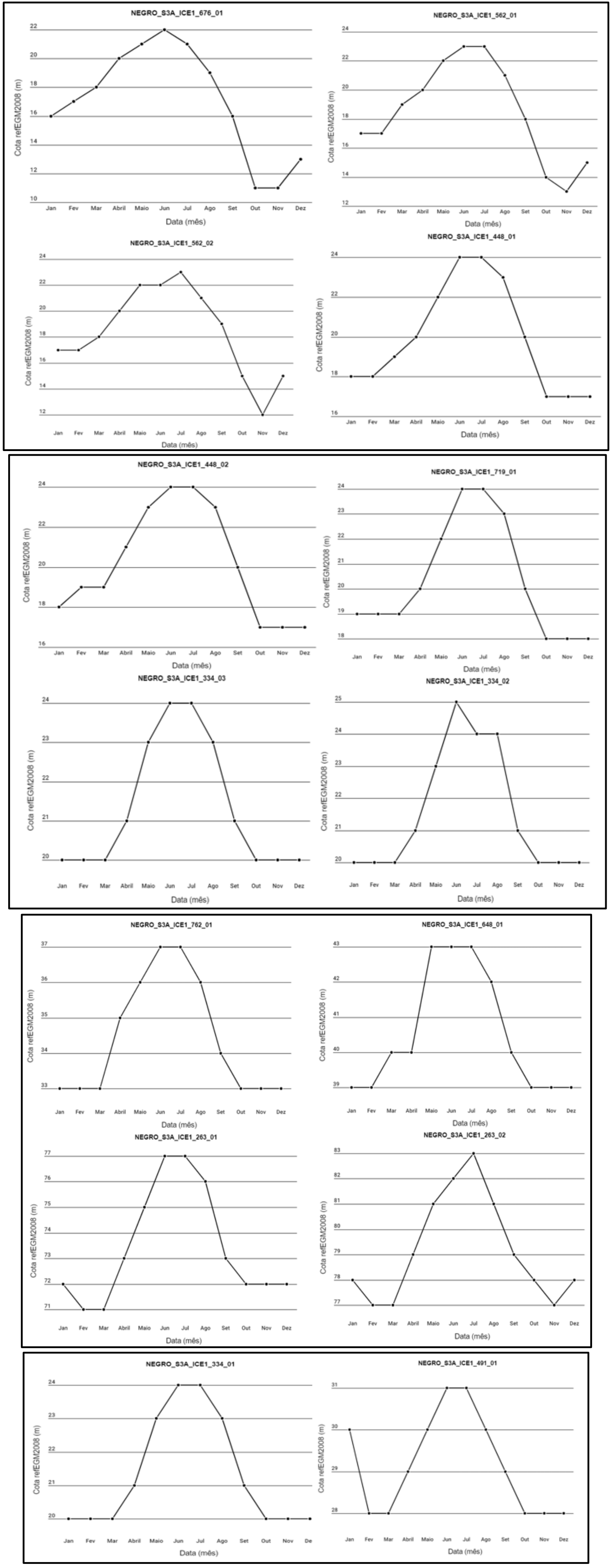
Source: Prepared by the Author, 2024.

Figure 2 – Variation in the amplitude of the water depth in the Negro River, in blue. Google Earth image mosaic, in the background.



Source: Prepared by the Author, 2024.

Figure 3 – Quotagrams of the virtual stations of the Rio Negro with identification of the quotas.



Source: Prepared by the Author, 2024.

Figure 3 shows that the Rio Negro has two well-defined hydrological periods throughout the year: (i) a period of ebb that begins in July and can extend until February, regularly presenting the minimum levels in October; and (ii) a period of flooding, which covers from February to July, where the maximum flows are found more frequently in the month of June. These minimum and maximum values corroborate Silva *et al*. (2011) who comment that for the equatorial hydrological regime the flood occurs during the period between the months of April and June and that the drought occurs during the months of September to November. Proving the results shown above, the CPRM Hydrometeorological Bulletin n.25 (2021) points out that the Negro River, in Manaus, has a hydrograph in which in 75% of the years of the historical series the maximum level occurred in the month of June, tending to start its ebb process, after this period, until it reaches the minimum level.

FINAL CONSIDERATIONS

In this study, 14 virtual stations from altimetric data from the Sentinel-3A mission were analyzed, using the Ice-1 FO treatment algorithm. This investigation made it possible to characterize that the Rio Negro has a modal hydrological regime, with two hydrological periods defined throughout the year, with asymmetric rises and recessions along the river. It was possible to evidence the periods of floods and ebbs, as well as the maximum and minimum levels of the river during a period of six and a half years, whose values occur more frequently in the months of June and October, respectively.

It is also known that the altimetric data are released after the passage of the satellite, contributing to the quali-quantitative characterization of the hydrological basins in the Amazon region, since it is a predominantly river transport region, the update of the traditional monitoring system can take from 6 to 12 months. It is in this context that virtual stations can be used as monitoring networks and even though the Sentinel-3A mission is not as dense as others, they have temporal sampling every 27 days, allowing quotas to be measured in areas not yet traditionally instrumented and difficult to access, as well as in areas outside the Brazilian territory. complementing and optimizing the network of hydrological studies.

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