FLOOD FORECAST IN MANAUS, AMAZONAS, BRAZIL

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ABSTRACT
The Amazon region has rivers of great contribution to the biodiversity balance and regional landscape. Among them, the stand out are the Negro River – the most extensive, the Amazon River – with the largest volume, the Purus River – a fish supplier, and the Madeira River – the most modified. Flooding in the Amazon is often widespread and sometimes severe for those who live very close to rivers, yet urban areas are often more socially impacted than rural areas, as flooding is part of the riverside population's daily life. Flood forecasting models are important for composing extreme event alerts as well as for knowledge of decision-makers, public agency representatives, and affected communities. This paper aims to present what is being done in Manaus about the Negro River floods, with the development of a flood alert dissemination project, which uses a linear regression statistical model, based on the historical series over 100 years. The follow-up to the one-year flood forecast begins the previous year, more precisely when the ebb ends and the rainy season begins. Several factors contribute to the flood event, but the main one is the rainy season and how the basin will behave during the six months of rising waters. Manaus station receives contributions from two major rivers: Negro and Solimões, which form the Amazon River downstream. The position of the city, allied to the difference in depth, speed, and flow of the rivers, added to the rainfall period in the basin reveal the flooding characteristic in this locality. Considering the last 15 years, the near-real flood forecast interval in 87% of cases reveals that the project has fulfilled the purpose of alerting the population and public representatives about the flood of Negro River.
Keywords: extreme events, flood forecast, Amazon rivers.

1 INTRODUCTION

The Amazon basin is the largest drainage basin in the world, covering about 40% of South America. The basin covers a total area of 7.05×10^6 km^2, approximately. The Amazon River system plays a significant role in the global hydrological cycle since its total river flow is greater than the combined flow of the ten next largest rivers. Amazon flow accounts for approximately one-fifth of the world's total river discharge to the oceans [1]. The Amazon region annual river regime is well defined and represents the variability of headwater rainfall [2]. Rainfall ranges from 1,500 to 3,000 mm annually, averaging about 2,000 mm in central Amazon [3]. Manaus, located in the Negro River, also has a so-called Equatorial regime and also presents its flood in the middle of the calendar year (June/July). The contributions of the Rio Negro are concentrated in watersheds whose main river gutters come from the northern hemisphere [2].

For the annual precipitation evolution, Sternberg [4] considered that in September is when there is the lowest rainfall, in the hydrographic area whose flow is most directly reflected in the Manaus post. In October, the basins' contribution to the south of Negro River, which receives the regime's precipitation, which grows from November to March, is accentuated. During this period there are large rainfall indices above the waterways south of Negro River, delimited by monthly isoietas of 250, 300 and up to 350 mm.

According to Witkoski [5], there are three types of rivers in the Amazon Basin: (i) the white-water rivers, which are born in the Andes and carry high fertility sediments – occur

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with the Japurá, Juruá, Purus, Solimões, Madeira, Amazonas and others; (ii) the black water rivers come from areas called podzolic soils, as is the case of the Negro and Urubu Rivers; and (iii) the clear water rivers that drain areas of the Central Highlands of Brazil and the Highlands of the Guianas [5].

Hydrological drought and flood extreme events were quantitatively defined to occur when daily water levels in Manaus fall below 15.8 m or rise above 29.0 m, respectively [6]. For areas of the Solimões-Amazon River in the near the municipality of Manaus, the hydrological periods were identified, as follows: (i) Flood: rising river level, between the 20 and 26 m; (ii) Flood: quota equal to or greater than 26 m; (iii) Downstream: downstream river level, between 26 and 20 m; and (iv) Drought: quota of 20 m or less [7].

In the Solimões-Amazonas River, however, there is a year-to-year variability inflow, partly related to fluctuations in rainfall. Rainfall decreases in the Amazon are partially associated with the phenomenon popularly known as “El Niño”: “El Niño” seems to produce severe drought or ebb and “La Niña” cause flooding intense [7], [8].

It is known that despite differences in catchment size and timing of the flood pulse, water levels at the Manaus station on the Negro River measure fluctuations of the Solimões–Amazon main stem due to the so-called backwater effect [6]. The water levels of the lower Rio Negro are controlled by the Solimões River. During the flood period of the Solimões River, the Negro River is dammed causing flooding in the city of Manaus. The Solimões water level signal dominates the level of Negro River stations up to 400 km away [9], [10].

The Amazonian plain contains two orders of entirely different landscapes: the floodplains and the firm lands. Floodplains are wetlands in the immediate vicinity of rivers and firm lands are the highest terrain, a few meters above water, at other points they reach moderate altitudes. The floodplain rivers flow from sedimentary formations that they have deposited themselves. Some of these rivers have curve courses, such as Juruá and Purus. In the Solimões–Amazonas route, the waters are split and linked by channels, forming islands that stretch in the current direction and divide the great river [4]. The large floodplain areas along the Solimões River gutter and the low slope downstream of the basin are responsible for flood wave attenuation [2].

Droughts and floods, part of the natural climate variability in those regions, have occurred in the past and will continue to happen in the future. The inhabitants of the region are well adapted to this hydrological inter annual dynamics and, over time, have been able to develop their livelihood strategies. During the floods of 2009 and 2012, the rising levels of the Solimões and the Negro Rivers, the two main branches of the Amazon River, caused floods in urban and rural areas along the riverbanks in Peruvian, Colombian and Bolivian Amazonia [11].

In this article we present an important project developed by Geological Survey of Brazil in Manaus, that presents every year three predictions of Negro River at Manaus station, called Negro River Flood Warning. The first forecast occur in March (for example, this year happened on 29 March), the second forecast occur in Abril (e.g. on 30 April 2019) and the third in May (e.g. on 31 May 2019). The main objective of this project is to offer to the society the information about the eventual flood and a high river preview in the flood time.

2 NEGRO RIVER FLOOD FORECAST PROJECT

In the Amazon, the river is a means of transport, provides food and clean water. Therefore, knowing the hydrological regime is important to provide information to those who live with the flood and ebb. Negro River in Manaus spends on average 234 days of rising and 130 days of descent (Fig. 1). The climb is smooth and striking, which facilitates predictability. Since

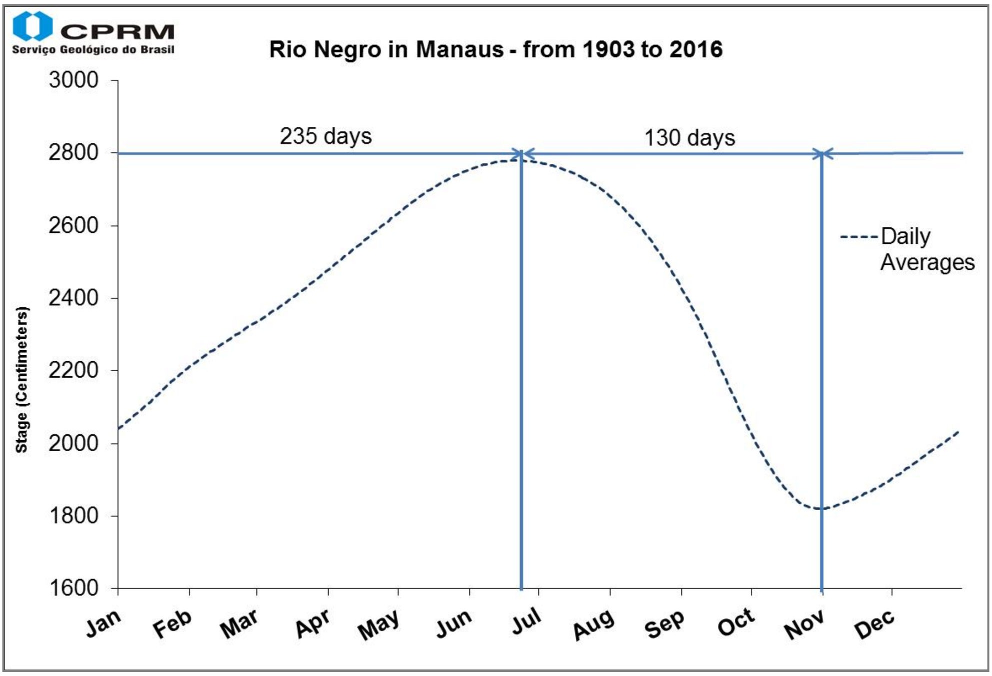

Figure 1: Length of the rise and fall of the Negro River at Manaus station.

1989, the Geological Survey of Brazil in Manaus has been developing the "Amazon Hydrological Alert System" where the annual flood and ebb monitoring process is performed in the Solimões–Negro–Amazonas system. Among the products generated by the project is the Manaus Flood Alert, which presents the forecast of the maximum quota to be reached by the Negro River in Manaus each year. The results are released to the relevant agencies and the press at the end of March, April and May, preceding the maximum Negro River quota, which usually occurs between June and July.

Thus, it is possible to do a good statistic job because, in Manaus Harbour, there is a measuring ruler, installed by the English since 1902, generating a historical series of 117 years. As Marengo et al. [11] observed the droughts of 2005 and 2010 and the floods in 2009 and 2012 were detected as the lowest daily minimum and the largest daily maximum, respectively, of the levels of the Rio Negro at Manaus, as we can see in Fig. 2. Barichivich et al. [6] examine the characteristics of individual flood events that indicates the recent floods not only occur more often but also have become more severe, such as the return period of a flood event exceeding either a duration of 70 days or a water level of 29.7 m besides they have occurred within an interval of only 3 years.

In Table 1, we present the ten floods with the highest quotas, six of which occurred in this decade, which may indicate a change in the flood pattern in Negro River. Any of the ten largest historical floods in Manaus already impacts the riverside population, as the descent is not immediate either; the physical result of the flood persists in the first month of ebb.

In 1953, Manaus and Negro River had an extreme flood recorded in 29.69 m, for more than 50 years, it was the higher level. Then in 2009, we had a great flood that exceeded 1953 and registered 29.77 m, in this event it was possible to notice that the Solimões had a different

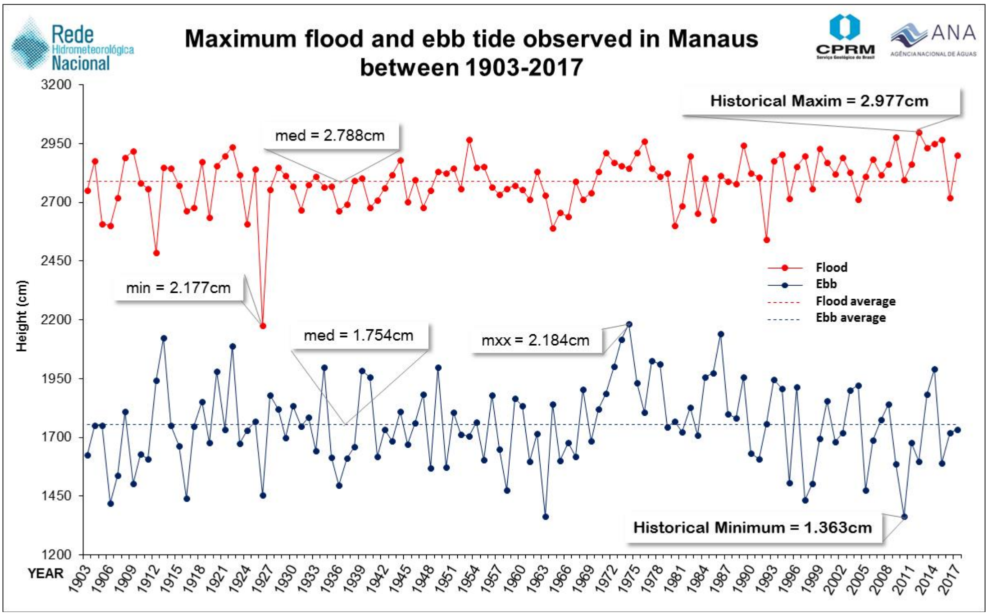

Figure 2: Manaus Harbour maximum and minimum ruler heights.

Table 1: The biggest floods in Manaus Station.

Position	Year	Water level	Date	Flood days
1	2012	29.97	29 May	230
2	2009	29.77	1 July	244
3	1953	29.69	9 June	221
4	2015	29.66	29 June	237
5	1976	29.61	4 June	197
6	2014	29.50	3 July	246
7	1989	29.42	3 July	261
8	2019	29.42	22 June	225
9	1922	29.35	17 June	227
10	2013	29.33	14 June	226

period of rise of the Negro, at the time when the Solimões had high quotas for the period in Manaus, the contribution of the Negro arrived and made the levels even higher this season and longer. Already in 2012, the whole basin had a great rise from February until May of the same year, when it reached a historical maximum of 29.97 m. In 2019, the first flood wave on Negro River in Manaus was influenced by Solimões and rainfall throughout the basin, similarly in the second phase of the flood (February and mid-March), however, in the third phase (April and May), what influenced the flood was the rise of the Upper Negro River in March, affected by the rains from the north of the state of Amazonas, when the waters were lowered to Manaus station, the quotas were already high, a fact that significantly influenced the mark of this flood, with a maximum record of 29.42 m, reaching 7th position in Manaus historical records.

To set up the monitoring of Negro River in Manaus, it is necessary to follow some stations located before and in different gutters that contribute to Manaus station, as illustrated in Fig. 3. These stations have rulers installed on the banks and are accompanied by local people daily. We call then as observers, through the National Water Network project supported by the National Water Agency, it is possible to pay financial aid to these observers and visit these stations at least four times a year. In the case of monitoring stations, the data is collected daily and recorded in specific logbooks. The record of rivers rise and fall in these seasons are recorded in a weekly newsletter and published on the homepage (www.cprm.gov.br) of the monitoring responsible sector and it has a great importance to the resident population, the State and city halls, as well as for academic researchers.

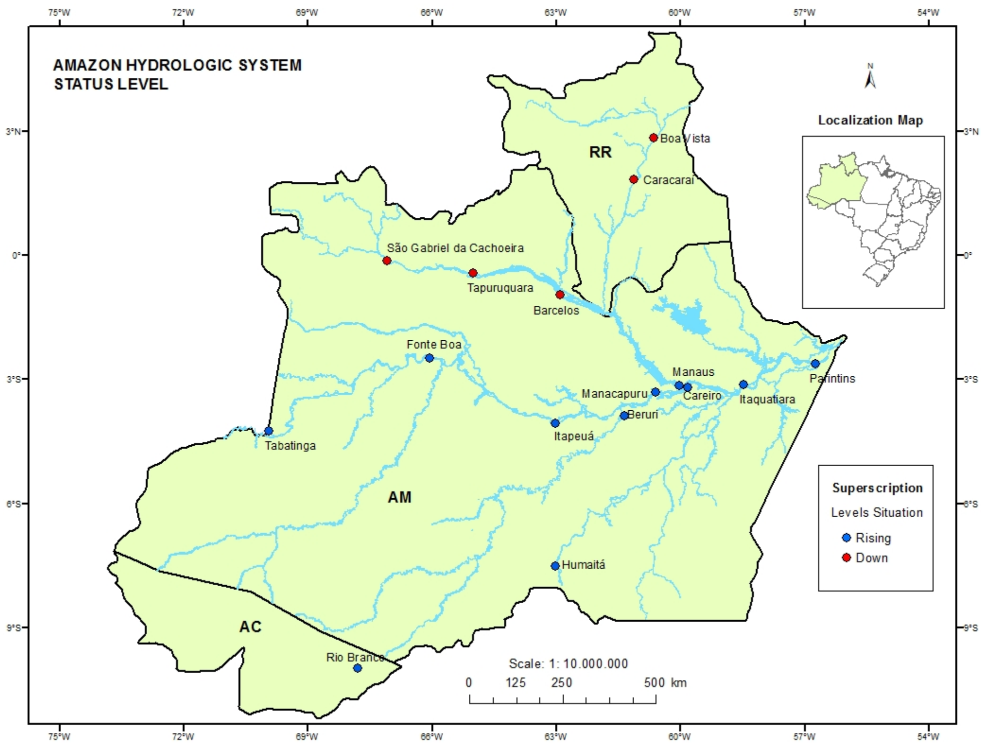

Figure 3: Hydrological monitoring stations accomplished by flood alert. *(Source: Adapted from CPRM/SGB [12].)*

Geological Survey of Brazil forecasts are based on a simple linear regression, where the maximum annual quotas are correlated with the forecast dates, which are 31 March, 30 April and 31 May (see Fig. 4). Statistical models of simple or multiple linear regressions are efficient for long-term prediction of Manaus flood peaks, with the advantage of use facility, despite the disadvantage of not accurately determining the date of occurrence of the event.

3 HYDROLOGICAL DATA ANALYSIS OF MANAUS FLOODS

Flood frequency analysis has a local basin perspective and is based on the assumption that floods are the consequence of a random process such that are independent and identically

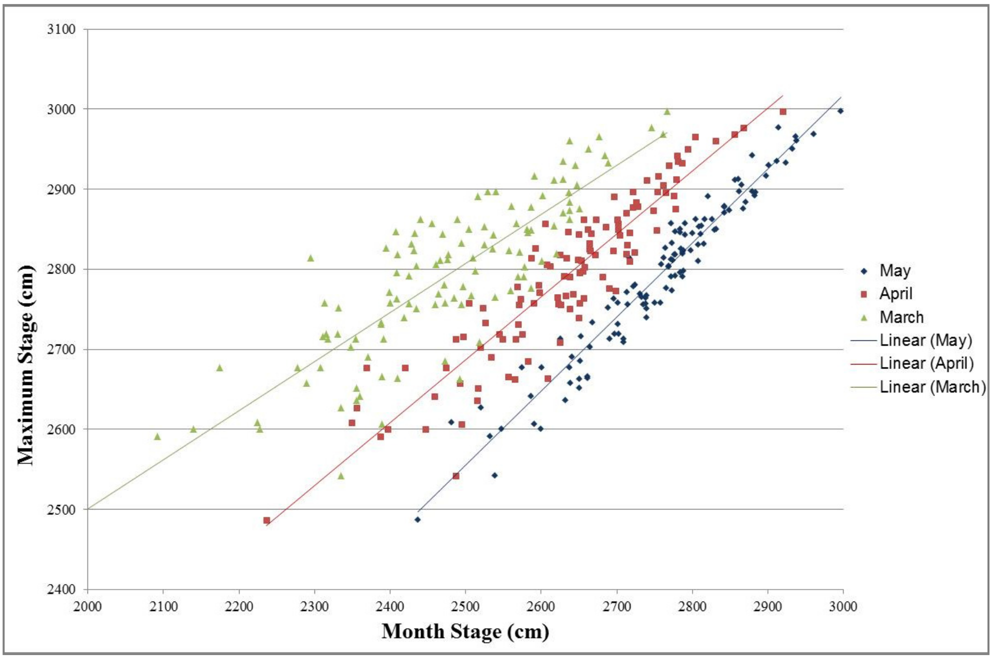

Figure 4: Simple linear regression used in Manaus flood forecast.

distributed. However, this assumption has been questioned on the basis that climate, land use and other factors that determine flood occurrence are likely changing with time [13].

We understand the flood as a natural phenomenon that is part of the rivers dynamics, for the Manaus Civil Defence, when Negro River reaches a height of 27 m, the river population already feels the direct impact of the flood; by historical series, this quota has a return period of 10 years (T = 10). When the river reaches a height of 29 m, it is already considered an emergency water level, with a return period of 17 years (T = 17); when the river is at this stage, the sectors responsible for the city install walkways and help to smooth out the flood impact.

In Manaus, 117 floods were catalogued, of which 6% occurred in May, 75% in June and 19% in July (Fig. 5). In Table 2, we present the monthly river discharges in two stations (Paricatuba and Manacapuru) before Manaus, where we can see the increased flow of the Black and Solimões Rivers; the months of March, April and May reveal the contribution that arrives in the basin and that leads to the flood period of the year.

Considering Table 2, it is possible to see the differences in discharge between the Negro and Solimões Rivers and also the increasing flow in the years of the biggest floods (2009 and 2012). CPRM (Geological Survey of Brazil) measured these flows to understand if much difference occurs between the months preceding the flood, thus we can detach:

- In the flood of 2009, in the month of January, the discharge was the average of other years. Already in 2012, the flow in January was already with great measurements and this for both gutters (Negro and Solimões). This proves that the 2012 flood has already started with high quotas due to the basins contributions.

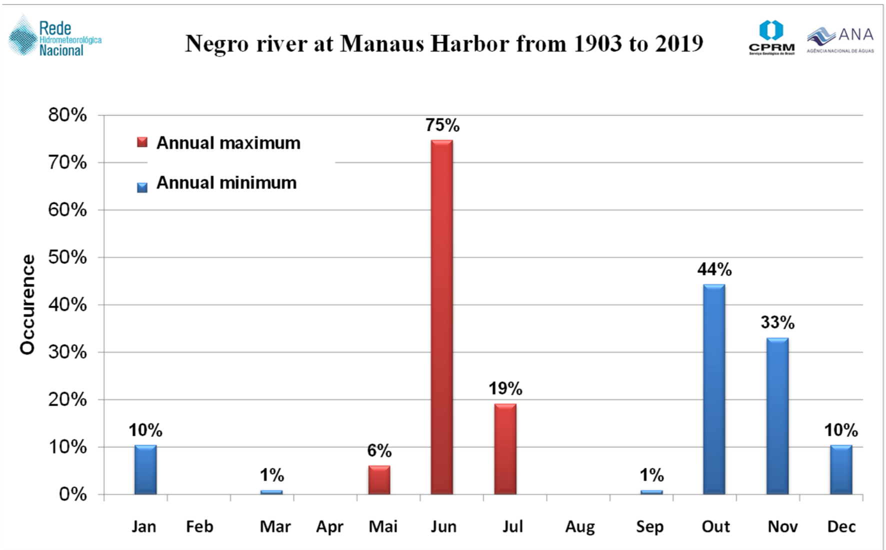

Figure 5: Monthly distribution of maximum and minimum water levels in Negro River.

Table 2: Monthly river discharges (m^3/s). *(Source: Adapted from CPRM/SGB [12].)*

Year	Section	River	January	February	March	April	May	June
2008	Paricatuba	Negro	24.854	19.708	24.060	22.119	29.823	61.411
2009	Paricatuba	Negro	38.142	41.423	30.056	35.032	34.820	37.212
2010	Paricatuba	Negro	8.685	10.092	9.266	20.625	45.452	58.192
2011	Paricatuba	Negro	23.924	20.302	33.242	31.250	55.629	64.892
2012	Paricatuba	Negro	24.085	27.225	38.071	44.882	62.591	55.268
2008	Manacapuru	Solimões	85.953	103.874	108.764	118.886	127.161	125.028
2009	Manacapuru	Solimões	85.301	104.337	116.431	128.542	136.241	143.218
2010	Manacapuru	Solimões	88.072	91.185	100.073	110.047	118.654	123.738
2011	Manacapuru	Solimões	63.139	81.787	92.116	105.277	124.130	125.241
2012	Manacapuru	Solimões	105.641	115.078	122.247	143.086	145.726	148.177

- The year flood impact may be reflected in the following year, as Solimões dam Negro River, the high quotas at the Manaus station in 2009 impacted Negro River flow in 2010, which can be noticed by the flows below average in January, February and March.
- An average flood year, Negro River has increased flow in the months of May and June. Already Solimões has this increase in March and April. Already in an above-average flood year, the flow of Solimões grows in February.

The long-term average (1903 to 2019) of the annual flood peaks is 2,788 cm, with a standard deviation of 115 cm, the historical record was 2,997 cm in 2012. In Fig. 6, we present the graph with the highest water level of evolution in Manaus station. Featured

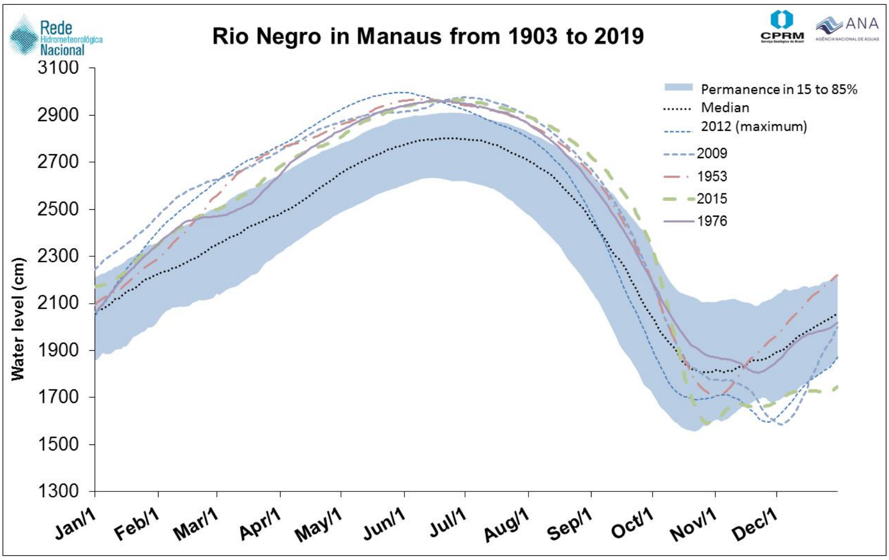

Figure 6: Permanence curve and Negro River largest floods.

maximum height are above the permanence curve which is in the range of 15–85%. Since the maximum water level with 15% of frequency is 2,891 cm.

In Table 3, we present the latest forecasts of the alert and the water level of each year. Each alert forecast has a minimum and maximum range, and an average quota. Thus, in this chart, it is possible to see that in the interval of 15 years, there were 13 hits and two approaches, an efficiency of 87%, which indicates that the forecast model is valid.

Table 3: Alert forecasts and recorded maximum harbour quota in Manaus.

Year	1st Forecast March (m)	2nd Forecast April (m)	3rd Forecast May (m)	Maximum quota (m)
2019	28.49–29.19	28.47–29.17	29.03–29.33	29.42
2018	27.45–28.15	27.35–28.05	28.20–28.70	28.38
2017	29.25–29.95	29.15–29.85	28.96–29.46	29.00
2016	26.60–27.20	26.90–27.50	26.97–27.57	27.19
2015	28.89–29.59	28.92–29.62	29.39–29.89	29.66
2014	28.79–29.49	28.84–29.44	29.29–29.60	29.50
2013	28.75–29.45	28.76–29.46	29.28–29.71	29.33
2012	29.06–29.96	29.06–29.96	29.97–30.27	29.97
2011	27.64–28.34	27.78–28.48	28.28–28.92	28.62
2010	27.08–27.78	27.60–28.30	27.84–28.53	27.96
2009	29.33–30.03	29.25–29.95	29.15–29.59	29.77
2008	28.62–29.32	28.08–28.78	28.24–28.70	28.62
2007	27.08–27.78	27.48–28.18	27.48–28.18	28.18
2006	28.62–29.32	28.38–28.88	28.73–29.23	28.84
2005	28.51–28.91	28.35–28.75	28.08–28.20	28.10

Also in Table 3, we can consider:

- In this interval (2005–2019), related to the largest floods, the alert forecast has a similar efficiency (83%), analyzing the first alert, there was a distance, only in 2019.
- Considering in this interval, the largest floods, the alert forecast has a similar efficiency, analyzing the first alert, there was a distance, only in 2019.
- Disclosure of the forecast is important, but what should be considered is the size of the likely flood within the range of acceptable variations. In practical terms, the objective is more qualitative (large, medium, low full) than quantitative accuracy.

4 CONCLUSIONS

Negro River levels have been measured since September 1902, with a historical series of 117 years. Predictive studies can be performed using the most diverse statistical and hydrological methodologies. However, we can see that the most important thing is to offer a warning service to the population on the banks and who depend on the river to guarantee their activities. This paper presents selected data that help to understand the hydrology of the region and compose the weekly western Amazon hydrological monitoring bulletin and the three annual alerts in Negro River.

Of the last ten major floods, six are concentrated in this decade, a fact that highlights that these events can become more frequent and thus, knowing the dynamics of rising waters are is something to be conducted by universities and technical sectors that study and operate in the waters from Amazon. The Geological Service of Brazil acts in this monitoring as the sector that collects this primary data and realized the need to disclose the flood forecast and warning project, which presents a possible level range of the Rio Negro for the current year.

As reported, we consider a height of 27 m in Negro River as an alert quota with a return period of 10 years, and when the river reaches a height of 29 m, it is considered an emergency water level, with a return period of 17 years. These levels mean that the waterfront population will feel a kind of impact in their usual activities. Statistical studies, such as linear regression, allows us to obtain a forecast flood level in Manaus from the upstream river stations. In this sense, it is worth noting that the annual flood peaks is 2,788 cm, with a standard deviation of 115 cm, the historical record was 2,997 cm in 2012. Besides, the featured maximum water levels are above the permanence curve which is in the range of 15–85%. Since the maximum height with 15% of frequency is 2,891 cm. However, more important than river level prediction is the estimation of the Manaus flood size within the range of acceptable variations. Even so, our forecasting model has a good result as it is within the flood range and over 80% within the year's maximum height.

This study shows that providing access through roadway infrastructure can provide greater development and better quality of life in rural communities in the Amazon without neglecting the need to control natural resource exploitation and to preserve the environment. Keeping up with the Amazon hydrology is not an easy task, it is dynamic and complex, but understanding the system and the floods evolution, with the slow rise of the waters in approximately 230 days, goes beyond studying the water levels and statistics, is trying to listen and see what nature and the waterfront people try to pass in response to our questions.

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