ANALYSING THE FLOOD WARNING OF NEGRO RIVER IN MANAUS

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ABSTRACT

The magnitude of the Amazon basin, associated with geological, geomorphological and hydrological factors, as well as the distribution of rainfall, contribute to the existence of large rivers, both in extension and flow, such as the Negro and Solimões rivers, which are selected to be evaluated in this study. Manaus city is bathed by the Negro river, near the confluence of the two rivers, in which the water level of Negro river is controlled by Solimões river level. This study proposes to analyse a project named Negro River Flood Warning System that presents a river level or stage forecast about Negro river by the Geological Survey of Brazil in Manaus since 1989, where the annual flood and ebb monitoring process is performed in the Solimões, Negro and Amazonas hydrological system. Flood forecasting models are important for the composition of extreme events alerts, as well as for the knowledge of decision-makers, representatives of public agencies and affected communities. Many factors contribute to the flooding event: how the various tributaries are integrated down the river main stem and how the basin behaves during the six months of flooding in the rainy season. For the forecast, it is important to monitor the evolution of the level of rivers such as Negro and Solimões, understanding the dynamics of the basin and also the events associated with major floods that have already occurred, as recorded in the historical series of the Port of Manaus, all this combined with a statistical methodological approach. In the Manaus alert system, linear regression analysis is used. According to results obtained for the past 15 years, the flood forecast interval reveals that the forecast in 87% of cases has fulfilled the objective of presenting a stage very close to the water level peak. Furthermore, it was noticed that a height of 27 m in Negro river turned to be an alert quota with a return period of 10 years. Once the river water level reaches a height of 29 m, it can be considered a 'severe flood water level' with a return period of 17 years.

Keywords: Amazon basin, flood forecast, Negro river.

1 INTRODUCTION

Amazon is one of the most impressive hydrological basins of the world. In this basin, the Amazon river is the longest river, depicting a length of 6,992.15 km from its headwater in the Peruvian Andes to its outlet in the Atlantic Ocean, and the Amazon drainage area covers about 6,200,000 km^2 [1]. Its basin covers about 40% of South America and portions of six countries. 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 next ten largest rivers in the worldwide rank. Amazon flow accounts for approximately one-fifth of the world's total river discharge to the oceans [2]. Rainfall ranges from 1500 to 3000 mm annually, averaging about 2000 mm in the central Amazon [3]. The maximum rainfall in the southernmost parts of the Amazon river basin usually occurs in December, January and February. The maximum rainfall in the central basin along the Solimões–Amazon main stem is in February, March and April and six months earlier than maximum rainfall in the northernmost parts of the basin (June–July–August) [4].

The Amazon basin, therefore, has three main water sources for its rivers: the Andes, the Brazilian shield and the Guiana shield. There is also a central region, where vast areas of the

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flood plain are flooded every year, more specifically contributing to the formation of wetlands known as ‘várzeas’ [5]. The main Amazon channel, called Solimões river above the confluence with Negro river, carries water primarily from the Andean origin. It should be noted that the northern tributaries originated in the Andes, such as Iça and Japurá rivers, cross the Subandean trough and central plain to reach the main stream. Negro river drains primarily the forested area in Guianas, and its major tributary, Branco river, drains a drier region [6]. The most well-known example to characterize the union of those different river types can be found near Manaus, where the Negro river, a black water river, joins the Solimões, a white water river, to create what is known as the ‘meeting of the waters’ [7].

In the Amazon river basin, backwater effects regulate the flow dynamics in the downstream reaches of main rivers. As examples of these effects in the basin, there is the influence of the main Amazon River on its tributaries’ water levels as discussed in [8] and [4]. Hydrological regimes within the basin vary significantly. The peak water discharge of the Solimões/Amazonas, Madeira and Negro rivers are lagged in time. For the upper Negro river, the high water period arrives in the second half of the year [5]. The discharge of the Amazonas river, which usually peaks in April–June, has been highly variable since the beginning of the 1980s, with observed discharges relatively very low in the time span of high water flows in 1980, 1985, 1992, 1995 and 2004 and, on the contrary, high water flows exceeding 50 000 m^3/s in 1986, 1993, 1999 and 2012 [9].

The floods that occur on the edge of Manaus and its surroundings are usually associated with the water contribution of the Solimões river and its tributaries on the right bank and, to a lesser extent, with the water contribution of tributaries on the left bank. Those floods have a long journey time due to the huge size of the hydrographic basin and due to the small slope observed along the beds of its main river course. This fluvial geomorphology facilitates predicting high water stream flows several days in advance. The relatively low returning period of floods of magnitudes considered to be potentially harmful, which is around 11 years, can also be credited to the vastness of the Amazon basin and to its small average slope. It takes about seven to eight months on average, the time period along which the water level rises in the whole basin [10].

Once the differences in catchment size and timing of the flood pulse are significative when the whole Amazon and Negro basins are compared, water levels at the Manaus station located in the Negro river measure somehow water fluctuations of the Solimões–Amazon main stem due to the so-called backwater effect [11]. Backwater effects are evident as depicted in records of river water level collected along the lowermost stretch 300–400 km of the Negro river [4]. For the sake of clarity, Solimões river is the name adopted before the Negro river outlet, while Amazon river is the name adopted for the main course of the river after Negro river outlet in Manaus.

The exchange of water between the floodplain and main river course is up to 30% of the flow of the main stem. It is derived directly from water storages on the floodplain and from flow driven by local small courses crossing through the floodplain [6]. The stream flow in large river systems generally shows a stronger response to seasonal rainfall patterns than to individual rainstorm events. This behaviour results in an annual cycle closely related to the main rainfall season in the Amazon basin. The affluents of the Amazon river are integrated downstream along the main river course. Such spatial fluvial connection leads to the production of a single monomodal flood wave that occurs with regularity on an annual basis [7]. The abnormal rise of the Negro river can be attributed to a rare coincidence of flood peaks of the various rivers that comprise it [12].

On the other side, it should be noted that the Amazonian system is very dynamic, resulting in droughts and floods that are part of the natural climate variability. In the Amazon basin, the river is also a medium of transport, while providing food and clean water. The understanding of the hydrological regime is important to provide information to those who live with the flood and ebb. 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 in the region. For this reason, the Geological Survey of Brazil in Manaus has been developing the 'Amazon Hydrological Alert System' since 1989, where the annual flood and ebb monitoring process is performed in the Solimões – Negro – Amazonas system [13]. Therefore, this paper proposes to examine the forecasting procedure of the maximum stage water lever reached by the Negro river in Manaus. Complementarily, the referred project presents every year three predictions of Negro river at Manaus station, here-in called Negro River Flood Warning. The paper is divided in the next following sections: (ii) analysing the flood at Manaus Station considering the long-term average from 1903 to 2019; (iii) the forecast methodology based on linear regression analysis and (iv) results and concluding remarks about this hydrological research and applied work.

2 ANALYSING THE FLOOD AT MANAUS STATION

Negro river in Manaus spends on average 235 days rising and 130 days with recession in terms of water levels (Figure 1). The climb is smooth and striking, which facilitates predictability. Since 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 to the press at the end of March, April and May, preceding the maximum Negro river quota, which usually occurs between June and July.

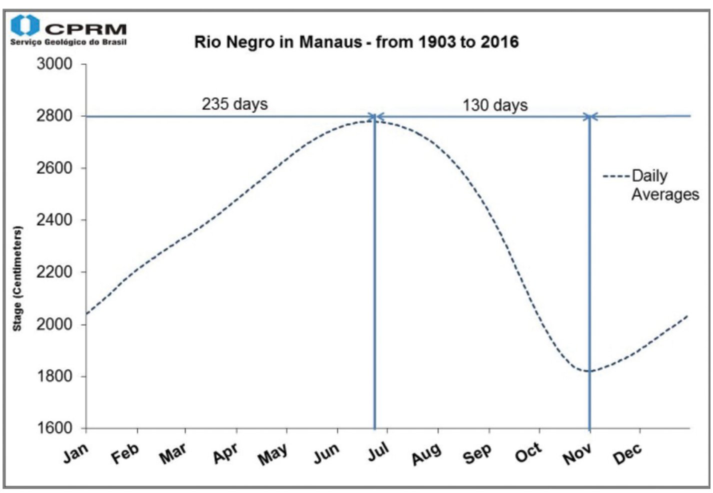

Figure 1: Long-term rise and fall behaviour of the Negro river hydrograph at Manaus station (1903–2016) [13].

Negro river level in Manaus is controlled by a monitoring scheme including some stations located before and in different gutters that contribute to Manaus stream flow gauge. Those fluviometric stations have water level stage meters installed on the banks and are daily accompanied by local people. The record of rivers rises and falls in these seasons are registered in a weekly newsletter and published on the institutional homepage (*www.cprm.gov.br/sace*) of the monitoring responsible sector, and it has great importance to the resident population, to the state administrative level and to city halls, as well as to academic researchers [13].

Negro river levels have been measured since September 1902, with a historical series of 117 years. Analysing this historical series, 6% of the floods occurred in May, 75% in June and 19% in July (Figure 2) [14]. The Manaus gauge provides an accurate, long-term record of water level stage; it has been maintained at the same site by Manaus Harbour (Figure 3) over the period of record.

Mean daily water levels at the Manaus Harbour records since 1903 assists the Geological Survey of Brazil (SGB-CPRM) to identify severe droughts (15.8 m) and floods (29.0 m) in Manaus and to characterize their corresponding frequency, duration and severity. These river levels are critical for the functioning of the harbour and are used to declare emergency status in the city [11].

The flood monitoring process for the current year starts at the end of the previous year along with the beginning of the rainy season. For the Geological Survey of Brazil, this is the first wave of the flood. In January of the current year, the evolution of rising levels in the Solimões river is measured in the stations located nearby the affluents outlets contributing to the main river.

In Negro river, the rise of river water levels in stations located at the headwaters is evident in February and March. For the flood alert of each year, it is necessary to monitor the flooding

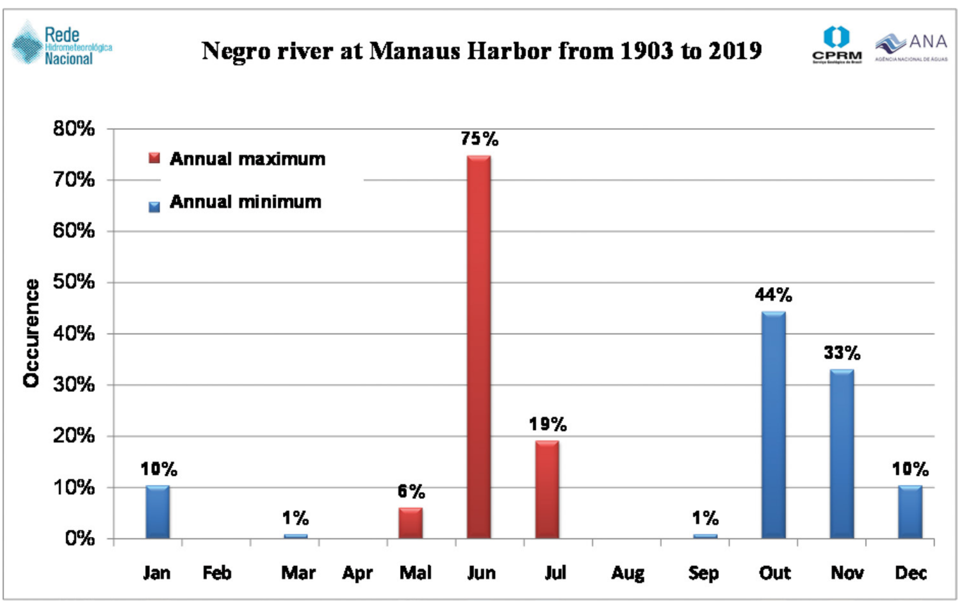

Figure 2: Long-term monthly distribution of maximum and minimum water levels in Negro River [13].

Figure 3: Manaus hydrological station at the harbour in the maximum (2012) and minimum water levels (2013) registered in the site.

progress of the rivers that contribute to the flooding of Negro river in Manaus since the beginning of the year under analysis.

In this sense, these two areas are important to be monitored: the upper Negro river in São Gabriel and the upper Solimões river in Tabatinga. In 2019, during the beginning of the flood period, it was possible to observe different behaviours in comparison to other years with a regular flood at these stations. For example, in Tabatinga, there was a flood in early January, which dropped at the end of this month, and rose again in February and maintained high quotas until the middle of May. This high level was close to the maximum river water level observed on that location. The other station evaluated, namely São Gabriel da Cachoeira, presented a water level increase in February, decrease in March, and then regain back with more speed in April, reaching water level close to high quotas for the refereed period at this point of the river (Figure 4).

For the set of monitoring stations, it is important to compare the range with the normal blue range of Figures 4a, 4b and 4c and also to compare it with the maximum level for the period. This serves as an initial indicator that the flood of that year will be considered high. The response of these rises in river water levels at the headwater stations to the rainy season is more immediate than at the Manaus station. For example, as the basin dynamically absorbs and distributes the rainfall contribution along the corresponding period of analysis, with occurrences in São Gabriel da Cachoeira and Tabatinga taking about 30 days to arrive at Manaus station, it should be noted that the discharge can flow with stronger intensity or be distributed in several and diverse floodplain areas.

As Trigg [7] explains, the floodwater transference from the main channel to the floodplain and the subsequent draining of the floodplain occurs through a combination of overbank diffusive flow and channelized flows through numerous floodplain channels. Therefore, for monitoring purposes, it is important to observe the basin behaviour along the whole flood period.

Meade *et al.* [4] establishes a comparison of the water level cotagram for Manaus at the lower Negro river in contrast to the upper Negro river and also in comparison to the mainstream Solimões river at Manacapuru. Those results show that water level in the downstream reaches of the Negro river reflect water level measurements made in the mainstream Solimões river. Figure 4C shows Manacapuru fluviometric station, while Filizola *et al.* [5] report that it

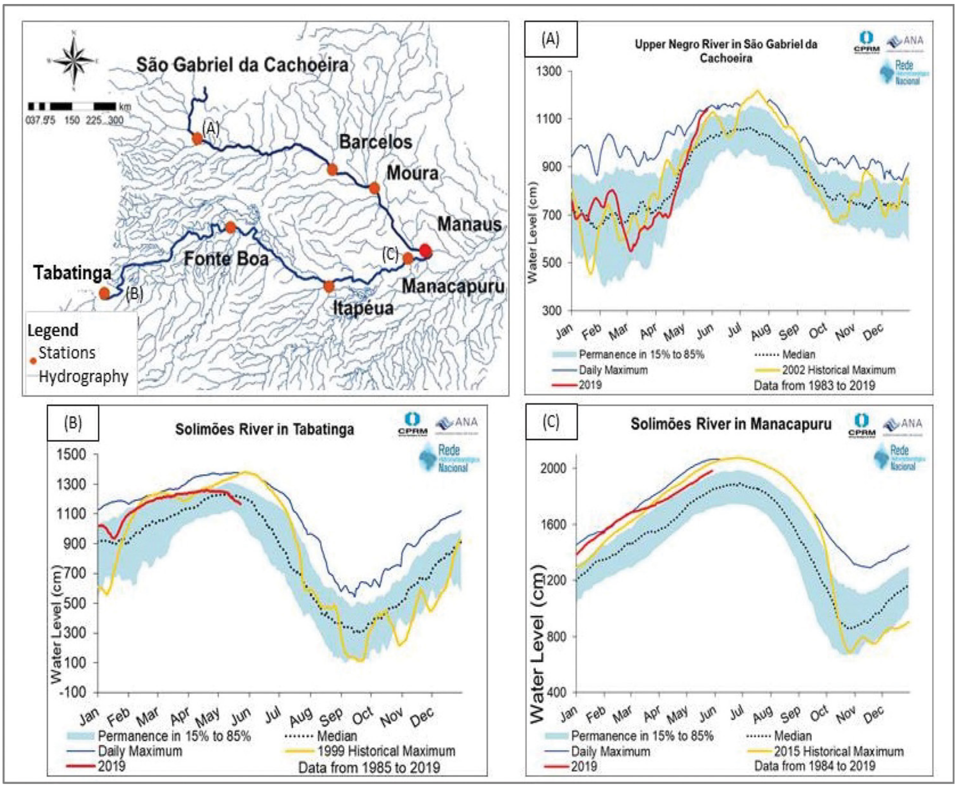

Figure 4: The hydrological station locations in Negro and Solimões rivers (upper left) and the following graphs for the variations of water level: a) São Gabriel da Cachoeira station in Negro river in 2019 compared to other years with high levels; b) Tabatinga station in Solimões river in May 2019; c) Manacapuru station in Solimões river in May 2019.

is also the last hydrometric station prior to the confluence with the Negro river, which is one of the largest and most important Amazon's tributaries in terms of water discharge, draining an area of approximately 700,000 km^2.

Table 1 presents the ten largest floods with the highest water levels, noting that six (6) of them took place in this decade, which might indicate a change in the flood pattern of occurrences in the Negro river. Any of the ten largest historical floods in Manaus already impacted the riverside population. It should be noted that the stream flow descent is not immediate either; as a result, the physical result and associated damages due to the flood persist along the first month of ebb.

During the major floods of 2009 and 2012, rising water levels in the Solimões and Negro rivers caused flooding in urban and rural areas along riverbanks in the Peruvian, Colombian and Bolivian Amazon [10]. For example, in 2009, the second highest flood took place at Manaus Station. Indeed, not only Manaus registered a flood record in the first half of the year 2009. At least five other locations also recorded maximum indices for their historical series, namely Manacapuru, Itapéua, Parintins, Careiro and the community called Forte de Nossa Senhora das Graças, situated in the gutter of Juruá [12].

Table 1: The biggest floods in Manaus station.

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

In another case, referred to the year 2012, the flow in January already presented larger water level measurements for both Negro and Solimões rivers. In addition, when comparing stream flows, both in Manacapuru and in Paricatuba, the discharges obtained in the months preceding the flood were much higher than those recorded in 2011 [2]. The Negro river provides a significant contribution (35%) to the whole basin in terms of water discharge [5].

Figure 5 presents the monthly river discharges during the flooding period in two stations, namely Paricatuba in Negro river and Manacapuru in Solimões river, where we can see the increased stream flows of the Negro and Solimões rivers. The months of March, April and May reveal the contribution that arrives in the basin and that leads to the flooding period of the year. Predictive studies can be performed using the most diverse statistical and hydrological methodologies.

Considering Figure 5, we can verify that Solimões river is indeed one of the biggest rivers in terms of water discharge, since all the Andean tributaries from the north of the Equator and some from the southern part of the Amazon river basin are represented in the total amount of water passing through the Manacapuru station, that is the last hydrometric station prior to the confluence with the Negro river. Furthermore, discharges presented in Figure 5 confirm what [15] reported about the Amazon river discharge contribution, mentioning that 39% came from the Negro river and 61 % from the Solimões river.

Figure 5 still makes it possible to notice the differences in discharge between the Negro and Solimões rivers and also the increasing stream flows in the years of the largest floods (2009 and 2012). SGB-CPRM (Geological Survey of Brazil) measured those flows in two hydrological stations before and next to Manaus to understand if much difference occurs among the months preceding the flood time span. As we compare the two biggest floods (Figure 5), it is possible to identify that the discharge in January 2009 represents the average flow of other years. On the other side, in 2012, the flow in January was at that time with larger measurements for both Negro and Solimões rivers. This fact indicates that the 2012 flood had already started with high water levels due to the corresponding basin contributions.

To analyse the flooding at the Manaus station, it is necessary to monitor the evolution of the water level of the rivers rising in the different stations, making it possible to identify the differences between Negro and Solimões rivers. In addition, such monitoring allows us to understand the dynamics of the entire basin and of other flooding events that occur in the

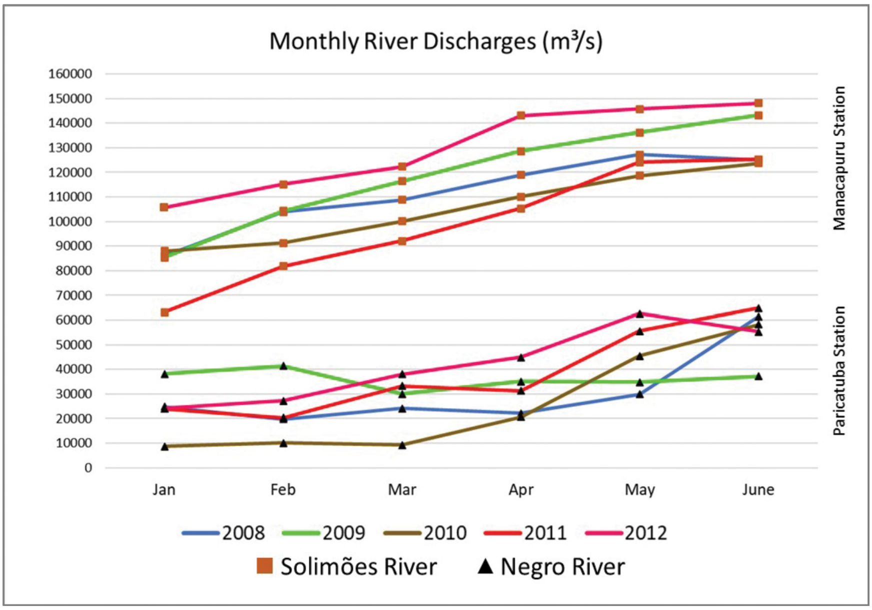

Figure 5: Monthly river discharges (m^3/s). Source: adapted from CPRM [10].

Negro river at the Manaus station. Considering the important historical series recorded at this station and the use of statistical methods to analyse hydrological data, it was possible to build up a flood forecasting model for the Manaus station located in the Negro river.

3 THE FORECAST METHODOLOGY

According to information disposed on the CPRM website, the flood forecast and alert system consist of informing the population in the case of rising water levels in the Negro river, which might present some danger of causing flooding. It is based on hydrometeorological monitoring and knowledge of the dynamics of hydrological processes, allowing to monitor and predict the evolution of flood waves in prone flooding areas. The forecast and alert system allows the avoidance of the surprise factor, reducing losses due to the flooding of roads, vehicle entrapment, floods of material goods and equipment in residential, commercial and industrial buildings. The alert facilitates preventive actions to isolate and remove people and property from areas subject to flooding, taking into account future water levels predicted by the hydrological forecasting system.

The Flood and Alert System in Manaus is a non-structural measure adopted in order to minimize the damage caused by floods and leaks in river basins. The operation of the flood alert system in Manaus has been working satisfactorily, with institutional cooperation involving the Civil Defense, the State Government, the City Hall and the various press media.

In terms of an average flood year behaviour at the monthly scale, Negro river presents increased flow in the months of May and June, while Solimões river depicts this increase in March and April. On the other hand, in an above-average flood year, the flow of Solimões river increases in February. Figure 6 illustrates the three (3) main floods in Negro river and the flood in 2019 for the purpose of comparison. The flood in 2012 reached a maximum level of 29.97 m in May, but this flood had not started high, if we examine the month of January.

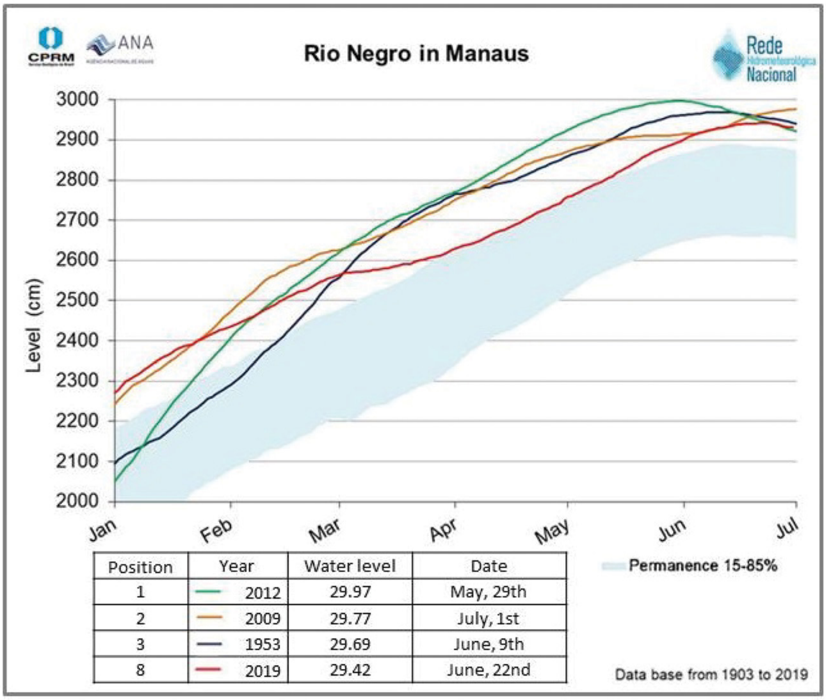

Figure 6: The main floods in Manaus station on the period of the flood alert in comparison to the flood in 2019.

The year of 2019 had a big flood, and still in January had high levels, similarly to the second biggest flood that occurred in 2009; both floods were amplified in February and reached the highest level in June (2019) and July (2009), respectively. If we look at the ten largest floods, the average number of days in this period corresponds to 231 days (Table 1). From Figure 2, we know that the month of June is the month in which the flood reaches its peak in 75% of cases examined. Thus, the flooding period in 2019 had 225 days, peaked in June, and it was a relevant case, occupying the 8th rank in terms of magnitude in the flood record.

The comparison of the rise in the level of the Negro river with the years of major floods is important for understanding the current year flood, but it needs to be accompanied by a method that expands the consolidation of the dataset. Thus, for the annual forecast, the Geological Survey of Brazil in Manaus uses the analysis of the historical series recorded in the Manaus Harbour based on the method of linear statistical regression. Statistical models of simple or multiple linear regression are efficient for long-term predictions of flood peaks in Manaus, with the advantage of being easy to use by non-specialized users, despite the disadvantage of not determining exactly the date of the event. Linear regression is a statistical technique used to estimate the relationship between variables, investigating the expected value of a dependent random variable *Y*, given the values of the independent random variables *X*, considering that there is a functional relationship between variables *Y* and *X*. A regression is called linear when the response to the independent variables is defined by a linear function [16].

In this sense, a simple linear regression equation is assumed to be given by

$$Y = \alpha + \beta X + e \tag{1}$$

where: Y is the dependent variable, X is the independent variable, α and β are the model coefficients, and 'e' denotes the errors or residuals of the regression. Figure 7 illustrates a typical relationship based on the regression model expressed by Equation 1.

At Manaus station, the correlations among the peak flood and the previous maximum water levels from March to May for the 1903-2019 time span are gradually more significant, resulting in the simple linear regression equations presented in Figure 8. Therefore, considering the water level data of the long-term from 1903 to 2019 for each month, the forecast is based

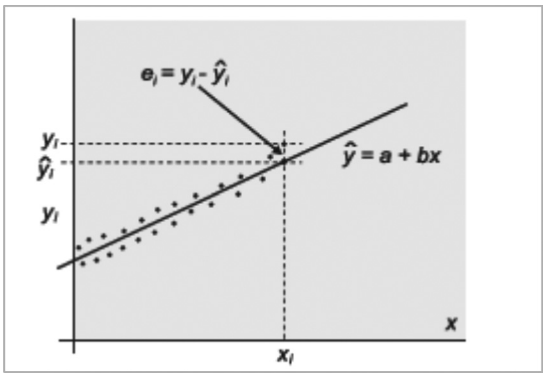

Figure 7: Relationship between Y and X and derived regression line [16].

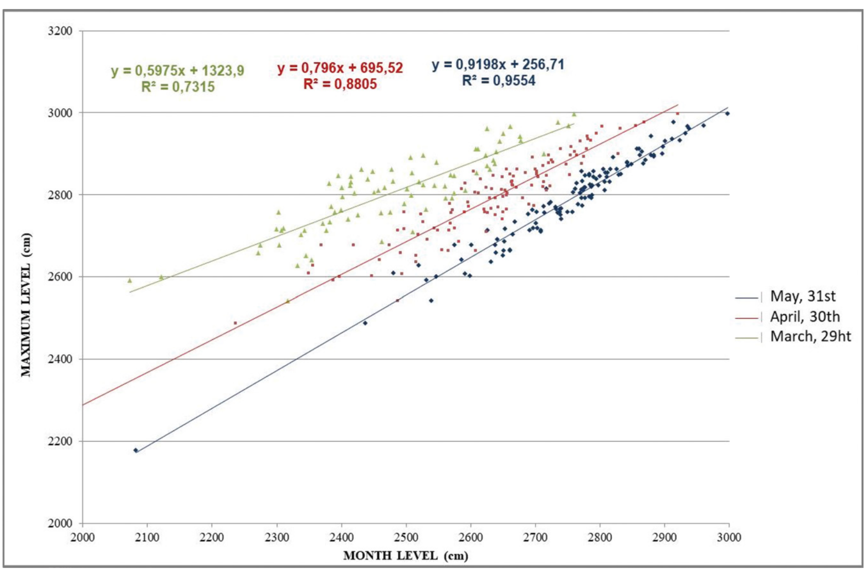

Figure 8: Simple linear regression equations developed for Manaus flood forecast.

in the simple linear regression model. Such approach results in each of the equations used for each level of alert, where the green line represents the first forecasting alert, the red line represents the second and the blue line depicts the third one.

As Figure 8 is observed and as values are obtained by means of the equations generated by the linear regression method, jointly with the application of such procedure since 1989, the following considerations can be presented:

i. The water levels in March explain 73% of annual floods and even with a lower precision it has an advantage for preventive actions, since March levels, in general, do not cause an emergency. The simulation can be done with Equation 2, with the interval of variation of the expected flood estimated at ±35 cm to the result of the probable flood estimate (Hc).

$$\text{Hc (cm)} = 0.598.\ \text{HMAR} + 1324.00 \tag{2}$$

ii. The water levels in April explain 88% of annual floods and provide better precision on the size of the future flood concerning the March forecast. The predictions of the probable flood can be made by Equation 3, and the range of variation of the expected flood is estimated by adding the value ±35 cm to the result of the probable flood estimate (Hc).

$$\text{Hc (cm)} = 0.796\ \text{HAPR} + 696.00 \tag{3}$$

iii. The water levels in May explain 95% of annual floods; however, in cases of large floods, due to the proximity to the period of maximum water levels, flooding situations in certain critical areas may be possible. The flood estimate can be made by Equation 4, while the variation interval is obtained by adding ±30 cm to the result of the probable flood estimate (Hc).

$$\text{Hc (cm)} = 0.920\ \text{HMAY} + 257.00 \tag{4}$$

iv. In Equations 2, 3 and 4, Negro river level on the forecast day is represented by HMAR, HAPR and HMAY.

v. From October to January, the degree of correlation is not significant. Therefore, it should not generate expectations of flooding, even with abnormal levels in this period.

4 RESULTS

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 March 31(first alert), April 30 (second alert) and May 31 (third alert). Statistical models of simple or multiple linear regressions are efficient for long-term prediction of Manaus flood peaks. The long-term average from 1903 to 2019 of the annual flood peak is 2788 cm, with a standard deviation of 115 cm, while the historical highest peak was 2997cm in 2012. Figure 8 illustrates the graph with the evolution of the highest water level in Manaus station, in which we can see that the 3rd forecast of the Manaus alert is the closest to the peak level of the Negro river in Manaus each year, considering the last 30 years of the forecast presentation.

Figure 9 shows the flood forecast in 2019, the same as presented in the case of the third flood alert, obtained by observing the historical series and the estimation made based on the linear regression model adopted. The third alert is the forecast closest to the flooding event, so the probability that the level of the Negro river level in the forecast is closer to the actual level is greater.

Figure 10 summarizes the latest forecasts of the Alert System and the water level observed in each year. Each alert forecast has a minimum and maximum range and an average water level. Thus, in this chart, it is possible to see that, in the interval of 15 years, from 2005 to

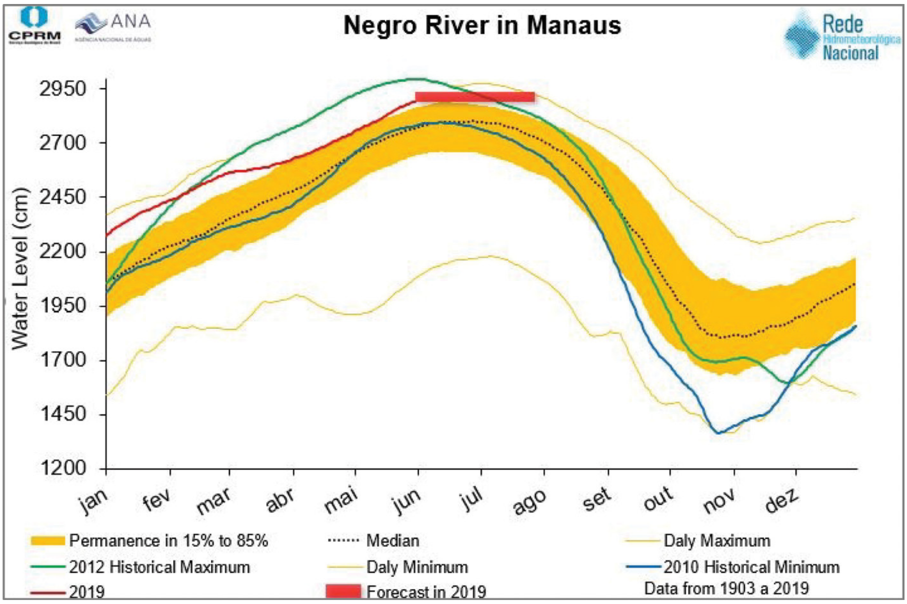

Figure 9: Third flood forecast in 2019 at Manaus station.

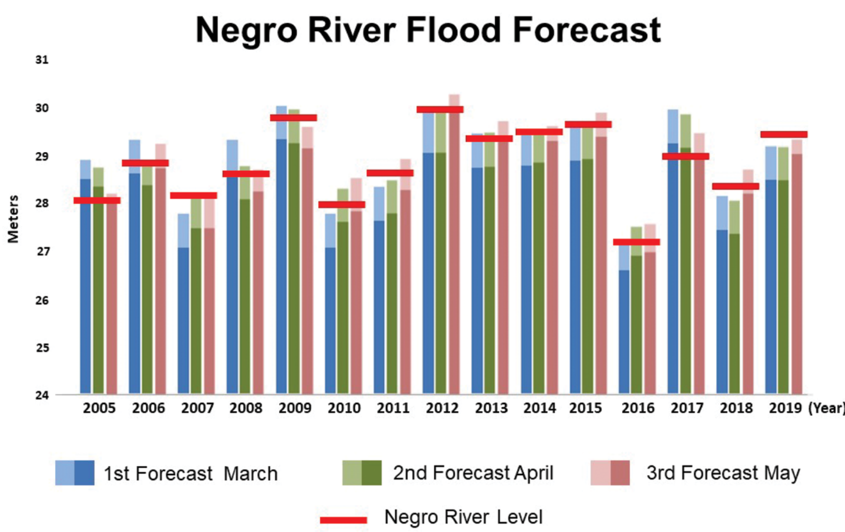

Figure 10: Alert forecasts and recorded maximum river level at Manaus Harbour.

2019, using the linear regression equation, there were 13 correct forecasts and 2 approximate forecasts, achieving an efficiency of 87%, which indicates that the forecast model is valid. Disclosure of the forecast is important, but what should be considered is the magnitude of the likely flood within the range of acceptable variations. Thus, the objective is more to have a better qualitative estimate with respect to the type of flood (large, medium, low) than to achieve an accurate quantitative estimative for the flood.

5 CONCLUSIONS

Predictive studies could be performed using the most diverse statistical and hydrological methodologies. On the other hand, we should emphasize that the most important task is to offer a reliable warning service to the population living on the banks and that depend on the river and mostly on its water level to guarantee their activities. For the 2005-2019 time span, from the last ten (10) major floods, six (6) are concentrated in the last ten years, a fact that highlights that these events can become more frequent.

Moreover, increasing knowledge can be generated and accumulated with respect to the dynamics of rising waters as universities and technical sectors get more involved in the study and especially in contributing to better manage waters along the Amazon basin. Under this framework, the developed procedure for estimating floods at Manaus Harbour intends to set the stage presenting a simple methodology based on a linear statistical regression equation that already provides useful and operational information to the management agencies in the region and to society. Taking that into account, we can foresee several types of hydrological models already developed and applied to the Amazon basin to be challenged in the sense of better estimating floods in order to compare with such type of operational procedure here-in presented.

More specifically, as reported, we consider a height of 27 m in Negro river as an alert water level or threshold with a return period of 10 years. When the river reaches a height of 29 meters, it is then 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. In this sense, it is worth noting that the annual flood peak is 2788 cm, with a standard deviation of 115 cm, while the historical highest water level was 2997cm in 2012. 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.

As a final word, hydrological studies, mainly along the Amazonian fluvial systems, are continuous and dynamic. The task of dealing with complexity and diversity in the Amazon basin goes beyond registering the water level and derive corresponding statistics, demanding the development of more integrated holistic studies and operational strategies to expand the ways of monitoring the rivers and disseminate the information to the populations directly and not directly physically involved.

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