MODELING OF AN EXTREME FLOODING EVENT IN THE AMAZON BASIN USING THE WRF-HYDRO MODEL

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Abstract: In the Amazon, the frequency of extreme events has been increasing notably in recent decades. In the months of April, May and June 2021, the city of Manaus faced the greatest flood in 119 years, reaching the Rio Negro a level of 29.98 m. In view of this, the present work aims to evaluate the performance of the WRF-Hydro model in simulating precipitation during an extreme flood event in the Amazon Basin. The simulations were performed with 1 km spatial resolution and 250 m channel network for the period from 04/30 to 06/05 2021. Such applications were evaluated using comparisons of the variability of accumulated precipitation with observed data from National Water Agency rainfall stations. The results showed a tendency for the model to underestimate the accumulated precipitation, slightly reproducing some observed precipitation patterns. It is concluded that the tool presents a capacity for precipitation estimation, with potential for operational purposes.

Keywords: Amazon; Rio Negro Basin; WRF-Hydro.

MODELAGEM DE UM EVENTO EXTREMO DE INUNDAÇÃO NA BACIA AMAZÔNICA UTILIZANDO O MODELO WRF-HYDRO

Resumo: Na Amazônia, a frequência de eventos extremos vem aumentando notadamente nas últimas décadas. Nos meses de abril, maio e junho de 2021, a cidade de Manaus enfrentou a maior cheia em 119 anos, chegando o rio negro em um nível de 29,98 m. Em função disso, o presente trabalho tem o objetivo avaliar o desempenho do modelo WRF-Hydro na simulação da precipitação durante um evento extremo de inundação na Bacia Amazônica. As simulações foram realizadas com resolução espacial de 1 km e rede de canais de 100 m para o período de 30/04 a 05/06 de 2021. Tais aplicações foram avaliadas usando comparações da variabilidade da precipitação acumulada com dados observados de estações pluviométricas da Agência Nacional de Águas. Os resultados mostraram uma tendência do modelo subestimar a precipitação acumulada, reproduzindo levemente alguns padrões observados de precipitação. Conclui-se que a ferramenta apresenta capacidade de estimativa da precipitação, com potencial para fins operacionais.

Palavras-chave: Amazônia; Bacia do Rio Negro; WRF-Hydro.

1. INTRODUCTION

Floods are among the most common natural disasters related to deaths, destruction, and economic losses in many places around the world. According to the World Water Resources Development Report (2021), during the period 2009-2019, floods caused nearly 55,000 deaths (including 5,110 in 2019 alone), affected another 103 million people (including 31,000 in 2019), and caused $76.8 billion in economic losses ($36.8 billion of which was in 2019 alone). Globally, flooding and extreme precipitation events have increased by more than 50% in the last decade, occurring at a rate four times higher than in 1980 [1].

In the Amazon, the frequency of extreme events has been increasing notably in recent decades. There is growing evidence that the hydrologic cycle of the Amazon basin has intensified since the late 1990s [2]. A prominent feature of the changing hydrology of the Amazon is the occurrence of recent floods that are usually widespread and sometimes severe for those living very close to the rivers, but urban areas are usually more socially affected than rural areas [3].

In the months of April, May and June 2021, the city of Manaus faced the greatest flood in 119 years, reaching the Rio Negro a level of 29.98 m. According to [4], extreme events of drought and flood were quantitatively defined when daily water levels in Manaus fall below 15.8 m or rise above 29 m, respectively [2], and flood: rise in river level, between 20 and 26 m.

The Negro River basin is inserted in the great Amazon Basin, inheriting, therefore, the same natural characteristics of that region. Despite the differences in the size of the basin, the water levels of the lower Negro River, in Manaus, are influenced by the main course of the Solimões-Amazonas. During the flood period, the Rio Negro is barred by the Solimões River (backwater effect) causing flooding in the city of Manaus [3].

Hydrological modeling, proposed in this work, using the coupling of Hydrological Models with Numerical Weather Prediction Models (NWP), aims at understanding the hydrological processes of the Earth's surface [5]. The main model of this type, Weather Research and Forecasting Model (WRF) - Hydro, the object of this work, was originally conceived as a coupled model framework designed to facilitate the coupling of the Weather Research and Forecasting Model (WRF) and land hydrologic model components [6] and [7]. The WRF-Hydro system represents the state of the art with respect to water resources and enables improved representation of land surface flows and terrestrial hydrologic processes related to the spatial redistribution of surface, subsurface, and channel waters at very high spatial resolution (typically 1 km or less) using a variety of physics-based approaches [6].

The WRF-Hydro modeling system was developed by NCAR (US National Center for Atmospheric Research) in partnership with NASA (National Aeronautics and Space Administration) to simulate flooding, hydrometeorological variables, spatial distribution of water resources [1], with the goal of providing an enhanced numerical tool to meet worldwide needs for water resources planning, environmental impact assessment, risk prediction, and mitigation. Further details when the numerical and computational structure of the model can be obtained in [3].

This model has been tested and recognized as a powerful tool in several studies in different watersheds around the globe. Recently, for example, [8] and [9] use WRF-

Hydro for operational flood forecasting in the Sarantapotamos basin in Greece and the USA, respectively. [10] estimates the flow of the Brahmaputra River located between India and Bangladesh, verifying good results in model performance. [5] simulates typical 24-hour storm events, providing a reference for model application. In Brazil, the works of [11], [12] and [6] applied the WRF-Hydro model in Brazilian watersheds.

In this context, the main objective of this study is to simulate the precipitation and river level of the Rio Negro in the extreme event of a flash flood in the Rio Negro watershed located in the Amazon between April 30 and June 6, 2021, causing deluge, flooding, and inundation in the city of Manaus registering the largest flood in history since records began in 1902. For this first work the model precipitation output data will be initially analyzed, to later examine the modeled river elevation data in the next steps of this study. In addition, to validate the capability of WRF-Hydro, the simulated data is compared with data collected by ANA (Agência Nacional de Águas) telemetric stations located along the course of the Black River. The study of these events, as well as estimates of hydrometeorological variables are of great importance, since there are no data from stations along the entire river bed and such data constitute indispensable information for projects of structures for harnessing water resources, besides providing efficient planning and management of these resources.

2. METHODOLOGY

2.1 Study area description

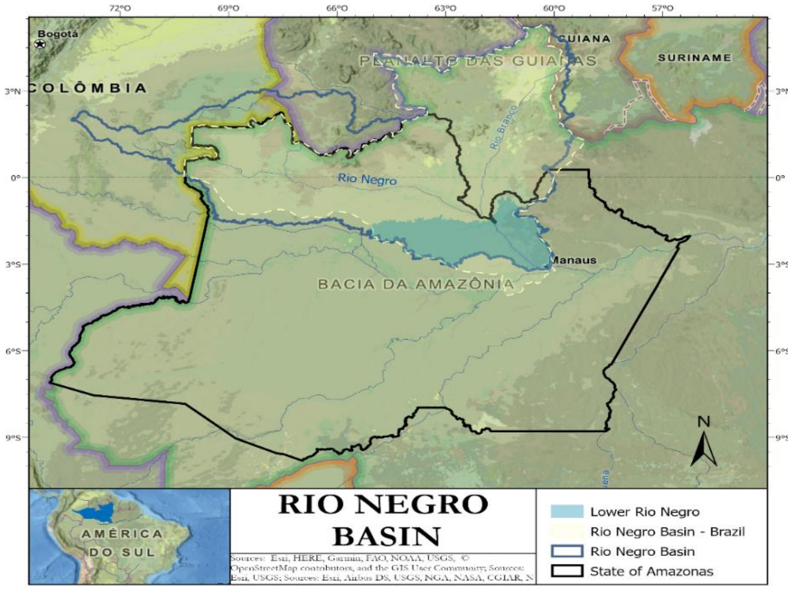
The Negro river basin in Amazonia has a total surface area of about 696,810 km², occupying areas in four countries: 82.8% in Brazil, 9.9% in Colombia, 5.9% in Venezuela and 1.5% in Guyana. The Negro River is formed by the confluence of the Uaupés and Içana rivers. From this point it receives contributions from several tributaries, of which we can highlight: Cassiquiare river, Demini river and, mainly, Branco river (tributaries on the left margin). Near Manaus, the confluence of the Negro River and the Solimões River occurs and the Amazon River is formed [13].

The headwaters of the Black River are located in Colombia, where it is called the Guiania River. When it enters Brazil through the North of the State of Amazonas it is called the Black River, and runs for about 1,700 km until its mouth in the Amazon River, having 1,070 km of rivers with favorable conditions for navigation [14].

The Rio Negro Basin has the wettest climate in the Amazon Basin, with average annual rainfall values between 2,000 and 2,200 mm, reaching levels greater than 3,500 mm in the upper Rio Negro region. The river's flood period is from May to August, while the dry period is from December to February [15].

The city of Manaus, located in the lower Rio Negro, is commonly affected by extreme rainfall events of a damaging nature in recent decades, however, recent floods are not only occurring more frequently, but have also become more severe, exceeding a duration of 70 days or a level of 29.7 m [3]. In this regard, the present study aims to simulate the extreme event of flash flood between April 30 and June 05, 2021, causing flash floods and flooding in the city of Manaus and the level of the ruler of the Port of Manaus reached 30 m on 06/05/2021. Then the statistical comparison of the data simulated by the coupled model (WRF-Hydro) with the observed data was performed. Figure 1 illustrates the basin under study and its location.

Figure 1. Rio Negro Basin



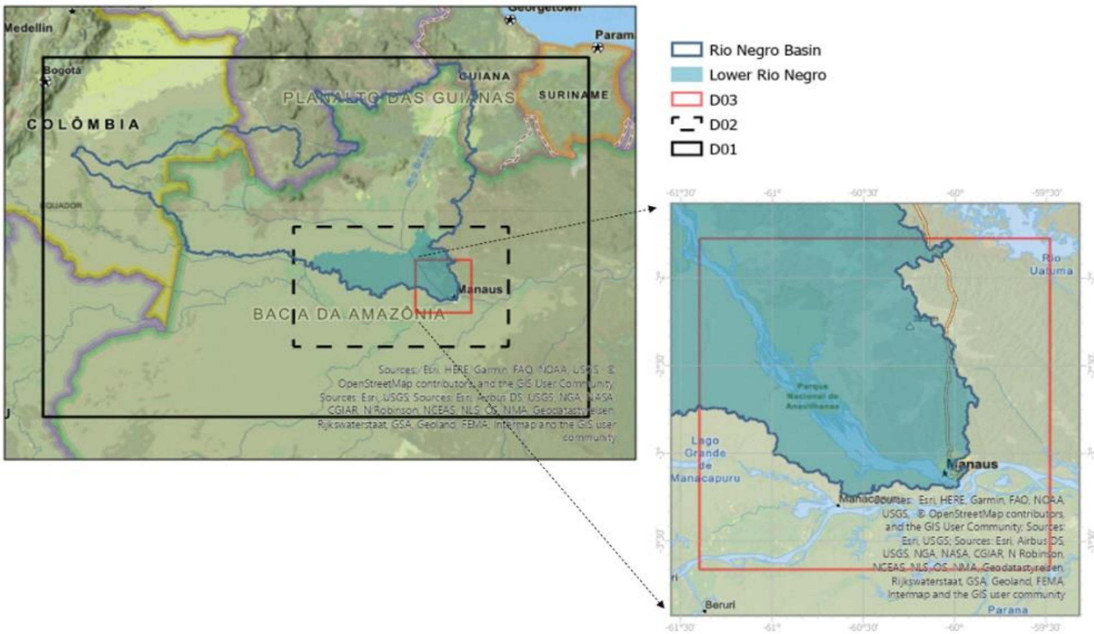
Source: Author (2021).

2.2 Simulation details

2.2.1 The WRF Model

The Numerical Weather Prediction Model (NWP) WRF, produces high resolution (1-10 km) simulations of meteorological variables such as precipitation [1]. The WRF model (version 3.6) was used to generate initial conditions of soil moisture, soil temperature, soil water content, temperature of the topmost soil layer, atmospheric forcing, among other variables for the WRF-Hydro model run over the basin under study, covered by three nested domains of 9, 3 and 1 km resolution, as presented in Figure 2.

Figure 2 – Location of the three nested domains in Rio Negro Basin



In Figure 2, the domain of interest (D03) has a horizontal resolution of 1 km and 35 vertical levels with model top pressure set at 50 hPa. An overview of the spatial configurations is shown in Table 1.

Table 1. Details of the model configuration

Region	**Domain**	**Horizontal resolution**	**Cell numbers**	**Number of levels η**
	D01	9 km	232x160	
Bacia do	D02	3 km	274x160	35
Rio Negro	D03	1 km	214x211	

The simulation was started at 0000 UTC on 04/29 extending until 1800 UTC on 06/05. The first 24 hours of simulations were considered as "spin-up", which is the model adjustment time and excluded from the evaluations. The initial and boundary conditions employed in the simulations come from the NCEP-FNL (National Centers for Environmental Prediction - Final Analysis), with horizontal resolution of 0.25° x 0.25° and temporal resolution of six hours. The topography and land use and land cover data are provided by the USGS (United States Geological Survey).

The WRF model presents several physical parameterizations that must be chosen according to the characteristics of the site under study and the objective that one wishes to achieve. Based on the existing literature, the physical parameterizations shown in Table 2 were chosen.

Table 2. Physical parameterizations of the WRF model

Category	**Parameterization Selected**
Microphysical processes	WRF Single-Moment 3-class
Cumulus option	Grell-Freitas
Planetary boundary layer	Mellor-Yamada Nakanishi and Niino
Surface Layer	MM5 similarity
Radiation scheme	RRTMG
Land surface model	Noah MP
Projection	Lambert

1.2.2 The WRF-Hydro Model

When generating the input files for the WRF-Hydro model, the file with routing data of the hydrographic channel network with a resolution of 100 m was created, using the pre-processing tool ArcGIS Pro (Geographic Information System – GIS). This tool creates high resolution fields in routing grids such as flow direction, underground flow and channel routing processes required to be used as input data in the WRF-Hydro model.

WRF-Hydro mainly includes a Land Surface Model (LSM) module and a hydrologic module that provides a framework of multiple land physics options, including surface water and groundwater flow, channel flow, and reservoir or bucket model to account for river base flow. In this study, WRF-Hydro version 5.2.1 was configured in its fully coupled mode for running with WRF. The main settings of WRF-Hydro are shown in Table 3.

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Table 3. The parameterizations of coupled WRF-Hydro model

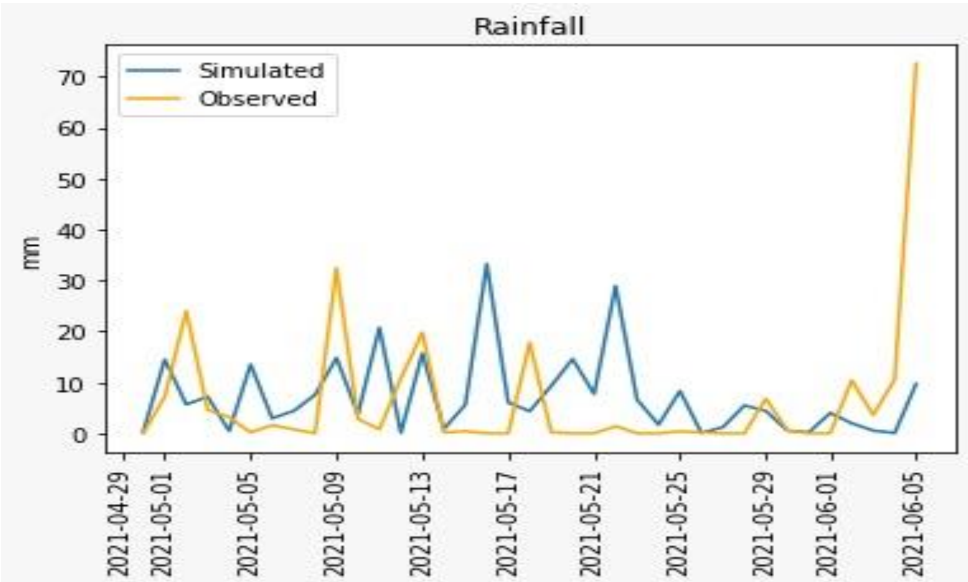
Category	**Parameterization Selected**
NWP model	WRF model
Land surface model	Noah LSM
Subsurface flow (i.e., Interflow)	Distributed hydrology soil and vegetation model
Overland flow	D8 method
Baseflow	Exponential storage-discharge function
Channel routing	Diffusive wave-gridded

After the simulations of the WRF- Hydro model data for the period under study, data post-processing was performed. Daily observational data from telemetry stations monitored by ANA were used to validate the simulation.

3. RESULTS AND DISCUSSION

Among the meteorological variables, precipitation is the most difficult to be estimated using numerical models. The spatial and temporal discontinuity of the mechanisms that control the formation of precipitation in each region has different factors, depending on the location and time of year. The verification of extreme precipitation events on a regional scale is a complex task. But among all the difficulties in simulating this variable, Figure 4 shows the results of the simulations of the WRF-Hydro model in the simulated values when compared to those observed in the ANA rainfall.

Figure 3. Daily behavior of simulated and observed accumulated precipitation



As it is possible to verify in Figure 3, this period was marked by a great volume of precipitation that triggered the rise in the level of the Negro River, causing flooding in the city of Manaus. When analyzing the graph one can see that WRF-Hydro underestimates the precipitation values on most days. It is also observed that the model was able to capture some rainfall peaks, reasonably reflecting the rainfall distribution characteristics.

The performance of the WRF-Hydro model was evaluated by comparing simulated precipitation data with observed data at the location of interest. The statistical evaluation procedure was used and relied on the following parameters: in the indices written below (Eqs. 1, 2, and 3), o and p refer to the observed and model-predicted measurements, respectively. The bar indicates mean and "σ "the deviation.

NMSE (Normalized Quadratic Error) $= \overline{(X_o - X_p)^2} \Big/ \overline{X_p}\,\overline{X_o}$, (1)

FAT2 (Factor of two), fraction of data that are between $0.5 \leq (X_p / X_o) \leq 2$, (2)

MBE (Mean error) $MBE = \frac{1}{n}.\sum_{i=1}^{n}(X_p - X_o)$. (3)

The NMSE parameter reflects the dispersion of the measured values. The best results are achieved when the values of NMSE and MBE are close to zero, the value of FAT2 close to one. Table 4 presents the statistical metrics calculated for model performance analysis.

Table 4. Statistical comparison between observed and simulated data

Station	NMSE	MBE	FAT2
Manaus	2,97	-7,28	0,42

By analyzing the statistical indicators (Table 4), the MBE is negative, indicating a tendency to underestimate the accumulated precipitation. When analyzing the Factor of 2, corresponding to the dispersion of the points, it was below 0.5, showing a high deviation between the estimated and observed data.

Finally, it should be recognized that the number of sampling points (rainfall stations) used in this study is small, considering the high spatial variability of precipitation in this region. However, the low density of rainfall stations (active and/or with a consistent data series), is still characteristic of the northern region of the country.

4. CONCLUSION

The present work is characterized as an initial study to evaluate the performance of the WRF-Hydro model in simulating precipitation during an extreme flood event in the Amazon region.The presented results show that the simulations obtained values with low agreement index, underestimating them in most of the period. However, this tendency to underestimate the WRF-Hydro occurs due to lack of calibration in the model initialization. For the next steps the simulated river level data will be analyzed, as well as the sensitivity tests of the model in response to different parameterization schemes. Finally, the WRF-Hydro model shows itself to be a computational tool with great potential in water resource management and risk estimation and mitigation.

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