Modeling of an Extreme Flooding Event in the Amazon Basin Using the WRF-Hydro Model

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In the Amazon, the frequency of extreme events has been increasing notably in recent decades. In April, May, and June 2021, the city of Manaus faced the greatest flood in 119 years, and the Rio Negro reached at a level of 29.98 m. Because 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 a 250 m channel network from April 30 to June 5, 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. We concluded that the tool presents a capacity for precipitation estimation, with potential for operational purposes.
Keywords: Amazon. Rio Negro Basin. WRF-Hydro.

Introduction

Floods are among the most common natural disasters related to deaths, destruction, and economic losses in many places. 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 April, May, and June 2021, the city of Manaus faced the greatest flood in 119 years, reaching the Rio Negro at a level of 29.98 m. According to Bittencout and Amadio [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, and flood: rise in river level, between 20 and 26 m [2].

The Negro River basin is inserted in the great Amazon Basin, inheriting the same natural characteristics of that region. Despite the differences in the basin size, the water levels of the lower Negro River in Manaus are affected 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 principal model of this type, the Weather Research and Forecasting Model (WRF) - Hydro, is the object of this work. It 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 according

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De Souza and colleagues an Gochis and colleagues [6,7]. The WRF-Hydro system represents the state-of-the-art for water resources and also enables a better 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).It was created to simulate flooding, hydrometeorological variables, and the spatial distribution of water resources [1], to provide an enhanced numerical tool to meet worldwide needs for water resources planning, environmental impact assessment, risk prediction, and mitigation. Further details about the numerical and computational structure of the model can be described by Maciel and colleagues [3].

This model has been tested and recognized as a powerful tool in several studies in different watersheds around the globe. Recently, for example, Galanaki and colleagues [8] and Kim and colleagues [9] use WRF-Hydro for operational flood forecasting in the Sarantapotamos basin in Greece and the USA, respectively. White and colleagues [10] estimate the flow of the Brahmaputra River located between India and Bangladesh, verifying good results in model performance. Liu and colleagues [5] simulate typical 24-hour storm events, providing a reference for model application. In Brazil, the works of De Souza and colleagues [6], White and colleagues [11], and Silva and colleagues [12] 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 from April 30 and June 6, 2021, which caused deluge, flooding, and inundation in the city of Manaus registering the major flood in history since records began in 1902. For this first study, the model precipitation output data was 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 are compared with data collected by ANA (Agência Nacional de Águas) telemetric stations located along the course of the Rio Negro. The study of these events estimates hydrometeorological variables, and was of great importance since there are no data from stations along the entire river bed and such information is considered essential for projects of structures for harnessing water resources, besides providing efficient planning and management of these resources.

Material and Methods

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: the 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 also have 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 floods 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.

<u>Simulation Details</u>

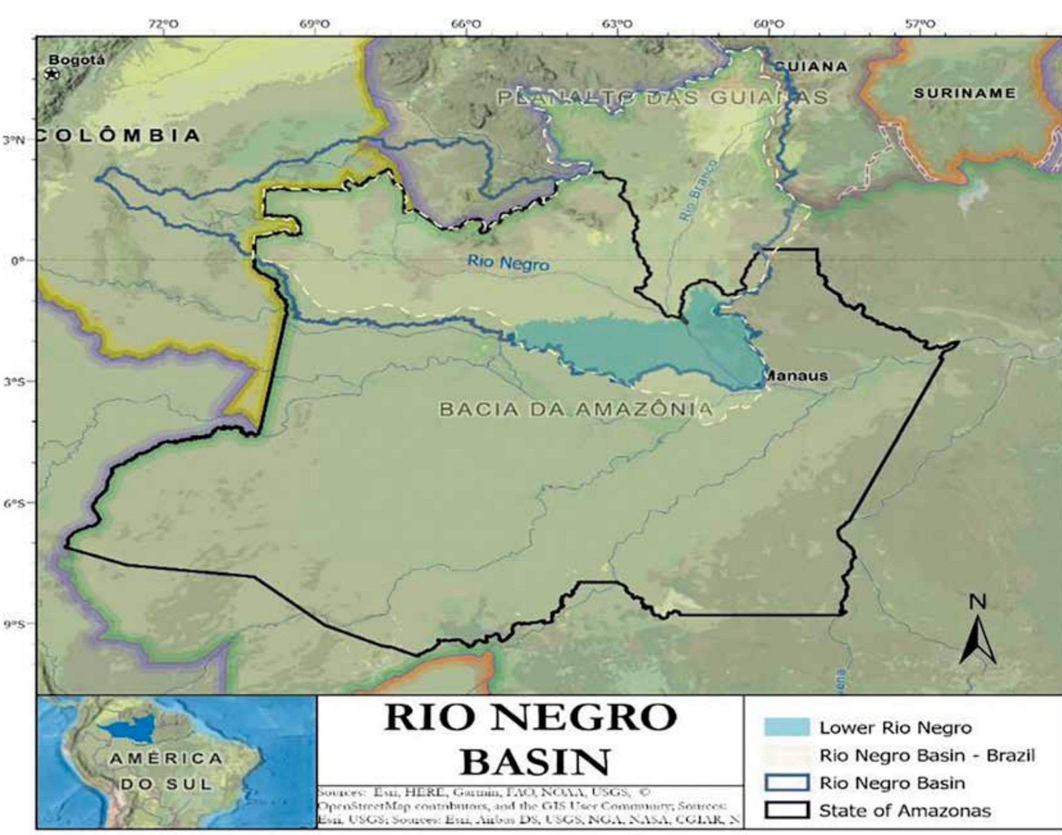
The WRF Model

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, the temperature of the topmost soil layer, and 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 (Figure 2).

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. Table 1 shows an overview of the spatial configurations.

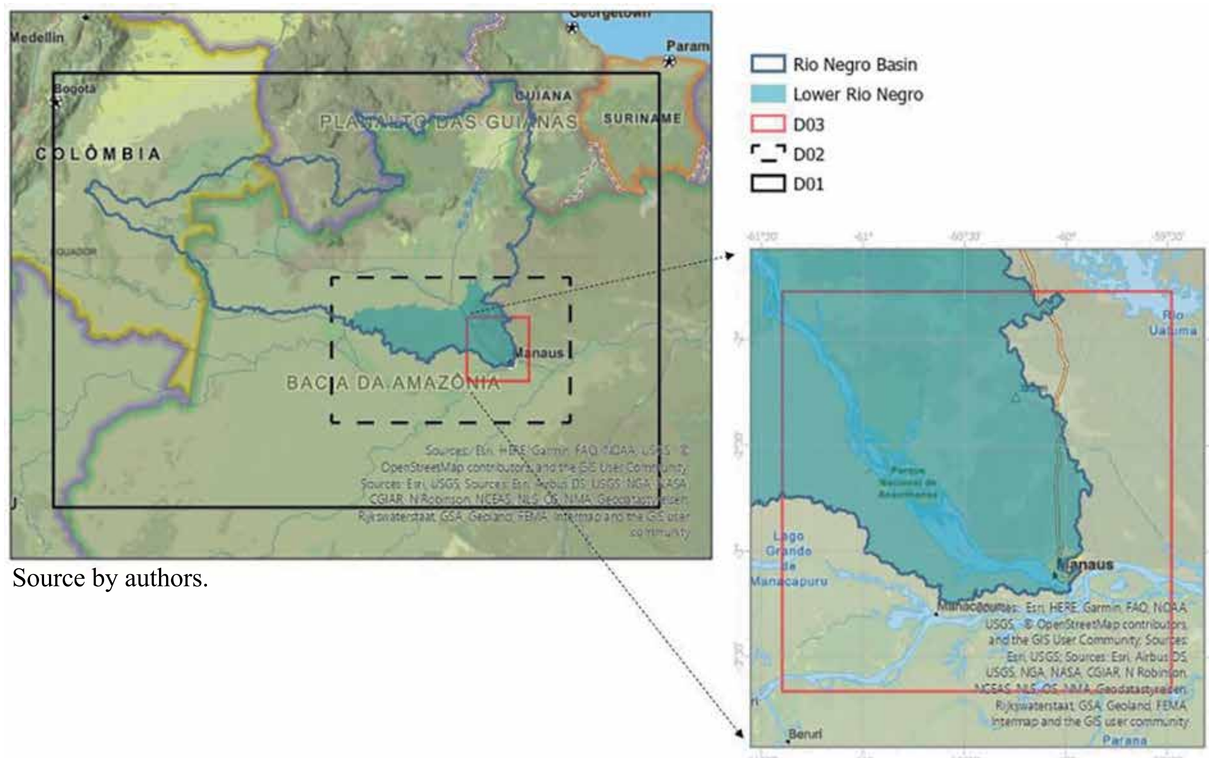
The simulation was started at 0000 UTC on 04/29, extending until 1800 UTC on 06/05. The first 24 hours of simulations were considered as spin-up, which is the model adjustment time, and it was excluded from the evaluation performance. The initial and boundary conditions employed in the simulations come from the NCEP-FNL (National Centers for Environmental Prediction - Final Analysis), with a horizontal resolution of 0.25° x 0.25° and temporal resolution of six hours. The topography

Figure 1. Rio Negro basin.



Source by authors.

Figure 2. Location of the three nested domains in the Rio Negro basin.



Source by authors.

Table 1. Details of the model configuration.

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

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 local under study and the objective that one wishes to achieve. Based on the existing literature, the physical parameterizations (Table 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. Table 3 shows the main settings of WRF-Hydro.

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.

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 extreme precipitation events on a regional scale is a complex task. Figure 4 shows the results of the simulations of the WRF-Hydro model in the simulated values compared to those observed in the ANA rainfall.

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.

Analyzing the Figure 3, we can note that WRF-Hydro underestimates the precipitation values on most days. It is also observed that the model can 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 the mean and σ the deviation.

NMSE reflects the dispersion of the measured values. The best results are achieved when while for NMSE and MBE are close to zero, and the value of FAC2 was close to one. Table 4 presents the statistical metrics calculated for model performance analysis.

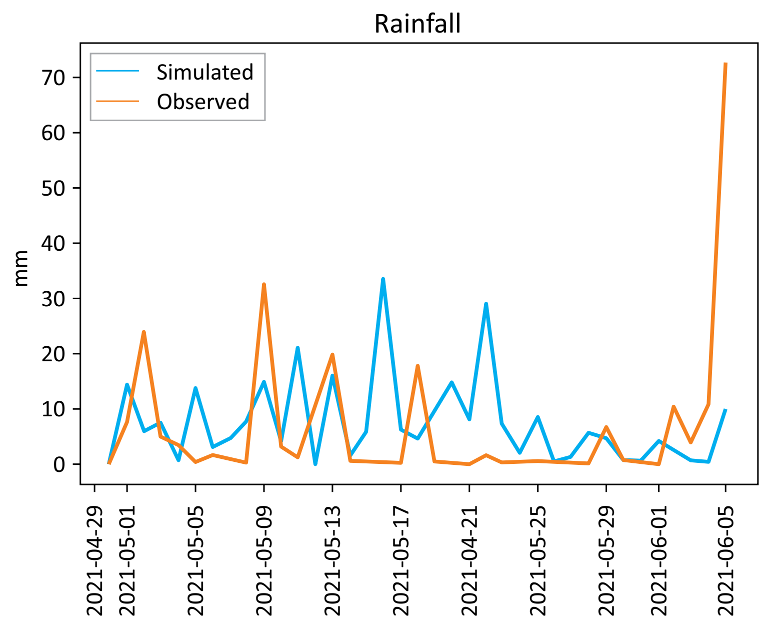
Table 2. Physical parameterizations of the WRF model.

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

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

Figure 3. Daily behavior of simulated and observed accumulated precipitation.



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

FAC2 (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)

By analyzing the statistical indicators (Table 4), the MBE is negative, indicating a tendency to underestimate the accumulated precipitation. It was below 0.5, suggesting a high deviation between the estimated and observed data. Finally, we 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.

Table 4. Statistical comparison between observed and simulated data.

Station	NMSE	MBE	FAC2
Manaus	2.97	-7.28	0.42

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 a low agreement index, underestimating them for most of the period. However, this tendency to underestimate the WRF-Hydro occurs due to a 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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