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Performance analysis of the lisflood hydrological model in a flood event in the madeira river basin

Abstract

The largest recorded flood of the Madeira River (largest tributary of the Amazon River) occurred in 2014, remaining above the flood level for 90 days, reaching the maximum level on March 30, at 19.69 m. Among the various tools capable of assisting in monitoring and forecasting floods are hydrological models, such as LisFlood, a distributed hydrological model of the rainfall-runoff type. Thus, the objective of this research was to evaluate the performance of the LisFlood model for maximum flows in the Madeira River basin. There were a total of 7 river gauge stations calibrated and subsequently validated, distributed across 5 sub-basins. The calibration process was carried out using a multi-objective method, applying the NSGA II as an optimization algorithm, with the model's performance being evaluated by the NSE and KGE metrics. The calibration and validation results demonstrated, in general, that the LisFlood model performed well between the simulated and observed flow values for the Madeira River basin. The average of the 07 stations analyzed was 0.81 for KGE and 0.69 for NSE, for the calibration process. In validation, the average metrics were 0.78 in KGE and 0.67 in NSE. In relation to the historic flood event that occurred in 2014, it can be seen that the model followed the maximum flow peak observed at the Porto Velho station, with a difference in the simulated flow of 17% lower than the observed flow, for the year 2014, demonstrating good efficiency of LisFlood in simulating maximum flow. Thus, the study demonstrated that the application of the LisFlood model in large basins is effective in simulating maximum flows, satisfactorily simulating extreme flood peaks.

Keywords: flooding, hydrological model, calibration, river madeira, lisflood

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Abbreviations: CPRM, mineral resources research company; JRC, joint research center; ANA, national water and basic sanitation agency; ECMWF, European center for medium-range weather forecast; SNIRH, national water resources information system; MMAyA, ministry of environment and water of Bolivia; CEMADEN, national center for natural disaster monitoring and alerts; NSGA II, non-dominated sorting genetic algorithm *II;* NSE, nash-sutcliffe efficiency; KGE, kling-grupta efficiency

Introduction

The Madeira River, located at the confluence of the Beni and Mamoré rivers on the border between Brazil and Bolivia, serves as the primary tributary of the Amazon River, encompassing approximately 23% of the vast Amazon basin. This river holds immense significance for the economic and social advancement of the region, owing to its navigability, which facilitates the transport of both passengers and cargo. Furthermore, the Madeira River basin plays a pivotal role in supporting agricultural irrigation and the generation of electrical energy, further contributing to the area's overall development (ANTAQ, 2011 as cited in Vergasta et al., 2021).[1]

In 2014, the Madeira River experienced the largest flood event ever recorded, with waters persistently exceeding flood levels for a 90 days. This unprecedented inundation culminated on March 30th, when the river reached a peak level of 19.69 m.[2] This calamitous event had far-reaching repercussions, severely impacting both economic and social activities within the region.

The flood led to the suspension of vital waterway services and the closure of the BR-364 highway, exacerbating the crisis in the municipalities of Guajará-Mirim, Nova Mamoré, Abunã, and the entire State of Acre. These communities found themselves cut off from the rest of Brazil, amplifying the isolation and challenges faced during this critical period.[3]

After this historic flood, the Madeira River Crisis Room was created, coordinated by the National Water Agency – ANA, with the participation of several public and private institutions, allowing monitoring and forecasting the evolution of floods.[2]

Among the various tools capable of assisting in flood monitoring and prediction are hydrological models. In this context, LisFlood, a distributed rainfall-runoff hydrological model developed by the Joint Research Center (JRC) of the European Commission, emerges as a pivotal instrument for monitoring and providing early flood warnings.[4] LisFlood's application has predominantly been within the European continent, serving diverse purposes in water resource studies, including flow forecasting, regulatory initiatives, and drought monitoring. Currently, its most prominent applications are within the EFAS (European Flood Alert System) and GloFAS (Global Flood Awareness System, v3.1) frameworks.[5]

Given the significant socioeconomic relevance of the Madeira River basin in the northern and central-western regions, it becomes imperative to broaden the array of tools available for hydrological monitoring. Therefore, the aim of this research was to assess the performance of the LisFlood model for maximum flows in the Madeira River basin. In this way, experimenting with a new tool to be used in Madeira's flood control.

Materials and methods

The study area of this research is represented in Figure 1, with the municipality of Porto Velho, in the State of Rondônia, at its most downstream limit. The spatial data used in this study encompassed topography, hydrology, land use, and various other factors. These datasets, essential for our analysis, were provided by the JRC group. Additionally, the meteorological variables utilized in this research were sourced from reanalysis products furnished by the European Center for Medium-Range Weather Forecast (ECMWF - ERA5). It is important to note that all the data employed maintained a consistent spatial resolution of 10 km.

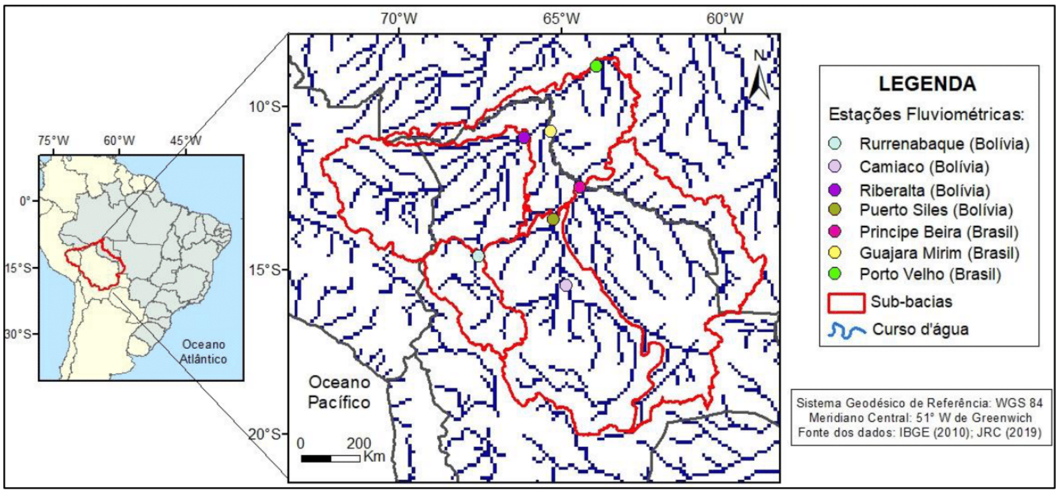

Figure 1 Location of the study area and analyzed fluviometric stations.

Source: Author.

To facilitate our hydrological assessment, a total of seven fluviometric stations were calibrated and subsequently subjected to rigorous validation. These stations were strategically distributed across five sub-basins. It's noteworthy that for the purpose of this process, we did not incorporate data pertaining to reservoirs and lakes.

The historical datasets for stations within Brazil were sourced from the ANA National Water Resources Information System (SNIRH/ANA). For stations situated in Bolivia, the observed flow data were obtained through a collaborative effort between Cemaden and the Ministerio de Medio Ambiente y Agua de Bolivia (MMAyA). To ensure the reliability of our results, calibration and validation periods were established in alignment with the uninterrupted observed flow data available for each fluviometric station. In most cases, the calibration phase spanned a decade (from 2000 to 2010), while the validation phase encompassed up to seven years (from 2010 to 2017).

The LisFlood hydrological model used in this study is a spatially distributed model designed to be applied over a wide range of spatial and temporal scales. LisFlood is grid-based, and applications so far have employed grid cells of as little as 100 metres (for medium-sized catchments), to 5,000 metres for modelling the whole of Europe and up to 0.1° (around 10 km) for modelling on a global scale. Although the model's primary output product is channel discharge, all internal rate and state variables (soil moisture, for example) can also be written as output. Among the various processes included in LisFlood, standard components described below and represented in Figure 2 stand out.[5]

I. a 3-layer soil water balance sub-model;

II. sub-models for the simulation of groundwater and subsurface flow (using 2 parallel interconnected linear reservoirs);

III. a sub-model for the routing of surface runoff to the nearest river channel;

IV. a sub-model for the routing of channel flow

The calibration process was conducted using a multi-objective approach, with the NSGA II optimization algorithm applied. This process involved the calibration of nine parameters, as detailed in Table 1. Following each execution of the LisFlood model, a series of simulated flow rate values was generated. These simulated values were then used to compute efficiency metrics by comparing them with the observed values. In assessing the model's performance, we employed the Nash-Sutcliffe Efficiency[6] and Kling-Grupta Efficiency metrics (KGE - Kling, Fuchs, Paulin, 2012),[7] which have the mathematical equations:

Equation 1: $NSE = 1 - \sum_{i=1}^{n} \frac{\left(Q_{c(i)} - Q_{o(i)}\right)^2}{\left(Q_{o(i)} - Q_{o(i)}\right)^2}$

Equation 2: $KGE = 1 - \sqrt{(r-1)^2 + (\alpha-1)^2 + (\beta-1)^2}$

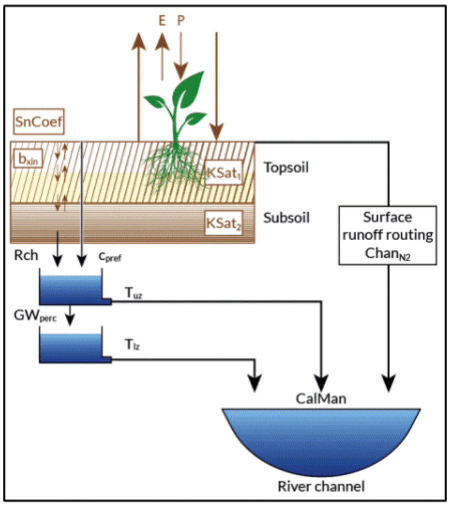

Figure 2 Overview of the LISFLOOD model. *P*: precipitation; *E*: evaporation & evapotranspiration; *SnCoef*: snow melt; *bxin*: infiltration; *ChanN2*: surface runoff; *GWperc*: drainage from upper- to lower groundwater zone; *Tuz*: outflow from upper groundwater zone; *Tlz*: outflow from lower groundwater zone; *Rch*: drainage from subsoil to upper groundwater zone; drainage from top- to subsoil; *Cpref*: preferential flow to upper groundwater zone. Source: Van der Knijff, DE Roo, 2020.

Table 1 Parameters used for LisFlood calibration

Parameter name	Description	Units
Upper Zone Time Constant	Time constant for the upper groundwater zone	[days]
Lower Zone Time Constant	Time constant for the lower groundwater zone	[days]
Gw Perc Value	Groundwater Percolation	[mm day-1]
Gw Loss	Loss of groundwater	[mm day-1]
b-Xinanjiang	Infiltration capacity of water in the soil	[-]
Power Pref Flow	Power in the preferencial flow equation	[-]
Cal Chan Man1	Multiplier applied to Manning's roughness (drainage channel)	[-]
Cal Chan Man2	Multiplier applied to Manning's roughness (second routing line)	[-]
Adjust Normal Flood	Applied to potential evapotranspiration rates	[-]

Legend: $Q_{o(i)}$ is the observed streamflow, $Q_{c(i)}$ is the streamflow calculated by model at time-interval i (Eq. 1). And r is the linear correlation observations and simulations, α a measure of the flow variability error, and β a bias (Eq. 2). Ultimately, from the array of resulting solutions, we made an empirical selection, opting for the solution that offered the most favorable balance between the various evaluated metrics.

Results

In general, the LisFlood model demonstrated commendable performance when it came to aligning simulated and observed flow values within the Madeira River basin, as illustrated in Table 2. Across the seven stations under analysis, the KGE averaged at 0.8144, while the NSE stood at 0.6994 during the calibration phase. However, during the validation stage, the model experienced a slight regression in its performance, with the KGE averaging at 0.7859 and the NSE at 0.6752. For a visual representation of this comparison, please refer to Figure 3, where you can observe graphs depicting the side-by-side contrast between observed and simulated flow data.

Table 2 Metric results for calibration and validation

Fluviometric Station	KGE		NSE	
	Calibration	Validation	Calibration	Validation
Rurrenabaque (Bolívia)	0.7099	0.6334	0.554	0.5849
Camiaco (Bolívia)	0.8517	0.8549	0.7208	0.7112
Riberalta (Bolívia)	0.7718	0.8157	0.6887	0.6295
Puerto Siles (Bolívia)	0.8946	0.7879	0.8186	0.5928
Príncipe da Beira (Brazil)	0.8471	0.7641	0.6903	0.7554
Guajará Mirim (Brazil)	0.745	0.7532	0.6338	0.6218
Porto Velho (Brazil)	0.8809	0.8925	0.79	0.831

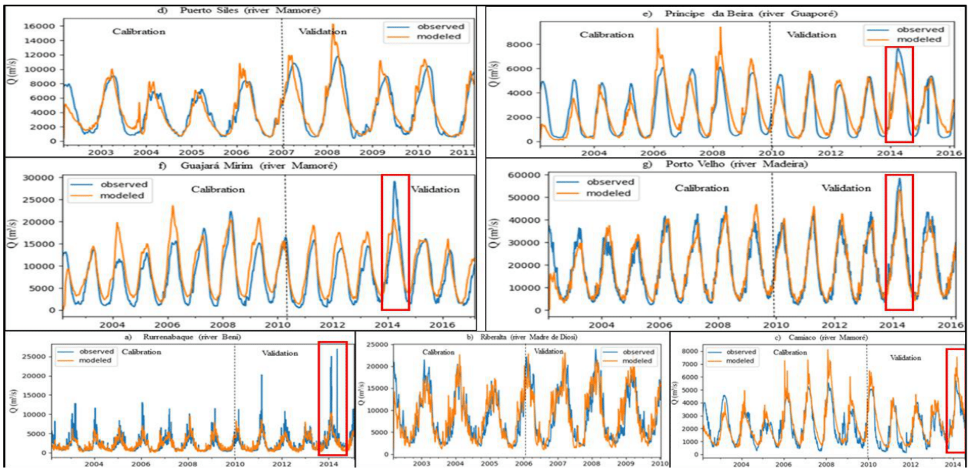

Figure 3 Comparison of observed flow (blue) and simulated flow (orange) for the calibration and validation period for the 07 fluviometric stations. Highlighted in red for the period of the greatest flooding in the basin.

Discussion

At the furthest downstream station, Porto Velho, a crucial monitoring point for Madeira's flood assessment, the LisFlood model exhibited outstanding performance. During the calibration period, the KGE yielded a value of 0.8809, and this excellence continued into the validation phase, recording value of 0.8925. These results underscore the model's exceptional suitability for this specific location, a sentiment corroborated by the NSE metric's satisfactory performance.

In the context of the historic flood event of 2014, the LisFlood model closely tracked the observed peak flow at the Porto Velho station. Notably, the simulated flow registered a mere 17% deviation below the observed flow for the year 2014, underscoring the model's efficacy in replicating maximum flow dynamics.

In the broader context of the Madeira River basin, it is evident that there were instances where the simulated flow surpassed the observed flow, indicating a propensity for flow rate overestimation. This overestimation could potentially be attributed to a factor contributing to the diminishing modeling accuracy of LisFlood. Moreover, it is crucial to take into account the precipitation variable employed within the model. Given that it relies on reanalysis data, there exists the possibility of inconsistencies with the actual climatic conditions prevalent in the region. This disparity between model inputs and real-world climate data may also play a role in influencing the model's performance.

Conclusion

This study underscores the efficacy of utilizing the LisFlood model in extensive river basins, particularly in accurately simulating maximum flow scenarios. The model's ability to satisfactorily replicate extreme flood peaks, such as those observed in the 2014 event within the Madeira River basin, showcases its potential as a valuable tool for conducting hydrological research and flood event monitoring in Brazil.

Looking ahead, it is advisable to extend the application of LisFlood to various river basins, exploring its capabilities in studying not only maximum flow dynamics but also minimum flow conditions and flow regulation. This broader application will contribute to a comprehensive understanding of its versatility and utility in addressing a wide range of hydrological processes.

Acknowledgments

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Conflicts of interest

The author declares there is no conflict of interest.

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