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Mechanisms and scenarios of the unprecedent flooding event in South Brazil 2024

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Abstract. In May 2024, an extraordinary precipitation event in southern Brazil triggered record floods in South Brazil, specially over a complex system that includes rivers as Jacuí and Taquari, draining into Guaíba and Patos Lagoon. It resulted in unprecedented impacts on local population and infrastructure. Considering past observations and projections indicating an increase in flood events in the region due to climate change, understanding the flooding processes in the region is essential for better preparing cities for future events like the May 2024 flood. In this context, hydrodynamic modelling serves as an important tool for reproducing and analysing this past extreme event. This study aims to assess the detailed hydrodynamic mechanisms and processes that occurred during this historical flood event and scenarios of direct interventions for flood control that came into the public debate after the event. The focus is on the most populated areas at the Metropolitan region of Porto Alegre (RMPA) capital city. We calibrate and validate a two-dimensional hydrodynamic model to accurately replicate the May 2024 flood. The results demonstrated that the model accurately represents the 2024 May flood, with average NSE, RMSE and BIAS of 0.82, 0.71 meters and -0.47 meters, respectively, across the main rivers in the basin. Furthermore, the flood extent simulation represented 83% of the affected area, as compared to high-resolution satellite images. Our analysis of the mechanisms that influenced the event showed that the Taquari River was the main responsible for the peak in the RMPA, while the Jacuí River contributed the most to the duration of the flood. The synchronization of the flood peaks from both rivers could have increased water levels by 0.82 meters. Evaluated hydraulic interventions for flood mitigation demonstrated that the effectiveness of the proposed measures varied by location, with usually low influence in the RMPA water levels (lower than 0.38 m). Major lessons related to the behaviour of river-lagoon hydrodynamic systems and to the relevance of structural measures for such cases are discussed, which are of broader interest for future research and decision making around the globe.

1. Introduction

The May 2024 flood that occurred in South Brazil can be considered the worst natural disaster in Brazilian history given its magnitude, spatial coverage and impacts (Collischonn et al., 2025). The flood affected hundreds of thousands of people, displacing entire neighborhoods, causing widespread damage to urban infrastructure and agricultural lands, while also leading in numerous fatalities.

Floods becomes a major concern and one of the most relevant disasters in terms of impacts, with the potential to disrupts societies on a unprecedent scale. The rising frequency and severity of flood events are closely linked to ongoing climate change, as global temperatures increase due to global warming (IPCC, 2021), affecting the hydrological cycle and leading to more intense and frequent rainfall events (Alfieri et al., 2016; Burrell et al., 2007; Goodess, 2013; Wasko et al., 2021). However, the relationship between climate change and flood is complex, with impacts vary regionally and influenced by multiple factors (Blöschl, 2022; Goodess, 2013).

Floods in southern Brazil, situated at the sub-tropical and temperate portions of South America, have increase significant in recent decades, which has been supported by both historical data and climate projections (Ávila et al., 2016; Bartiko et al., 2019; Brêda et al., 2023; Chagas et al., 2022). These studies suggested an increase in heavy rainfall events and maximum discharge in the region due to climate change, but also attributing to changes of the El Niño-Southern Oscillation (ENSO) and in the South American Convergence Zone (SACZ). In instance, Chagas et al. (2022) analysed streamflow data across South America and showed that flooding in Southern Brazil is on the rise and indicating a possible link with ENSO variations. Breda et al. (2023) demonstrated that different climate models, based on CMIP5 scenarios, predict a continued increase in flood frequency due to heightened extreme precipitation events in the region. The same southern regions of Brazil experienced catastrophic flooding in May 2024, triggered by extreme rainfall that surpassed previous water level record.

The major impacted areas in southern Brazil during the May 2024 floods are situated in the Rio Grande do Sul State (RS), including the capital city Porto Alegre. Rainfall observed data indicated that precipitation has exceeded 500 millimeters within a two-day period, with some locations accumulating up to 900 millimeters in 35 days (Collischonn et al., 2024). As consequence, flood has achieved breaking-record levels in many cities in the Patos Lagoon basin, which covered half of Rio Grande do Sul state. Several impacts in population and cities infrastructure were observed in the Metropolitan Region of Porto Alegre (RMPA), where nearly 40% of the state's population (over 4 million people) resides. According to official government surveys, approximately 300,000 people were directly affected by the flood in the RMPA, with the situation worsened by the failure of flood protection systems. Given these devasting impacts, there is a critical need to employ advanced assessments tools such as hydrodynamic modeling, to better understand and manage such extreme events. A complete comprehensive hydrological description the disaster is given by Collischonn et al. (2025).

The Patos Lagoon basin, where the main May 2024 disaster occurred, is a single natural system in the world. The watershed is constituted by a combination of fast mountainous rivers and one large slow floodplain river downstream, all flowing to a relatively short and wide river named Guaíba River (which is also called a lake due to its physical characteristics), and downstream the Guaíba inflows to the Patos Lagoon itself, which is an extensive water body and the greatest choked lagoon in the world (Kjerfve, 1986). After the disaster, many questions were raised regarding the function of the natural system: the relevance of the upstream rivers, the slopes generated by water inflows and even if extra outlets in the lagoon to the sea would not have avoided the flooding at upstream areas (Hunt et al., 2024; Silva et al., 2024a). From our understanding the tool to answer some of those questions is a hydrodynamic model capable of properly representing the system, that must be properly validated using gauge observations but also state-of-the-art remote sensing data.

Hydrodynamic modelling has been widely used for flood assessment, including models such as HEC-RAS (USACE, 2016), LISFLOOD-FP (Bates and De Roo, 2000) and Delft3D (Lesser et al., 2004). These are physically-based models to represent flow across natural systems, providing accurate flood propagation and extent. Additionally, they have the ability to reproduce floods with high-resolution details, enabling the reconstruction of record-breaking events and the simulation of various scenarios.

Among different applications, Neal et al. (2011) assessed the 2007 United Kington floods using the LISFLOOD-FP two-dimensional model to simulate water levels in urban areas, validating flood extent with satellite imagery. Marengo et al. (2023) utilized HEC-RAS 2D model to examine flood inundation extent resulting from an extreme precipitation event in Recife, Northeast Brazil. In southern Brazil, there are few studies using hydrodynamic models to evaluate historical water levels in the Patos Lagoon basin (Alves et al., 2022; Fernandes et al., 2001, 2002; Möller et al., 1996). Alves et al. (2022) evaluated the ability of large-scale models to generate flood maps, comparing results with satellite image and flood extent from 2D hydrodynamic flood simulations. Fernandes et al. (2001) calibrated and validated the TELEMAC-2D model to simulate water levels over the Patos Lagoon, finding good agreement with observational data.

This study aims to enhance our understanding of flooding mechanisms in South Brazil, using the May 2024 flood as a benchmark, with focus on the RMPA region. Beyond being the first detailed hydrodynamic assessment of this unprecedented event at this singular environment, the present research is of broad interest due to other several reasons: a benchmark is set in terms of flood modelling validation using a two-dimensional hydrodynamic model and multiple data sources for RMPA; for the first time on authors knowledge altimetry information from SWOT mission (Biancamaria et al., 2016; Fu et al., 2024) is used to validate the modelling of such an extreme event; the contribution of each river was evaluated, as well as an assessment of a river peak synchronization scenario that could have worsened the event; the relevance of structural solutions for extreme floodings for environments controlled by both upstream and downstream characteristics is discussed; lessons and examples that can be used by decision makers from other locations with similar issues around the globe are discussed.

2. Study Area

The Patos Lagoon basin encompasses 182,000 km² (**Figure 1a**), with its headwaters situated in Rio Grande do Sul's north-central region, characterized by deep canyon valleys transitioning into vast lowlands. The primary upstream tributaries, Taquari, Jacuí, Caí, Sinos and Gravataí River, converge at the Jacuí Delta, forming a substantial estuary that leads the Guaíba River (**Figure 1b**).

The Guaíba River, an important freshwater system in Rio Grande do Sul, plays a key role in providing drinking water, supporting navigation, and facilitating irrigation for the area. Located adjacent to Porto Alegre, the state capital, it has an

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averaged depth of 2 meters, with certain spots reaching over 30 meters near its outlet to the Patos Lagoon. Spanning approximately 10 km in width and 50 km in length, the river covers roughly 480 km².

Water from the Guaíba River flows into the Patos Lagoon, which stretches across a considerable area (250 km in length and 40 km in width), with an average depth of 5 meters, before connecting to the coastal ocean. Consequently, tidal fluctuations influence the downstream water levels in the Patos Lagoon basin. Furthermore, wind forces significantly impact both the Patos Lagoon and the Guaíba River, with prevailing winds oriented in a NE-SW direction across the state. The wind changes the wate level in both systems, with SW (NE) wind restricting (facilitating) Guaíba flow into the Patos Lagoon, increasing (decreasing) Guaíba water levels up to 50 cm (Collischonn et al., 2025; Laipelt et al., 2025).

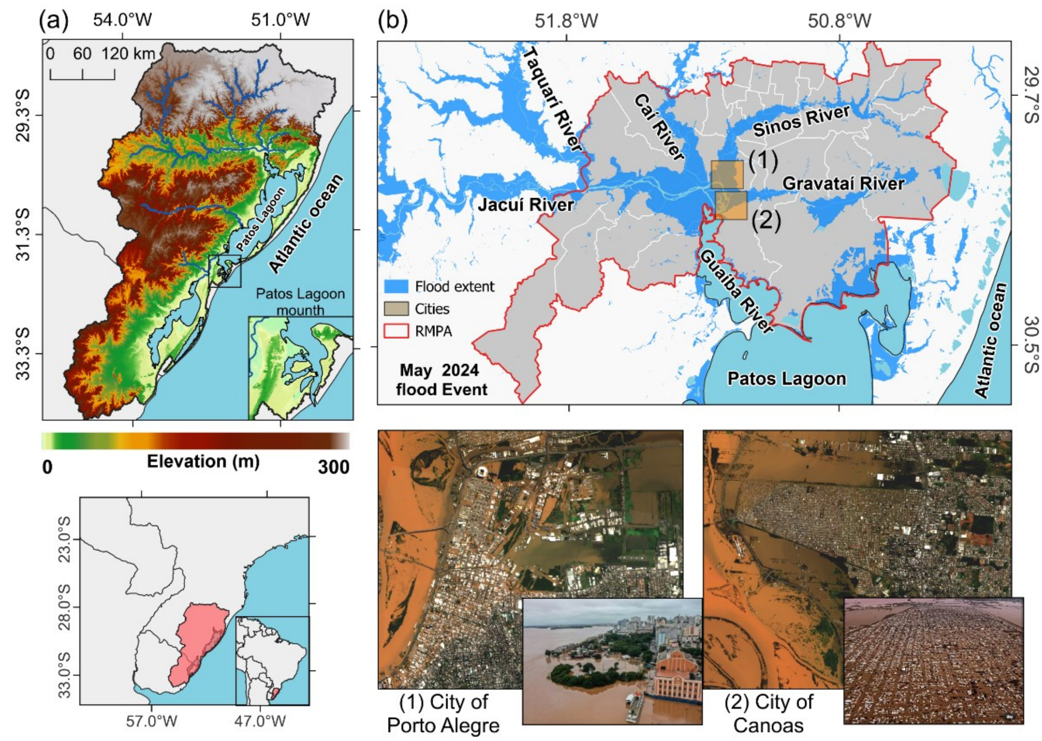

Figure 1: The Patos Lagoon basin, located in southern Brazil, features a mouth that connects to the Atlantic Ocean (a). The basin is fed by several primary tributaries, including the Taquari, Jacuí, Gravataí, Sinos, and Caí (b). These rivers experienced unprecedented flooding during the event in May, affecting densely populated as the state's capital, Porto Alegre, and cities in the Metropolitan Region of Porto Alegre (RMPA). Satellite imagery of the flood on 5 May 2024 is from © 2024 Planet Labs PBC.

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3. Material and methods

3.1. Digital terrain model and bathymetry

For the two-dimensional simulation of the flood, we used the ANADEM Digital Terrain Model (DTM) product provided by the Brazilian Water and Sanitation Agency (ANA). ANADEM is a freely available DTM for South America that was obtained from the COPERNICUS GLO-30 DEM provided by the European Spatial Agency (ESA) (AIRBUS, 2020) by removing vegetation bias (AIRBUS, 2020)(Laipelt et al., 2024).

To enhance the representation of the water bodies in the hydrodynamic simulation, modifications were implemented in the ANADEM product. For the Jacuí, Gravataí, Sinos and Caí Rivers, an interpolated bathymetry based on cross sections from different publicly available data was used, developed and validated by François (2021). Due to insufficient data for the Taquari River, we reduced the water elevation in the MDT by approximately 4 meters between the upstream boundary condition and the confluence with the Jacuí River, based on manually calibration. The bathymetry for the Guaíba River and Patos Lagoon was derived from digitalized nautical charts provided by the Board Hydrography and Navigation of the Brazilian Navy. Lastly, we incorporated the ocean bathymetry from the General Bathymetric Chart of the Oceans (GEBCO) version 2024 (GEBCO, 2024) into the MDT to improve the representation of tidal dynamics in the Patos Lagoon estuary.

3.2. HEC-RAS model

We utilized HEC-RAS software (version 6.4.1) (USACE, 2016), developed by the U.S. Army Corps of Engineers, to simulate the May 2024 flood in the RMPA. The domain area coverage an area of 23,000 km² corresponding to a 650 km reach between upstream Jacuí and the Patos Lagoon outlet to the ocean. It was defined based on streamflow observations available during the flood event. Additionally, we included a 45 km portion of the ocean to represent the tidal effect in the simulation.

The simulation employed a two-dimensional hydrodynamic representation based on the shallow water equations. This model accounts for inertia and forces related to gravity, friction, pressure, turbulent viscosity, wind and Coriolis effects.

The simulation period ranged from April 28, 2024, to June 1, 2024, including a 10-day initial period for model spin up. We implemented a variable mesh resolution (**Figure 2b**), applying a 100-meter grid for primary rivers and floodplains, and a 500-meter grid for upland areas to enhance computational efficiency.

As upstream boundary condition, we used discharge time series from the main rivers of the the Patos Lagoon Basin. Data were acquired from the Brazilian Water and Sanitation Agency (ANA) network (https://www.snirh.gov.br/hidrotelemetria/, accessed in July, 2024) (**Figure 2a**). Detailed information is provided in **Supplementary Table 1**. For the downstream boundary condition, we utilized tidal level time series from the Brazilian coast monitoring system (SIMCosta) network (https://simcosta.furg.br/home, accessed in August, 2024), located at the Pato Lagoon mouth, which connects to the Atlantic Ocean.

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For meteorological inputs, we incorporated wind data from the National meteorological Institute of Brazil (INMET) (https://bdmep.inmet.gov.br/, accessed in August, 2024) to represent its impact on the Patos Lagoon and Guaíba River. Winds forces in the simulation were computed based on Eulerian method and using (Hsu, 2003) drag formulation, which assumes a logarithmic wind velocity profile, modifying the aerodynamic roughness length in the simulation.

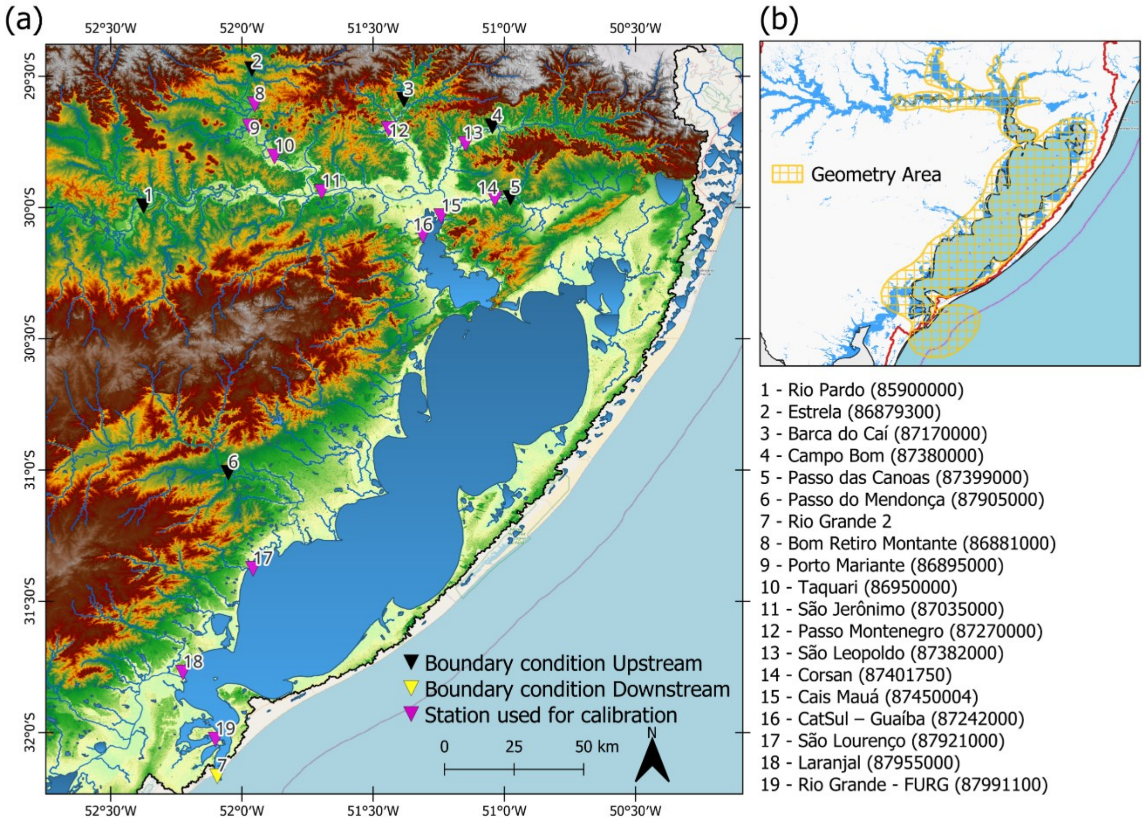

Figure 2: The locations and corresponding names of the gauge stations used for upstream conditions (black markers), downstream conditions (yellow markers), and calibration/validation (pink markers) are shown in (a). The delineated geometry area (yellow) used for the two-dimensional simulation is shown in (b).

Initial values of Manning's roughness coefficient were derived from the literature, followed by manual calibration for the study period to ensure optimal accuracy. **Supplementary Table 2** presents the Manning's roughness values utilized in this study, varying between 0.025 to 0.035 for the main channel and 0.08 to 0.3 for the floodplains. Prior studies have modelled Patos Lagoon basin using Manning coefficients between 0.015 to 0.04 (António et al., 2020; Hillman et al., 2007; Marques et al., 2009; Martins and Fernandes, 2004), while values for the Guaíba River have ranged from 0.025 to 0.040 (Marques et al., 2009; Possa et al., 2022; Seiler et al., 2020). In the absence of specific data, the calibration of Manning's coefficient for the main

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channel was based on general hydrodynamic applications (Chow, 1959). For the floodplain, Manning's roughness coefficient values were calibrated by testing a range from 0.05 to 0.15, following the HEC-RAS manual guidelines (USACE, 2016).

3.3. Water level, streamflow and flood extent validation

To evaluate the accuracy of the two-dimensional hydrodynamic model, we performed a validation of water levels, streamflow, and flood extent. We utilized water level time series from independent gauge stations situated across the study area, as outlined in **Figure 2a** (more details in **Supplementary Table 3**), excluding stations used for boundary conditions. The hydrodynamic model's performance was also evaluated using Surface Water and Ocean Topography (SWOT) observations (Biancamaria et al., 2016; Durand et al., 2010; Fu et al., 2024), as previous studies have shown that SWOT data adequately represented the flood event (Laipelt et al., 2025). SWOT is a collaborative effort between the Centre Nacional d'Éstudes Spatiales (CNES) and the National Aeronautics and Space Administration (NASA), providing high-resolution data for oceans and inland water bodies (rivers, lakes, reservoirs and wetlands). Equipped with a Ka-band interferometer sensor, SWOT provides instantaneous observations of water surface elevation (WSE) and water slope for rivers wider than 100 meters, with a revisit frequency of 21 days.

The accuracy of the flood extent generated by the two-dimensional model was verified using a high-resolution, clear-sky image captured on May 6, 2024, near the peak flow over the RMPA. This image was captured by the Planet RapidEye constellation (Planet Application Program Interface: In Space for Life on Earth. San Francisco, CA) which provides imagery with spatial resolution of 5 meters per pixel and includes four multispectral bands (blue, green, red, and infrared). To determine the flood extent from the Planet image, we calculated the Normalized Difference Water Index (NDWI) using **Equation 1**:

$$NDWI = \frac{(\alpha_{green} - \alpha_{infrared})}{(\alpha_{green} + \alpha_{infrared})} \qquad (1)$$

where α_{green} is the green band and $\alpha_{infrared}$ is the infrared band.

The accuracy of the simulated streamflow was evaluated by comparing it to 6 field measurements conducted using an Acoustic Doppler Current Profile (ADCP) instrument between May 5, 2024, and May 31, 2024 (Silva et al., 2024a). The measurements were collected from two areas close to the Cais Mauá station site, and the results are displayed in **Table 1,** and more details can be found in (Andrade et al., 2024).

Measurements on days 5 and 6 were made at the cross section of "Ponta da cadeia", while measurements on days 9 to 31 were made 8 km downstream, at the cross section of the "Ponta do Dionísio". Measurements at the "Ponta da cadeia" are possibly underestimations of the total river streamflow, since on days 5 and 6 water was flowing over the floodplains west of the main river, and over the islands of the Jacuí Delta region, by passing the "Ponta da cadeia" cross section.

Table 1: Gauge station used for calibration of the model as well as its location. Source: Silva et al. (2024) and Andrade et al. (2024).

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Date	Streamflow (m³/s)	Cross section
5 May 2024	30,180	Ponta da cadeia
6 May 2024	29,852	Ponta da cadeia
9 May 2024	23,000	Ponta do Dionísio
15 May 2024	22,069	Ponta do Dionísio
22 May 2024	8,355	Ponta do Dionísio
31 May 2024	7,989	Ponta do Dionísio

3.4. Performance metrics

The following metrics were used for the water level model's performance: Root Mean Square Error (RMSE), the Nash-Sutcliffe Efficiency coefficient (NSE) and the Mean Average Error (BIAS), as showed in **Equations 2**, **3** and **4**, respectively. To compare with the observations, the water level time series of the model were extracted from the simulation at the locations corresponding to the gauge stations.

$$RMSE = \frac{1}{2}\sqrt{\sum_{i=1}^{n}(O_i - P_i)^2} \quad (2)$$

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O_i})^2} \quad (3)$$

$$BIAS = \frac{1}{n}\sum_{i=1}^{n}(O_i - P_i) \quad (4)$$

where O_i is the observed and P_i the predicted values and n the number of samples.

The flood extent produced by the two-dimensional model was validated by comparing the percentual pixels agreement to the water mask satellite observation based on **Equation 5**. To ensure compatibility, we adjusted the satellite flood extent's spatial resolution to 30 meters, aligning it with the simulation-generated flood extent.

$$H = 100\% \frac{P_{sim} \cap P_{obs}}{P_{obs}} \quad (5)$$

where P_{sim} is the number of flood pixels obtained from the simulation and P_{obs} the number of flood pixels identified with satellite imagery.

3.5. Simulation experiments

The first main result is the model validation itself, which calculate values were compared to level gauges, streamflow measurements, flood extensions and SWOT altimetry data. These results are followed by studies of the hydraulic mechanisms of the flood, which included the relevance of each river that drains to the Guaíba River water levels and the assessment of the synchronization of the water level peaks that reach the Guaíba River.

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Finally, a set of hydraulic interventions experiments was organized. For each experiment, three scenarios were evaluated, varying the channel width from a feasible engineering solution for flood control (100-meter width) to a more challenging solution (500-meter width), with a median alternative (250-meter width). The channels were assigned a Manning's roughness coefficient of 0.02 and integrated into the MDT using HEC-RAS tools. Additionally, for these simulations, a refined mesh with a 50-meter cell size was used to model the intervention areas.

The following scenarios for flood control were tested:

Channel connecting Jacuí to Guaíba: This experiment investigated the construction of an open channel connecting the Jacuí and Guaíba River, as shown in **Figure 3a**. We tested multiple width scenarios (100, 250 and 500 meters), with 7000 meters in length, and its depth adjusted according to upstream and downstream bathymetric data for both rivers.

Channel connecting Patos Lagoon to the Ocean: The second experiment involved designing a hypothetical open channel connecting the Patos Lagoon to the Atlantic Ocean in the northeastern part of the lagoon (**Figure 3b**). In this evaluation, we applied a tidal water level time series, identical to that used for the downstream boundary condition of the Patos Lagoon, as the boundary condition at the channel's exit. The length of the channel was defined as 17,000 meters, with and 10 meters in depth.

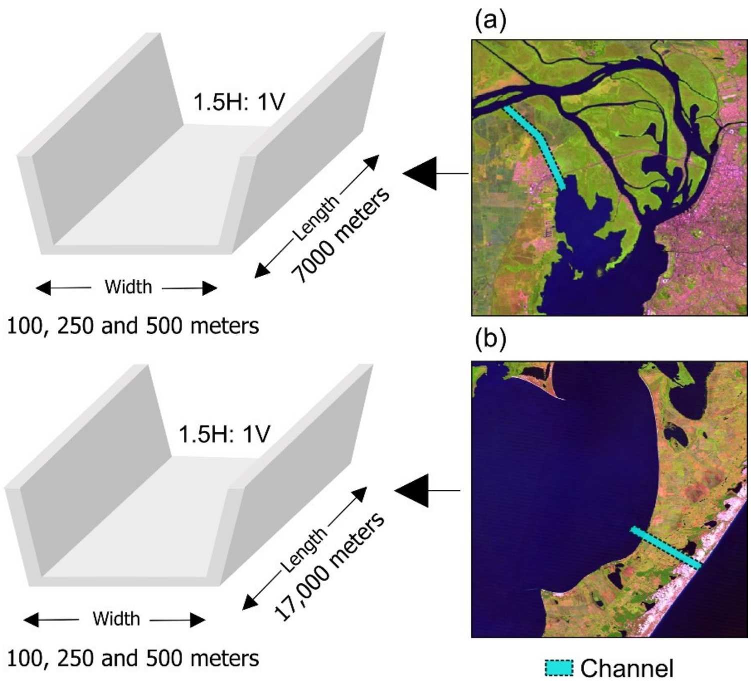

Figure 3: Three scenarios with different hydraulic structures were evaluated to mitigate flood in the RMPA. (a) An open channel connecting Jacuí and Guaíba River; (b) A channel connecting Patos Lagoon with the ocean. Image courtesy of NASA.

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4. Results and Discussion

4.1. Model Validation

4.1.1. Water level

Figure 4 shows a comparison between simulated water levels from the two-dimensional hydrodynamic model and measurements from gauge stations and SWOT. The simulation was able to capture the flow peak in most of the stations, showing an average BIAS of -0.47 meters between the water level peak in the stations, ranging from -2.17 meters in the Bom Retiro station to 0.36 meters in the Taquari station. On the other hand, low flow in the Taquari River stations were not captured by the simulation, with difference of -3.5 meters and -3.4 meters for Bom Retiro and Porto Mariante stations, respectively, suggesting an inconsistency with the representation of the river man channel in the MDT.

Performance metrics revealed an average NSE of 0.82, with a range of 0.68 to 0.92, The RMSE averaged 0.71 meters, with values ranging from 0.10 to 1.68 meters. Differences between simulated and observed water levels exhibited relatively low BIAS, ranging from -0.2 to 0.82 meters, with an overall average below 0.07 meters. An exception was noted at the Cais Mauá gauge station, where official records diverged from the simulation after May 15. This discrepancy is explained as a measurement error resulting from the emergency relocation of the station due to flood damage (Collischonn et al., 2024). To ensure accurate flood representation at the location, the simulation was also compared with data from a nearby experimental station (https://www.tidesatglobal.com/, accessed in September 2024), yielding a consistent agreement with the results (NSE=0.85; RMSE=0.32 meters; BIAS=-0.12 meters). Nevertheless, the metrics obtained demonstrated the essential requirements for a hydrodynamic model capable of providing locally relevant estimates (Fleischmann et al., 2019).

Additionally, the study compared simulated water levels with SWOT observations during the flood event. Both representations aligned well with water level observations from stations. The comparison between the simulation and SWOT observations revealed an average BIAS of 0.13 meters. SWOT data effectively captured water level variations along the main rivers of the Patos Lagoon basin, providing valuable validation for hydrodynamic simulations. **Figure 5** displays a profile line obtained by SWOT on May 6, (near the peak in the RMPA) compared with the simulation for the same overpass (~11h a.m.) between Jacuí River and Guaíba River. Both results exhibited similar water slopes, with SWOT observing a slope of 7.05 cm/km, while the 2D simulation indicated a slope of 6.45 cm/km. These findings underscore the severity of the flood event, as the water slope increased by almost 10 times compared to low flow conditions.

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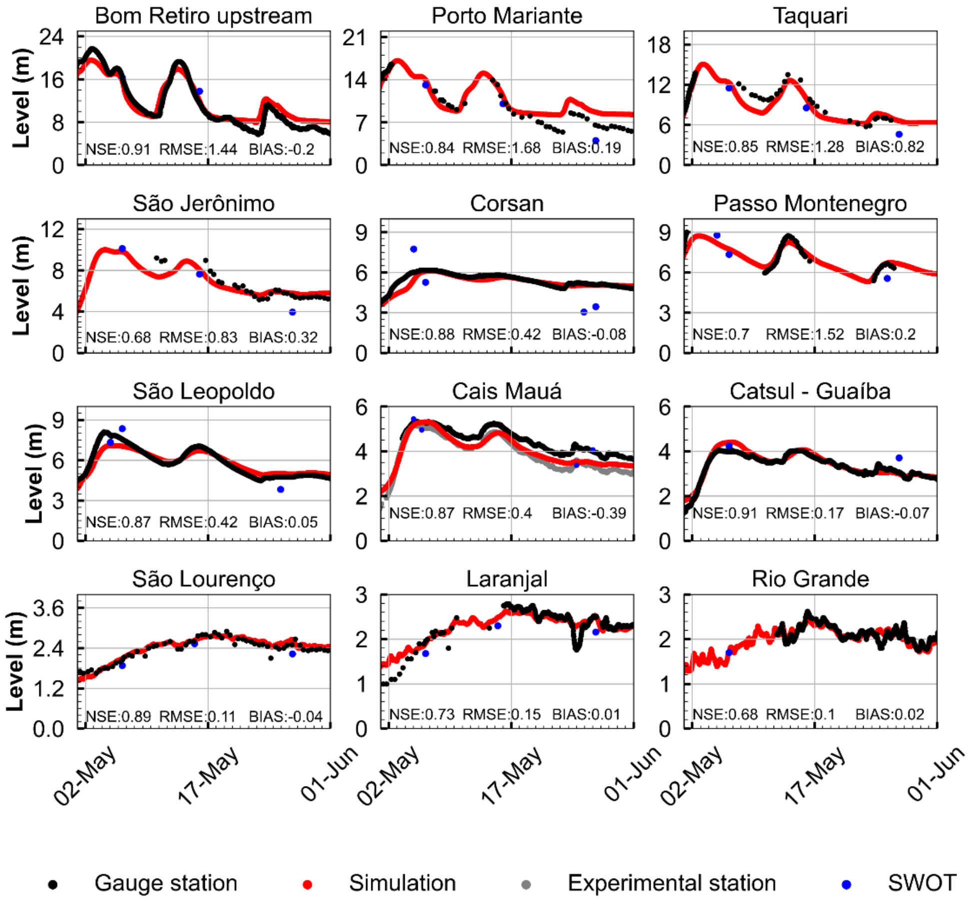

Figure 4: Water level simulations (red) compared to observations at nine-gauge stations observations (black) located in the study area. Water surface elevation (WSE) from the SWOT mission (blue). The grey line in the Cais Mauá plot corresponding to experimental.

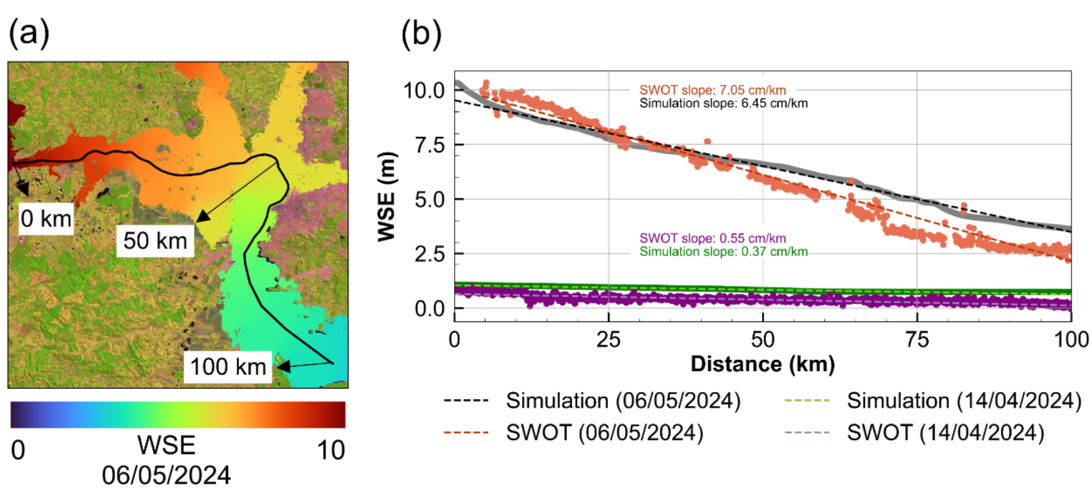

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Figure 5: Water surface elevation (WSE) slope from 2D simulation (a) compared with SWOT data observation from 6 May for a profile line between Jacuí and Guaíba River (b). Both results showed steep water slope changes (SWOT= 7.05 cm/km and Simulation = 6.45 cm/km) compared to low waters stable conditions (SWOT= 0.55 cm/km and Simulation = 0.37 cm/km). Image courtesy of NASA.

4.1.2. Flood extent

The comparison between the flood extent captured by high-resolution optical satellite imagery and that generated by 2D simulation is presented in **Figure 6**. While our validation was constrained to the flood extent within the simulation boundaries, excluding areas affected beyond, the model exhibited strong agreement with the flood extent observed in the May 6 satellite images. The simulation achieved an 83% agreement with the satellite data according to **Equation 5**. Nevertheless, this validation approach has certain limitations due to variations in peak flow across the basin. For instance, the satellite image timing aligns closely with the peak water levels in the RMPA, but it was captured approximately 5 days after the upstream peak (e.g., Taquari River).

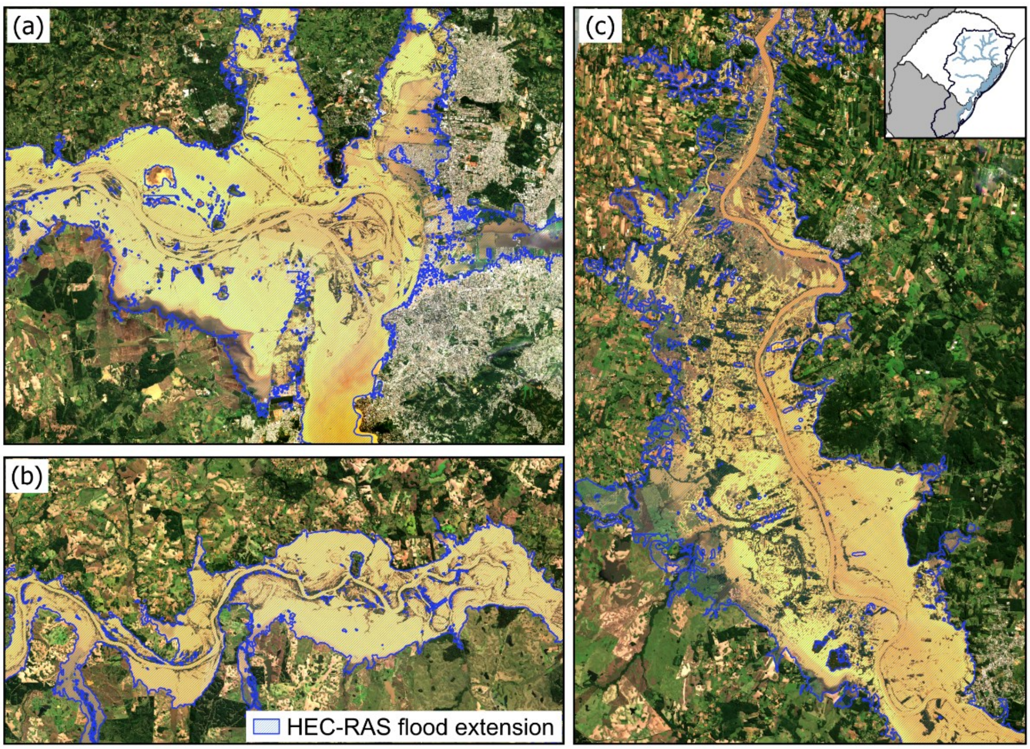

Figure 6: Validation of the flood extent, based on optical satellite images captured by the PlanetScope constellation on May 6 (© 2024 Planet Labs PBC), which was near the peak water levels in the RMPA. The simulated flood extent (indicated by the

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blue line) revealed a closely matched the satellite observations, including in the areas of the RMPA (a), Jacuí River (b) and Taquari River (c).

4.1.3. Streamflow

Simulated streamflow was compared to field measurements during the flood event, as shown in **Figure 7**. Measurements were collected from two nearby locations "Ponta do Dionísio" and "Ponta da cadeia" (**Figure 7a**). Due to their proximity of both sections (around 6 km), we only compared the simulation with the "Ponta do Dionísio" measurements, as they were very similar. The results indicated that both the magnitude and temporal progression of the simulated streamflow are similar to observations (**Figure 7b**). The peak streamflow observed was 30,180 m³/s on May 5 at 6:00 PM, while the simulation estimated 30,724 m³/s for the same time. The model's overall bias error was 1088 m³/s, corresponding to a percentage error of 5.4%, which is under the expected uncertainty of a measurements under this extreme condition (McMillan et al., 2018). For individual sections, the average errors were 1062 m³/s and 1115 m³/s for "Ponta da cadeia" and "Ponta do Dionísio", respectively.

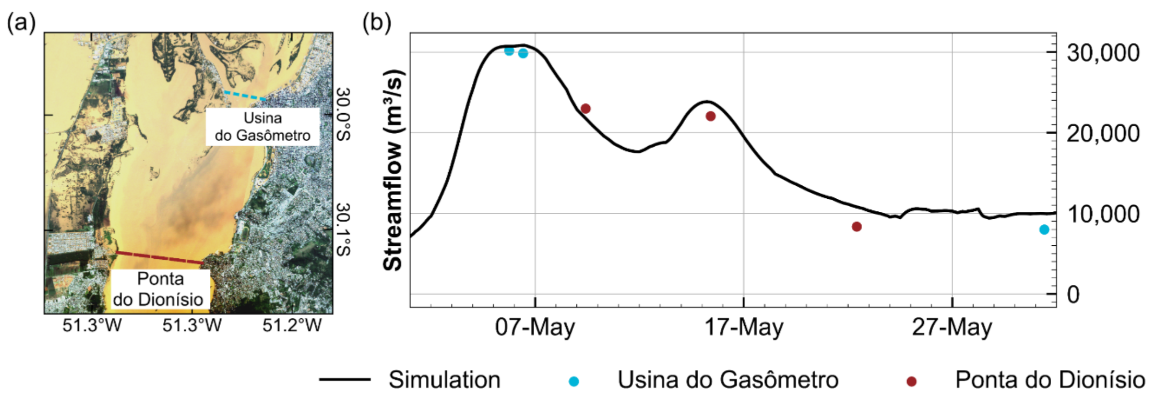

Figure 7: Streamflow observations were collected during the 2024 flood in the Guaíba River with Acoustic Doppler Current Profiler (ADCP) instrument in the Ponta do Dionísio (red dash line) and "Ponta da cadeia" (blue dash line) sections (a). Observations were compared with simulation data from the two-dimensional model, showing good agreement (b). Image courtesy of NASA.

4.2. Hydraulic mechanisms of the flood

Based on the validated model, we simulated different scenarios in the RMPA to better understand the hydraulic mechanisms that influenced the event. The contribution of the main rivers to the flooding in the RMPA was analysed by eliminating each river's contribution to assess its impact on flooding levels. Additionally, a possible extreme scenario was simulated, in which the peak flood of the main rivers (Jacuí and Taquari) was synchronized.

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4.2.1. River flood contribution

The analysis revealed that the Jacuí and Taquari rivers are the primary contributors to RMPA flooding, whereas the remaining rivers that flow into the Guaíba River (Caí, Gravataí, and Sinos) have a minimal effect on RMPA water levels in general. Our findings indicate that if the Taquari River's flood contribution were eliminated (**Figure 8**, yellow line), the maximum water level would drop from 5.4 to 4.2 meters, highlighting the Jacuí River's critical role in RMPA flooding. This scenario would also result in a delay of the peak water level by approximately 4 days compared to the May flood event. Conversely, removing the Jacuí River's contribution (**Figure 8**, blue line) would make the Taquari River the primary contribution. The Taquari River's flow characteristics would cause an earlier peak in the RMPA by about 1 day. Under these conditions, the peak water level would lower xx meters to 4.75 meters, and the flood behaviour would exhibit two peaks like the actual event (**Figure 8**, black line), unlike the scenario where the Taquari River's contribution was removed.

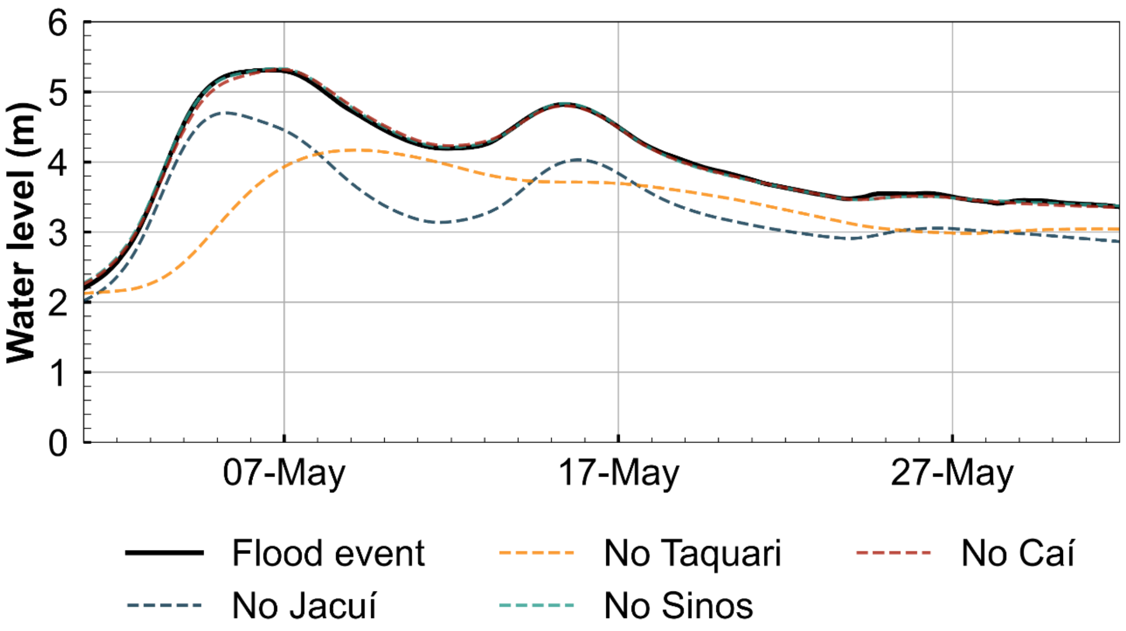

Figure 8: To evaluate the impact of each river on flooding, we eliminated the contributions of individual rivers (Taquari, Jacuí, Sinos, Gravataí, and Caí). This analysis revealed that the Jacuí and Taquari Rivers are the primary contributors to flooding in the RMPA. Excluding the Taquari River's input during the May flood would reduce the peak flood level to 4.25 meters, while removing the Jacuí River's contribution would result in a peak flood level of 4.75 meters. In both scenarios, the peak flood level would still exceed the flood threshold for RMPA cities.

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4.2.2. River flood synchronization

We accessed the contribution of Jacuí and Taquari Rivers for the flood in the RMPA. Considering that both rivers have distinct flow propagation regimes, we simulated a scenario in each both Jacuí and Taquari flood peaks would arrive at RMPA at the same time. After several testes, we anticipated the boundary condition hydrograph of the Jacuí River at Rio Pardo by approximately 4 days to represent maximum synchronization.

Figure 9 presented the result, which indicate an increase in the water level peak in the RMPA by 0.82 meters, whereas the flood extent in this scenario would have increase by 8% over the study area. In this hypothetical scenario, maximum water levels could have been nearly 6 meters, which is equivalent to the estimated to be the actual maximum flood level of the protection system of the city of Porto Alegre, the state's capital.

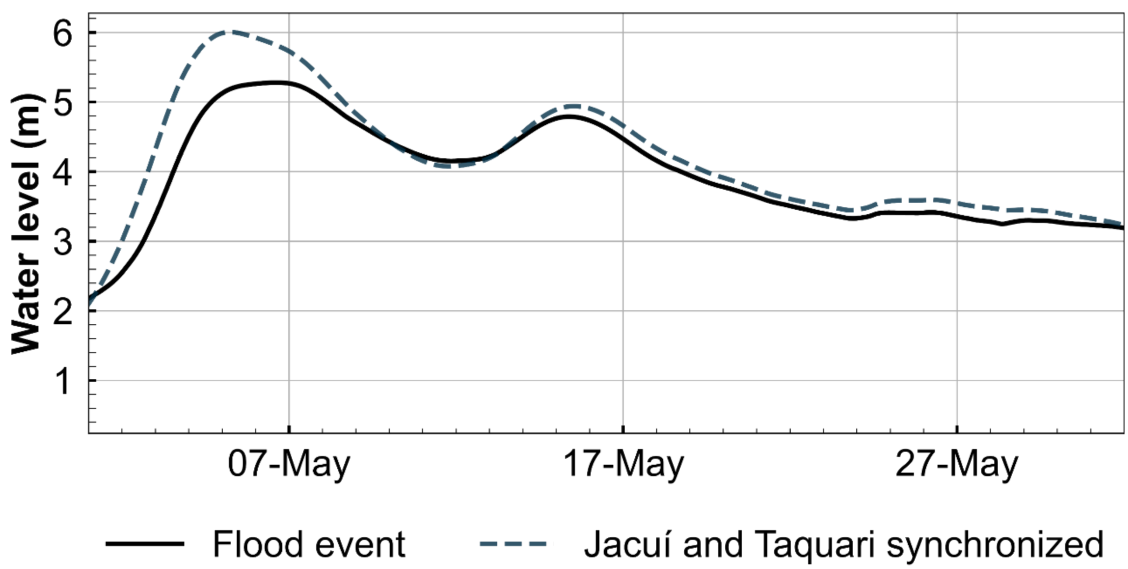

Figure 9. Comparative of the flood event water level simulation (black line) and synchronizing water level peak of the Jacuí and Taquari Rivers (grey dashed line) arriving in Porto Alegre. In the RMPA, the maximum water level peak increased to 6 meters.

4.3. Hydraulic interventions for flood control

To evaluate alternatives for mitigating flooding in the RMPA, we utilized the validated 2D model of the May flood event and designed two distinct hydraulic interventions in the studied region to test their efficacy. The location and evaluation of two channel openings were based on suggestions from studies as flood mitigation measures for future events in the RMPA (DRRS, 2024; Hunt et al., 2024) , despite the absence of further efficacy evaluations.

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4.3.1. Jacuí-Guaíba channel

Results from the experiment modelling the impact of a new channel connecting the Jacuí and Guaíba River were analysed at specific locations within the study area. At Point A (**Figure 10a**), upstream from the channel structure, the maximum water level decreased by 0.1 meters for the 100-meter width scenario and 0.27 meters for the 500-meter width scenario. At Point B, located in the northeastern part of the Jacuí Delta (**Figure 10b**), the channel's effectiveness was less pronounced, resulting in water level reductions of 0.05 meters (100-meter width), 0.12 meters (250-meter width), and 0.19 meters (500-meter width) across the evaluated scenarios. Finally, at the Cais Mauá station (Point C), the flow peak in Porto Alegre showed minimal change (**Figure 10c**), with the maximum water level decreasing by less than 0.1 meters in all scenarios tested.

Thus, the proposed structural intervention to reduce water levels over the Guaíba River and the Jacuí Delta seems ineffective. Water level reduction promoted by this intervention are small compared to the water level variation during the flood and compared to the model´s uncertainty. Even with the widest channel design—which would require the most significant intervention and investment—the results show that water level reductions would be small.

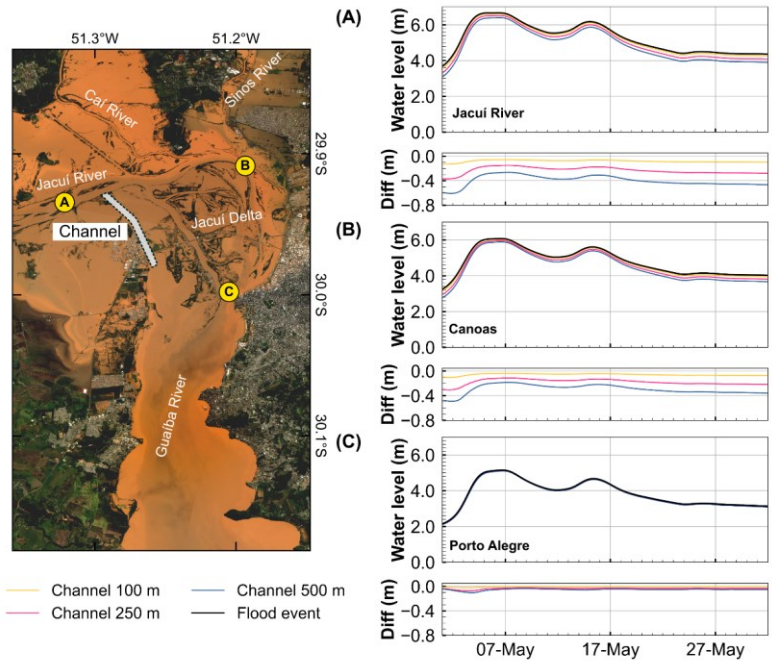

Figure 10. Experimental Design 1 for mitigating flooding in the RMPA involved a channel connecting the Jacuí and Guaíba River. Points A, B, and C illustrate the channel's effectiveness in reducing water levels around the Jacuí Delta. Image courtesy of ESA.

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4.3.2. Patos Lagoon channel

According to model results (**Figure 11),** the connection between the Patos Laggon and the Atlantic Ocean by a new channel could lower average water levels in the lagoon, while having minimal impact on the maximum flow peak upstream in the Guaíba River. The water levels at the Point C (Cais Mauá station location) indicated that the maximum flow peak remained unchanged, with a decreasing of less than 0.1 meters of the maximum water level in all the scenarios. On the other hand, it was noted a decrease of the flood duration by approximately 2 days compare to May flood event (**Figure 11a**).

Similar results were observed at Point D (**Figure 11b**) and Point E (**Figure 11c**), where the proposed hydraulic intervention was not effective in reducing the water level peak, although it did reduce the average water level and flood duration. At Point D, located in the middle-south part of the Guaíba River, the reduction in the maximum peak was minimal (same as for Point E). However, the water levels showed maximum decreases of 0.08 meters for the 100-meter scenario, 0.14 meters for the 250-meter scenario, and 0.32 meters for the 500-meter scenario. The maximum decrease in water levels observed at Point E ranged from 0.09 meters (100-meter scenario) to 0.38 meters (500-meter scenario) in the lagoon.

Considering that none of the three scenarios demonstrated significant changes in water levels across the evaluated regions, we conclude that the proposed structural measure is ineffective in preventing further flood events in the RMPA.

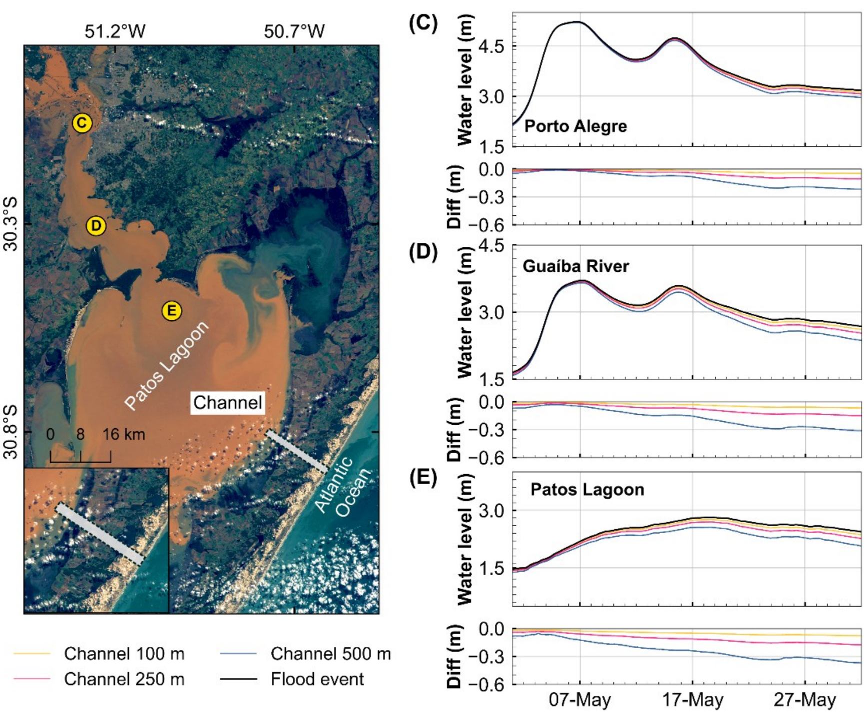

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Figure 11. Experimental Design 2 for mitigating flooding in the RMPA considered a channel connecting the Patos Lagoon and the Atlantic Ocean in the northeast part of the lagoon. Points C, D and E illustrated the influenced of the channel in reducing flood in the region. Image courtesy of NASA.

4.4. Uncertainties regarding the two-dimensional model

In this study we calibrated and validated a two-dimensional hydrodynamic model using HEC-RAS software to simulate the May 2024 flood in southern Brazil, Patos Lagoon basin. There are some limitations regarding the model design for evaluating flooding in the study region. First, the results are depended on the DTM model data and bathymetry accuracy, which may reproduce flow propagation uncertainties due to DTM errors or limitations in its spatial resolution (30 meters). We used the ANADEM model, which demonstrates some accuracy improvements compared to other publicly available DEMs such as SRTM, COPDEM and FABDEM (Laipelt et al., 2024) for South America, with simulation results showing good agreement with observation data. Second, the upstream boundary conditions used in the model's design do not cover all the tributaries rivers of the study region due to lack of in-situ observations, which may lead to local underestimations. We expect that the complete set up of independent sources validations adopted, including measured streamflow's, level gauges, satellite flooded areas and water slopes serves as quality control for models' system good representation and uncertainties understanding.

Among the flood mitigation scenarios, we additionally evaluated the sensitivity of the simulation for different parameters and proposed structures. Manning's roughness coefficient for the water bodies may influence the potential of the channels to mitigate flooding in the study region. Our sensitivity analysis showed that varying Manning's roughness coefficient in the Guaíba River between 0.025 to 0.045 would influence water flow peak in the Cais Mauá station (Point C) in -0.91 meters and 0.32 meters, respectively.

Furthermore, we utilized SWOT altimetry observations to verify the model's water level accuracy and to confirm water slope during the event, yielding results that aligned well with simulations. The application of SWOT mission data proved to be a valuable resource for acquiring information in areas with limited monitoring, enhancing our comprehension of flood dynamics and serving as supplementary data for validating hydrodynamic models.

4.5. Recommendations for flooding management strategies in the region

Measures to mitigate flooding impacts are urgent need for locations that are experiencing an increase in in extreme flood events due to climate change (Alfieri et al., 2016; Wang et al., 2022; Wasko et al., 2021), as the case of southern Brazil. We assessed different flooding scenarios based on the unprecedented flood that devasted the RMPA in May 2024, focusing on its potential impact on densely populated areas.

Our results of the hydraulic interventions showed that even the most effective configuration could only reduce peak flows by nearly 13% in the capital Porto Alegre, which is insufficient to prevent flooding in the affected areas. These findings suggest that the hydraulic interventions tested in this study would be of limited benefit in reducing the flooding due to the extreme rainfall in May 2024.

In this context, studies indicates that structural measures such as dike walls, levees may not be the most effective strategies for flood mitigation in the context of climate change (Alfieri et al., 2016; Burrell et al., 2007; Serra-Llobet et al., 2022), and in some scenarios could potentially increase flood hazard (Blöschl, 2022; Ommer et al., 2024). The implementation of protective structures also encourages development and investment in high-risk areas, potentially leading to more severe consequences when its failure, phenomenon kwon as the "levee effect" (Di Baldassarre et al., 2018). For instance, Porto Alegre's flood protection system, developed in the 1970s following historic floods in 1941 and 1967, the false sense of security encouraged increased urban development near these systems, which were the areas most affected during the May 2024 flood. The city Canoas, the second most populated city in the RMPA, experienced similar issues, with urbanization near its dike systems resulting in failures and a high number of houses being impacted by flooding (Collischonn et al., 2025).

To reduce the consequences of extreme flood events in the Patos Lagoon basin more non-structural interventions seems relevant. These included adopting zoning policies to limit development in flood-prone areas (Poussin et al., 2012; De Risi et al., 2015; Serra-Llobet et al., 2022). For example, spatial zoning measures in the Netherlands were found to have a risk reduction capacity of 25 to 45% (Poussin et al., 2012). Other important non-structural approaches include early warning systems, flood forecasting, and efforts to increase public awareness and improve behaviour responses to floods (Alfieri et al., 2012; Henriksen et al., 2018; Perera et al., 2020). Additionally, collaborative framework with public participation can also lead to more cost-efficient solutions to increase flood risk assessments across communities (Henriksen et al., 2018). The advantaged of non-structural measures included lower costs, greater sustainability, and easier of implementation (Dawson et al., 2011; Kundzewicz, 2002). Therefore, cities can mitigate flood risks by reducing population exposure to extreme floods without relying solely on structural solutions (Hall et al., 2006; Majidi et al., 2019), due to their complexity and high maintained costs, and often only minimalize impacts, and are challenging to adapt to climate change scenarios (Burrell et al., 2007; Serra-Llobet et al., 2022).

5. Conclusion

Our study evaluated different flood scenarios in southern Brazil's RMPA region, based on historical flood May 2024 flood. The analysis was based using 2D hydrodynamic modelling, which was validated using water level, flood extent and streamflow data, demonstrating accurate representation of the May 2024 event.

Our findings address the following scientific questions:

(i) The Taquari River was responsible for most of the flow peaks in the RMPA, while the Jacuí River contributed to the flood's duration. Others (Caí, Sinos and Gravataí) flowing into the Guaíba River did not significantly impact overall water levels in the RMPA, although contributed to localized flooding.

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(ii) Synchronized flow peaks of the Jacuí and Taquari Rivers in the Guaíba River would have increased water levels by 0.82 meters, exacerbating the flood scenario in the RMPA. At the Cais Mauá station, water levels would have exceeded 6 meters, surpassing the threshold for the flood protection system developed for the city of Porto Alegre. This scenario, constructed using May 2024 flood conditions but advancing the Jacuí River's flow peak by approximately 4 days, presents a significant risk to the state capital and remains plausible under heavy rainfall conditions common in the region.

(iii) The proposed hydraulic structures of additional channels alternatives would not have been sufficient to prevent RMPA flooding entirely. Our results suggested that the reduction in flooding would depend on location, despite having minimum effectiveness for the cities surrounding the severely affected RMPA.

We want to highlight the delimitations of these experiments, which only consider hydraulic impacts within the Patos Lagoon basin. Implementing interventions in the natural hydrodynamic system must account for factors such as engineering availability, implementation costs, and maintenance expenses. Additionally, these hydrodynamic alterations could negatively impact the environment, potentially causing erosion, navigation issues, reduced agriculture productivity and salinization, particularly in the case of an open channel connecting the Patos Lagoon to the ocean.

The analyses reported in this study can aid decision-makers in improving flood management strategies for RMPA region, emphasizing the vital role of hydrodynamic models in predicting and evaluating hydraulic interventions, as well as identifying opportunities for non-structural measures. Future research should benefit of high-resolution (1 to 5 meters) data based on Light Detection and Ranging (LiDAR) sensors to assess the impact of urbanization on regional flooding and identify risk zones in the context of increased flooding due to climate change.

Finally, from a broader worldwide perspective, we expected that the presented methods would serve as a framework benchmark for other locations studies regarding climate change and floods adaptation, and that our results can serve as example for structural and non-structural measures selection and evaluation.

Data availability

The water level data used in this study are provided by the Brazilian Water Agency and Sanitation (ANA) (https://www.snirh.gov.br/hidrotelemetria/, accessed in July, 2024). The tidal data is available at the SIMCosta platform (https://simcosta.furg.br/home, accessed in August, 2024). The meteorological data are available at (https://bdmep.inmet.gov.br/, accessed in August, 2024) by the National Meteorological Institute of Brazil (INMET). SWOT data can be accessed through the NASA Earth Data repository (https://search.earthdata.nasa.gov/search, accessed in June, 2024). The digital terrain model (DTM) is publicly available on Google Earth Engine platform.

Author contributions

LL, FMF and RCDP contributed to the study's conception and design. LL and FMF wrote the manuscript draft. LL performed model simulations analysed the data. RCDP, MS, WC, EETJ and AR reviewed and edited the manuscript.

Competing interests

The author declares that there is no conflict of interest.

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References

AIRBUS: Copernicus DEM: Copernicus digital elevation model product handbook, Report AO/1-9422/18/IL G, 2020.

Alfieri, L., Salamon, P., Pappenberger, F., Wetterhall, F., and Thielen, J.: Operational early warning systems for water-related hazards in Europe, Environ Sci Policy, 21, 35–49, https://doi.org/https://doi.org/10.1016/j.envsci.2012.01.008, 2012.

Alfieri, L., Feyen, L., and Di Baldassarre, G.: Increasing flood risk under climate change: a pan-European assessment of the benefits of four adaptation strategies, Clim Change, 136, 507–521, https://doi.org/10.1007/s10584-016-1641-1, 2016.

Alves, M. E. P., Fan, F. M., Paiva, R. C. D. de, Siqueira, V. A., Fleischmann, A. S., Brêda, J. P., Laipelt, L., and Araújo, A. A.: Assessing the capacity of large-scale hydrologic-hydrodynamic models for mapping flood hazard in southern Brazil, RBRH, 27, 2022.

Andrade, M. M., Piazera, M., Luz, R. da, Nunes, J. C. R., Scottá, F., and Silva, T.: Flow measurements with ADCP on the Guaíba River, during the highest water level recorded in history - May 2024 (floods in the State of Rio Grande do Sul, Brazil), RBRH, 29, 2024.

António, M. H. P., Fernandes, E. H., and Muelbert, J. H.: Impact of Jetty Configuration Changes on the Hydrodynamics of the Subtropical Patos Lagoon Estuary, Brazil, Water (Basel), 12, https://doi.org/10.3390/w12113197, 2020.

Ávila, A., Justino, F., Wilson, A., Bromwich, D., and Amorim, M.: Recent precipitation trends, flash floods and landslides in southern Brazil, Environmental Research Letters, 11, 114029, https://doi.org/10.1088/1748-9326/11/11/114029, 2016.

Di Baldassarre, G., Kreibich, H., Vorogushyn, S., Aerts, J., Arnbjerg-Nielsen, K., Barendrecht, M., Bates, P., Borga, M., Botzen, W., Bubeck, P., De Marchi, B., Llasat, C., Mazzoleni, M., Molinari, D., Mondino, E., Mård, J., Petrucci, O., Scolobig, A., Viglione, A., and Ward, P. J.: Hess Opinions: An interdisciplinary research agenda to explore the unintended consequences of structural flood protection, Hydrol Earth Syst Sci, 22, 5629–5637, https://doi.org/10.5194/hess-22-5629-2018, 2018.

Bartiko, D., Oliveira, D. Y., Bonumá, N. B., and Chaffe, P. L. B.: Spatial and seasonal patterns of flood change across Brazil, Hydrological Sciences Journal, 64, 1071–1079, https://doi.org/10.1080/02626667.2019.1619081, 2019.

Bates, P. D. and De Roo, A. P. J.: A simple raster-based model for flood inundation simulation, J Hydrol (Amst), 236, 54–77, https://doi.org/https://doi.org/10.1016/S0022-1694(00)00278-X, 2000.

Biancamaria, S., Lettenmaier, D. P., and Pavelsky, T. M.: The SWOT Mission and Its Capabilities for Land Hydrology, Surv Geophys, 37, 307–337, https://doi.org/10.1007/s10712-015-9346-y, 2016.

Blöschl, G.: Three hypotheses on changing river flood hazards, Hydrol Earth Syst Sci, 26, 5015–5033, https://doi.org/10.5194/hess-26-5015-2022, 2022.

Brêda, J. P. L. F., Cauduro Dias de Paiva, R., Siqueira, V. A., and Collischonn, W.: Assessing climate change impact on flood discharge in South America and the influence of its main drivers, J Hydrol (Amst), 619, 129284, https://doi.org/https://doi.org/10.1016/j.jhydrol.2023.129284, 2023.

Burrell, B. C., Davar, K., and Hughes, R.: A Review of Flood Management Considering the Impacts of Climate Change, Water Int, 32, 342–359, https://doi.org/10.1080/02508060708692215, 2007.

Chagas, V. B. P., Chaffe, P. L. B., and Blöschl, G.: Climate and land management accelerate the Brazilian water cycle, Nat Commun, 13, 5136, https://doi.org/10.1038/s41467-022-32580-x, 2022.

Chow, V. Te: Open-channel Hydraulics, McGraw-Hill, 1959.

Collischonn, W., Ruhoff, A., Filho Cabeleira, R., Paiva, R., Fan, F., and Possa, T.: Chuva da cheia de 2024 foi mais volumosa e intensa que a da cheia de 1941 na bacia hidrográfica do Guaíba, Porto Alegre, 1–8 pp., 2024.

Collischonn, W., Fan, F. M., Possantti, I., Dornelles, F., Paiva, R., Sampaio, M., Michel, G., Magalhães Filho, F. J. C., Moraes, S. R., Marcuzzo, F. F. N., Michel, R. D. L. M., Beskow, T. L. C., Beskow, S., Fernandes, E., Laipelt, L., Ruhoff, A., Kobiyana, M., Collares, L. G., Buffon, F., Duarte, E., Lima, S., Meirelles, F. S. C., and Allasia, D.: The exceptional hydrological disaster of April-May 2024 in southern Brazil, Revista Brasileira de Recursos Hídricos, 1, https://doi.org/10.1590/2318-0331.302520240119, 2025.

Dawson, R. J., Ball, T., Werritty, J., Werritty, A., Hall, J. W., and Roche, N.: Assessing the effectiveness of non-structural flood management measures in the Thames Estuary under conditions of socio-economic and environmental change, Global Environmental Change, 21, 628–646, https://doi.org/https://doi.org/10.1016/j.gloenvcha.2011.01.013, 2011.

DRRS: Programa do Governo Holandês de Redução de Risco de Desastres e Suportes a Surtos (DRRS). Final Report., 2024.

Durand, M., Fu, L.-L., Lettenmaier, D. P., Alsdorf, D. E., Rodriguez, E., and Esteban-Fernandez, D.: The Surface Water and Ocean Topography Mission: Observing Terrestrial Surface Water and Oceanic Submesoscale Eddies, Proceedings of the IEEE, 98, 766–779, https://doi.org/10.1109/JPROC.2010.2043031, 2010.

Fernandes, E., Dyer, K. R., and Niencheski, L. F.: TELEMAC-2D calibration and validation to the hydrodynamics of the Patos Lagoon (Brazil), J Coast Res, 34, 470–488, 2001.

Fernandes, E. H. L., Dyer, K. R., Moller, O. O., and Niencheski, L. F. H.: The Patos Lagoon hydrodynamics during an El Niño event (1998), Cont Shelf Res, 22, 1699–1713, https://doi.org/https://doi.org/10.1016/S0278-4343(02)00033-X, 2002.

Fleischmann, A., Paiva, R., and Collischonn, W.: Can regional to continental river hydrodynamic models be locally relevant? A cross-scale comparison, J Hydrol X, 3, 100027, https://doi.org/https://doi.org/10.1016/j.hydroa.2019.100027, 2019.

François, F. S.: Modelagem hidrodinâmica de áreas suscetíveis a inundação no município de nova Santa Rita (RS), Trabalho de Conclusão de curso, Universidade Federal do Rio Grande do Sul, Porto Alegre, 2021.

Fu, L.-L., Pavelsky, T., Cretaux, J.-F., Morrow, R., Farrar, J. T., Vaze, P., Sengenes, P., Vinogradova-Shiffer, N., Sylvestre-Baron, A., Picot, N., and Dibarboure, G.: The Surface Water and Ocean Topography Mission: A Breakthrough in Radar Remote Sensing of the Ocean and Land Surface Water, Geophys Res Lett, 51, e2023GL107652, https://doi.org/https://doi.org/10.1029/2023GL107652, 2024.

GEBCO: GEBCO 2024 Grid, https://doi.org/doi:10.5285/1c44ce99-0a0d-5f4f-e063-7086abc0ea0f, 2024.

Goodess, C. M.: How is the frequency, location and severity of extreme events likely to change up to 2060?, Environ Sci Policy, 27, S4–S14, https://doi.org/https://doi.org/10.1016/j.envsci.2012.04.001, 2013.

Hall, J. W., Sayers, P. B., Walkden, M. J. A., and Panzeri, M.: Impacts of climate change on coastal flood risk in England and Wales: 2030–2100, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 364, 1027–1049, https://doi.org/10.1098/rsta.2006.1752, 2006.

Henriksen, H. J., Roberts, M. J., van der Keur, P., Harjanne, A., Egilson, D., and Alfonso, L.: Participatory early warning and monitoring systems: A Nordic framework for web-based flood risk management, International Journal of Disaster Risk Reduction, 31, 1295–1306, https://doi.org/https://doi.org/10.1016/j.ijdrr.2018.01.038, 2018.

Hillman, G., Rodriguez, A., Pagot, M., Tyrrell, D., Corral, M., Oroná, C., and Möller, O.: 2D Numerical Simulation of Mangueira Bay Hydrodynamics, J Coast Res, 2010, 108–115, https://doi.org/10.2112/1551-5036-47.sp1.108, 2007.

Hsu, S. A.: Coastal Meteorology, in: Encyclopedia of Physical Science and Technology, Elsevier, 155–173, https://doi.org/10.1016/B0-12-227410-5/00114-9, 2003.

Hunt, J. D., Silva, C. V., Fonseca, E., de Freitas, M. A. V., Brandão, R., and Wada, Y.: Role of pumped hydro storage plants for flood control, J Energy Storage, 104, 114496, https://doi.org/https://doi.org/10.1016/j.est.2024.114496, 2024.

IPCC: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/9781009157896, 2021.

Kjerfve, B.: COMPARATIVE OCEANOGRAPHY OF COASTAL LAGOONS, in: Estuarine Variability, edited by: Wolfe, D. A., Elsevier, 63–81, https://doi.org/10.1016/B978-0-12-761890-6.50009-5, 1986.

Kundzewicz, Z. W.: Non-structural Flood Protection and Sustainability, Water Int, 27, 3–13, https://doi.org/10.1080/02508060208686972, 2002.

Laipelt, L., de Andrade, B., Collischonn, W., de Amorim Teixeira, A., Paiva, R. C. D. de, and Ruhoff, A.: ANADEM: A Digital Terrain Model for South America, Remote Sens (Basel), 16, https://doi.org/10.3390/rs16132321, 2024.

Laipelt, L., de Paiva, R. C. D., Fan, F. M., Collischonn, W., Papa, F., and Ruhoff, A.: SWOT Reveals How the 2024 Disastrous Flood in South Brazil Was Intensified by Increased Water Slope and Wind Forcing, Geophys Res Lett, 52, e2024GL111287, https://doi.org/https://doi.org/10.1029/2024GL111287, 2025.

Lesser, G. R., Roelvink, J. A. v, van Kester, J. A. T. M., and Stelling, G. S.: Development and validation of a three-dimensional morphological model, Coastal engineering, 51, 883–915, 2004.

Majidi, A. N., Vojinovic, Z., Alves, A., Weesakul, S., Sanchez, A., Boogaard, F., and Kluck, J.: Planning Nature-Based Solutions for Urban Flood Reduction and Thermal Comfort Enhancement, Sustainability, 11, https://doi.org/10.3390/su11226361, 2019.

Marengo, J. A., Alcantara, E., Cunha, A. P., Seluchi, M., Nobre, C. A., Dolif, G., Goncalves, D., Assis Dias, M., Cuartas, L. A., Bender, F., Ramos, A. M., Mantovani, J. R., Alvalá, R. C., and Moraes, O. L.: Flash floods and landslides in the city of Recife, Northeast Brazil after heavy rain on May 25–28, 2022: Causes, impacts, and disaster preparedness, Weather Clim Extrem, 39, 100545, https://doi.org/https://doi.org/10.1016/j.wace.2022.100545, 2023.

Marques, W. C., Fernandes, E. H., Monteiro, I. O., and Möller, O. O.: Numerical modeling of the Patos Lagoon coastal plume, Brazil, Cont Shelf Res, 29, 556–571, https://doi.org/https://doi.org/10.1016/j.csr.2008.09.022, 2009.

Martins, F. and Fernandes, E.: HYDRODYNAMIC MODEL INTERCOMPARISON FOR THE PATOS LAGOON (BRAZIL), 2004.

McMillan, H. K., Westerberg, I. K., and Krueger, T.: Hydrological data uncertainty and its implications, WIREs Water, 5, e1319, https://doi.org/https://doi.org/10.1002/wat2.1319, 2018.

Möller, O. O., Lorenzzentti, J. A., Stech, JoséL., and Mata, M. M.: The Patos Lagoon summertime circulation and dynamics, Cont Shelf Res, 16, 335–351, https://doi.org/10.1016/0278-4343(95)00014-R, 1996.

Neal, J., Schumann, G., Fewtrell, T., Budimir, M., Bates, P., and Mason, D.: Evaluating a new LISFLOOD-FP formulation with data from the summer 2007 floods in Tewkesbury, UK, J Flood Risk Manag, 4, 88–95, https://doi.org/https://doi.org/10.1111/j.1753-318X.2011.01093.x, 2011.

Ommer, J., Neumann, J., Kalas, M., Blackburn, S., and Cloke, H. L.: Surprise floods: the role of our imagination in preparing for disasters, Natural Hazards and Earth System Sciences, 24, 2633–2646, https://doi.org/10.5194/nhess-24-2633-2024, 2024.

Perera, D., Agnihotri, J., Seidou, O., and Djalante, R.: Identifying societal challenges in flood early warning systems, International Journal of Disaster Risk Reduction, 51, 101794, https://doi.org/https://doi.org/10.1016/j.ijdrr.2020.101794, 2020.

Planet Application Program Interface: In Space for Life on Earth. San Francisco, CA :

Possa, T. M., Collischonn, W., Jardim, P. F., and Fan, F. M.: Hydrological-hydrodynamic simulation and analysis of the possible influence of the wind in the extraordinary flood of 1941 in Porto Alegre, RBRH, 27, e29, https://doi.org/10.1590/2318-0331.272220220028, 2022.

Poussin, J. K., Bubeck, P., Aerts, J. C. J. H., and Ward, P. J.: Potential of semi-structural and non-structural adaptation strategies to reduce future flood risk: case study for the Meuse, Natural Hazards and Earth System Sciences, 12, 3455–3471, https://doi.org/10.5194/nhess-12-3455-2012, 2012.

https://doi.org/10.5194/egusphere-2025-1285
Preprint. Discussion started: 9 May 2025

De Risi, R., Jalayer, F., and De Paola, F.: Meso-scale hazard zoning of potentially flood prone areas, J Hydrol (Amst), 527, 316–325, https://doi.org/https://doi.org/10.1016/j.jhydrol.2015.04.070, 2015.

Seiler, L. M. N., Fernandes, E. H. L., and Siegle, E.: Effect of wind and river discharge on water quality indicators of a coastal lagoon, Reg Stud Mar Sci, 40, 101513, https://doi.org/https://doi.org/10.1016/j.rsma.2020.101513, 2020.

Serra-Llobet, A., Jähnig, S. C., Geist, J., Kondolf, G. M., Damm, C., Scholz, M., Lund, J., Opperman, J. J., Yarnell, S. M., Pawley, A., Shader, E., Cain, J., Zingraff-Hamed, A., Grantham, T. E., Eisenstein, W., and Schmitt, R.: Restoring Rivers and Floodplains for Habitat and Flood Risk Reduction: Experiences in Multi-Benefit Floodplain Management From California and Germany, Front Environ Sci, 9, https://doi.org/10.3389/fenvs.2021.778568, 2022.

Silva, R. A. G., Reis, R. C. S., Ramos, D. M., Belém, A. L., Puhl, E., and Manica, R.: Análise de Abertura de Novo Canal de Maré na Lagoa dos Patos para Atenuação de Cheias no Rio Guaíba, RS, in: II FLUHIDROS - Simpósio Nacional de Mecânica dos Fluidos e Hidráulica e XVI ENES - Encontro Nacional de Engenharia de Sedimentos, 2024a.

Silva, T. S., Toldo Jr., E. E., Nunes, J. C. R., Castro, N., Funke, N., Nievinski, F., Manica, R., Puhl, E., Fick, C., Scottá, F., Silva, M. L. R., and Ävila, I. M.: Nota Técnica - Vazões no Rio Guaíba durante os picos da enchente de maio de 2024, 1–2 pp., 2024b.

Silva, T. S., Toldo Jr., E. E., Nunes, J. C. R., Castro, N., Funke, N., Nievinski, F., Manica, R., Puhl, E., Fick, C., Scottá, F., Silva, M. L. R., and Ävila, I. M.: Nota Técnica - Vazões no Rio Guaíba durante os picos da enchente de maio de 2024. U, 2024c.

USACE: HEC-RAS river analysis system hydraulic reference manual. Version 5.0, 2016.

Wang, T., Lu, Y., Liu, T., Zhang, Y., Yan, X., and Liu, Y.: The determinants affecting the intention of urban residents to prepare for flood risk in China, Natural Hazards and Earth System Sciences, 22, 2185–2199, https://doi.org/10.5194/nhess-22-2185-2022, 2022.

Wasko, C., Nathan, R., Stein, L., and O'Shea, D.: Evidence of shorter more extreme rainfalls and increased flood variability under climate change, J Hydrol (Amst), 603, 126994, https://doi.org/https://doi.org/10.1016/j.jhydrol.2021.126994, 2021.