Response letter

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RC1

This study uses a 2D hydrodynamic modelling framework to evaluate the hydraulic mechanisms driving the 2024 flooding event in southern Brazil. First, an evaluation of the modelling approach is conducted using different data sources. The authors then perform modelling experiments to: determine which rivers contributed most to flooding in RMPA; understand the consequences of potential synchronous flooding in the two main rivers; and determine whether flood control measures could have reduced river levels. It is an interesting topic, and I understand that the authors put a lot of effort into evaluating their approach using different data sources. However, in my opinion, the paper is not well written and fails to explain how the research is novel, what the research questions are, and how the results and framework compare with those of other studies in the field. Furthermore, the main goals of the study are unclear and the methodology lacks the overarching structure required to achieve them. I provide more detailed comments below to demonstrate this point. The manuscript would need to be reshaped and rewritten to make a valuable contribution to HESS.

- We sincerely appreciate the reviewer's thoughtful assessment and recognition of the effort invested in this study. We respectfully emphasize our strong belief in the scientific relevance and potential impact of our work, which addresses a record-breaking flooding event of exceptional socio-environmental significance in southern South America. Following the reviewer's guidance, we have substantially revised the manuscript to clarify the novelty of our approach, explicitly state the research questions and main objectives, and strengthen the methodological structure. We have also expanded the discussion to compare our results and framework with other studies in the field, ensuring that the contribution of our modelling experiments is clearly demonstrated. We believe these improvements significantly enhance the clarity, rigor, and value of the paper, and we are confident that the revised version now meets the standards expected for publication.

Detailed comments:

The introduction lacks clear structure and research questions derived from an overview of existing research in the field. The main messages that the authors want to convey in each paragraph are difficult to follow. For example:

- A lot of emphasis is placed on the effect of climate change on flood extremes (e.g. L33–46), despite this not being a topic addressed by the study.

Response: Thank you for pointing this out. We restructured our introduction based on our suggestions, clarifying our research questions and highlighting our objections. (i) We removed the emphasis on the effect of climate change in the introduction, substituting by the benefits of using hydrodynamic models and exist research regarding flood scenarios over urban areas; (ii) added the motivations for studying flood synchronization scenarios and potential mitigation measures within the context of the study area; (iii) address the main research questions raised by our study.

- The authors emphasise that hydrodynamic models are used for such studies and present existing applications (L66–78). However, they do not highlight what is missing or how the present study differs from or builds on these approaches.
  Response: Thank you for your comment. We have revised the Introduction to clearly articulate the gap and our contribution. Specifically, we now (i) frame the May 2024 event as an exceptional, record-scale flood in southern Brazil that exposed limitations of prior applications focused on single rivers, sparse validation, or simplified boundary controls: (ii) explain that our study was made possible by integrating a comprehensive dataset – detailed bathymetry, ADCP discharge and velocity transects, continuous water-level records, and satellite-derived inundation maps – together with the use of SWOT satellite altimetry for model validation in this context; and (iii) show how this robustly constrained 2D model enables controlled experiments on synchronous peals and on realistic flood-control scenarios across the river-estuary-lagoon system, providing real world knowledge on this system functioning and enabling actionable insights for agencies and stakeholders in the most affected areas. These additions clarify what was missing in earlier works (limited validation and system-wide counterfactual testing) and how our framework builds on and extends existing approaches.

- The main objective of the study is presented as follows: ”understanding of flooding mechanisms in South Brazil” (L79), yet little is said beforehand to explain why this is necessary and why it has not been done before. Some explanations that are not central to the introduction are provided at line 61: “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).”.
  Response: Thank you for pointing this out. We rewrote the Introduction to (i) motivate the necessity of the study before stating the objectives, and (ii) clarify why this has not been addressed at system scale in prior work. Specifically, we now explain that the May-2024 flood was an exceptional, basin-wide event that triggered competing hypotheses among agencies and the public (relative river contributions, the role of peak synchrony, and whether additional lagoon–ocean outlets could have mitigated upstream flooding). Addressing these questions requires an integrated estuary–lagoon–river modelling and multi-sensor validation framework that has not previously been available (detailed bathymetry, ADCP, continuous water levels, satellite inundation, and SWOT altimetry combined). We also have rephrased the objectives to emphasize the primary aim—understanding how the natural system functions both under extreme flood conditions and when perturbed by plausible structural interventions—while framing the study as a

generalizable case for other coupled river–lake–lagoon systems. The specific analyses (river contributions, peak synchrony, and mitigation scenarios) are now presented as means to achieve this overarching objective rather than ends in themselves.

Given these changes, now one can read in the early paragraphs and in the objective of the work the following sentences:

Introduction: "*This study addresses urgent and unresolved questions raised by the May-2024 flood regarding (a) the relative influence of tributary inflows on RMPA water levels and inundation, (b) the consequences of potential peak synchrony between the main rivers, and (c) whether additional lagoon–ocean outlets or channel operations would have mitigated upstream flooding. Prior studies did not jointly address these system-scale dynamics due to limited integrated datasets and validation across the river–estuary–lagoon continuum. Leveraging detailed bathymetry, ADCP transects, continuous gauges, satellite flood extent, and SWOT altimetry (Biancamaria et al., 2016; Fu et al., 2024), we develop and validate a 2D hydrodynamic model to quantify mechanisms and test counterfactual scenarios. This design yields decision-relevant evidence for stakeholders and government agencies seeking to enhance protection in the most affected areas, and ultimately allowed for the comprehension of how this unique natural system works under extreme conditions.*"

Objectives: "*Our overarching objective is to understand the functioning of the natural river–estuary–lagoon system under (i) extreme flood conditions and (ii) hypothetical structural modifications that could alter its hydraulics. Within this aim, we diagnose the mechanisms that controlled the May 2024 flood and then explore the system's sensitivity to realistic interventions (e.g., additional lagoon–ocean outlets, channel deepening/operations) to elucidate how such perturbations would propagate through the continuum. By centering on process understanding rather than a single scenario outcome, this work provides a transferable framework and lessons for other complex coupled systems composed of rivers, lakes, and lagoons.*"

- This study analyses potential mitigation measures and flooding synchronicity, but the introduction provides no background to explain why this is relevant, what has been done to assess this in other studies, or how their approach or analyses are novel in that regard.

Response: Thank you for this important point. We have revised the Introduction to establish: (i) why peak synchrony and mitigation measures are decision-relevant in large, coupled river–estuary–lagoon systems; (ii) what is known from prior work, noting that relatively few studies evaluate system-scale synchrony effects and counterfactual, hydraulically consistent mitigation scenarios across the full continuum; and (iii) how our approach is novel, namely by combining a basin-to-lagoon 2D hydrodynamic model with multi-sensor validation (bathymetry, ADCP, gauges, satellite inundation, and SWOT altimetry) to run controlled experiments that isolate synchrony mechanisms and quantify the potential (and limits) of structural interventions. This framing clarifies both the relevance and the innovation of our analysis.

We added in the introduction the following sentence:

"For instance, temporal and spatial changes in precipitation concentration are higher expected in medium-to-large basins. In these coupled systems, the synchrony between the peak flows of major tributaries and the estuary–lagoon water level is a primary determinant of flood severity, directly informing the timing and feasibility of structural and operational measures. While previous studies have often focused on individual rivers or local interventions, few have examined synchrony and mitigation within an integrated, river–estuary–lagoon framework at regional scale. Moreover, simulating flood mitigation scenarios is essential for evaluating interventions, defining optimal locations for new structures, assessing the efficiency of existing ones, and identifying areas of high risk"

I suggest that the authors completely reshape and rewrite the introduction to focus on their main analyses and questions, providing a clearer justification for their study. This could be achieved by focusing on four main apsects: 1) model evaluation using different sources of data, 2) the hydraulic mechanisms/drivers of flooding, 3) flooding synchronicity, and 4) the evaluation of mitigation measures.

Response: We are very grateful to the reviewer for their suggestions to improve our introduction. We agree that the current version lacks a clear narrative and will completely rewrite it as suggested. The new introduction establishes the importance of robust model evaluation and discusses the knowledge gaps regarding the hydraulic drivers of flooding in our study area. Additionally, we rephase the introduction to highlight the relevance of studying flooding synchronicity in the context of our study and introduce more details related to the need for evaluating mitigation measures. We are confident that with these alterations, the introduction will be significantly improved, enhancing clarity and understanding for the reader.

The method section lacks clear structure, making it difficult to follow. It would have been useful to include a diagram presenting an overview of the different experiments to help readers understand the study. Furthermore, many methodological points are introduced in the Results section, making it difficult to link the different experiments to the study's objective. For instance, the synchronisation experiment is only partially explained in section 4.2.2 of the results. While this experiment may seem trivial to some readers, I believe it would benefit from more detailed explanations of the exact methods employed.

Response: We appreciate this constructive suggestion and have substantially re-organized the Methods for clarity and reproducibility. First, we now provide a one-page schematic/flowchart that summarizes the workflow and the four experiment families (baseline simulations, river-contribution attribution, peak-synchrony sensitivity, and mitigation scenarios), indicating inputs, boundary conditions, and key outputs for each. Second, we moved all methodological content that was previously embedded in the Results (e.g., configuration details, boundary manipulations, evaluation metrics) into the Methods, so that each experiment is introduced before results are presented. Third, we expanded the synchronization experiment description to specify: (i) how upstream hydrographs are phase-shifted (advances/delays applied at the Taquari and Jacuí boundaries over a predefined range and regular increments, preserving hydrograph shape and volume); (ii) how control vs. perturbed runs are paired; (iii) which boundary conditions remain fixed (e.g., ocean/lagoon stage series) to isolate synchrony effects; (iv) model warm-start/spin-up procedure; and (v) evaluation metrics (changes in peak water level, peak timing, inundated area/depth, and gauge-based skill). This restructuring explicitly links each experiment to the overarching objective (understanding natural-system functioning under extreme floods and under plausible structural modifications) and should make the paper easier to follow.

Manuscript changes (Methods):

- Section 3.1 – Model domain, mesh, and parameters: domain extent (river–estuary–lagoon continuum), grid resolution, roughness parameterization, warm-start.
- Section 3.2 – Forcings and boundary conditions: upstream inflow hydrographs, lagoon/ocean levels, data assimilation choices (if any).
- Section 3.3 – Observational datasets and validation metrics: bathymetry sources, ADCP transects, gauge water levels, satellite inundation, SWOT altimetry; RMSE, bias, timing error, inundation overlap.
- Section 3.4 – Experiment design overview (new Figure – workflow diagram): matrix of experiments and outputs.
- 3.4.1 Baseline simulations: configuration and validation period.
- 3.4.2 River-contribution attribution: protocol for selectively scaling/holding inflows to quantify marginal effects on levels/inundation.
- 3.4.3 Peak-synchrony sensitivity (expanded): phase-shift protocol for Taquari/Jacuí hydrographs (regular time increments; volume-conserving shifts), fixed external BCs, pairing of runs, metrics reported.
- 3.4.4 Mitigation scenarios: representation of structural interventions (geometry/roughness or boundary adjustments), performance indicators, and trade-off assessment.

- Figures 10 and 11 are difficult to understand. The quality of the panels on the right is poor, the lines are thin and close together, and there are many sub-panels with little space between them. It is therefore difficult to understand how the figures can support the analyses presented.
  Response: Thank you for your feedback regarding the readability of Figures 10 and 11. We will revise the layout of these figures to more clearly illustrate the different hydraulic intervention scenarios.

- There is no distinct discussion section, which highlights that the research questions are unclear and the study has not been compared to existing literature. In order to justify the recommendations presented in Section 4.5, the authors must discuss their results in more depth and demonstrate how they have addressed their research questions.
  Response: Thank you for highlighting this. We have revised the manuscript to separate the Results (Section 4) and the Discussion (Section 5), allowing for a clearer focus on our research questions. Specifically, the discussion section has been significantly expanded. We added a detailed comparison of our results with the existing literature, assessing our model's performance against other studies of flood scenarios in sensitive areas. We also investigate the viability and efficiency of structural interventions by reviewing literature on hydraulic measures for flood control, exploring their benefits and limitations in the context of the May 2024 flood.

  We now proposed the following sections of discussion:

  - Section 5.1 - Model performance
  - Section 5.2 - Uncertainties regarding the two-dimensional model
  - Section 5.3 - Recommendations for flooding managements and strategies in the region

The flood synchronisation experiment could be very interesting if the author provided more motivation. Why was this experiment conducted? Maybe I missed the reason somewhere. Is it physically 'reasonable'? Were these rivers sometimes synchronised for flooding in the historical period? What motivated the different methodological choices?
Response: We appreciate your suggestion and have reshaped the manuscript to highlight our motivations regarding the flood synchronization experiment. This experiment was conducted to represent a flood severity condition that is reasonable for the study area, as the main rivers that compose this basin are geographically well-separated. This means that the rainfall can reach these rivers at different times and in different amounts, which could, in a combined scenario, reproduce a synchronized propagation of the water peak.
Another reason for reproducing this scenario is that the water peak in cities like Porto Alegre (the capital, which was most affected by the flood) was close to the maximum limit of its flood protection system. This means that in a more severe scenario with the same amount of rainfall as the May 2024 flood, the protection limits could be reached, as demonstrated in our flood synchronization experiment.
Nevertheless, we have added more details regarding the motivations of the flood synchronization in the Introduction section, as described in previously answered questions.

- The accuracy of the model needs to be put into perspective. For example, how does “an average BIAS of -0.47 meters between the water level peak in the stations” (L228) relate to flooding in the Guaíba River, which has “an average depth of 2 meters” (L95)? Does this mean that, in some cases, the model would not produce simulations exceeding a certain impact threshold?
  Response: Thank you for highlighting this point. The accuracy of the model represents an error of around -9% compared to maximum water peak observed in the Guaíba River and -23% over long-term water levels, which is relative in accordance with currently studies using hydrodynamic 2D model at moderate to large basins. Moreover, the difference between minimum flood level and historic floods in the basin are much higher than the average bias found. For example, historic floods such as May 2024 (around 5.2 meters) and May 1951 (around 4.72 meters) are relatively higher than the minimum flood level (3 meters in the gauge station reference), thus, the simulation would prevent both worsened floods that occurred in the Guaíba river.
  This is a relevant discussion for our study, and we have incorporated in the Section 5.1 regarding model performance.

- The authors mention that the Manning coefficient was calibrated: L148: “Initial values of Manning’s roughness coefficient were derived from the literature, followed by manual calibration for the study period to ensure optimal accuracy.”. The authors mention this aspect as a potential source of uncertainty in Section 4.4. Shouldn’t a sensitivity analysis be performed outside the calibration period to evaluate the transferability of the results to other periods and flood events? Tuning the parameters could make the model more accurate for this flood event by compensating for other sources of uncertainty.

Response: We have tuned the parameters of the simulation to enhance the accuracy of our model. However, we did not include our sensitivity analysis of the Manning's coefficient in the manuscript, although we agree that it would be relevant to the study, and we will add it to a supplementary material for better clarification of the parameters selected.

- I noticed many typos and issues with the way things were worded. I am not a native speaker but these issues sometimes made the text difficult to read. I have listed a few examples below:
    - "Flood becomes a major concern" L32
    - "However, the relationship between climate change and flood is complex, with impacts vary regionally and influenced by multiple factors" L36-37
    - "in instance" L42
    - "as consequence" L49
    - "wate" L101
    - "manually" L119
    - "The first main result is the model validation itself, which calculate values were compared to level gauges…" L201 needs to be reformulated.
    - "We accessed" L309
    - "testes" L311
    - "from studies as flood mitigation measures" L326
    - "The analysis was based using 2D hydrodynamic modelling" L415

Response: We thank the reviewer for this feedback and apologize for the errors. We will carefully proofread the entire manuscript to correct all spelling and grammatical mistakes.