Authors' Response to Editors/Reviewers of

Response to Reviewer 2 on "A Raster–Vector Framework for Multi-Scale Hydrological–Hydraulic Modeling Across Large Domains"

GMD,

RC: ***Reviewers' Comment***, AR: Authors' Response, ☐ Manuscript Text

We sincerely thank Reviewer 2 for the careful reading of our manuscript and for the constructive comments provided. Below, we respond point by point to the issues raised and indicate how the manuscript will be revised accordingly.

1. General comments

RC: ***The manuscript presents a raster-vector framework for multi-scale hydrological-hydraulic modeling over large domains. The proposed framework is technically interesting, clearly presented, and supported by effective workflow figures. The use of sub-grid river networks and sub-grid drainage areas within the open-source smash platform is a useful contribution.***

AR: We thank the reviewer for this positive assessment and for recognizing the methodological contribution of the proposed open-source raster–vector H&H framework.

Indeed, one of the central contributions of this work is the use of sub-grid topographic information for both river-network and drainage-area representation, which aims to effectively address the spatial and structural mismatch between coarse-grid hydrological models and fine-scale vector-based river hydraulics in multi-scale H&H modeling.

RC: ***However, the current manuscript mainly demonstrates framework feasibility, geometric consistency, mass conservation, and computational efficiency. Stronger validation and a clearer discussion of limitations are needed before broader claims about improved flood modeling can be fully supported.***

AR: We thank the reviewer for this comment. As also clarified in our response to Reviewer 1, the present work does not aim to demonstrate optimized predictive performance for flood modeling, but to introduce and evaluate a reproducible raster–vector H&H framework for multi-scale modeling across large domains.

The numerical experiments were therefore intentionally based on a simple and controlled modeling setup, with a one-year evaluation period after a one-year warm-up, hydrological parameters previously calibrated at the 1 km scale, simplified hydraulic geometry, uniform friction, and no H&H recalibration at coarser resolutions (5 and 10 km scales).

This setup is sufficient to evaluate the numerical and physical consistency of the proposed framework across spatial resolutions. The analysis focuses both on the geometric consistency of the preprocessing workflow, through the representation of sub-grid river networks and drainage areas, and on the behavior of the coupled H&H simulations across scales, including simulation stability, mass conservation, and computational efficiency, rather than on optimized predictive skill.

We acknowledge that the manuscript should specify this positioning more clearly. In the revised manuscript, we will therefore clarify the scope, limitations, and intended contributions of the study in order to avoid any ambiguity regarding predictive-performance claims.

2. Major comments

RC: ***First, the evaluation period is too limited. The simulations use 2018 as warm-up and only 2019 for performance analysis. A one-year test may not adequately sample floods, low-flow periods, seasonal variability, or interannual climate variability. The authors should either extend the evaluation period or state more clearly that the results demonstrate feasibility rather than robust flood-prediction skill.***

AR: We thank the reviewer for this comment. As indicated in the previous response, we will clarify the scope and objectives of the manuscript in order to avoid any ambiguity regarding the intended contributions of the study.

The objective of the present work is to assess the feasibility, internal consistency, and behavior of the proposed raster–vector H&H framework across spatial resolutions, rather than to demonstrate improved flood-modeling skill. In this context, the selected simulation period was considered sufficient for the proposed analysis.

RC: ***In addition, the hydraulic component needs stronger validation. The model produces discharge and water depth, but the evaluation focuses mainly on discharge at gauges. Since the manuscript motivates future assimilation of water-surface observations, the authors should evaluate water levels, water depths, flood extent, or travel time where possible. Without this, the added value of the hydraulic model over simpler routing remains only partly demonstrated.***

AR: We thank the reviewer for this relevant comment. As clarified previously, the objective of this work is not to perform a comprehensive evaluation of flood-modeling predictive skill, but rather to assess the feasibility, internal consistency, and behavior of the proposed raster–vector H&H framework across spatial resolutions under a simplified and controlled modeling setup.

We also note that the hydraulic solver used in this study relies on the well-established local inertial formulation, which has already been extensively validated in the literature (e.g., Bates et al. 2010; Yamazaki et al. 2013; Pontes et al. 2017; Hoch et al. 2019). The objective of the present manuscript is therefore not to validate the numerical scheme itself, but to assess its implementation within the proposed H&H framework.

In the initial manuscript, this assessment was based on discharge simulations at gauging stations, which already provided convincing evidence of the consistency of the coupled modeling chain across spatial resolutions, especially considering the simplified hydraulic parametrization adopted in this study and the absence of H&H recalibration at coarser resolutions.

Nevertheless, we agree that a complementary assessment of the hydraulic component, through the simulated water depth (the second state variable of the Saint-Venant equations alongside discharge), is important to provide a more complete evaluation of the framework, particularly considering the future perspective of assimilating multi-source water-surface observations (e.g., SWOT) for the estimation of the unknown hydraulic parameters bathymetry and friction at the network scale.

Accordingly, the revised manuscript will include an additional hydraulic assessment based on both simulated water-surface elevations (WSE) and water depths. First, an indicative comparison between simulated and observed WSE will be performed at gauging stations for the 1 km baseline configuration. Second, the consistency of simulated water-depth dynamics across spatial resolutions will be evaluated by comparing the 5 km and 10 km simulations against the corresponding 1 km reference simulation, following an inter-resolution assessment strategy similar to that adopted by Modi et al. (2025).

Together with the discharge assessment, these complementary WSE and water-depth analyses provide a more comprehensive evaluation of the numerical and physical consistency of the coupled H&H simulations.

RC: ***Third, the manuscript should better clarify the practical use case of the framework. If the main goal is future assimilation of water-surface observations, the authors should explain what is still required before that can be achieved, including observation operators, parameter identifiability, uncertainty treatment, and validation against water surface data. If the main goal is efficient large-domain flood simulation, the***

authors should provide stronger evidence that the approach scales beyond the current basin and remains computationally feasible for larger river systems.

AR: We thank the reviewer for this relevant comment. The proposed framework is intended to provide a physically consistent and computationally efficient basis for large-domain H&H simulations, while also establishing the methodological foundation for future water-surface observation assimilation.

Regarding the future assimilation of water-surface observations, we clarify that the present work does not yet provide a complete data assimilation framework. Instead, it provides the methodological foundation for such developments, including the raster–vector preprocessing strategy, the sub-grid river-network representation, and the conservative hydrology–hydraulics coupling. The hydraulic solver implemented here has not yet been made numerically differentiable, which is an essential step currently under development. Ongoing work focuses on using the H&H preprocessing strategy proposed in this paper to couple the one-dimensional hydraulic model `DassFlow-1D` (Brisset et al., 2018; Larnier et al., 2020; Pujol et al., 2020; Larnier et al., 2025) with the `smash` hydrological model (Pujol et al., 2026). The aim is to chain the gradients of both solvers in order to build a fully differentiable hydrological–hydraulic framework. `DassFlow-1D` already supports advanced variational data assimilation, including spatial regularization and regionalization schemes for the inversion of distributed parameters such as bathymetry and friction, while explicitly accounting for modeling and observation uncertainties. This will be clarified in the revised paper.

Regarding efficient large-domain flood simulation, the present manuscript demonstrates the feasibility of the framework on the Garonne basin, which covers 50,100 km^2 and represents a significant application domain for coupled H&H modeling at the spatial resolutions considered. The coupled H&H simulations already show encouraging computational efficiency over the two-year simulation period, with maximum simulation times of approximately 4 min at 1 km resolution. To further support this point, and as also indicated in our response to Reviewer 1, the revised manuscript will also include preprocessing times, showing that mesh generation remains below approximately 2 minutes for the finest BDALTI 1 km configuration and below 10 seconds for the MERIT 10 km configuration.

To illustrate the potential for scaling, consider the Amazon River basin, which covers approximately 7,000,000 km^2 and stands as the largest basin on Earth. Given our performance at 1 km resolution on the Garonne basin (50,000 km^2), a 10 km resolution simulation over the Amazon would require roughly 1.4 times the number of computational cells used in the Garonne study at 1 km. Consequently, assuming linear scaling, H&H simulation times for an Amazon-scale domain at 10 km resolution would remain on the order of a few minutes. For a 1 km resolution over the Amazon, which represents 140 times the cell count of the Garonne at 1 km, the resulting simulation time would be on the order of several hours. While these estimates are indicative, as computational cost may not scale strictly linearly with domain size and network density, they provide encouraging evidence regarding the computational feasibility of applying this framework to continental-scale domains. Furthermore, these estimates assume serial execution, and we note that parallelization strategies, while not addressed in the present study, could further reduce these computational times.

While the present study remains a proof-of-concept application over a single relatively large basin, we agree that applications to larger regional or national domains will still be required before fully assessing the scalability and transferability of the framework. This point will be clarified in the revised manuscript.

3. Specific comments

RC: ***Please explain whether the current method is expected to work equally well in low-gradient floodplains, braided rivers, strongly regulated basins, or basins with dense small tributary networks.***

AR: We thank the reviewer for these relevant remarks.

Regarding low-gradient floodplains and flat areas, these challenges are addressed during the first preprocessing step of the framework through the DEM conditioning procedure described in Section 2.2.1 of the manuscript. Indeed, flat and low-relief areas can hinder the calculation of flow directions where elevation data often fails to capture crucial hydrologic features controlling drainage connectivity. To address these challenges, we apply a stream burning technique that enforces mapped drainage patterns into the raw DEM by lowering elevations along the reference river network, thereby improving the definition of flow paths in low-relief areas. In addition, a complementary conditioning procedure based on depression filling is applied to ensure continuous drainage connectivity over the full domain. The combined application of stream burning and depression filling produces a hydrologically corrected DEM with continuous flow paths preserving drainage connectivity while matching mapped river networks.

We should also note here, as indicated in Section 2.2.1 of the manuscript, that the burned DEM resulting from the stream-burning conditioning step is used only for flow directions computation. It is not used to retrieve the topographic attributes required for hydrodynamic modeling. Indeed, as described in Section 4.1.4 of the manuscript, the effective geomorphological bed elevations and resulting hydraulic slopes are derived from a hydrologically adjusted elevation profile, following the approach of Yamazaki et al. (2012). This adjustment ensures a monotonic downstream decrease in elevation along the drainage network, thereby producing smooth longitudinal river profiles required for slope and flow calculations in the hydraulic model.

We also clarify that the present hydrodynamic configuration is limited to 1D in-channel routing and does not explicitly represent floodplain inundation dynamics or channel–floodplain exchanges. Extending the framework toward an explicit representation of floodplains is a possible perspective for future work, potentially through the integration of sub-grid floodplain storage parametrization, as used for example in the large-scale flood model CaMa-Flood (Yamazaki et al., 2011), and/or through the use of available large-scale floodplain datasets (Nardi et al., 2019).

Regarding braided rivers, the present routing scheme relies on the D8 algorithm (O'Callaghan and Mark, 1984), as described in Section 2.2.2 of the manuscript. The D8 method routes flow from each grid cell toward only one of its eight neighboring cells following the direction of steepest downward slope. As a consequence, the D8 algorithm remains a single-flow approach that does not allow flow dispersion and therefore cannot explicitly represent braided river systems. Alternative multiple-flow-direction approaches exist and can better represent such complex drainage structures (e.g., Tarboton 1997). Nevertheless, the D8 method remains the most widely used approach in large-scale hydrological modeling due to its deterministic non-dispersive behavior, simple implementation, and computational efficiency with large raster datasets (Getirana et al., 2009; Kotyra and Chabudziński, 2023). Therefore, loops in the reference hydrographic network associated with braided rivers were removed during an upstream cleaning procedure in order to obtain a dendritic river network structure with multiple upstreams and a single downstream flow direction.

Regarding strongly regulated basins, we note that the Garonne basin already constitutes a highly anthropized system including numerous dams and flood diversion channels, as indicated in Section 3.1 of the manuscript. However, the present study focuses exclusively on natural flow processes and therefore only considers the mapped natural river network. Hydraulic infrastructures such as dams, reservoirs, and artificial diversion channels are not represented in the current framework configuration.

Regarding dense small tributary networks, in the present study, as stated in Section 3.2.1 and as also explained in our response to Reviewer 1, retaining only the main rivers and major tributaries was a deliberate methodological choice. This filtering ensures consistency between the mapped river network and the grid resolutions considered, up to 10 km, while preserving realistic drainage patterns and avoiding stream-collision artifacts that may arise when upscaling narrow, low-order streams. It therefore provides a balance between hydrographic detail and computational efficiency for the relatively large-domain H&H modeling objective of the study. We acknowledge that the appropriate level of river-network density may depend on the targeted application, spatial resolution, available calibration observations, and potentially the spatial coverage of satellite observations in the perspective of future data assimilation applications. Nevertheless, the proposed framework itself is not restricted to the selected network density, and denser river networks could be considered in future applications provided that an appropriate balance between geometric consistency, computational cost, and observational constraints is maintained.

We will further clarify this point in the revised manuscript while explicitly acknowledging this scale-dependent limitation of coarse-resolution network derivation and emphasizing the need to select a network density consistent with the target grid resolution and modeling objectives.

RC: ***The conclusion should include a concise limitations paragraph covering short evaluation period, one-way coupling, simplified channel geometry, limited hydraulic validation, and testing in one basin.***

AR: We thank the reviewer for this important comment. We agree that a concise limitations paragraph should be added to the conclusion, and we will revise the manuscript accordingly.

As explained throughout our responses to both reviewers, the revised manuscript will more clearly state the scope of the study. The objective is to demonstrate the feasibility and internal consistency of the proposed raster–vector H&H framework across spatial resolutions, rather than to optimize flood-modeling performance. This clarification of the study scope will help justify the simplified modeling setup adopted in the present work, including simplified H&H parameterization, the relatively short H&H simulation period, and the application to a single basin.

In this context, the Garonne basin already constitutes a relatively large, heterogeneous, hydrologically complex, and challenging test case for evaluating the proposed framework under controlled conditions.

The conclusion will explicitly recall that these choices were considered sufficient for the methodological objectives of the study, while also acknowledging that they remain limitations with respect to a full hydrological and hydrodynamic validation. In addition, further applications to larger basins will still be required before drawing broader conclusions regarding flood-modeling performance or transferability of the framework.

Regarding the one-way coupling strategy, we acknowledge that hydrodynamic processes do not currently provide dynamic feedback to the hydrological component. As already indicated in the conclusion of the manuscript, the modular structure of the framework within the `smash` environment nevertheless provides perspectives toward future developments of fully two-directional hydrology–hydraulics coupling configurations.

That said, the present work represents a first version of the framework and a first level of modeling complexity, intended to evolve toward more advanced configurations through future developments. These developments include, in the first place, the assimilation of water-surface observations, but also more broadly two-way coupling strategies, explicit floodplain representation, more physically based hydrological models, and full Saint-Venant routing schemes.

Such developments are facilitated by the collaborative open-source structure of the `smash` modeling environment, which involves contributions from different groups of scientists and engineers.

We will therefore better distinguish in the revised conclusion between the current achievements of the manuscript, the present limitations of the framework, and the future perspectives of this work.

References

Bates, P. D., Horritt, M. S., and Fewtrell, T. J.: A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling, Journal of Hydrology, 387, 33–45, , 2010.

Brisset, P., Monnier, J., Garambois, P.-A., and Roux, H.: On the assimilation of altimetric data in 1D Saint-Venant river flow models, Advances in water resources, 119, 41–59, https://doi.org/10.1016/j.advwatres.2018.06.004, 2018.

Getirana, A. C. V., Bonnet, M.-P., Rotunno Filho, O. C., and Mansur, W. J.: Improving hydrological information acquisition from DEM processing in floodplains, Hydrological Processes, 23, 502–514, , 2009.

Hoch, J. M., Eilander, D., Ikeuchi, H., Baart, F., and Winsemius, H. C.: Evaluating the impact of model complexity on flood wave propagation and inundation extent with a hydrologic–hydrodynamic model coupling framework, Natural Hazards and Earth System Sciences, 19, 1723–1735, , 2019.

Kotyra, B. and Chabudziński, L.: Fast parallel algorithms for finding the longest flow paths in flow direction grids, Environmental Modelling & Software, 167, 105 728, , 2023.

Larnier, K., Monnier, J., Garambois, P.-A., and Verley, J.: River discharge and bathymetry estimation from SWOT altimetry measurements, Inverse Problems in Science and Engineering, pp. 1–31, https://doi.org/10.1080/17415977.2020.1803858, 2020.

Larnier, K., Garambois, P.-A., Emery, C., Pujol, L., Monnier, J., Gal, L., Paris, A., Yesou, H., Ledauphin, T., and Calmant, S.: Estimating Channel Parameters and Discharge at River Network Scale Using Hydrological-Hydraulic Models, SWOT and Multi-Satellite Data, Water Resources Research, 61, e2024WR038 455, , e2024WR038455 2024WR038455, 2025.

Modi, P., Yamazaki, D., Hirabayashi, Y., Revel, M., and Zhou, X.: How Spatial Resolutions Impact the Large-Scale River Hydrodynamic Model Simulations: Analysis Focuses on Model Physics, Journal of Advances in Modeling Earth Systems, 17, , 2025.

Nardi, F., Annis, A., Di Baldassarre, G., Vivoni, E. R., and Grimaldi, S.: GFPLAIN250m, a global high-resolution dataset of Earth's floodplains, Scientific Data, 6, 180 309, , publisher: Nature Publishing Group, 2019.

O'Callaghan, J. F. and Mark, D. M.: The Extraction of Drainage Networks from Digital Elevation Data, Computer Vision, Graphics, and Image Processing, 28, 323–344, , 1984.

Pontes, P. R. M., Fan, F. M., Fleischmann, A. S., de Paiva, R. C. D., Buarque, D. C., Siqueira, V. A., Jardim, P. F., Sorribas, M. V., and Collischonn, W.: MGB-IPH model for hydrological and hydraulic simulation of large floodplain river systems coupled with open source GIS, Environmental Modelling & Software, 94, 1–20, , 2017.

Pujol, L., Garambois, P.-A., Finaud-Guyot, P., Monnier, J., Larnier, K., Mosé, R., Biancamaria, S., Yesou, H., Moreira, D., Paris, A., and Calmant, S.: Estimation of multiple inflows and effective channel by assimilation of multi-satellite hydraulic signatures: The ungauged anabranching Negro river, Journal of Hydrology, 591, 125 331, https://doi.org/10.1016/j.jhydrol.2020.125331, 2020.

Pujol, L., Garambois, P.-A., Larnier, K., et al.: Basin-Scale Variational Hydrological-Hydraulic Model Calibration for River Discharge Estimation Using SWOT Altimetry, Authorea, , 2026.

Tarboton, D. G.: A new method for the determination of flow directions and upslope areas in grid digital elevation models, Water Resources Research, 33, 309–319, , 1997.

Yamazaki, D., Kanae, S., Kim, H., and Oki, T.: A physically based description of floodplain inundation dynamics in a global river routing model, Water Resources Research, 47, , 2011.

Yamazaki, D., Baugh, C. A., Bates, P. D., Kanae, S., Alsdorf, D. E., and Oki, T.: Adjustment of a spaceborne DEM for use in floodplain hydrodynamic modeling, Journal of Hydrology, 436-437, 81–91, , 2012.

Yamazaki, D., de Almeida, G. A. M., and Bates, P. D.: Improving computational efficiency in global river models by implementing the local inertial flow equation and a vector-based river network map, Water Resources Research, 49, 7221–7235, , 2013.