Coupled 2D hydrologic-hydraulic catchment scale flood modeling with data assimilation capabilities: the DassHydro platform

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Abstract: This work presents the new DassHydro computational platform which includes a sequential coupling of the SMASH (Spatially Spatially distributed Modelling and ASsimilation for Hydrology models) hydrological model and the DassFlow (Data assimilation for free surface flows) multi-D hydraulic model. The complete code has advanced Variational Data Assimilation (VDA) capabilities, applicable to the whole chain. Preprocessing tools for automatic domain meshing and coupling as well as visualisation tools are included. Numerical simulations of floods at high resolution with the integration of multi-sensor data reducing uncertainties are thus possible. Each model is built from similar technologies: efficient Fortran solvers (with computations in parallel if required), adjoint codes generated by the automatic differentiation tool TAPENADE, Python interfacing based on the F90Wrap tool. The test cases show the capabilities of information transfer from the local generation of runoff at hydrological pixel scale on catchments to downstream river network and floodplains. Moreover, given observables especially on the hydraulic domain, the calibration of large dimension hydrological parameters is possible. The DassHydro platform is available online as an open source code including detailed documentations.

Keywords: Floods, inundation, High Resolution modeling, 2D hydrology, river hydraulics, data assimilation

Résumé : Ce travail présente la nouvelle plateforme de calcul DassHydro qui comprend un couplage séquentiel du modèle hydrologique SMASH (Spatially distributed Modelling and ASsimilation for Hydrology models) et du modèle hydraulique multi-D DassFlow (Data assimilation for Free surface Flows). Le code complet dispose de capacités avancées d'assimilation de données variationnelle applicables à l'ensemble de la chaîne. Des outils de prétraitement pour le maillage automatique du domaine et le couplage, ainsi que des outils de visualisation, sont inclus. Le code permet alors de réaliser des simulations numériques d'inondations à haute résolution en intégrant des données (provenant de plusieurs capteurs) et donc en réduisant les incertitudes. Chaque modèle est construit à partir de technologies similaires : des solveurs numériques Fortran (en parallèle si nécessaire), des codes adjoints générés par l'outil de différenciation automatique TAPENADE, une interface Python basée sur l'outil F90Wrap. Les cas tests montrent les capacités de transfert d'information depuis la génération locale des écoulements superficiels à l'échelle des pixels hydrologiques des bassins vers les réseaux fluviaux et les plaines inondables en aval. Grâce aux observations sur le domaine hydraulique, il est possible de caler les paramètres hydrologiques qui sont de grande dimension. La plateforme DassHydro est disponible en ligne sous forme de code ouvert avec documentations détaillées.

Mots-clefs : Crues, inondation, modélisation haute résolution, hydrologie 2D, hydraulique fluviale, assimilation de données

1. Introduction

Faced with the major socio-economic challenges of flood forecasting in a context of climate change, multi-scale modeling approaches that take advantage of the maximum available information are needed to enable accurate forecasts. The processes involved are multi-physics, non-linear and multi-scale. The data available are multi-sourced and heterogeneous in space-time and nature. The construction of robust and accurate numerical tools are required to meet the operational needs in times of crisis.

This article presents a new integrated approach of spatialized hydrological-hydraulic modeling-assimilation for high-resolution flood forecasting, while integrating multi-sensor data to reduce uncertainties. The developed methodology enables the transfer of information between scales, from the local generation of runoff over areas of less than a km^2 to the propagation of floods over basins of several thousand km2, as well as the feedback of information.

To this end, the SMASH (Colleoni et al., 2022) hydrological and DassFlow 2D (Monnier et al., 2016; Pujol et al., 2022) hydraulic modeling platforms, have been coupled, in a sequential way (weak coupling). Both computational codes include multi-scale spatial modeling and Variational Data Assimilation (VDA) algorithms. The VDA technology is here applicable to the complete chain therefore enabling the estimation of uncertain parameter-states according to the multi-source data available. A fully interfaced Python chain has been developed to address both direct and inverse cartographic flood-inundation modeling. The interfacing is designed to allow read/write access to all Fortran variables, including state variables and model parameters, as well as multi-site cost function gradients with respect to the models parameters. The hydrological-hydraulic coupling is adapted to multi-scale structured hydrological drainage plans (SMASH mesh) and 2D hydraulic meshes. This article presents the developed methodology, the coupled SMASH-DassFlow chain, the VDA methodology applicable to the complete chain, and numerical results on cases of increasing complexity.

2. Methodology

This section presents the two models (SMASH and DassFlow), the coupling strategy adapted to multi-scale drainage schemes and the inverse VDA algorithm.
The first model is SMASH (Spatially distributed Modeling and data ASsimilation for Hydrology). This is a spatially distributed hydrological model with VDA capabilities (see Jay-Allemand et al. (2020); Colleoni et al. (2022) and references cited, https://smash.recover.inrae.fr). It contains conceptual representations and numerical approximations of dominant hydrological processes, while aiming to maintain relative parsimony. SMASH enables multiple spatio-temporal resolutions, and to compare operators and model structures. All models are defined on a regular grid and run "continuously". For each time step, they take as input grids of precipitation and potential evapotranspiration, and produce runoff routed according to a drainage plan.

DassFlow (Data Assimilation for Free Surface Flows, https://www.math.univ-toulouse.fr/DassFlow) is an open computational software package designed to simulate shallow free surface flows with VDA capabilities (Monnier et al., 2016; Pujol et al., 2022). The direct moel relies on robust second order finite volume schemes solving the shallow water

2D equations. Moreover, it enables 1D-like schemes (therefore low CPU-time consumption) with 2D zoom e.g. at branches intersections or in inundation areas, (Pujol et al., 2022). Mix of triangular and quadrangular elements can be used. The latest version presented here incorporates net rainfall source term or rainfall and infiltration source terms (not presented).

For each code (SMASH and DassFlow), the corresponding adjoint code is obtained by automatic differentiation using the TAPENADE tool (Hascoet & Pascual, 2013). This enables to tackle high-dimensional inverse problems (i.e. to estimate large dimension uncertain parameters). Both codes include a comprehensive Python interface for the Fortran computational code using F90Wrap (Kermode, 2020) and a Sphinx documentation. Both code sources and documentations are publicly available on GitHub as well as their coupling called DassHydro at HTTPS://GITHUB.COM/ORGS/DASSHYDRO-DEV/REPOSITORIES.

2.1. The hydrological model

Let us consider a 2D spatial domain $\Omega \subset \mathbb{R}^2$ that can contain multiple catchments, both gauged and ungauged, with a minimum of one gauged catchment, and $t > 0$ the physical time. The 2D spatial coordinates over Ω are denoted by x. The number of active cells within Ω is denoted N_x. A 2D flow directions map $\mathcal{D}_\Omega$ is obtained from terrain elevation processing, with the only condition that a unique point in Ω has the highest drainage area, and will be used for runoff routing.
Consider observed discharge time series $Q_g^*(t)$ at N_G observation cells of coordinates $x_g \in \Omega$, $g = 1..N_G$ ($N_G \geq 1$). For each observation cell, the corresponding gauged upstream subcatchment is denoted by Ω_g so that $\Omega_{ung} = \Omega \setminus \left(\cup_{g=1}^{N_G} \Omega_g\right)$ is the remaining ungauged part of the whole domain Ω. Note that this definition is suitable for the general regionalization case dealing with spatially independent and/or nested gauged catchments.

The rainfall and potential evapotranspiration fields are respectively denoted by $\boldsymbol{P}(x,t)$ and $\boldsymbol{E}(x,t)$, $\forall x \in \Omega$. Given an input drainage plan $\mathcal{D}_\Omega(x)$, the operator $\mathcal{M}_{rr}$ represents the dynamic hydrological model mapping $\boldsymbol{P}(x,t)$ and $\boldsymbol{E}(x,t)$ onto the scalar discharge field $Q(x,t)$ and the N_S-dimensional vector $\boldsymbol{h}(x,t)$ such that: $\forall (x,t) \in \Omega \times (0,T)$,

$$\boldsymbol{U}_{rr}(x,t) \equiv (\boldsymbol{h}, Q)(x,t) = \mathcal{M}_{rr}\left[(\mathcal{D}_\Omega, \boldsymbol{\theta}_{rr}, \boldsymbol{h}_0)(x); (\boldsymbol{P}, \boldsymbol{E})(x,t)\right] \tag{1}$$

where $\boldsymbol{\theta_{rr}}$ is the $N_{\theta_{rr}}$-dimensional vector of model parameters 2D fields that we aim to estimate regionally with the new algorithms proposed below. $\boldsymbol{h}$ represents the N_S-dimensional internal model state of $\mathcal{M}_{rr}$ compartments.
In this study, the distributed hydrological model $\mathcal{M}_{rr}$ is a parsimonious GR-like conceptual structure, which is the "gr-b" structure presented in Colleoni et al. (2023). The hydrological parameters vector is:

$$\boldsymbol{\theta_{rr}}(x) = (c_p, c_{ft}, k_{exc}, l_r)(x), \ x \in \Omega \tag{2}$$

where the four spatially varying parameter fields are the capacity of the production reservoir (c_p in [mm]), the capacity of the transfer reservoir (c_{ft} in [mm]), the parameter (k_{exc} in [mm/dt]) of the non-conservative water exchange flux, and the linear routing parameter (l_r in [min]).

In order to constrain and explain these spatial fields of conceptual model parameters $\boldsymbol{\theta_{rr}}(x)$ from descriptors $\boldsymbol{D}(x)$, we introduce a pre-regionalization operator $\mathcal{F}_R$ that is a descriptor-to-parameters mapping

The forward hydrological model is solved on a regular lattice $\mathcal{T}_\Omega$ composed of squares and continuously covering Ω. The spatial step dx is constant, the temporal step dt is constant too.

The cell-to-cell flow routing is performed using a 2D flow direction map $\mathcal{D}_\Omega$ obtained from terrain elevation processing, with the only condition that a unique point in $\mathcal{T}_\Omega$ has the highest drainage area, on top of the routing scheme. All physical descriptors are mapped onto model grid for simplicity here.

The numerical resolution of the ODE-based operator (1) relies on an explicit expression of its solution, approximated on the regular mesh $\mathcal{T}_r r$ of constant step dx_{rr} with a fixed time step dt_{rr}.

2.2. The 2D-1D hydraulic model

The hydraulic domain Ω_{hy}, $\Omega_{hy} \subset \Omega_{rr} \subset \mathbb{R}^2$, is a portion of a hydrographic network plus its floodplains, covered by a mesh $\mathcal{T}_{hy}$ which is meshed by a mix of triangular and quadrangular elements. The following 2D shallow water equations are solved over a time intervall $]0, T]$:

$$\mathcal{M}_{hy}: \quad \partial_t \mathbf{U}(x,y,t) + [\partial_x \mathbf{F}(\mathbf{U}) + \partial_y \mathbf{G}(\mathbf{U})](x,y,t) = [\mathbf{S}_g(\mathbf{U}) + \mathbf{S}_f(\mathbf{U}) + \mathbf{S}_{rr}(\mathbf{U})](x,y,t)$$

$$\mathbf{U} = \begin{bmatrix} h \\ hu \\ hv \end{bmatrix}, \ \mathbf{F}(\mathbf{U}) = \begin{bmatrix} hu \\ hu^2 + \dfrac{gh^2}{2} \\ huv \end{bmatrix}, \ \mathbf{G}(\mathbf{U}) = \begin{bmatrix} hv \\ huv \\ hv^2 + \dfrac{gh^2}{2} \end{bmatrix},$$

$$\mathbf{S}_g(\mathbf{U}) = \begin{bmatrix} 0 \\ -gh\nabla b \end{bmatrix}, \ \mathbf{S}_f(\mathbf{U}) = \begin{bmatrix} 0 \\ -g\frac{n^2\|\mathbf{u}\|}{h^{1/3}}\mathbf{u} \end{bmatrix}, \ \mathbf{S}_{rr}(\mathbf{U}) = \begin{bmatrix} p_n \\ 0 \end{bmatrix} \tag{3}$$

The water depth $[\mathrm{m}]$ and the 2D depth-averaged discharge $\mathbf{q} = (hu, hv)^T [\mathrm{m}^2/\mathrm{s}]$ are the state variables describing the flow. The model parameters are: g the gravity amplitude $[\mathrm{m}/\mathrm{s}^2]$, $b(x,y)$ the bottom elevation $[\mathrm{m}]$ and n the Manning-Strickler friction coefficient $\left[\mathrm{s}/\mathrm{m}^{1/3}\right]$.
The source term $\mathbf{S}_{rr}$ corresponds to the net rainfall term given by the hydrological model or directly given as $p_n = (r - i)$ with r the spatialized rainfall and i the infiltration calculated using an SCS or Green and Ampt model.
Initial conditions are considered like various Boundary Conditions (BC) useful in real-world contexts (see details in DassFlow documentation).
The friction source term can also be expressed following Ferguson (2007) as $\mathbf{S}_f(\mathbf{U}) = \begin{bmatrix} 0 \\ \alpha \left(\frac{D^\beta}{h^\beta}\right)^2 \|\mathbf{u}\| \, \mathbf{u} \end{bmatrix}$, with α, β two coefficients to be optimized and D a macro-roughness height. For $\beta = 1/6$ and $D = 1$, $n \equiv \alpha/\sqrt{g}$ the more standard Manning-Strickler's law is recovered.

This 2D shallow-water system is numerically solved using classical first order or or less classical actual second-order well-balanced finite volume schemes, demonstrated to be robust in presence of wet-dry front dynamics, (Monnier et al., 2016).
Moreover, the numerical solver enables the computation of a mix of 1D and 2D flows by employing the single finite volume solver. To do so, 1D-like reaches are built through meshing methods that cause the 2D solver to degenerate into 1D. They are connected to 2D portions that act as local zooms, for modeling complex flow zones such as floodplains and confluences, via 1D-like–2D interfaces, see Pujol et al. (2022).

2.3. The hydrological-hydraulic coupling approach

The coupling algorithm aims to obtain a 2D hydrological-hydraulic chain (weakly) coupled via fluxes-states remapping. Recall that $\mathbf{U} = (h, \mathbf{q})$. Then this weak coupling can be symbolized as: for $t \in (0, T)$,

$$\mathbf{U}(x', t) = \mathcal{M}(\mathbf{P}, \mathbf{E})(x, t) \text{ with } \mathcal{M} = (\mathcal{M}_{hy} \circ \mathcal{M}_{rr}),\ x' \in \Omega_{hy},\ x \in \Omega_{rr} \quad (4)$$

The resulting chain aims to: (i) transfer lateral fluxes from the spatially distributed hydrological model $\mathcal{M}_{rr}$ to the higher resolution hydraulic flow model $\mathcal{M}_{hy}$, from headwaters to the hydrographic network and flooplains while, (ii) to impose hydrological soil saturation state as initial condition if an infiltration model is used in the hydraulic model, (iii) enabling information feedback through multi-source VDA.
The resulting computational tool incorporates consistent state-flux mapping and inference capabilities applicable to the whole hydrological-hydraulic chain, and therefore enables to perform meaningfull parameters estimation.

Let us consider a structured hydrological mesh $\mathcal{T}_{rr}$ covering the catchment Ω_{rr} and a compatible unstructured hydraulic mesh $\mathcal{T}_{hy}$ of the river network and floodplains domain Ω_{hy}, $\Omega_{hy} \subset \Omega_{rr}$.

The first step consists to define the coupling interfaces denoted by Γ_{rr-hy}. Γ_{rr-hy} is composed of a finite number $N_{interface} = (N_{bc} + N_{lat} + N_{vert})$ flux coupling edges between the two meshes. This pertains to coupling a regular hydrological grid of relatively coarse resolution, for example at $dx_{rr} = 1km$, with an unstructured hydraulic mesh at relatively fine resolution, for example $dx_{hy} \approx 1m$.
The hydraulic mesh is automatically generated with Gmsh (Geuzaine & Remacle, 2009) from hydraulic domain outline, main channel closed outline and river network centerlines (ex. BD TOPAGE). Domain outlines and banklines are used to generate an unstructured mesh with Gmsh with simply here a refined mesh size on the main channel. The intersection of river centerlines and domain outlines enable to detect the location of the main Boundary Conditions (BC) for main inflows and downstream BC. The coupling with the hydrological model is then performed by matching for each hydraulic BC the closest headwater catchment on hydrological grid, by matching each of the remaining "hillslope" pixel with the closest centers of hydraulic cell adjacent to the domain border.

Next, the coupling approach aims to remap hydrological fluxes consistenly in space and time into the hydraulic model by respecting the mass conservation. (Note that this property is not so usual in codes).

We distinguish below "main inflows", i.e. inflows from main water courses draining the larger subcatchments (threshold based distinction), from "secondary lateral inflows" that is the remaining fluxes simulated by the hydrological model for lateral subcatchments of lower drainage area.
Then, the mass preserving coupling conditions are enforced in the hydraulic model $\mathcal{M}_{hy}$ as follows:

- **Main inflows** from the hydrogical model $\mathcal{M}_{rr}$ are imposed at hydraulic domain boundaries Γ_{hy} as: $Q^{x_{hy,k}}_{hy,in}(t) = Q^{x_{rr,k}}_{rr,out}(t), \forall t, k = 1..N_{bc}$.
- **Secondary lateral inflows** are imposed as mass source terms in Eq. (3): $p_n = Q^{x_{rr,k}}/A_k, k \in 1..N_{lat}$ with A_k the area of hydraulic cell k.

- **"In-domain" inflows** are imposed from the net rainfall flux simulated within the hydrological model as mass source terms in Eq. (3) with: $p_n = Q^{x_{rr,k}}/A_k, k \in 1..N_{vert}$.

In summary, inflow hydrographs are imposed as BC for clearly identified headwater catchments, as mass source term for others hillslope lateral catchements. Runoff production on the hydraulic domain is imposed either with net rainfall from the hydrological model or directly simulated with the hydraulic model if rainfall and infiltration terms are considered.

2.4. Data assimilation algorithms

Both codes, SMASH and DassFlow codes, include similar VDA features. Given a spatio-temporal flow model, given observables (provided by in situ and airborne sensors for instance), a VDA algorithm aims at estimating the unknown-uncertain input parameters of the model by minimizing the misfit between the observables and model outputs. We denote by θ_{hy} (resp. θ_{rr}) the unknown parameter of the hydraulic (resp. hydrological) model, and $\boldsymbol{\theta} = (\theta_{hy}, \theta_{rr})$; $\boldsymbol{\theta}$ is composed of spatio-temporal hydrological and/or hydraulic "control parameters".
The VDA method can be applied to one of the models only as in Monnier et al. (2016); Jay-Allemand et al. (2020) or to the complete hydrological-hydraulic chain $(\mathcal{M}_{hy}(\theta_{hy}) \circ \mathcal{M}_{rr}(\theta_{rr}))$. The unknown-uncertain parameter $\boldsymbol{\theta}$ is a-priori high-dimensional. As a consequence, the cost gradient computation relies on the composed adjoint model

$$(D_{\theta_{rr}}\mathcal{M}_{rr})^T(\theta_{rr}) \circ (D_{\theta_{hy}}\mathcal{M}_{hy})^T(\theta_{hy})$$

. The adjoint models are derived by automatic differenciation using the Tapenade software (Hascoet & Pascual, 2013).
We consider the cost function:

$$J(\boldsymbol{\theta}) = J_{obs}(\mathbf{U}(\boldsymbol{\theta})) + \alpha_{reg} J_{reg}(\boldsymbol{\theta}) \tag{5}$$

where $J_{obs}(.)$ and $J_{reg}(.)$ are differentiable, convex functions and α_{reg} is the regularization weight. The observation term J_{obs} is defined to account for multi-source as in e.g. Pujol et al. (2022) with depth, discharge or even surface velocity fields and multi-site observables as in e.g. Huynh et al. (2023), through scaled and potentially weighted terms accounting for data-model misfit on the hydrological and/or the hydraulic domain and/or the coupling interface. The optimization problem reads:

$$\boldsymbol{\theta}^* = \underset{\boldsymbol{\theta}}{\operatorname{argmin}} J(\boldsymbol{\theta}) \tag{6}$$

The optimization problem is numerically solved using the quasi-Newtion descent algorithm L-BFGS-B (Zhu et al., 1997). For more details on the formulations and algorithms, see e.g. Monnier (2020).

3. Results

We first test the coupled modeling chain on representative synthetic cases, highlighting (i) the impact of hydrological fluxes re-mapping choices, (ii) information feedback capabilities. Second, the chain is applied in a semi-automatic way with the preprocessing tools on a real case: the flood event of october 2018 of the Aude river at Carcassone, southern France.

3.1. Flux coupling - modeling choices and impacts

In this section, we validate the flux coupling approach and show the impact of flux coupling options. The hydrological domain is a squared watershed of $10km^2$ with flow direction held on the diagonal from the top left corner to the bottom right corner, all the flow directions above the diagonal are vertical while all the flow directions below the diagonal are horizontal. To complete the experimental setup, a simple rectangular channel is built such that it almost overlaps with the diagonal of hydrological model, its inflow boundaries are defined correspondingly to the hydrological model, see Fig. 1.

The hydrological model resolution is $dx_{rr} = 1km$ and $dt_{rr} = 1h$ while the hydraulic mesh is triangular with a resolution of $dx_{hy} = 100m$ with adaptative time step respecting the DassFlow numerical scheme criteria. The channel is approximately 1000 m wide and 5600 m long, a transmissive Neumann type BC is imposed at the outlet.

Considering 9 hydrographs from the hydrological model, the flux coupling is performed with 1 or 3 or 9 injections as BCs and the remaining injections as source terms. Numerical results enable to verify that injected mass remains the same whatever the injection scenario.
Regarding simulated outflows, the reference result is the black curve with all inflow hydrographs injected as BCs and propagated with the 2D shallow water model (black curve). It clearly depicts the impact of injecting 6 or 8 hydrographs as mass source terms on the outflow dynamics (blue and red curves). Note also the different dynamics obtained with the conceptual hydrological routing with one routing store per hydrological cell and an uniform parameter.

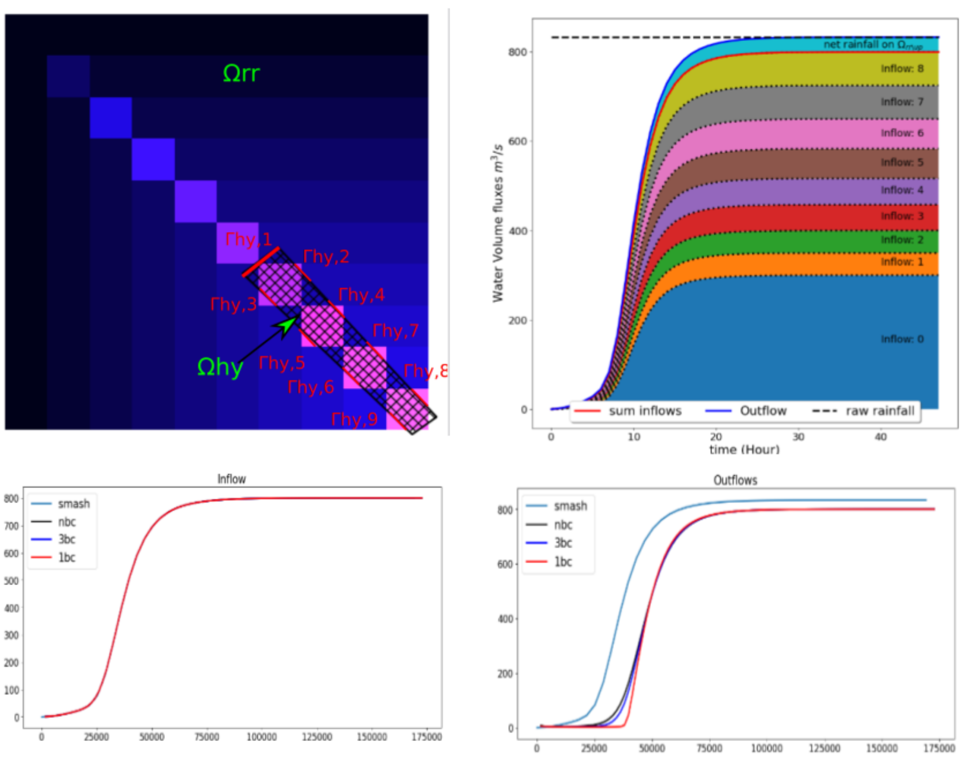

Figure 1. Synthetic case for forward coupling validation. (Top left) Hydrological and hydraulic mesh with 1 to 9 lateral boundary inferfaces $\Gamma_{1..9}$; (Top right) hydrological inflows considered ; (bottom left) cumulated inflow in function of injection repartition between BCs and source terms; (bottom right) simulated outflows with different configurations.

3.2. Hydraulic information feedback to hydrology

In this section, the inversion capabilities over a hydrological-hydraulic coupling are demonstrated on a multi-D confluence channel from Pujol et al. (2022) inflowed by two squared cathments, Fig. 2, similar to the one of the first synthetic case.

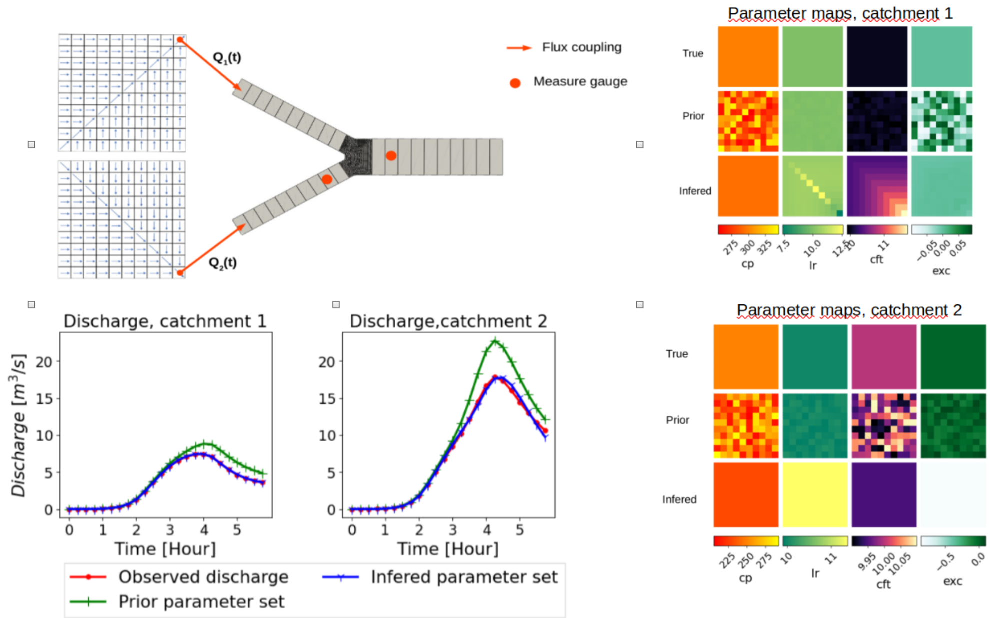

Figure 2. Hydrological inference from hydraulic observations. (Top left) Synthetic case with two square catchments, an idealized confluence channel with 1D-2D mesh from (Pujol et al., 2022) with 2 water depth observation stations; (bottom left) Hydrographs infered by hydraulic VDA and used as observation for hydrological VDA; (right) Infered hydrological parmeter maps from observations on the hydraulic domain.

A twin experiment is performed from a reference flow generated as follows: two different synthetic rainfall events are applied on the upstream subcatchments which are translated, via the hydrological model, into flood hydrographs (red curves) that are then inflowed on each upstream branch of the hydraulic domain modeled with a multi-D approach. Simulated water depth are observed, relatively densely in time (red dots), at one station in an upstream branch and in the downstream branch with mixed flows.
These observations are then used to perform an inversion with the VDA algorithm. First are retrieved upstream inflow hydrographs of the hydraulic model which are then used as observations (red curve) to infer hydrological model parameters. The infered parameters fields are presented on the right of Fig. 2 along with prior and target parameter fields - also used to generate prior (green curves) and target hydrographs (red curves) at the coupling interface.
The infered parameter sets, leading to hydrographs (blue curves) relatively similar to the target and hence relatively similar hydraulic behaviour downstream, while the infered parameter sets on each catchment unsurprisingly illustrate the issue of equifinality. Note that structural equifinality is visible for example on catchment 2 infered parameters which spatial average values represent a different functionning point of the model compared to "truth", and yet leading to similar outlet discharge for different internal simulated catchment behaviour. The spatial equifinality issue is illustrated on the first catchment with the spatialization infered for transfer and routing parameters, that follows catchment symetry (no regularization used here).
This test case shows the capability of performing hydraulic information feedback through the coupled spatially distributed hydrological-hydraulic chain by VDA.

3.3. Modeling of a real flood-inundation case

The modeling chain is applied to the Aude River basin (southern France), more precisely to the large flood event occurred in October 2018. The hydrological drainage plan at 1 km resolution is given as well as the closed lines describing hydraulic domain around Carcasonne City and main

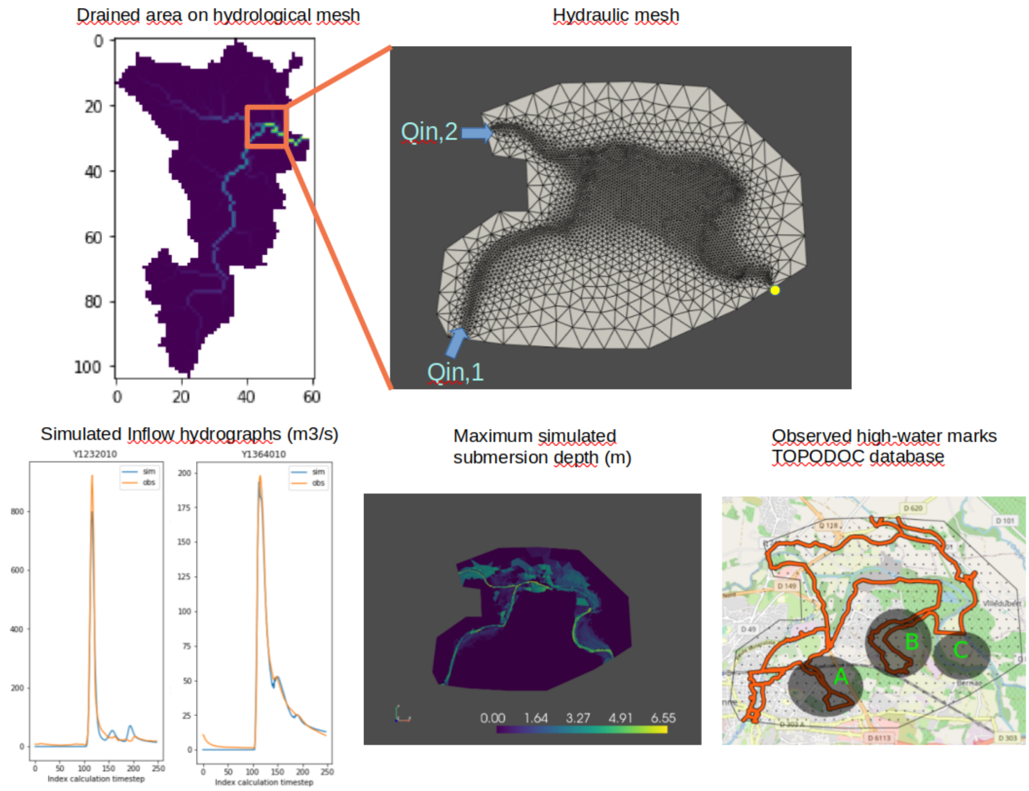

Figure 3. Modeling of the october 2018 flood event over the Aude basin. (Top) Hydrological and hydraulic meshes with two flux coupling points in blue. (bottom) Inflow hydrographs and resulting max flood flow depth compared to post flood extents.

channels, and an high resolution DEM at 5 m resolution (used in Hocini et al. (2021)). These data are used to generate the hydraulic mesh and coupling interface with the tool described above. The obtained hydrological-hydraulic coupling is illustrated in Fig. 3 with the obtained unstructured hydraulic mesh, flux coupling points and donwstream BC location. Note that it is possible to generate meshes at different resolutions for the hydrological model SMASH, from DEM resolution to larger ones, here set a resolution $dx = 1km$ which the one of the rainfall data grid.

The parameter fields of the hydrological model have been calibrated by VDA on the event, to best reproduce inflow hydrographs on multiple gauges within the catchemnt, especially for the two main inflows for hydraulic modeling over Carcasonne: the Aude and the Fresquel. The resulting hydraulic simulation, with a priori constant Manning friction $n = 0.03$, is illustrated in terms of maximum submersion depth map. This inundation pattern, obtained with a rough hydraulic mesh and uncalibrated hydraulic model, already shows some similarity with observed high-water marks. More advanced investigations and analysis are needed. Nevertheless, main discrepencies for three zones spotted may arise from: (A) unaccounted lateral contribution of a small subcatchment, (B) unaccounted bathymetric local singularity, (C) potential problem in bathymetry used for simulation and in high-water marks.

4. Conclusion and Perspectives

This contribution presents the development of a new integrated approach of spatialized hydrological-hydraulic modeling and VDA allowing the simulation of floods at high resolution, while integrating multi-sensor data in order to reduce uncertainties. Based on a coupling between SMASH and DassFlow 2D models along with automatic meshing tools, the approach enables the transfer of information between scales, from the local generation of runoff over areas smaller than $1km^2$ to the propagation of floods over basins and river networks, as well as performing feedback of information from multi-source data. The approach is showcased on two synthetic cases validating the mass conservation and pertinence of hydrological signals propagation in the coupling, as well as information feedback by VDA of hydraulic informations usable to infer hydrological parameter patterns. The approach is also sucessfully applied to a real case with automatic meshing tools.

Further work will focus on more complex coupling cases, multi-source data assimilation, and hybrid approaches with statistical learning.

Authors contributions PAG has initiated and supervised a significant portion of this research, while LV has upgraded the DassFlow software based on the provided description and conducted all the numerical results. JM has contributed to the supervision and to the writing of the paper.

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