Coupled 2D hydrologic-hydraulic catchment scale flood modeling and information feedback from multi-source variational data assimilation with DassHydro

Garambois P.-A., Monnier J.,
Villenave L.

Colloque SHF, « prévision des crues et inondations, avancées valorisations et perspectives »

27-28 novembre 2023, Toulouse

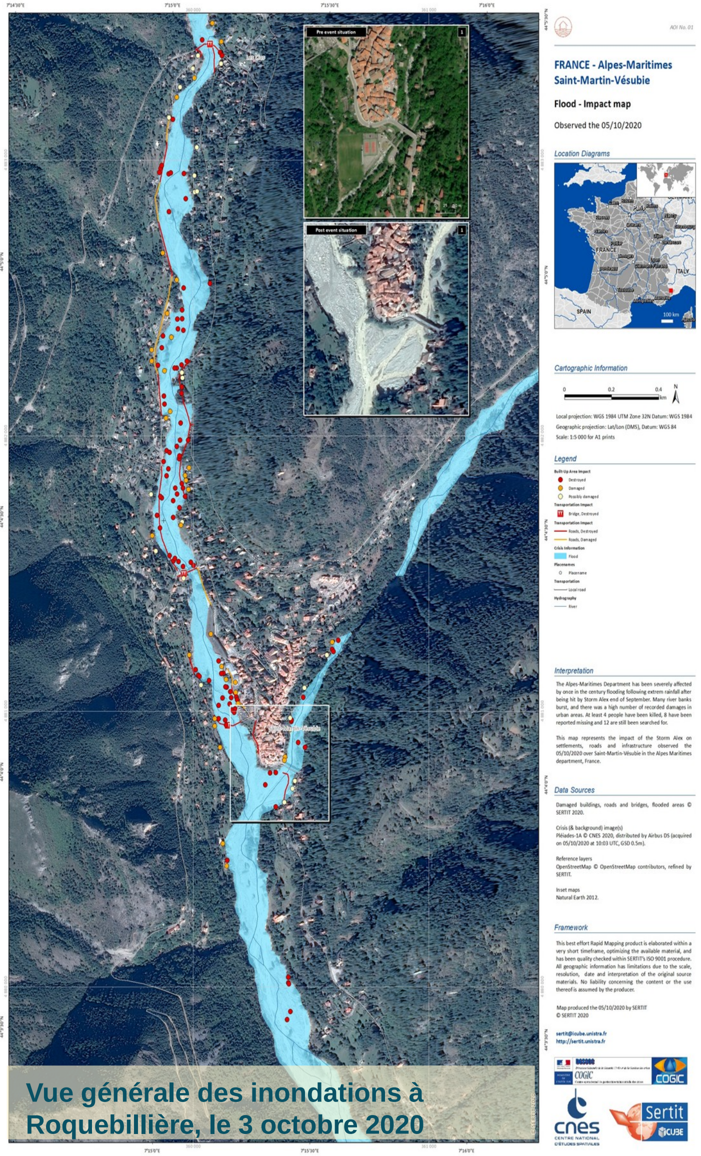
Contact: Pierre-André Garambois, INRAE, Recover, Aix-Marseille Univ.
pierre-andre.garambois@inrae.fr

Contexte – Crues et inondations, soudaines, dévastatrices

Gardon d'Alès (Gard) 8-9/09/2002

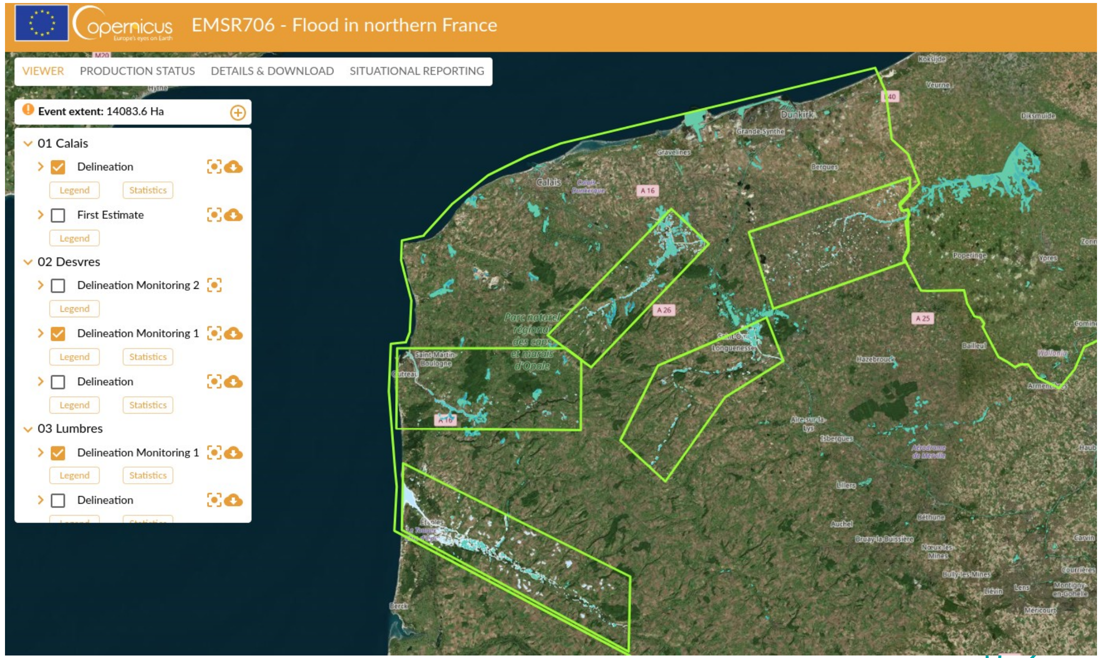
Nartuby en crue (Var), 14/06/2010

Zone inondée au Luc (Var), 24/11/2019 (sc : sécurité civile)



Vue générale des inondations à Roquebillière, le 3 octobre 2020

Panaches sédimentaires, réponses hydro-géomorphologiques, tempête Alex, Octobre 2020



Sentinel image of Novembre 2023 floods in North of France (Yesou et al. SERTIT)

Context - floods-inundation forecasting

Floods = first weather-related disaster in the world

dramatic increase of their impacts with global warming

Key challenge – operational needs: Performing accurate flood forecasts in terms of location, magnitude and timing of runoff and flooding, and identifying areas "at risk » ;

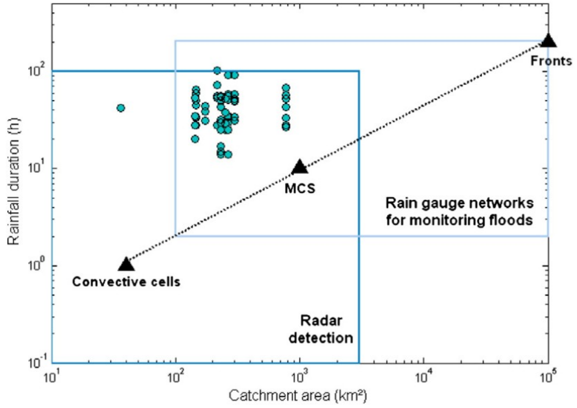
Forecast needed at high resolution and very rapidly (ex. ~ 10 min)

High uncertainties and difficult predictibility:

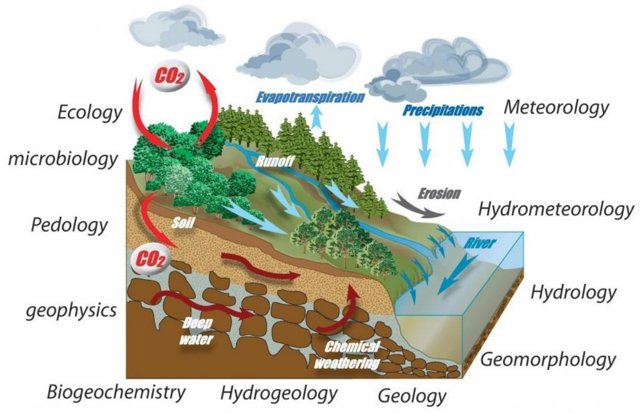
- Strongly variable, non linear and coupled physical processes (meteorology, hydrology, hydraulics, geomorphology),
- Limited observability, ungauged catchments ; *« no directly usable physical laws » in hydrology → avenue for Data science and assimilation, learning*
- Multiple-scales : local runoff ~ O(10m^2 - 1km^2) to large catchment ~ O(10^3 -10^{4}km^2)), temporality ~ minutes to days

MUFFINS project overarching goal :

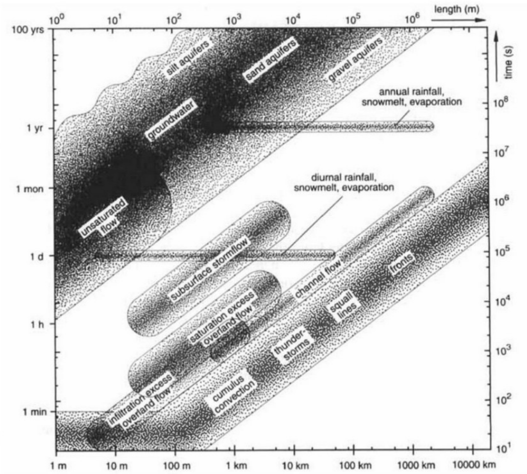
« New accurate and comutationally efficient flood forecasting approaches, enabling transferring information between modelings (meteo-hydrology-hydraulic-damage) and scales (from local runoff generation over areas lesser than 1-km2 to flood propagation on catchments of thousands km2), and taking advantage of innovative data (in situ, remote observation, opportunistic) to reduce forecasts uncertainties.



Flood trigerring rainfall spatio temporal scales (Garambois et al. 2014). Mesoscale convective systems scale from Orlanski, (1975), monitoring capacities from Borga et al., (2008)



The critical zone, home to surface processes and air-water-soil-rock-living organisms interactions (Source: CRITEX)



Hydrological processes on a range of characteristic spatio-temporal scales (Bloschl and Sivapalan 1995)

Context – MUFFINS project

MUFFINS: “MUltiscale Flood Forecasting with INnovating Solutions” (coord. Garambois), in continuity of the PICS ANR project (Payrastre et al.)

Pluridisciplinary consortium (Cerema, CCR, IMFT, IMT, INRAE, INRIA Lemon, Univ. Eiffel, Meteo Fr./SPC MedEst, Min. Ecol./SCHAPI)

Started on 1st march 2022 for 48 months, Funding of 597k€ from ANR

Project Goals :

- Understanding and specifying user needs (before, during, after crisis)
- Designing next generation flood warning chains based on users needs:
  - Ingestion of short-term rainfall forecasts
  - Regionalizable, learnable, multi-scale 2D hydrologic-hydraulic modelling chains,
  - Accuracy & speed for real-time computations at catchment scale
- Maximize information integration from multiple sources (in situ, satellite, opportunistic, databases)
- Demonstrations of the methods on Mediterranean catchments with multi-scale problems and rich data sets.

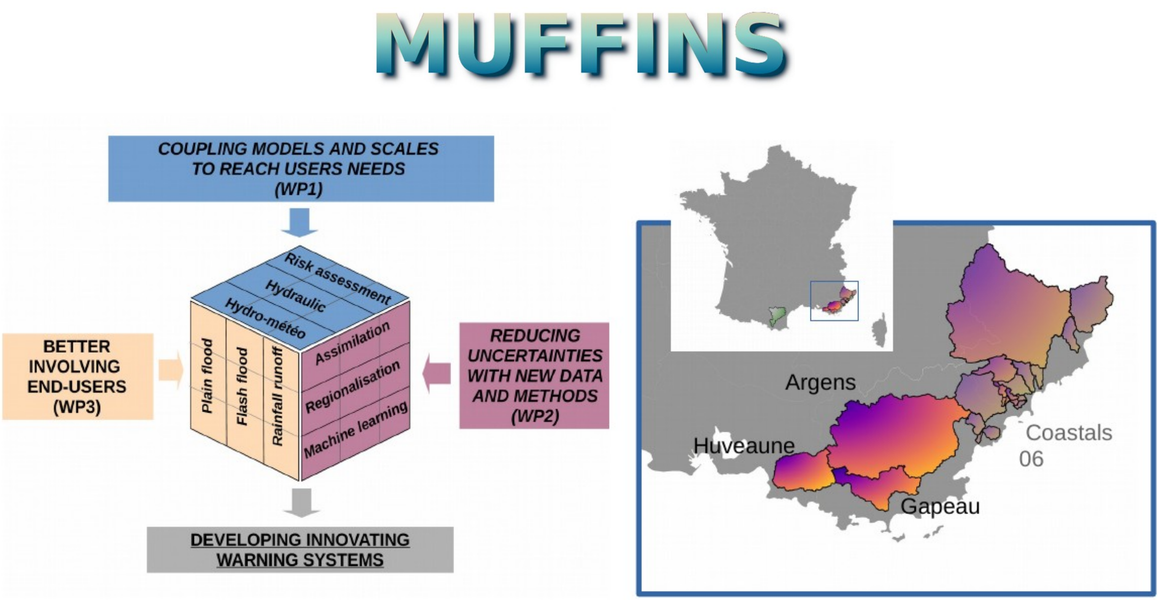
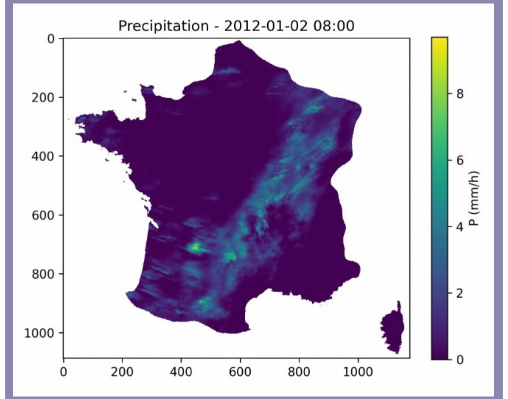


Figure 1. (Left) Overall objectives of the MUFFINS project and new insights. (Right) Main study catchments in the French Mediterranean region (magma), Aude catchment (green), fall-back/additional case.

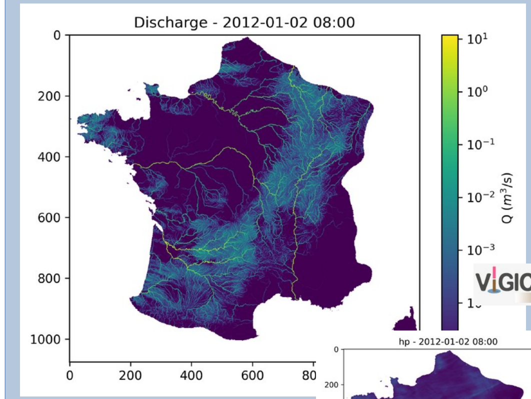
Context - Towards integrated flood modeling and data assimilation chains

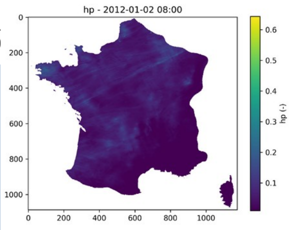
Research, developement and demonstrators in MUFFINS and NEPTUNE projects

Meteorological forcing

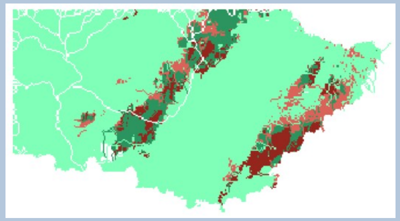


Hydrological response



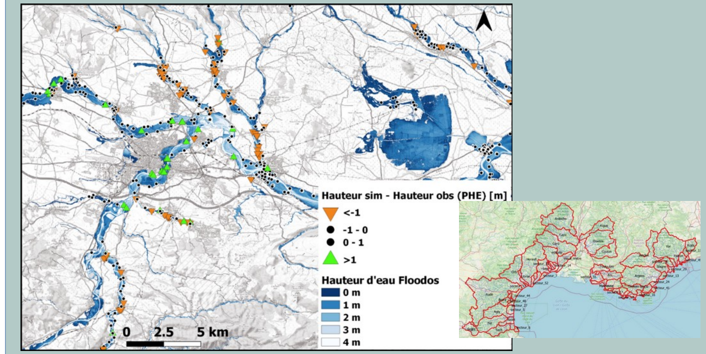


Discharge and moisture simulated with SMASH (Colleoni et al. 2022)

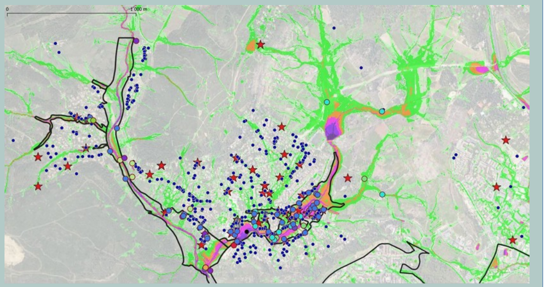


Hydrological evaluation of rainfal ensemble forecasts PIAF at t+3h (Godet et al. 2022)

High resolution hydraulics – fluvial flooding, runoff



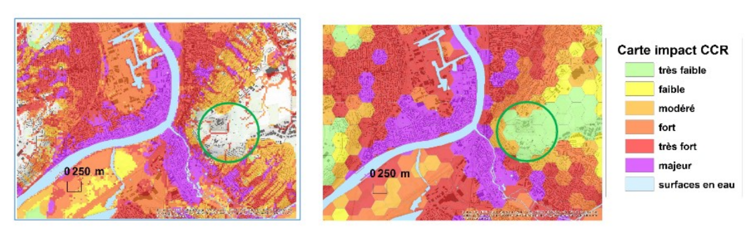
Catalogue of flood extents (Hocini et al. 2021; Payrastre, Nicolle et al. 2022)

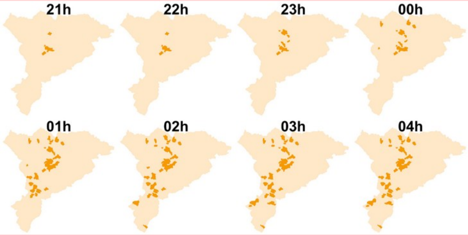


Runnof simulated with Cartino 2D (Telemac 2D) (Pons et al.)

Risk evaluation and impacts

Impacts map, CCR (Naulin et al.)

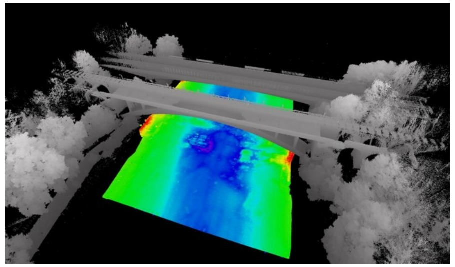




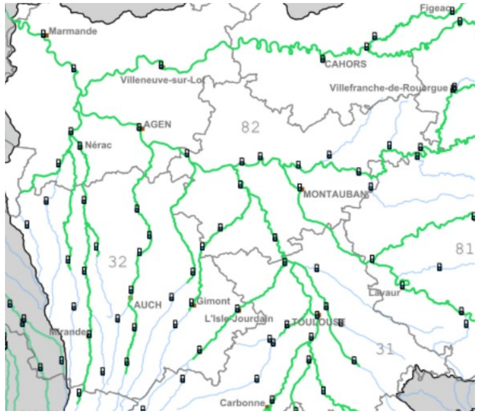
Localisation of rescue teams -SDIS (Charpentier-Noyer, Payrastre)

Context – multi-source heterogeneous flow data

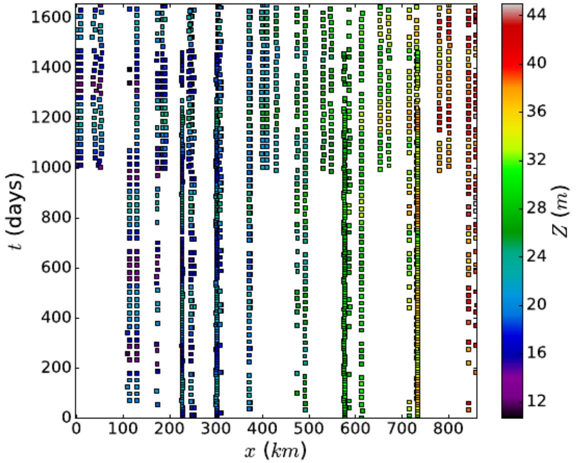
Various informative content at various scales



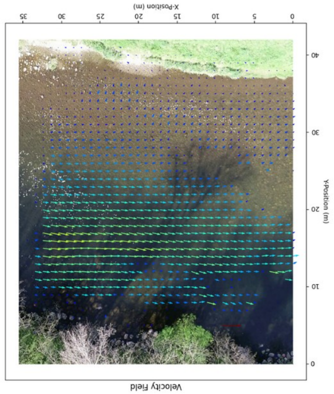
Drone Lidar, bathymetry, ...



In situ network – limnimeters, raintg curves...

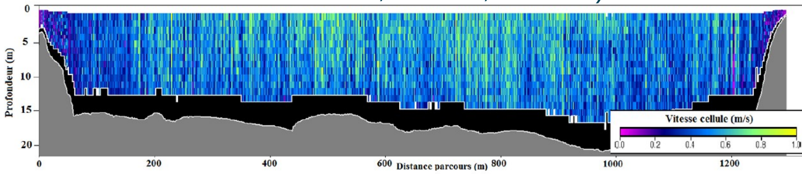


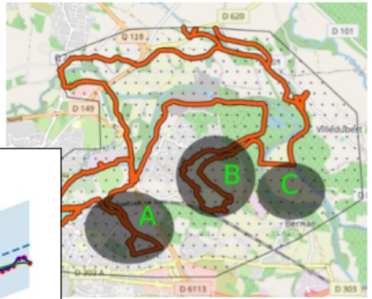
Hydraulic visibility on the Negro River from multi-mission altimetry (Malou et al. 2021)



Surface Velocity from video (Androme software, Pujol, Cassan et al.)

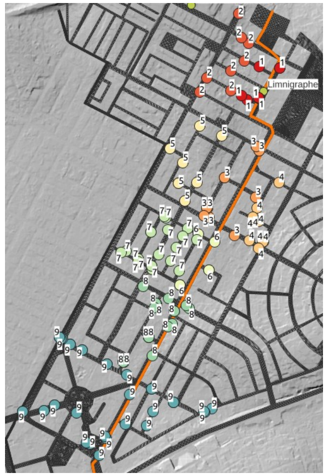
Velocity profile, discharge from Doppler curent profiler (Rio Negro at Novo Airao) (Paris, Garambois, Moreira, Calmant)



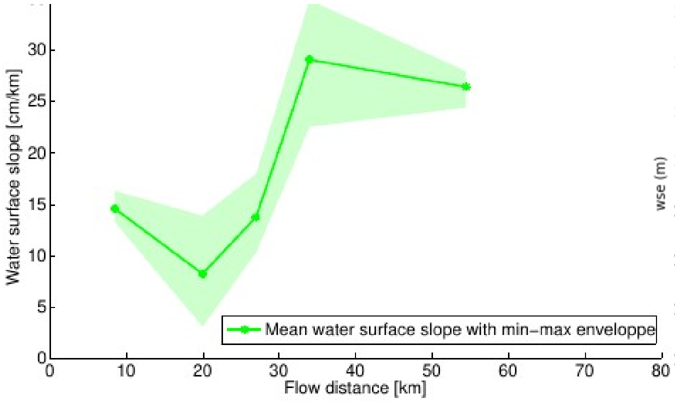


Flood marks / extents (Carcasonne 2018)

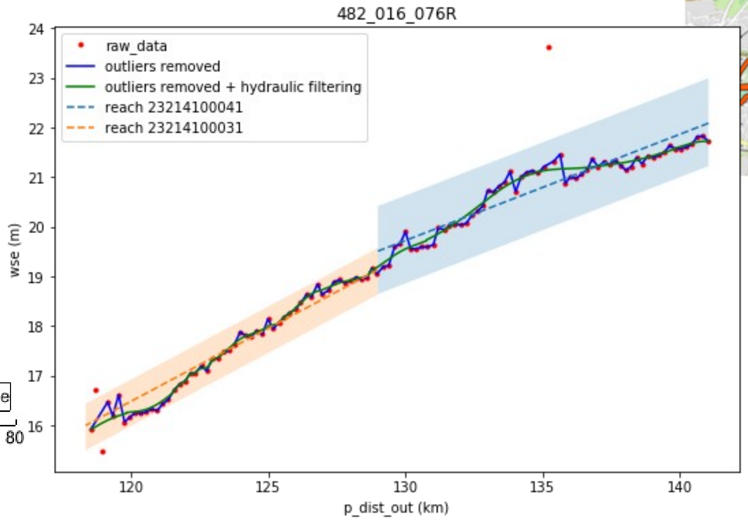
Dynamic extents (Sentinel, Maroni River, cf. Poster Larnier et al.)



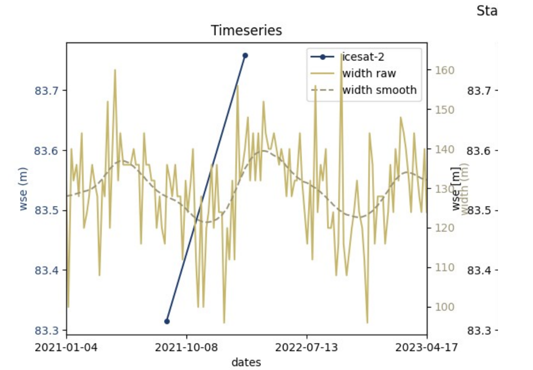
Max urban flood flow depth, video too, Abidjan (Pujol et al.),



Hydraulic visibility of Water surface slope from Nadir altimetry along Xingu River (Garambois et al. 2017)



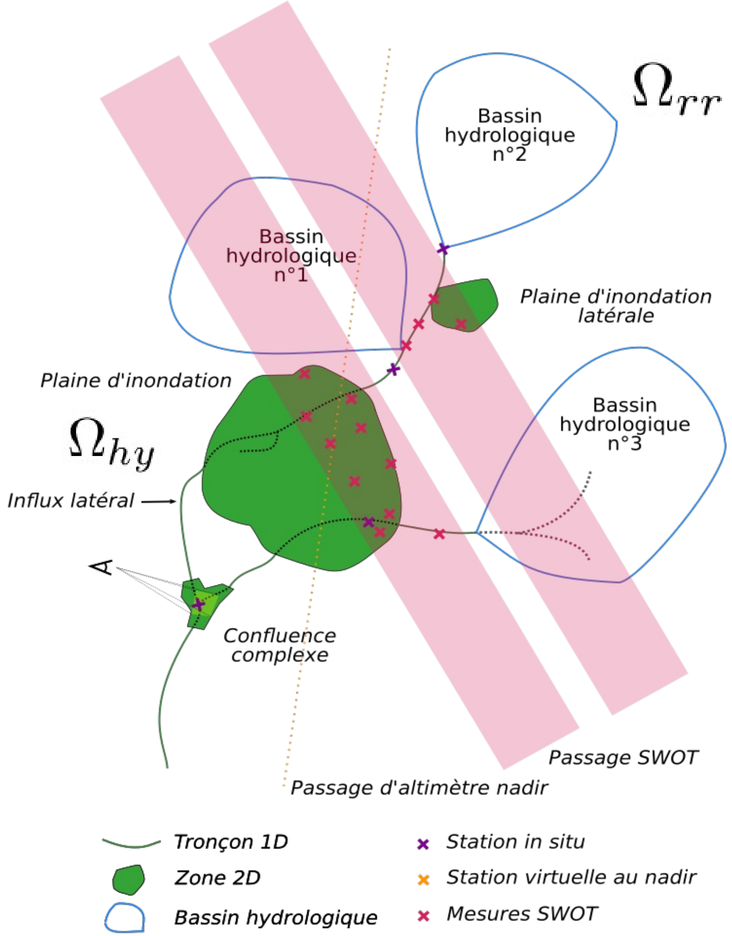
Remotely sensed flow lines – SWOT on the downstream Garonne, spring 2023 !



Scope

Integrated hydrological-hydraulic modeling of catchment river networks, Information feedback from multi-source observations

- **Multi-scale hydrological-hydraulic modeling (up to high resolution)**
  - Hydrology : runoff genesis from rainfall
  - Hydraulic : propagation into networks, flooding over floodplains, hillslope/urban runoff
- **Coupled differentiable numerical codes :**
  SMASH for hydrology + DassFLow for hydraulics => Dasshydro
- **Inverse algorithm** applicable to the whole toolchain (Variational data assimilation) to fuse multi-source observations over the catchment-river network
- **Method**: coupling with information feedback following **Pujol et al. 2022 GMD** (DassFLow Multi-D and a semi distributed state-space GR within) from **multi-source heterogeneous flow measurements** (see also Larnier et al. 2020 IPSE, Garambois et al. 2020 JoH, Pujol et al. 2021 JoH, Malou et al. 2022 JoH):
  - **h or Z (x,t) ; Z_max(x), h_max(x) if b(x) given…**
  - **W(x,t) or W_max (x)**
  - **V_surf (x,t)**
  - **V (x,t_gauging) ; by product Q(x,t) and uncertainty…**
  - **Opportunistic data…**



Conceptual view of integrated catchment-river network model with multisource data (Pujol PhD, 2022)

Méthodologie : modèles hydrologique et hydrauliques 2D

Modèle hydrologique spatialisé :

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

Paramètres spatialisés (structure GR4-like, SMASH from Colleoni et al. 2022)

$$\boldsymbol{\theta}_{\boldsymbol{rr}}\,(x) = (c_p, c_{ft}, k_{exc}, l_r)\,(x),\ \ x \in \Omega$$

Modèle hydraulique 2D shallow water:

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

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

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

Méthodologie : expression du couplage hydrologie-hydraulique 2D (multi-D)

Le couplage vise à obtenir une chaîne 2D hydrologie-hydraulique via un remapping d'états-flux.
Rappelons que $\mathbf{U}_{rr}=(h,\mathbf{q})$, le couplage s'écrit :

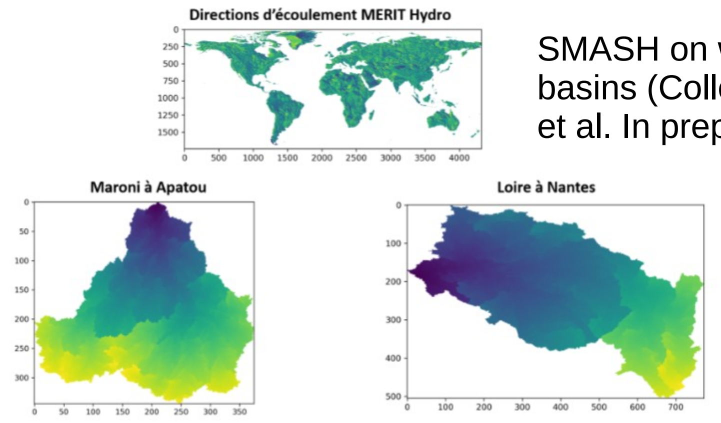
$$\mathbf{U}(x',t) = \mathcal{M}(\mathbf{P},\mathbf{E})(x,t) \;\; \text{with} \;\; \mathcal{M} = (\mathcal{M}_{hy} \circ \mathcal{M}_{rr}), \;\; x' \in \Omega_{hy}, \;\; x \in \Omega_{rr}$$

The resulting chain aims to:

1) Transfer lateral fluxes from the spatially distributed hydrological model M_{rr} to the higher resolution hydraulic flow model M_{hy} , from headwaters to the hydrographic network and flooplains while,

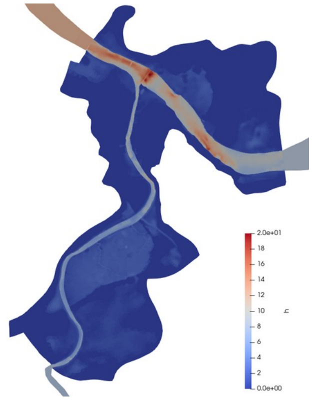
2) To impose hydrological soil saturation state as initial condition if an infiltration model is used in the hydraulic model, (nota dressed here)

3) Enable information feedback through multi-source VDA.



SMASH on world basins (Colleoni et al. In prep)

Figure: Maillage SMASH avec les directions d'écoulement MERIT Hydro. Eilander et al. 2020, https://doi.org/10.5281/zenodo.7936280

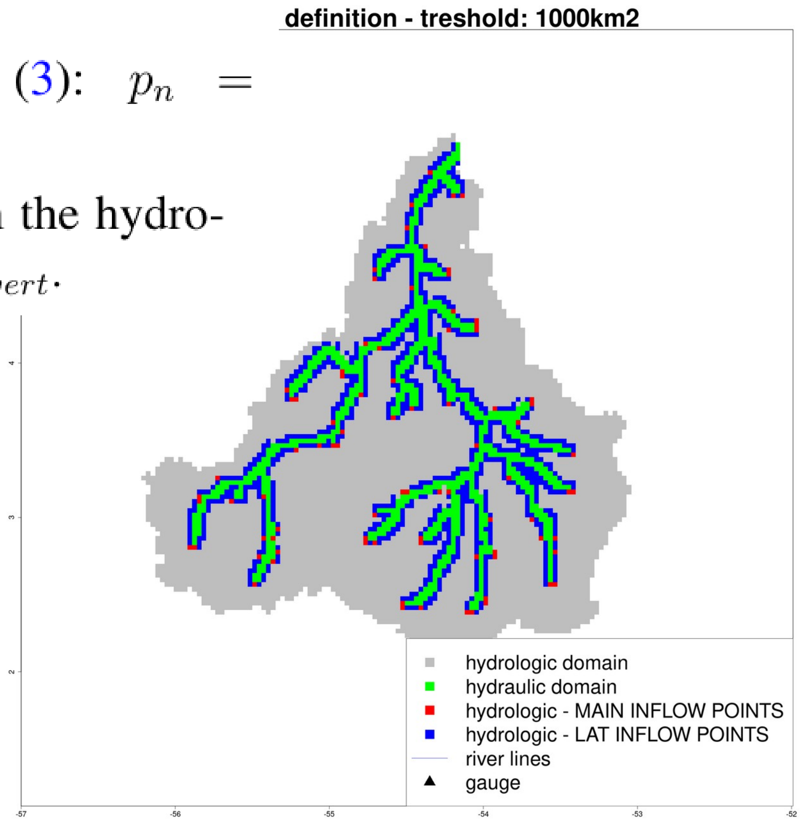


Méthodologie : algorithme d'assimilation appliqué au couplage

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}, $\Omega_{hy} \subset \Omega_{rr}$.

coupling interfaces : Γ_{rr-hy}. Γ_{rr-hy} $\quad N_{interface} = (N_{bc} + N_{lat} + N_{vert})$

- **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: $p_n = Q^{x_{rr,k}}/A_k, k \in 1..N_{vert}$.



Définition de points de couplage, Maroni (Scripts R, Villenave), Drained area threshold 1000km^2

Méthodologie : algorithme d’assimilation de données

Both SMASH and DassFlow codes include similar VDA features (adjoint models derived with Tapenade software (Hascoet and Pascaual 2013)). The unknown parameter of the hydraulic and hydrological model is :

$$\boldsymbol{\theta} = (\theta_{hy}, \theta_{rr})$$

The VDA method can be applied to one of the model 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 θ is a-priori high-dimensional. As a consequence, the cost gradient computation relies on the composed adjoint mode

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

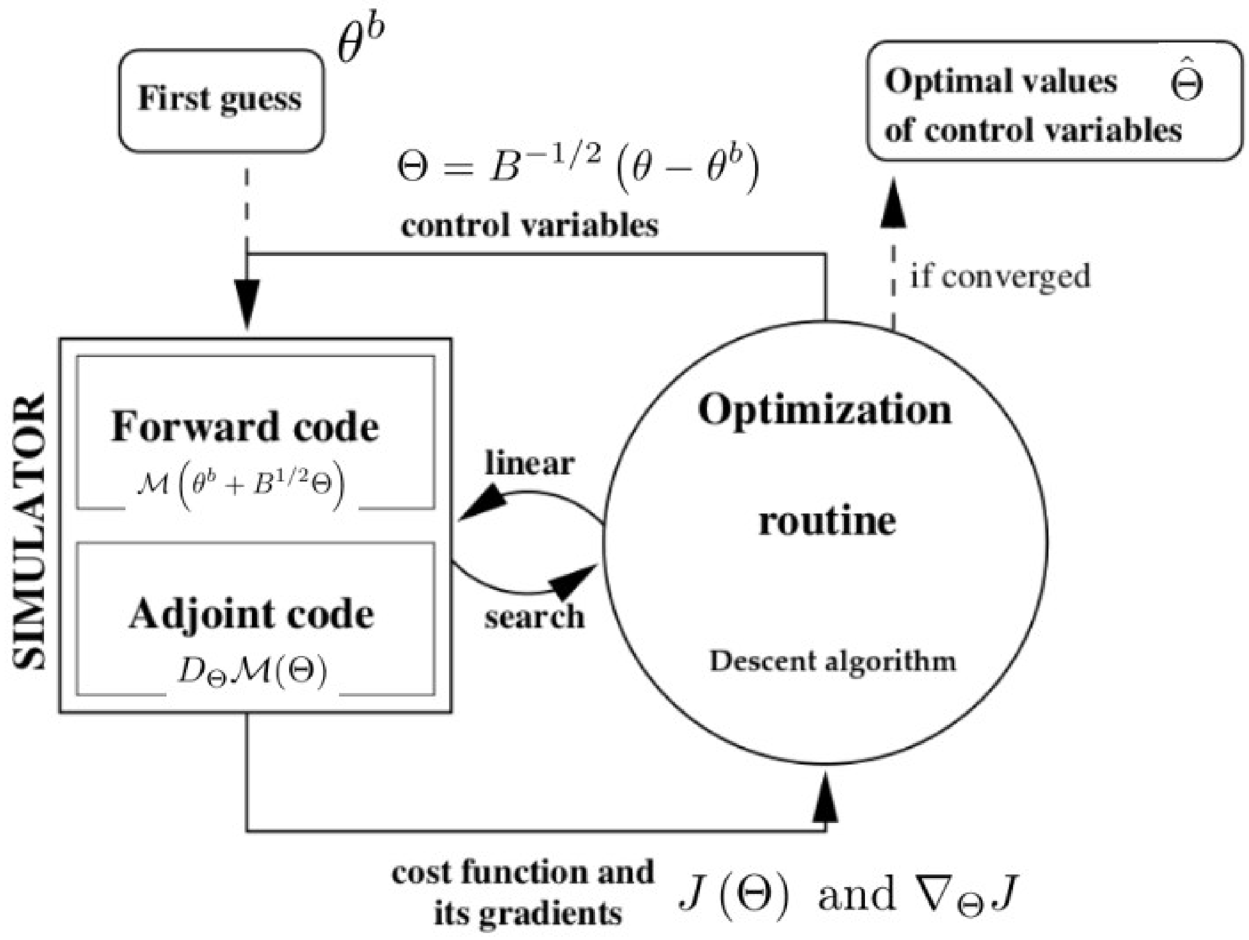
The cost function (convex and differentiable ; with multi-source observation term) :

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

The following optimization problem is solved with LBFGS algorithm with cost gradient computed with composed adjoint model:

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

Méthodologie : algorithme d'assimilation de données



$$j(\theta,\gamma) = \frac{1}{2}\left\|H(\theta) - Y^*\right\|^2 + \frac{\gamma^2}{2}\left\|B^{-1/2}\left(\theta - \theta^b\right)\right\|^2$$

$$J(\Theta) = \frac{1}{2}\left\|H\left(\theta^b + B^{1/2}\Theta\right) - Y^*\right\|^2$$

VDA algorithm (adapted from Monnier 2023), with variable change
(« peconditionning », not used in results presented after)

Results: Flux coupling - modeling choices and impacts, forward runs

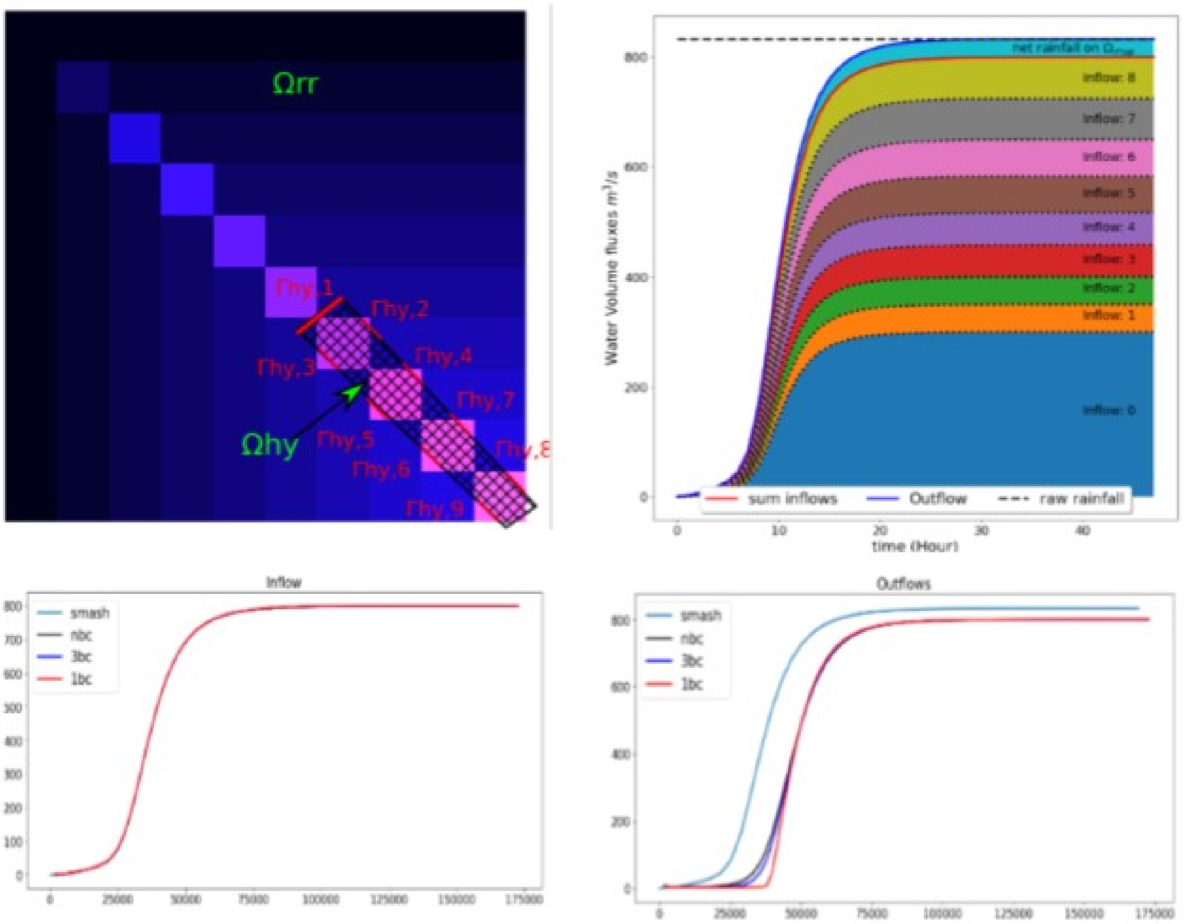


Figure 1. Synthetic case for forward coupling validation. (Top left) Hydrological and hydraulic mesh with 1 to 9 lateral boundary inferfaces $\Gamma_{1..9}$; (Top right) hydrological inflows considered ; (bottom left) cummulated inflow in function of injection repartition between BCs and source terms;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

Results: Hydraulic information feedback to hydrology
(Data assimilation through the chain, « backward hydrology »)

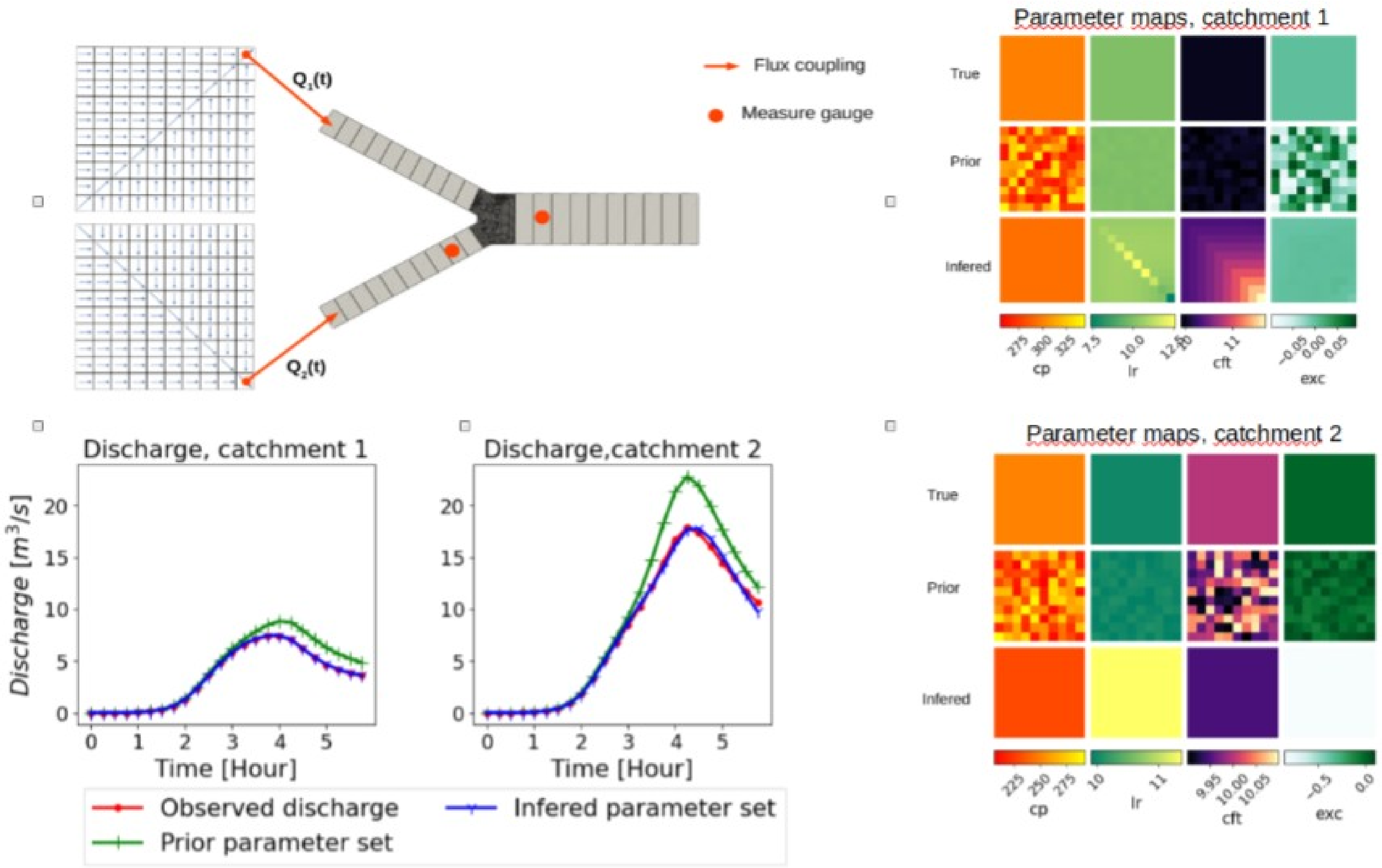


Figure 2. Hydrological inference from hydraulic observations. (Top left) Synthetic case with two square catchments, an idealized confluence channel with 1D-2D mesh from (Pujol et al., 2022) with 2 water depth observation stations; (bottom left) Hydrographs infered by hydraulic VDA and used as observation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

Results: Automatic modeling of a real inundation case (Aude 2018)

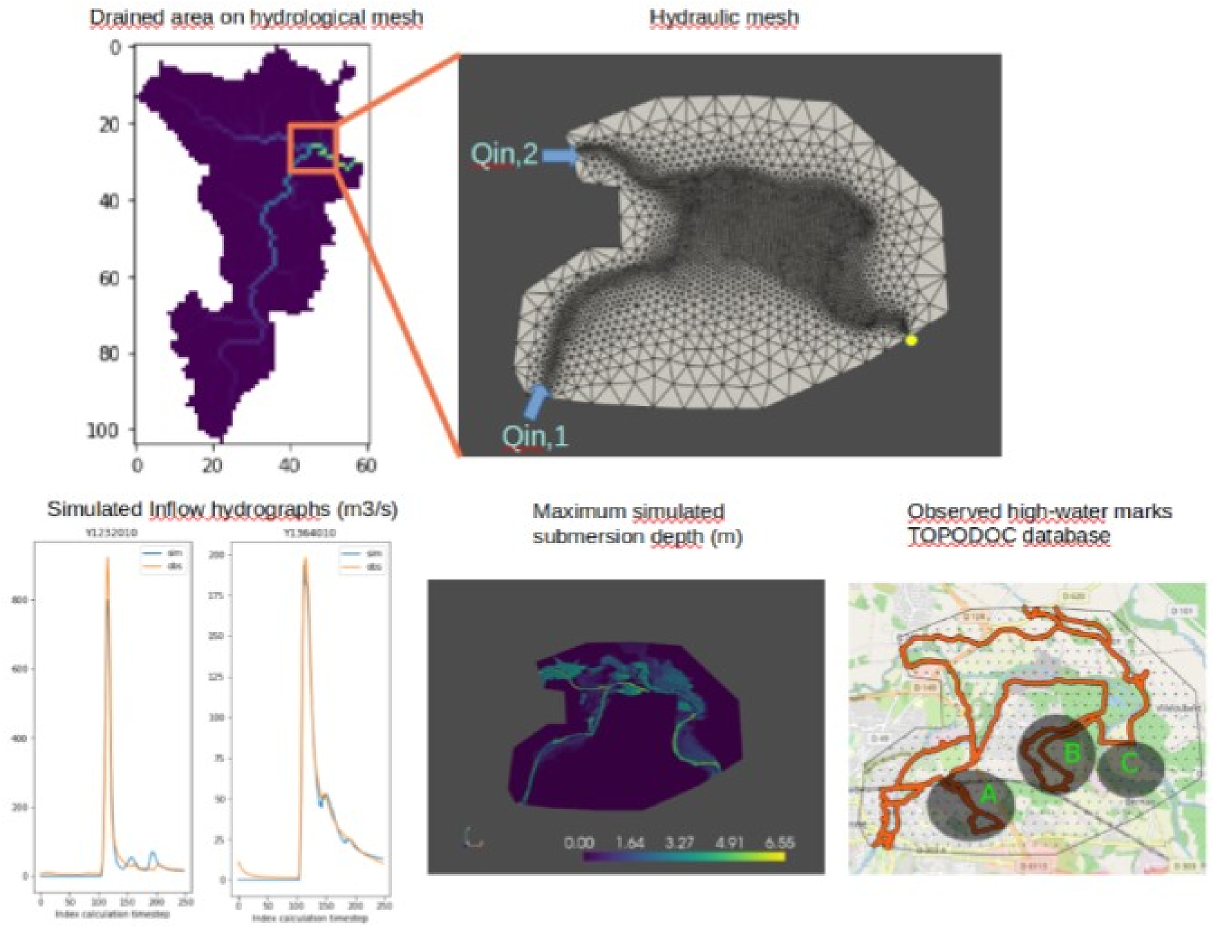


Figure 3. Modeling of the october 2018 flood event over the Aude basin. (Top) Hydrological and hydraulic meshes with two flux coupling points in blue. (bottom) Inflow hydrographs and resulting max flood flow depth compared to post flood extents.

Complex multi-resolution hydraulic modeling DassFlow 2D-1D

Adour Case, preproc not automatized yet – Pujol et al. 2022

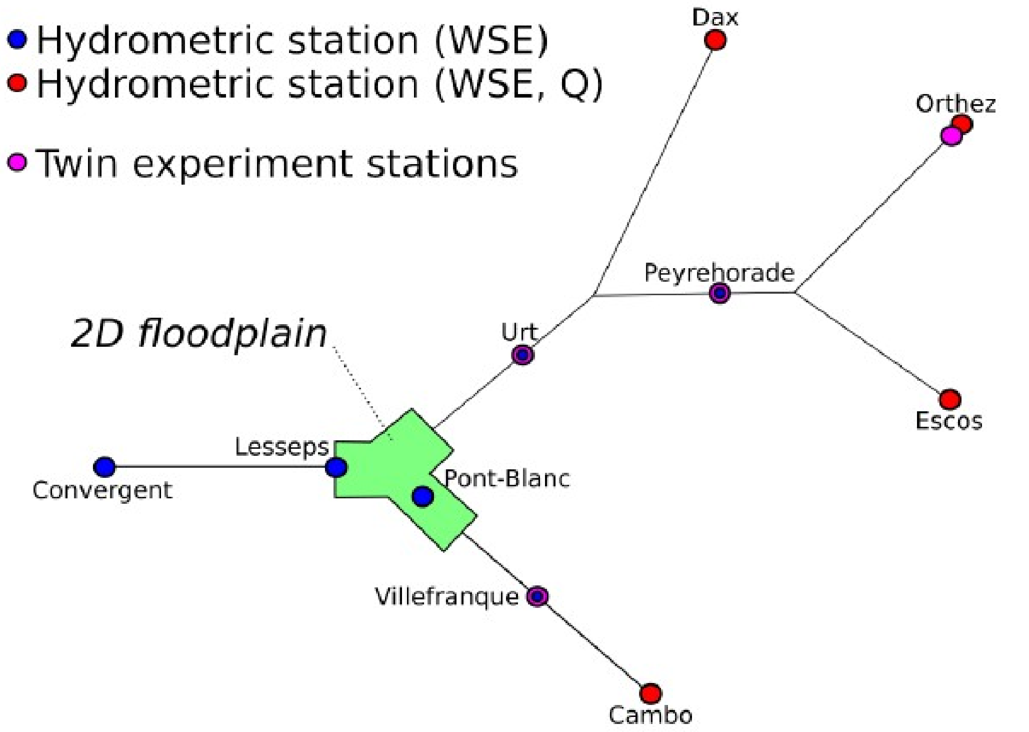


Figure 15. Schematic view of the complete Adour River network and observability. Dimensions in the diagram are not to scale: total river lengths equal $\approx 180\,\text{km}$; 2D floodplain area equals $\approx 5 \times 3\,\text{km}^2$. Tidal BC influence (from the downstream BC at Convergent) is observed up to Dax (and further upstream), Peyrehorade and Villefranque.

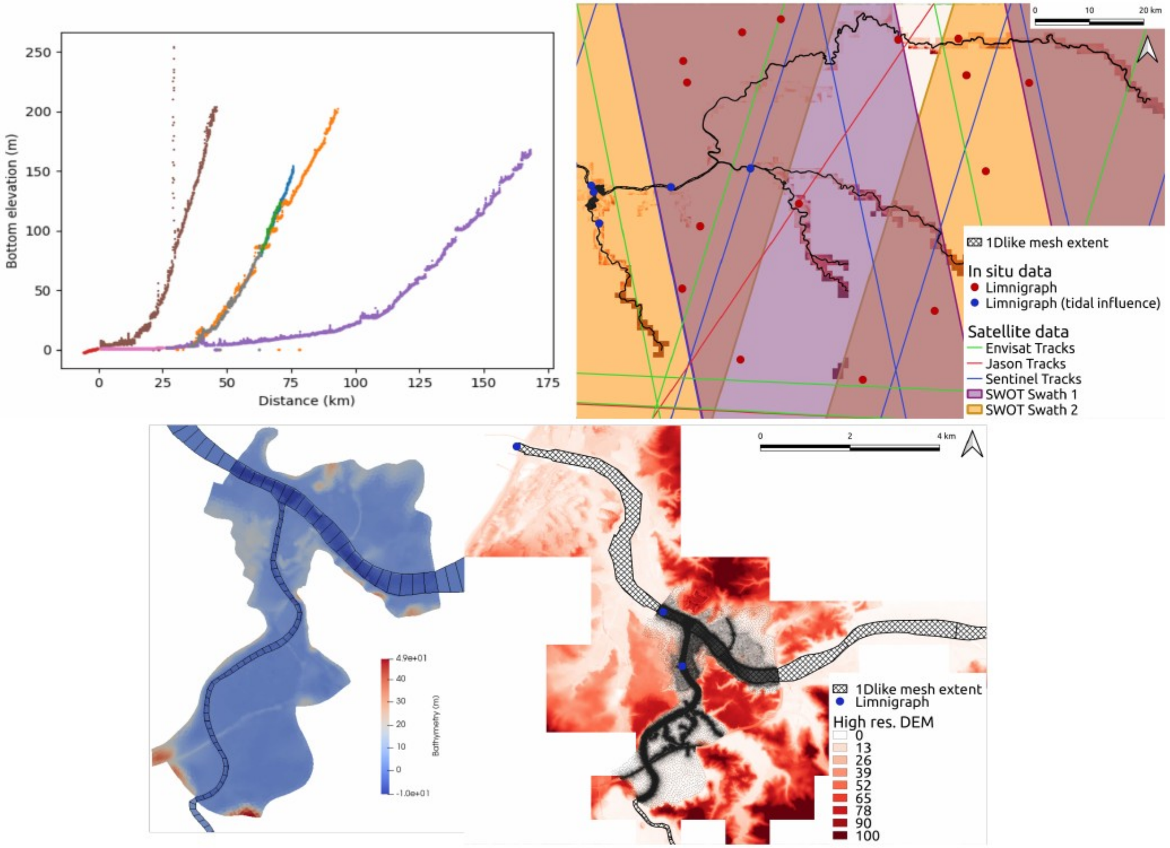


Figure 4. Adour river network upstream from Bayonne (tidal boundary), with observability from in situ stations (Banque HYDRO network) and satellite missions (altimetry from SWOT, Sentinel 3A-B, Envisat and Jason). High resolution DEM from LiDAR used to build 1Dlike network model and 1D2D model with urban flood at Bayonne.

Conclusions and perspectives

New integrated hydrological-hydraulic modeling and variational data assimilation chain :

Showcase on a synthetic and a real case with automatic meshing, validation of mass conservation and waves propagations. Sucessfully applied to a real case with automatic mesher-coupler

High resolution flood forecasting – information transfer between scales (local runoff to river network)

Multi-source data assimilation, information feedback to hydrology

High dimensional parameter maps estimation

Ongoig work and perspectives :

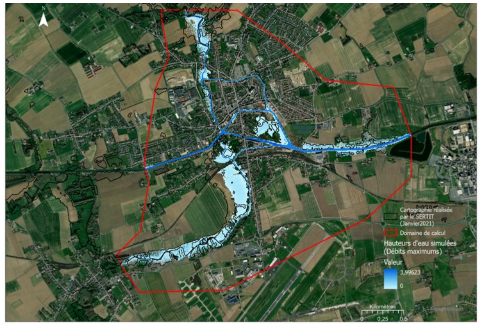
High resolution rainfall-runoff modeling and VDA (cf. Pujol et al. Poster), vertical couplings (states, fluxes) and multi-fidelity chain

Automatic differentiation of the whole numerical coupling (single adjoint model)

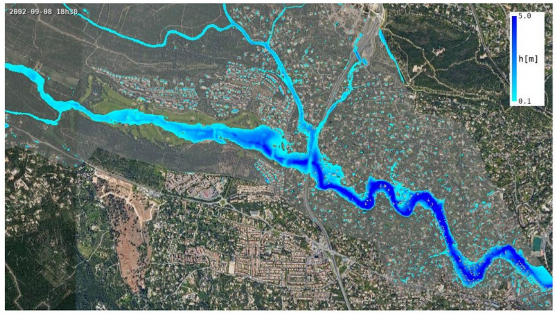
Coupling SMASH-Cartino2D (preprocessor-meshing, interoperability Telemac2D, DassFLow, …)

Add a regionalizaiton learning scheme to the whole chain (following Huynh et al. 2023 with SMASH, see poster)

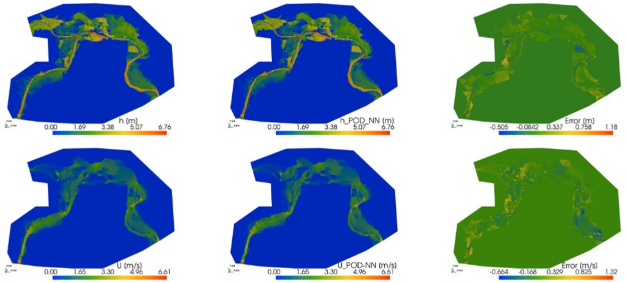
Application to MUFFINS cases, to the Garonne River for SWOT and images data assimilation, also 2D-1D setup of Pujol et al. (2022).



Merville case, DAssFlow2D (Pustoch et al., collab SERTIT-ENGEES-INRAE)



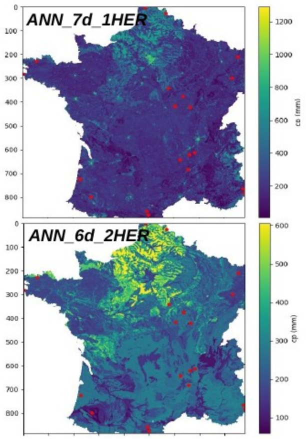
Nîmes case (extremeXP european project, Larnier et al.)



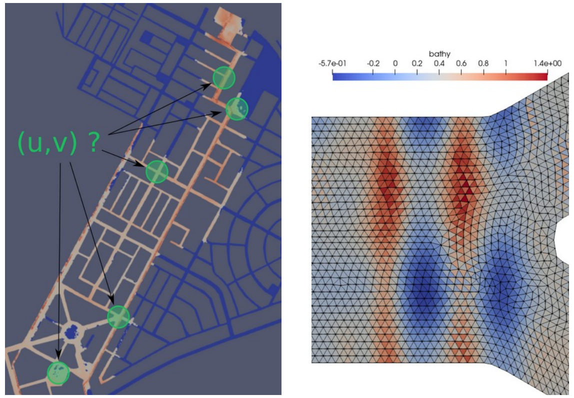
2D model surrogate, POD-NN for fast real time computations (Allabou et al., Aude at Carcassone 2018)

Exemples des cartes de cp avec régio ANN selon les zonages

=> variabilité selon les HER



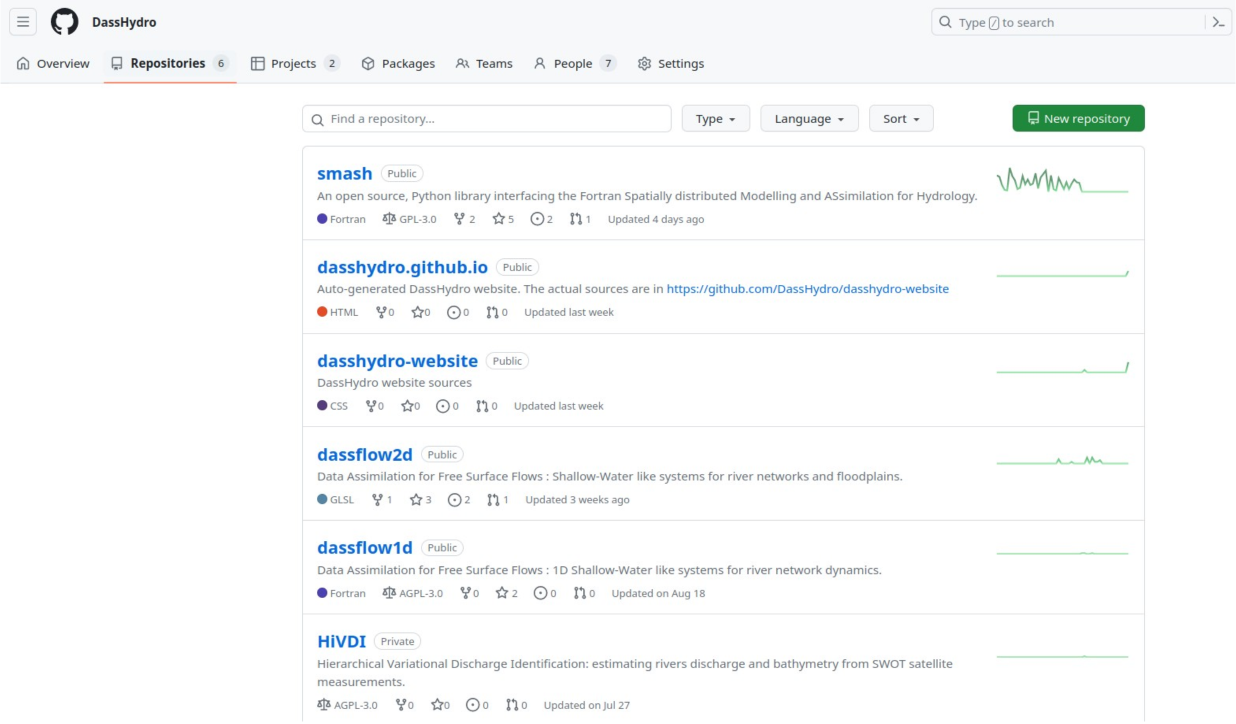
Algo de learning regional (Huynh et al. 23) plateforme smash



Assimilation de vidéos (Andromede, IMFT) dans DassFLow2D et inférence de débit/bathymetrie/friction (Pujol et al.)

DassHydro = SMASH+DassFlow

Our codes on Github https://github.com/DassHydro



Our website – MathHydroNum project team https://dasshydro.github.io/