River discharge and bathymetry estimations from altimetry data

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Objectives

This research project aims at developing inversion algorithms based on hierarchical flow models for ungauged rivers observed by altimetry instruments, in particular SWOT. These algorithms enable at estimating rivers discharge Q(x,t) and effective rivers bathymetry b(x) from Water Surface (WS) measurements.

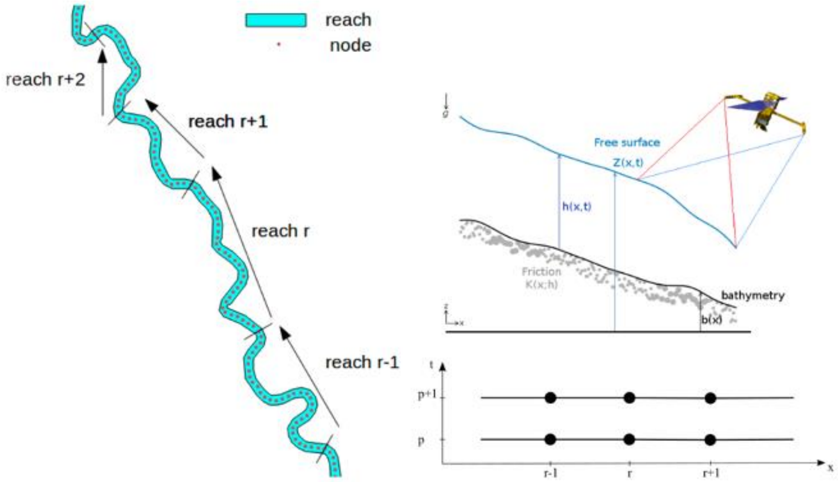

Fig. 1. (Left) Top view of an observed river with the two different scales.
At each reach r (large scale, cyan polygons) corresponds a set of WS measurements ($Z_{r,p}$, $W_{r,p}$, $S_{r,p}$). The low complexity flow model is solved at this scale.
At each node (small scale,n red circle) corresponds a true cross-section A_r and a set of WS measurements ($Z_{r,p}$,$W_{r,p}$).
At the computational grid points (smallest scale not shown here, dx = 100m), no SWOT like data is available. The Saint-Venant dynamic flow model is solved at this scale.
(Right)(Top) The inverse problem: inferring the flow discharge Q(x, t) (m^3 /s), the bathymetry b(x)(m) (equivalently the unmeasured lowest wetted cross-section $A_0(x)$) and an effective friction parameter K(x,t) from WS measurements (Z,W)(x,t).
(Right)(Bottom) Space-time grid of the observations: reach number r in x-axis, satellite overpass instant p (re-ordered from lowest to highest flowline) on the y-axis.

The H2iVDI algorithm

A key result of the researches is the H2iVDI (Hybrid Hierarchical Variational Discharge Estimation) algorithm presented in [LaMo20], see Fig. 1. It includes original hierarchical mathematical systems, state-of-the-art know-hows in Variational Data Assimilation (VDA) combined with Deep Neural Networks (DNN). Moreover, a complete hydraulic chain (0.5D -

1D - 2D) has been developed enabling to calibrate models for complex flows, see e.g. [PuGaetal20]. It also enables to generate stage-fall-discharge laws, [MaGaetal21].

The codes which include computational kernels and interfacing tools (Confluence benchmark chain, RiverObs and SWOT HR simulator, QGIS plugin) are open-source. They are available upon simple request on the DassFlow webpage [Dass].

The algorithm ingredients

The key ingredients and know-hows in the H2iVDI algorithm to infer the unknown river properties (discharge, bathymetry and friction) are the following:

- Multi-dimensional and multi-scale flows models: original low-complexity 0.5D system ([LaMoetal20, BrMoetal18, GaMo15]), classical 1D and 2D shallow flow models (the 1D and 2D models can be solved in a single formulation, the 2D model playing the role of a zoom);
- Advanced formulations of Variational Data Assimilation (VDA) incorporating non-trivial covariance operators, [LaMoetal20, BrMoetal18, MoCoetal16];
- Deep Neural Networks, [LaMo20];
- Analyses in space-time of the inverse problem to be solved through "Identifiability Maps" [BrMoetal18], [MoGaetal19];
- Integration of various databases: SWORD, MERIT-Hydro.

The H2iVDI algorithm enables to infer space-time discharge values $Q(x,t)$ plus an effective bathymetry $b(x)$ at fine scale (~200m long) with corresponding friction coefficients $K\big(Z(x)\big)$, Z(x) denotes the WS elevation.
After a "learning period" (typically one year), given newly acquired SWOT measurements, the algorithm enables at estimating the discharge values Q(r,p) (r being the reach and p the overpass) at large scale (a few km long) *in real computational time.*

The models and inversion algorithms have been developed both for 1D river networks (with multiple segments and junctions) or more complex network portions with 2D flow modeling at critical locations (confluences, anastomosed portions). More recently, this toolchain dedicated to SWOT observations has been extended to conventional Nadir altimetry and optical water extents, see e.g. [GaLaetal20, PuGaetal20, MaGaetal21].

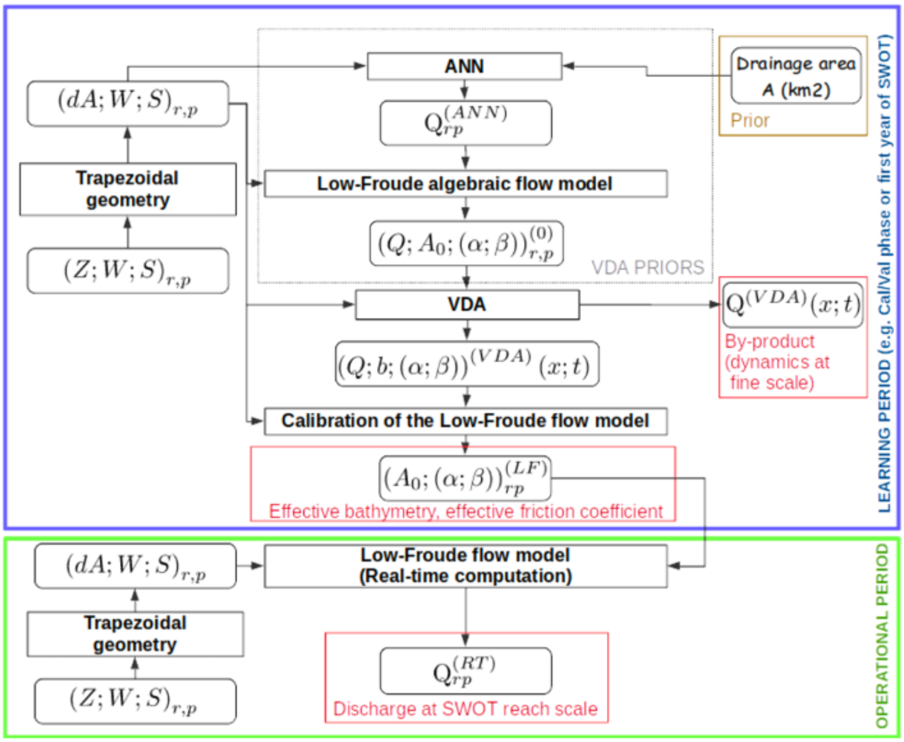

Fig. 2 from [LaMo20]. FlowChart of H2iVDI algorithm. Input data are the WS measurements (Z,W,S) at SWOT observation scale. Prior is a drainage area value A (km2) only, obtained from e.g. HydroSHEDS database. After the learning period (e.g. one year), effective bathymetry elevation b(x) (m), equivalently A0(x) (m2), and low-Froude effective friction coefficients K(x;h) are estimated (plus discharge values at the fine computational grid scale). Next, during the operational period, given newly acquired WS measurements, discharges are computed in real CPU-time at SWOT reach scale.

Obtained results (2021)

The inference capabilities have been thoroughly investigated for more than a dozen of worldwide rivers. The numerical experiments are based on various scenarios: Cal-Val or nominal SWOT revisiting (a dozen of worldwide rivers, PEPSI-2 datasets), using synthetic data, SWOT-HR simulator and RiverObs outputs (Sacramento river) and even an AirSWOT dataset (Willamette river, [Tuetal19]).

Below are presented the obtained results on ~100 km portions of the Garonne river (France), the Po river (Italy) and Sacramento river (USA). The rRMSE of the estimated discharge values (at the observation "hours scale") equals ~ 10%, see [LaMo20, LaMoetal20] for details.

Inference of the triplet $(Q(x,t), A_0(x), K(h))$ with the 1D flow model & VDA. Cal/Val configurations: 1 day revisit.

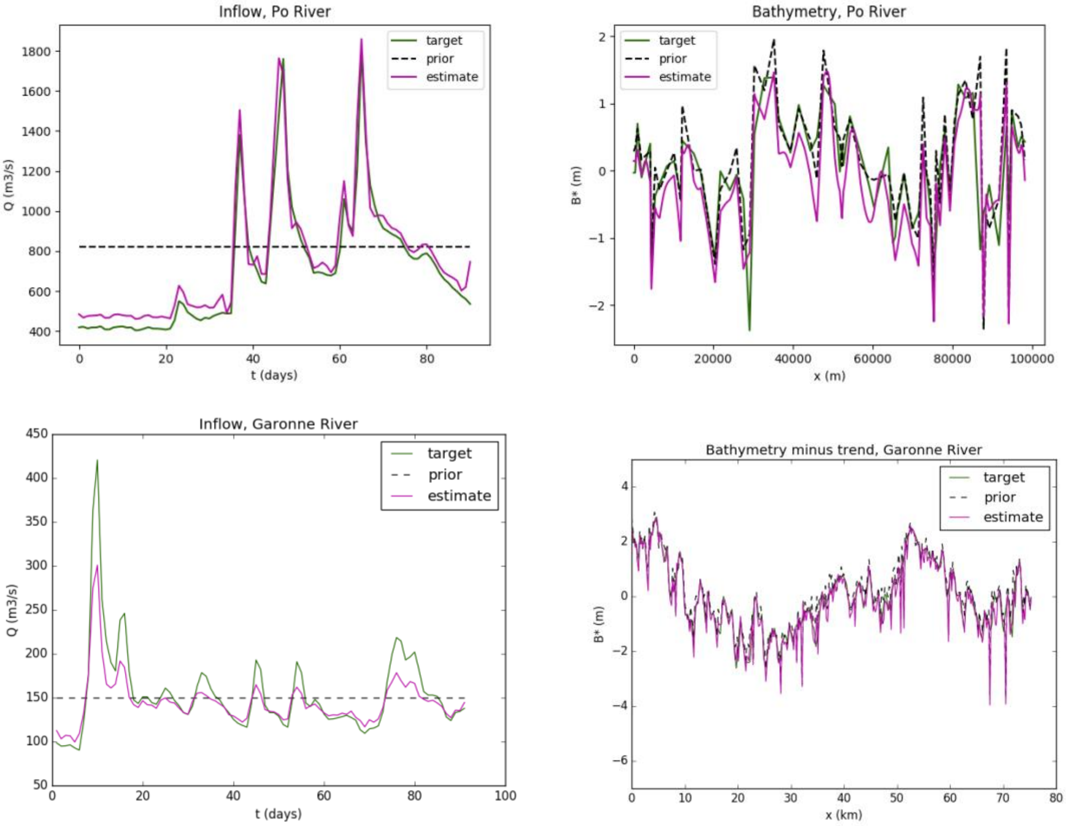

Fig. 3 from [LaMoetal20]. Infered (Q, A_0, K) from daily Cal/Val SWOT-like measurements, Garonne (upstream) and Po rivers. (Top and bottom left) Inflow discharge. (Top and bottom right) Bed elevation minus the elevation of a linear trend of real bed elevation. First guesses (="priors") are here provided by the low complexity flow model.

Inference of the triplet $(Q(x,t), A_0(x), K(h))$ from SWOT-HR data

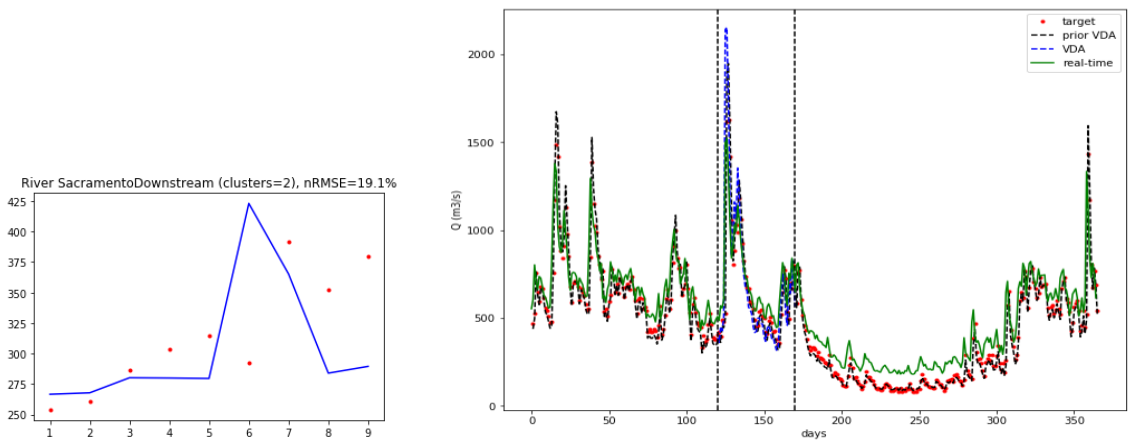

Fig. 4 from [LaMo20]. (Left) Inferred bathymetry for the Sacramento River (Downstream) vs reach number. (Right) Discharge estimation for the Garonne River (Downstream) vs time (in days).

(Dash black) prior discharge estimated by a hybrid low complexity inverse algorithm; (blue) Q inferred by VDA on an adequate assimilation window (vertical lines); (green) Q real-time compared to the (red dots) target ("true" values).

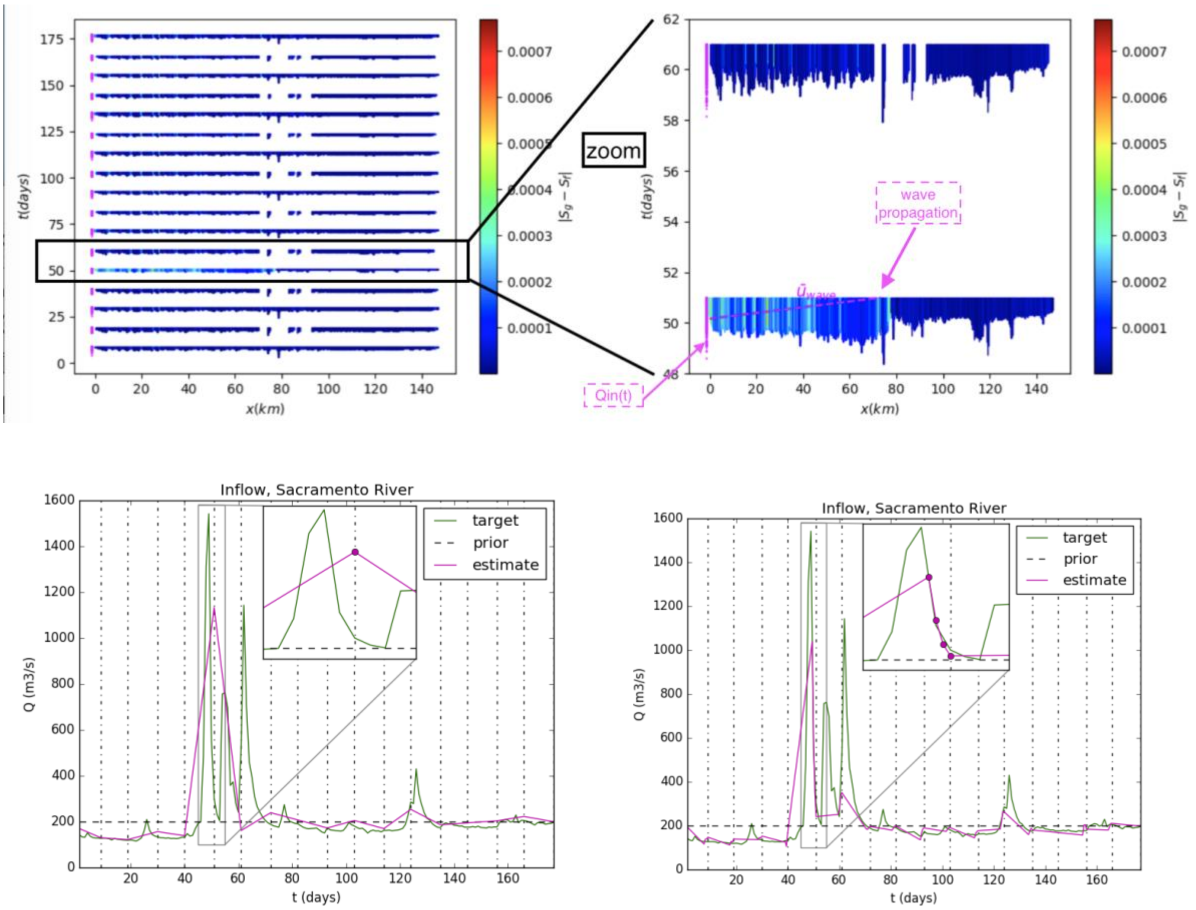

Fig. 5. (Up) The Identifiability Map (IM) from [BrMoetal19]. Overview in the (x,t)-plane of all the available information: the observed space-time windows, the hydraulic waves and misfit to the "equilibrium" (= local Manning-Strickler's law residual) (color bar).
Results of the IM analysis: (Up)® The time hours when the discharge may be reliably identified (pink points); (Down) Adaptive time grid of the identification process (therefore a better capture of the "signal").

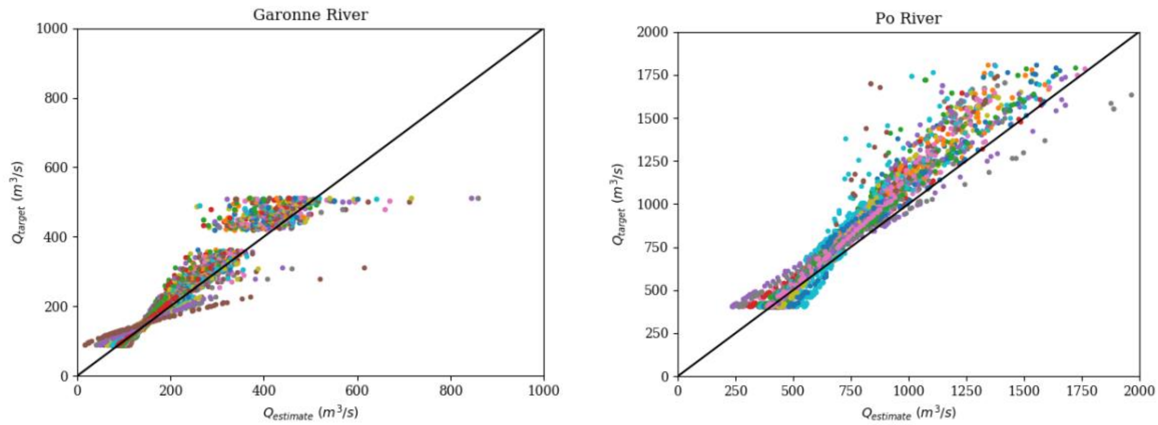

Fig. 6 from [LaMoetal20]. Passed the learning period, the re-calibrated low-complexity model enables to

provide discharge estimations corresponding to the newly acquired SWOT measurements in real CPU-time, [LaMoetal20].
Plot = reference value of discharge Qtarget (m3/s) vs the estimated one in real-time.
(L) Garonne rive®(R) Po river. rRMSE of differences: ~ 6 and 10% respectively.

Discharge inversions from historical Nadir altimetry time-series

The HiVDI algorithm [LaMoetal20] has been successfully applied to e.g. 8 years time-series of a historical Nadir altimetry dataset on a Xingu river portion (Amazon basin), see Fig. 3.

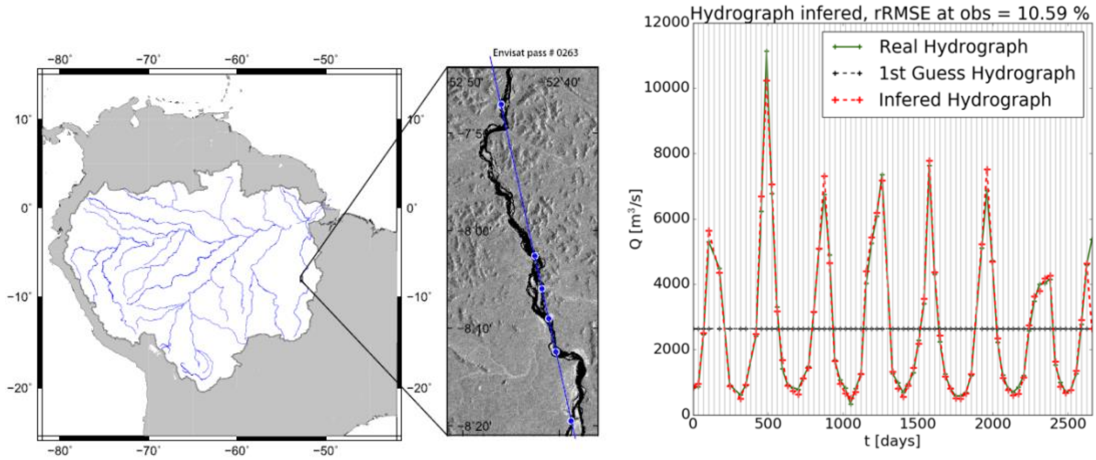

Fig. 7 from [GaLaetal20,GaCaetal17]. (Left) Xingu river portion (ungauged south Amazon tributary) observed by one ENVISAT track during 8 years. (Right) Discharge (m3/s) vs time(t): estimations by HiVDI algorithm and ENVISAT data (=reference values derived from altimetry rating curves).

River surface signal analysis and segmentation

Slopes and concavity of water surface elevation profiles are analyzed, next it may be translated in terms of hydraulic controls. This enables a consistent river segmentation, see [MoGaetal19].

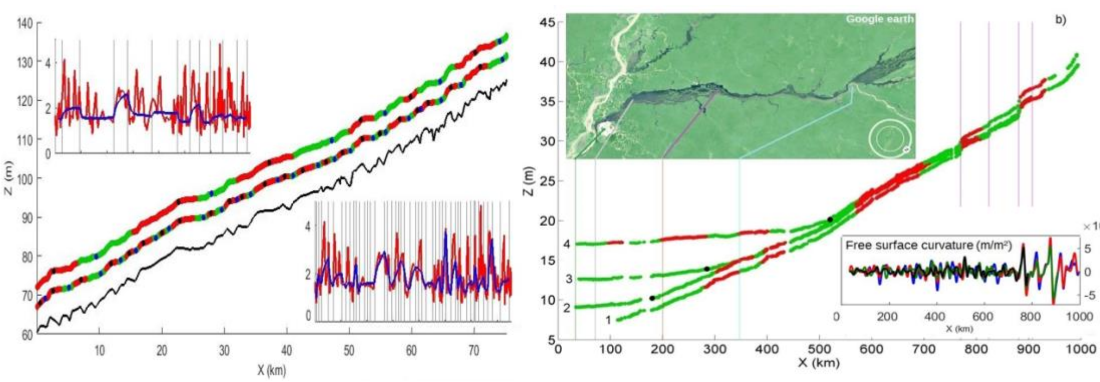

Fig. 8 from [MoGaetal19]. River surface signal analysis and control sections detection.
(Left) Segmentations of (upstream) Garonne river portion based on the water surface curvature of real free surface height profiles with different cutoff length (red-green lines). Subfigures: Flow depth h 'rerunned' on large and fine scale segmentations (red) compared to real depth profile (blue).
(Right) Large scale segmentation of 1000km long GPS WS profiles of the Rio Negro for 4 flow regimes. Hydraulic control: backwater effect from the downstream confluence with the Rio Solimoes (x=0).

Inferences in braided flows and flood plains - 2D modeling

The same VDA processes as described before have been developed for a 2D flow model enable to simulate finely braided portions and floodplains, see e.g. Fig. 9 (Top). In addition to the inference of the inflow discharge as in the previous 1D model cases, the VDA process is useful to finely analyze local sensitivities. These sensitivities may be with respect to the friction coefficient and/or the floodplain DEM (bathymetry), Fig. 9 (Bottom).

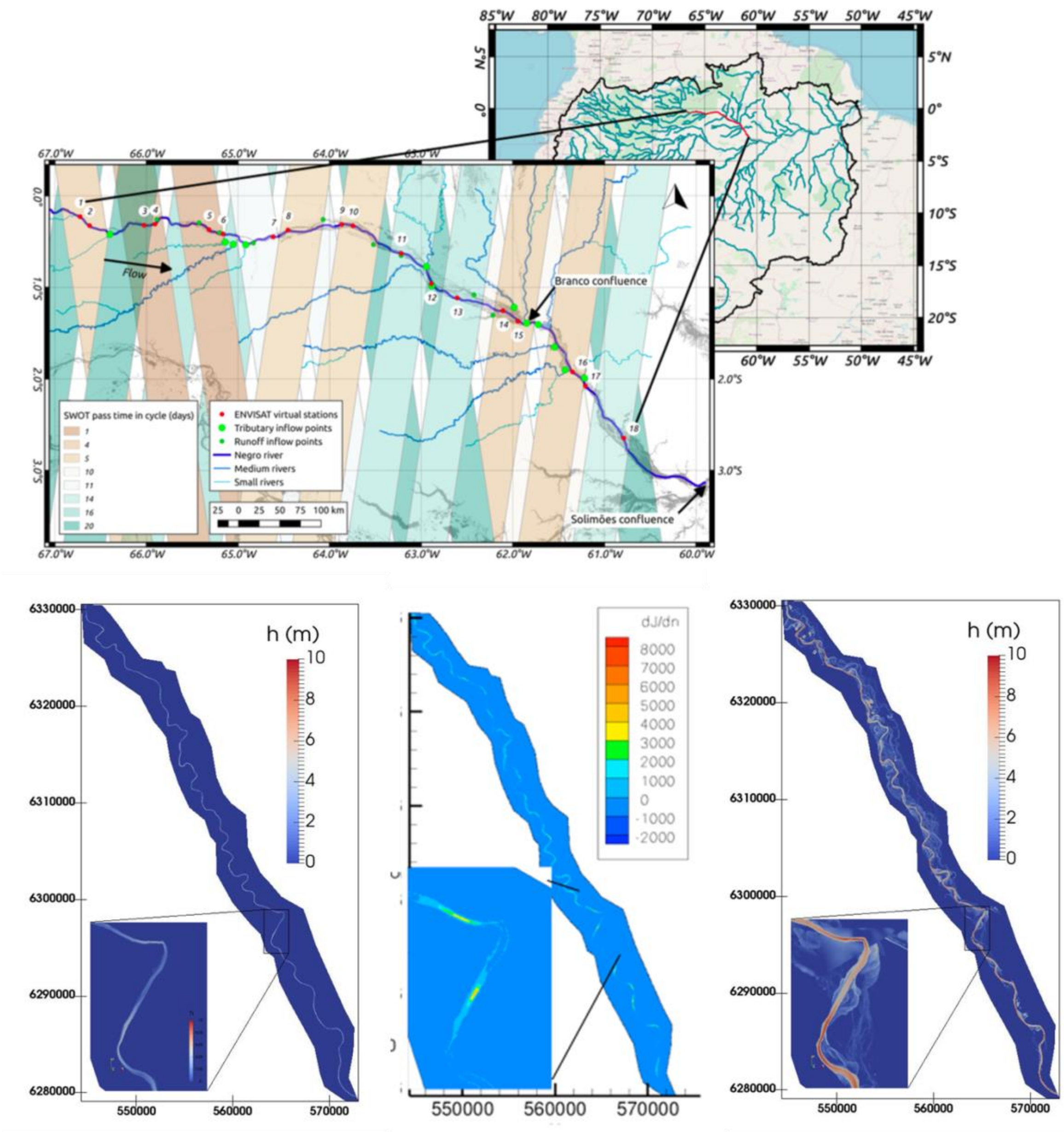

Fig. 9 from [PuGaetal20]. (Top). Negro river in the Amazon basin addressed by the hierarchical hydraulics model chain with hydrological model inputs. ENVISAT Virtual Stations are numbered from 1 to 18. SWOT-like swaths give an almost full spatial coverage of the reach.
(Bottom). Garonne river (Toulouse, France) from [MoCoetal16]. (Left) Water elevation for an in-bank flow (160m^3/s). (Middle) Sensitivity map wrt friction coefficient K (synthetic data). (Right) Water elevation during the 2000-year flood event (2100m^3/s).

Anticipated results (period 2020-2024)

- A complete integrated multi-dimensional, multi-scale river flow model, coupled with distributed catchment hydrology model(s) with multi-source data assimilation (cf. [PuGaMoetal21a,b]).
- Capabilities to infer more and more complex effective bathymetry and more accurate discharge values, at different scales.
- Fine multi-D hydrological-hydraulic chain deployment over the whole Maroni River basin, French Guyana, for assessment of first SWOT data on this Cal/Val site, for testing operational satellite hydrology forecasting.

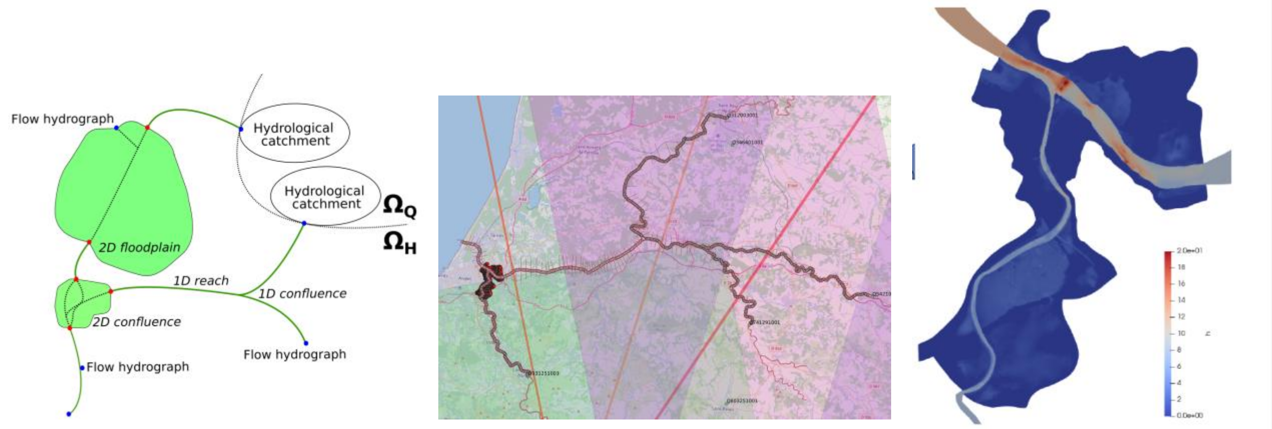

Fig. 9 from [PuGaMoetal21a,b]. (Left) Schematic representation of the multi-D hydrological-hydraulic model. (middle) bassin hydrological-hydraulic mesh: spatially distributed hydrological modeling for lateral/upstream inflows, 1D like river network with mesh based on bankfull water extents internally coupled to fine 2D zooms (ex. floodplains, confluences), (right) zoom on the flow depths simulated around the city of Bayonne with the multi-D chain (data courtesy: flood forecasting center SPC-GAD, INRAE).

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