Estimation of Inflows and Effective Channel from Satellite Observations: From Local to Hydrographic Network Scale

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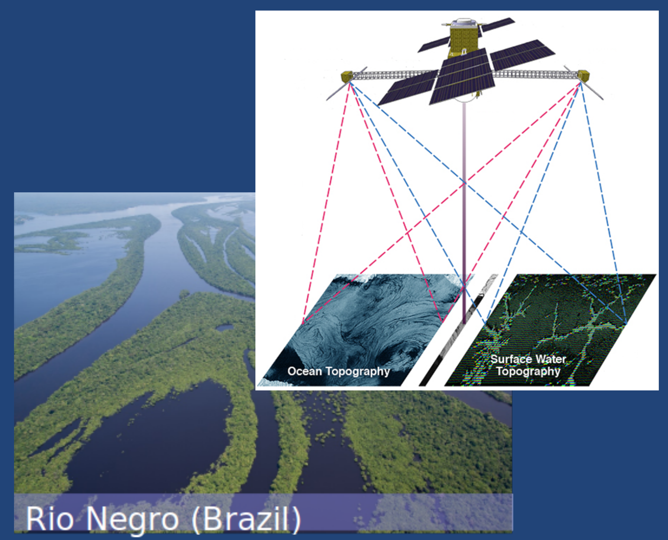
Context: satellite visibility of hydraulic signals

- NASA/CNES Surface Water and Ocean Topography (SWOT) satellite mission
- Wide swath altimetry
- Global measurements of inland water surface elevation, width and slope with temporal revisits and unprecedented spatial coverage
=> "**Hydraulic visibility**" (Garambois et al. 2017 ; Montazem et al 2019)

Goal : inversion of global river parameters from observations of WS variations (hydraulic signatures)



Scientific issues in infering (inflows, bathymetry, friction) from sparse WS observations:
- Discrepancy between real river network variabilities, models and WS observation scales
- Complex spatio-temporal variabilities of WS (hydrograph propagations, hydraulic controls, backwaters)
- Correlated influences of all sought flow controls on observable WS, equifinality-uniqueness issues

Focus: Inferability of multiple spatially distributed parameters, including lateral hydrographs
- Is it possible to infer effective river bathymetries for river networks?
- What are the consequences of the spatial distribution of temporally varied parameters on the resolution of the ill-posed problem ?

Modeling approach

The inverse method:
Hierarchical Variational Discharge estimation (HiVDI) (Larnier et al. 2019)

Minimization of misfit between observed WS elevation Z_{obs} and simulated WS elevation $Z(c)$ through modification of the sought control vector c containing inflows, bathymetry and friction values.

$$c = \left(Q^0_{in}, \dots, Q^P_{in}\,;\, Q^0_{lat,1}, \dots, Q^P_{lat,1}, Q^0_{lat,2}, \dots, Q^P_{lat,L}\,;\, b_1, \dots, b_I\,;\, \alpha_1, \dots, \alpha_N\,;\, \beta_1, \dots, \beta_N\right)^T$$

$$j_{obs}(c) = \tfrac{1}{2}\,\|(Z(c) - Z_{obs})\|^2_{\mathcal{O}} \qquad c^* = \mathrm{argmin}_c\, j(c)$$

Hydraulic model :
- 1D Saint-Venant model with classical Manning source term and lateral inflows*

$$\begin{cases} \partial_t A + \partial_x Q & = k_{lat} q_{lat} \\ \partial_t Q + \partial_x \left(\frac{Q^2}{A}\right) + gA\,\partial_x Z & = -gAS_f + k_{lat} U q_{lat} \end{cases}$$

- Effective friction law spatialized by patches

$$S_f = \frac{|Q|Q}{K^2 S^2 R_h^{4/3}} \qquad K(x, h(x,t)) = \alpha(x)\ h(x,t)^{\beta(x)}$$

* from hydrological model

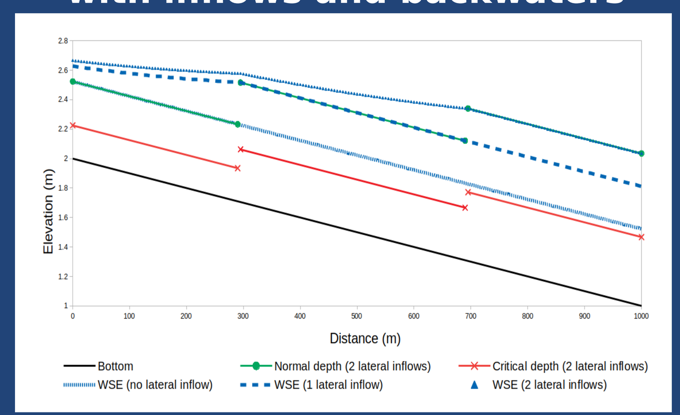
Results: small scale academic cases (low Fr)

Lateral hydrograph signatures
- downstream reach: the "total flow" is uniform with a water depth corresponding to the normal depth imposed downstream
- upstream reach: M1 backwater curve profile

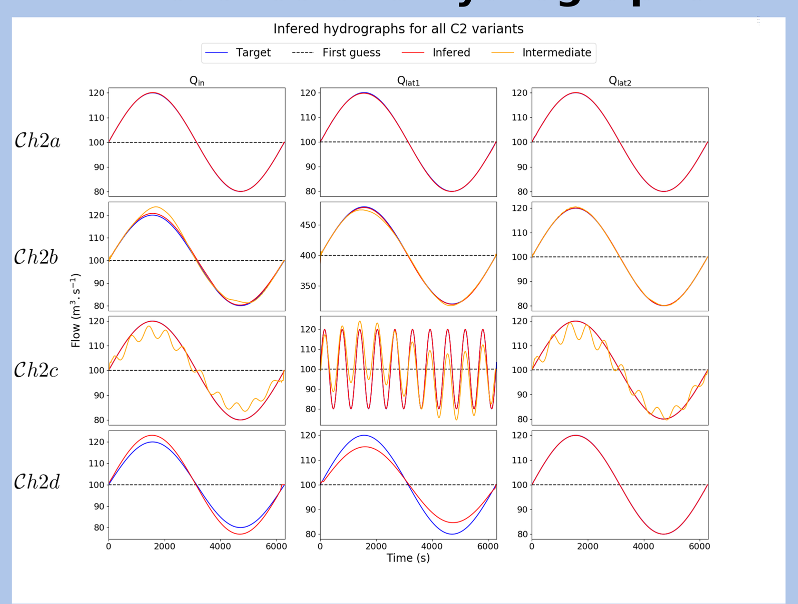
Case design: simple rectangular channel in sub- and super-critical flows. Twin experiment inferences.

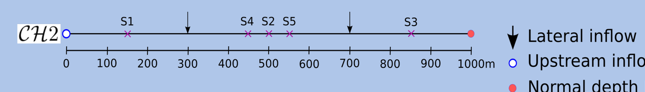
Aim: challenging inference setups in terms of observation repartition and signal overlap.

Steady low Froude flow lines with inflows and backwaters



Inference of 3 hydrographs





Inflow inferences ($Ch2$)
- $Ch2a$: reference case
- $Ch2b$: number of $Q_{lat,2}$ increased and thus its backwater infuence
- $Ch2c$: frequency of $Q_{lat,2}$ increased
- $Ch2d$: inadequate observation placement

Red: final inferences

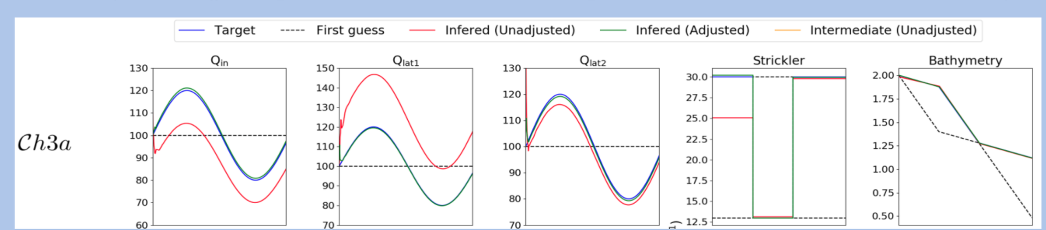
Orange: intermediate inferences, show behaviours less visible in final inferences

"Triplet" inferences ($Ch3a$)

Red: final inferences with given set of parameter weights. Equifinality between first inflow and friction patch. Compensation of lack of flow in downstream inflows.

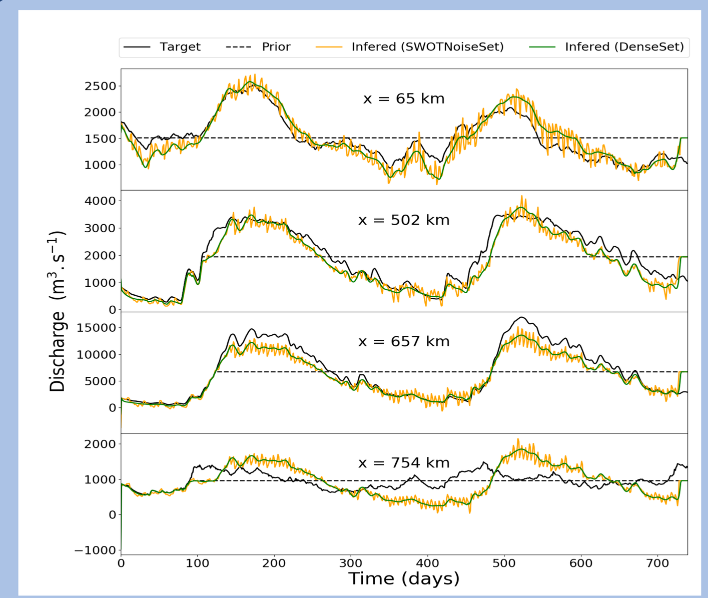
Green: final inferences with parameter weights adjusted through trial and error.

Inference of 3 hydrographs, 3 friction patches and 4 bathymetry points

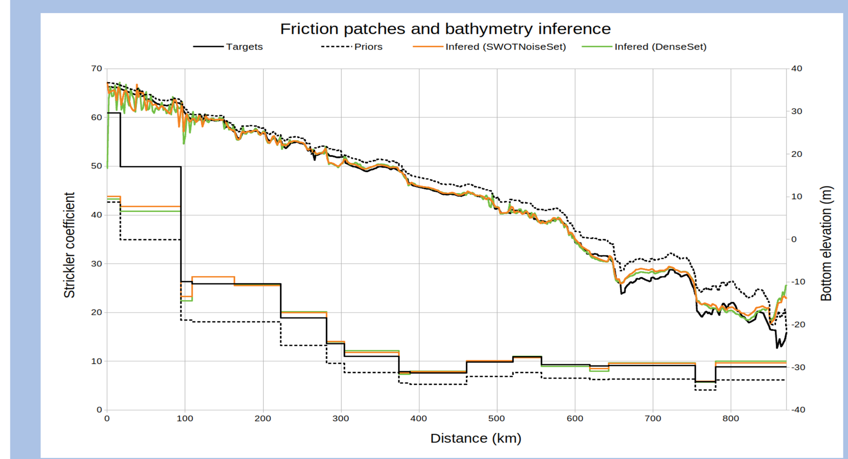


Results:
- Minimal spatial observation to infer: at least 1 station in either upstream or downstream signature
- Given sufficient temporal observability, inference of different signal frequencies
- Backwater effects and overlapping hydraulic signatures (from inflows and channel parameters) make the inversion more challenging

Results: Inference of inflows, bathymetry, friction from SWOT



Inference of Q for 4 major tributaries without a priori knowledge of hydrograph shape



Inference of 436 bathymetry points and 17 friction patches

Oscillations are due to the discrepancy between satellite revisit time and parameter discretization

Observations: Dense observations in time (green inferences) vs sparse SWOT-like observations (orange inferences)
Inverse problem: Simultaneous channel parameter and inflows inference

Results:
- Fair estimation of hydrograph shape without a priori knowledge
- Fair estimation of channel parameters, especially in upstream reaches (sensitive water height)
- Importance of a priori knowledge of bathymetry shape, especially in downstream reaches (backwater effect, low parameter sensitivity)

Conclusion

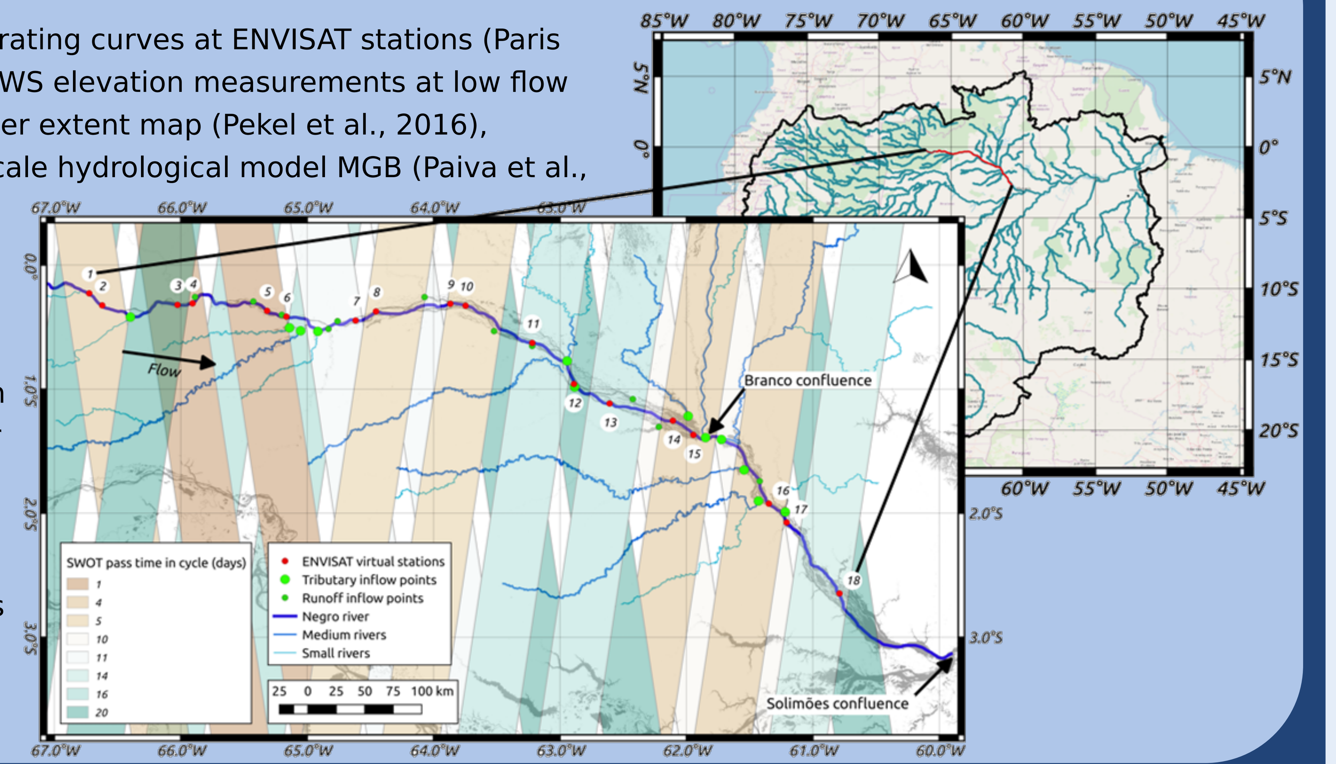
- Simultaneous inferences of spatially distributed channel parameters and inflows achieved for slow and fast responding reaches, including a real case (Negro River).
- SWOT-like osbervations enable accurate inferences given pertinent a priori information.
- Local bathymetry friction equifinality, inflows signals misattribution and varying sensitivity of water depth to parameters observed, especially in backwater effects.
- Perspectives: flow structure and hydraulic signature analysis, at the scale of river networks, to taylor and constrain integrated hydrological-hydraulic assimilation chains adapted to multisatellite datasets (heterogeneity, various sparsities and data errors).

Results: effective hydraulic-hydrology model built on multisatellite data

Study area: 871km of the Negro river

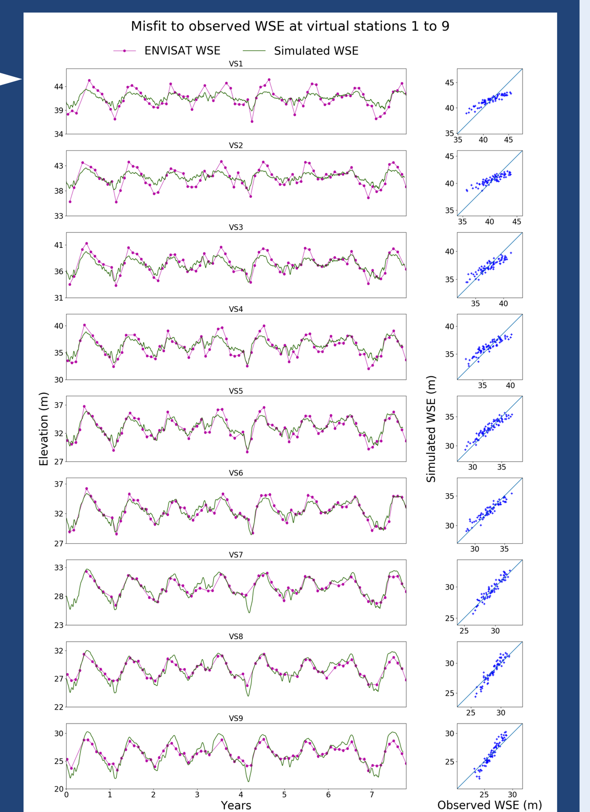
Data: 18 altimetric rating curves at ENVISAT stations (Paris et al., 2014), in situ WS elevation measurements at low flow (Moreira, 2016), water extent map (Pekel et al., 2016), inflows from large scale hydrological model MGB (Paiva et al., 2013)

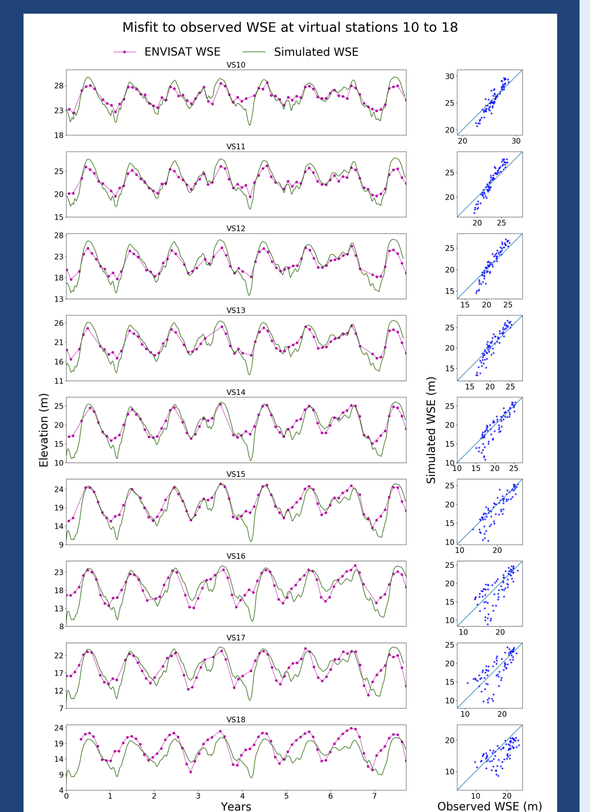
Caracteristics:
- 21 tributaries
- Multi-channel flow zones model through effective rectangular single channel
- Downstream backwater control from Negro-Solimoes confluence



Effective model fits ENVISAT WS altimetry

Downstream BC is modeled as rating curve, as backwater from WS forcing lowers parameter sensitivity

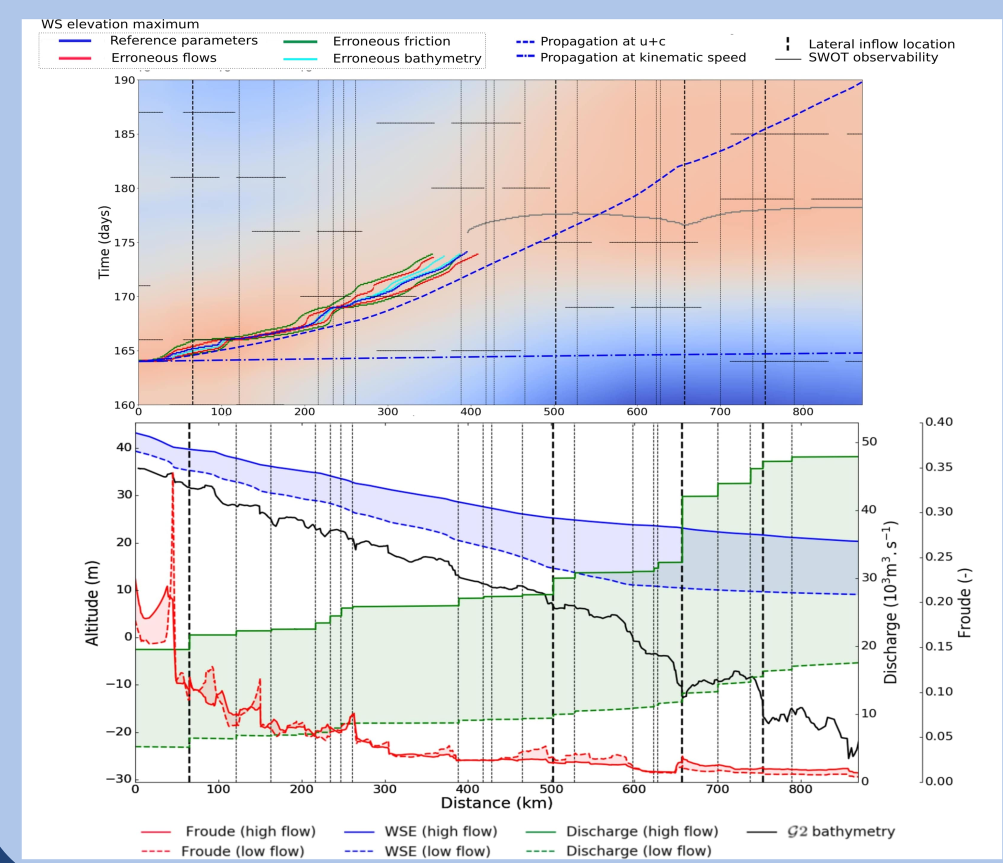




Identifiability map

Full blue line: Tracking of local WS elevation maximum
Dashed blue line: Tracking of intumescence travelling at kinematic speed

Approximate flood wave travel time : 26 days
SWOT revisit time : 21 days



Signal identifiability following (Brisset et al., 2018) with the addition of lateral inflows here

$$I_{ident} = T_{wave}/\Delta t_{obs}$$

Globally, $I_{ident} = 1.23$ but between each pair of lateral inflow, I_{ident} varies from 0.3 to 7.0. Identifiability indexes do not account for temporal signatures overlap or swath observations.

=> Global inverse problem (in space and time) is more complex with lateral inflow: need for integration of a priori knowledge into model.

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