Hydraulic visibility:
Depicting Hydraulic Variabilities From Water Surface Signatures

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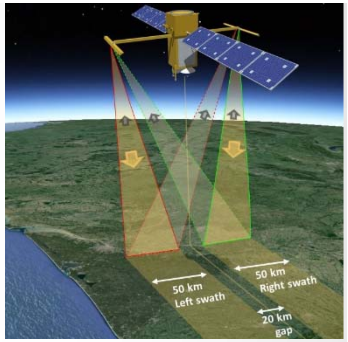
SWOT Science Team Meeting, June 2019, Bordeaux (France)
Hydrology Splinter Session

Outline:

- Increasing hydraulic visibility of river surface variabilities from the « local » scale to hydrographic networks scales: **hydraulic information gained from WS signatures**?
- How to **adapt and scale flow models** (and inverse methods) to make best use of more or less sparse and informative multisatellite data?

Hydraulic visibility:

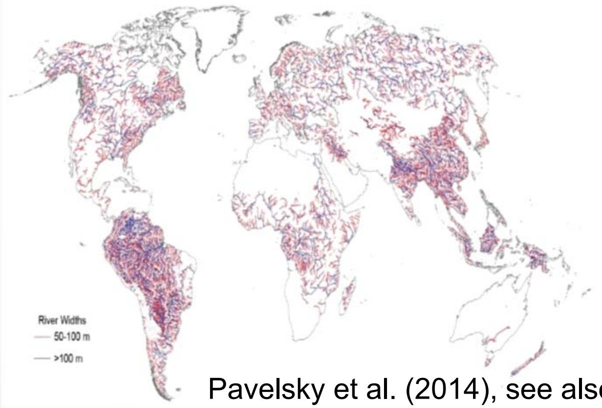
« Potential to depict a hydrological response, and hydraulic variabilities within a river section or network via remote sensing"



Expected observability from the SWOT mission:

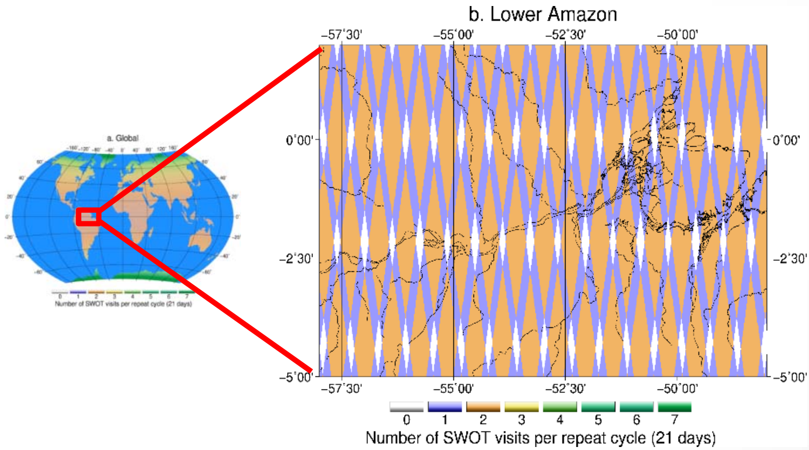
(Alsdorf et al., 2007; Durand, Fu, et al., 2010; Rodriguez et al., 2018)

Observable rivers
(width > 100m – target 50m)



Pavelsky et al. (2014), see also
« GRWL » in Allen and Pavelski (2018)

~ Global coverage every 21 days



See review on hydrology-hydraulics in a SWOT context
in Biancamaria et al., (2016)

"dense in space sparse in time" wrt. local hydraulic propagation (cf. Brisset et al. 2018)

- → **Which flow physics and controls are visible in spatio-temporal WS signatures?**
- → **Adequation between flows-models, scales-complexities and multisat. observations?**
- → **How to make best use of the forthcoming SWOT observations to estimate worldwide river discharge in case of uncertain river bathymetry-friction?**

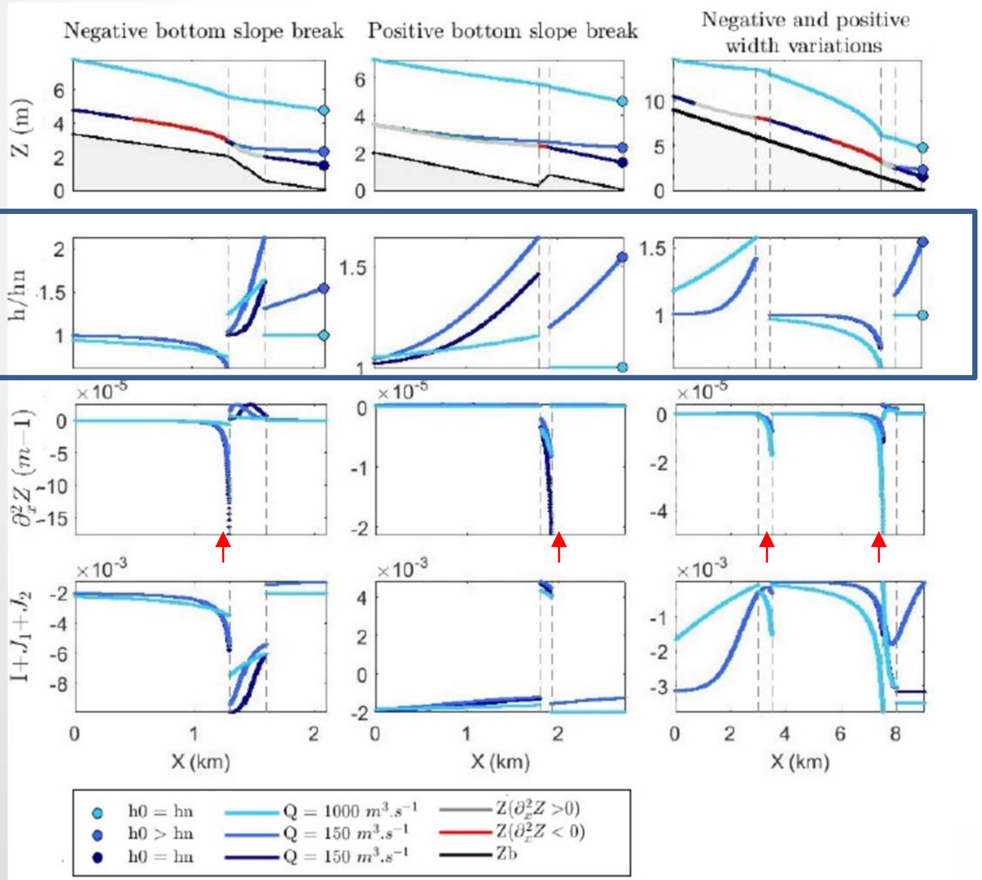
Hydraulic visibility defined from current satellite data in Garambois et al. (2017, HP); Montazem et al. (2019, GRL)

Hydraulic visibility from water surface signatures?

Elementary basis of synthetic rivers: HCs and WS deformations

"Downstream" part of hydrographic networks (W>100m)

Hypothesis: Low Froude flows @ obs. scale, locally steady here: $(1 - \mathrm{Fr}^2)\,\partial_x h = I - J_1 + J_2$



→ Hydraulic controls (HCs) = local max deviations to equilibrium (~hn)

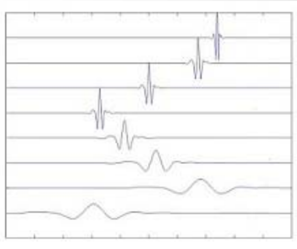
→ Local WS curvature extrema appear at/close from HCs

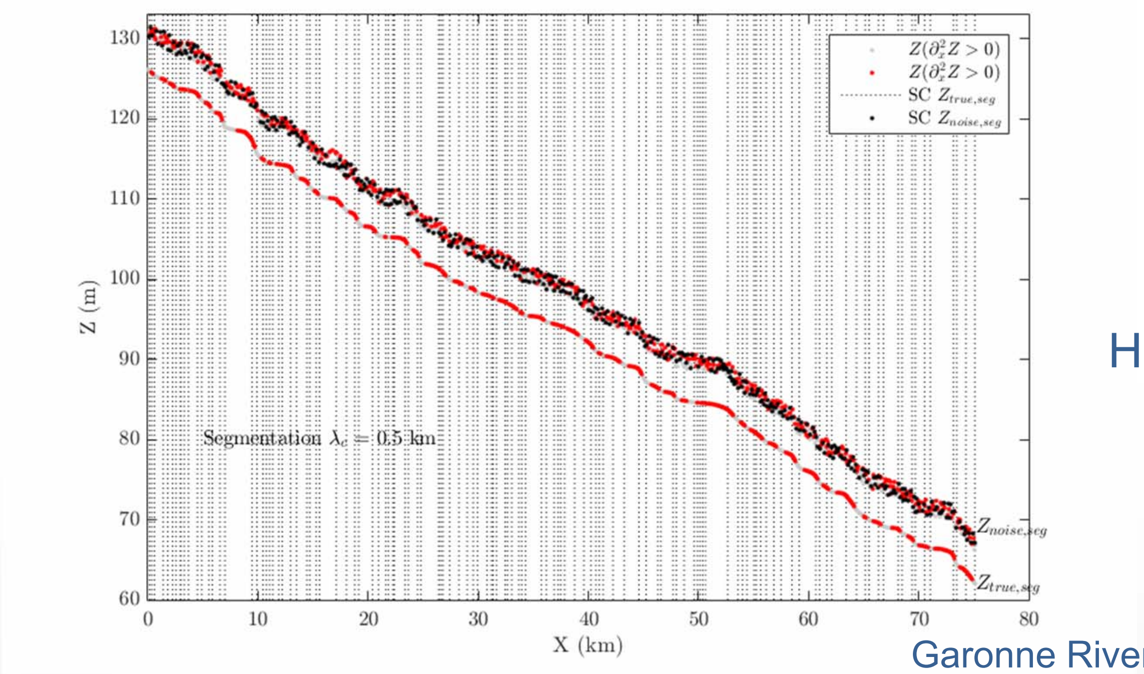
- **→ Equilibrium (~hn) between bottom pressure (I), friction (J1), lateral pressure (J2) to be considered for worldwide rivers study**
- **→ Local WS curvature extrema (~HCs) => proxy for reach bounds**

Montazem phD (2019), (Montazem et al. 2019, GRL)

Wavelet-based segmentation from WS curvature extrema – perfect snapshot

- **Hydraulic variabilities occur from fine to larger spatial scales**
  → **Wavelets (fundamental property = space-frequency localization)**,
  → Wavelet decomposition of (1D) altimetric profiles, filtering, segmentation on WS curvature extrema





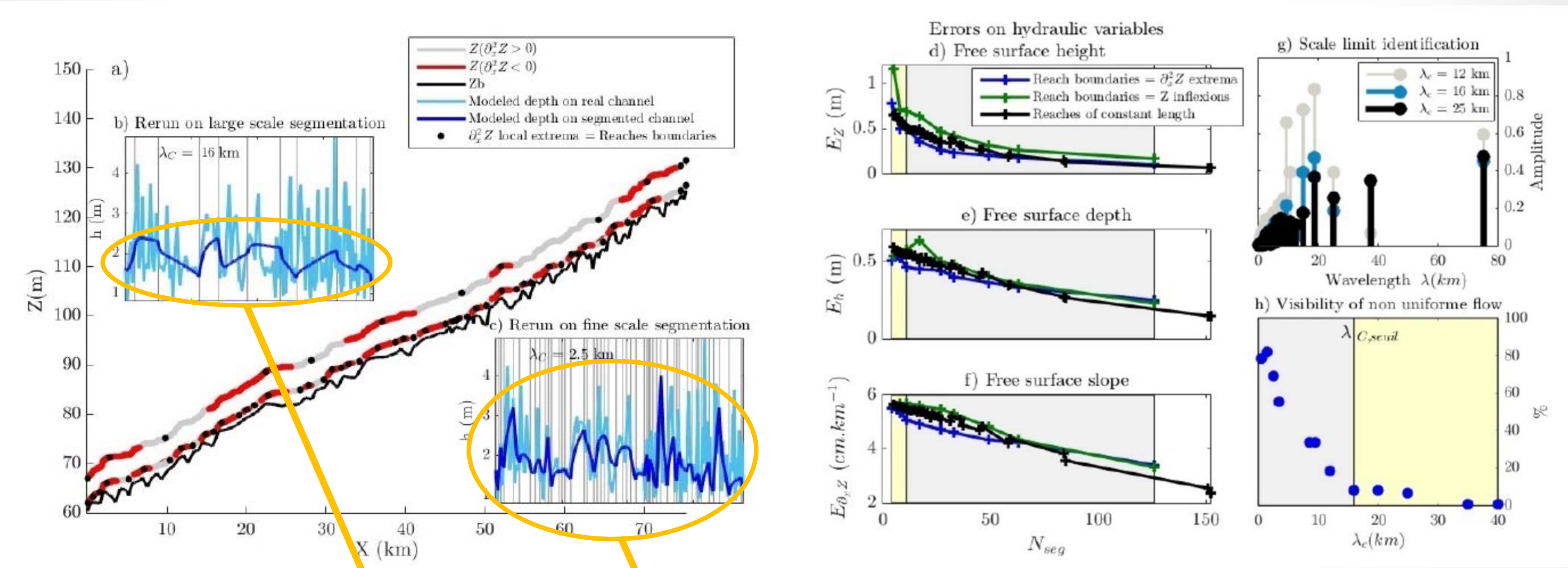
HCs = dashed lines

Garonne River case

→ **Preservation of the main HCs (given a filtering scale) considering their « altimetric » signature (Z, $\partial_x Z$, $\partial^2{}_x Z$)**

Montazem phD (2019), (Montazem et al. 2019, GRL)

Towards « hydraulic preserving » river segmentations
Forward model analysis



Garonne River case

Dark blue = "best flow line possible" while modeling on a given segmentation! → to be kept in mind while solving inverse pb from WS obs.

→ Increasing segmentation length = loss of local hydraulic nonlinearities
→ Physics based method enabling to preserve the main HCs locations and signatures

(Montazem et al. 2019, GRL)

Wavelet-based segmentation from WS curvature extrema
By product: Denoising toolbox; SWOT-like measurement errors

Automatic Hydraulic denoising

Hypothesis: at the observation scales, WS slope > 0

- Automatic wavelet determination from noisy altimetric profile
- Iterative de/recomposition and filtering until "hydraulic condition" is satisfied at each scale

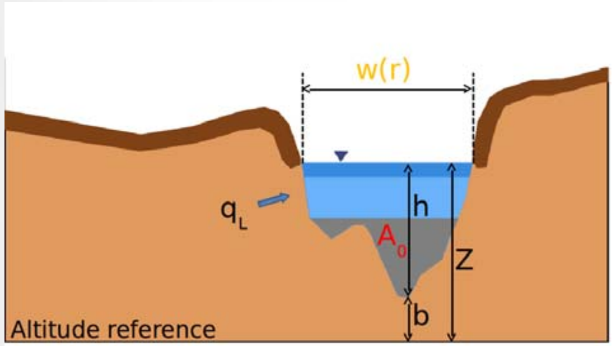
SWOT like observations on the Sacramento River (Source: Frasson et al.)

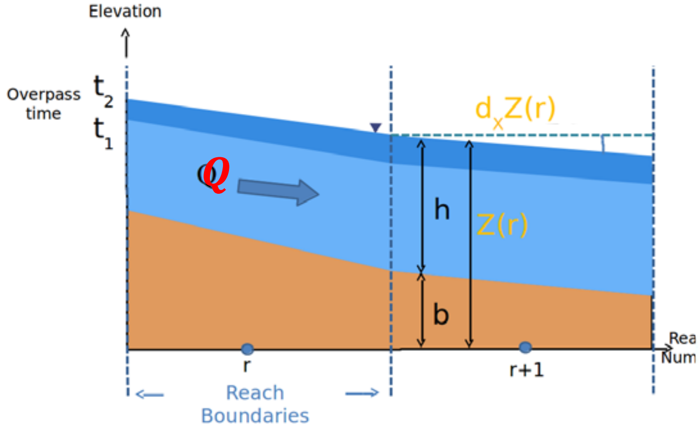
→ Fully automatic method, tested on several academic and SWOT like datasets
→ Toolbox under testing; datasets/cases/users are welcome!

Montazem phD (2019), (Montazem et al., 2019, GRL) (Montazem et al. *to be submitted*)

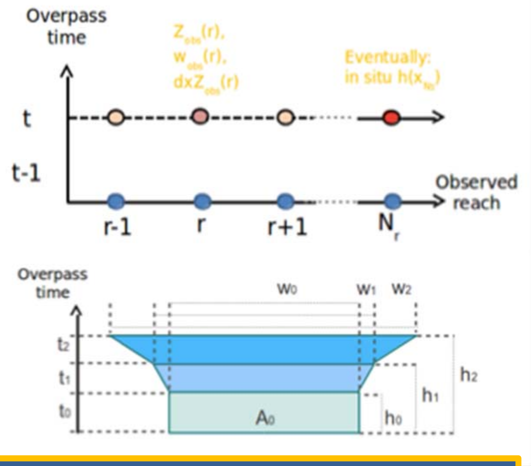
1D hydraulic inverse problems in a SWOT context

River surface snapshots, discrete « reach » obs (Z, W, Slope)

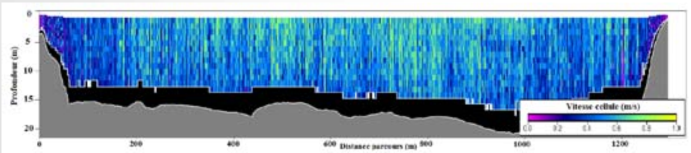




Temporal revisits

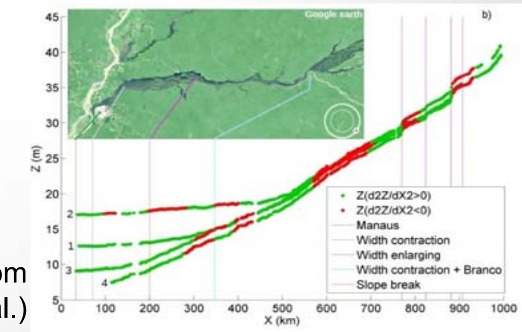


- → **1D Hydraulic unknowns (*triplet*): discharge Q, low flow Xsection A_{0r}, friction $K_r(h)$**
- → **Ill-posed inverse problems, roughness-friction equifinality**
- → **Essential feature: hydraulic propagation scales vs obs space-time scales**
  (see analysis in Brisset et al. (2018), Larnier et al. (2019))



An in situ velocity profile, Rio Negro at Novo Airão in 12/15 (ADCP Measurement - CPRM)

Ex. of in situ XS velocity & surface profiles (Rio Negro)



In situ GPS profiles (Moreira et al.), segmentation from large scale **WS curvature extremum ~ main hydraulic controls** (Montazem et al.)

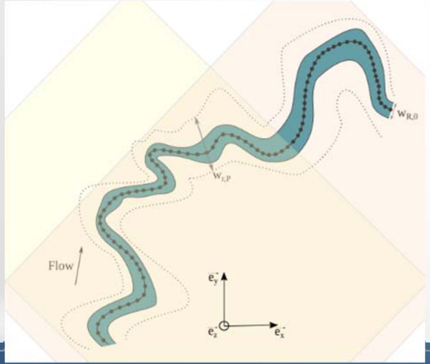
Inverse problems analysis in Garambois and Monnier (2015), Brisset et al. (2016,2018), Gejadze and Malaterre (2017),, Larnier et al. (2019)
See also inferences in Oubanas et al. (2018) in a similar data context (imposed downstream BC)

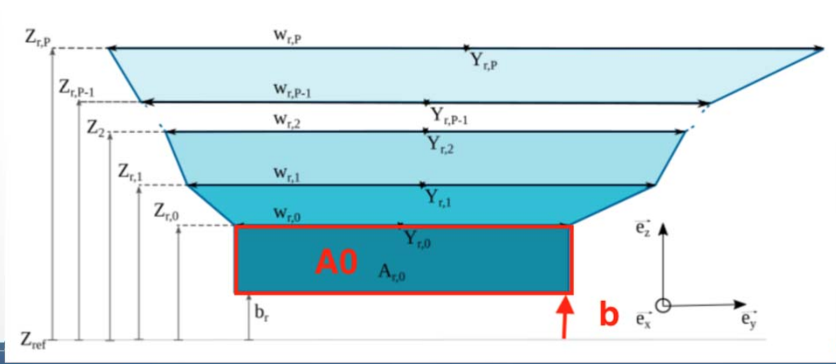
The flow model and inverse method

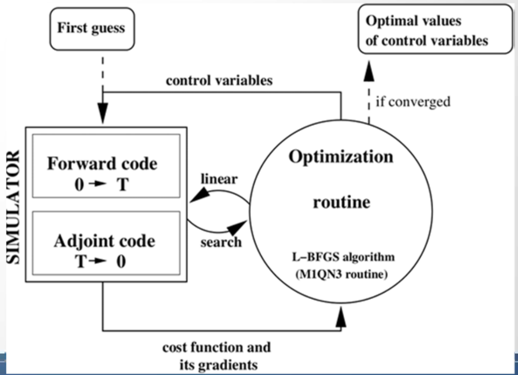
- **Flow model**: 1D (A,Q) Saint-Venant equations (hyperbolic with source term)

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

- **Resolution:** Classical finite volume method (**DassFlow1D**, cf. Brisset et al. 2018)
- **Inverse method (IMT, Icube):** "Hierarchical Variational Discharge estimation", HiVDI algorithm (Larnier et al., 2019) & dedicated bathymetry-friction treatments, q_l
- **Obs**: WS elevations and width; obs. cost function: $j_{obs}(c) = \frac{1}{2}\|Z_{obs} - Z(c)\|_N^2$
- **Sought (1D) parameters** (control vector c): $Q(t),\ K(x,h) = \alpha(x)h^{\beta(x)},\ b(x),\ Q_{lat}^L(t)$
- **Inverse problem**: $c^* = \text{argmin}\ \text{j}(c)$ solved with $\nabla j(c)$ computed by adjoint method using preconditioning (HiVDI)



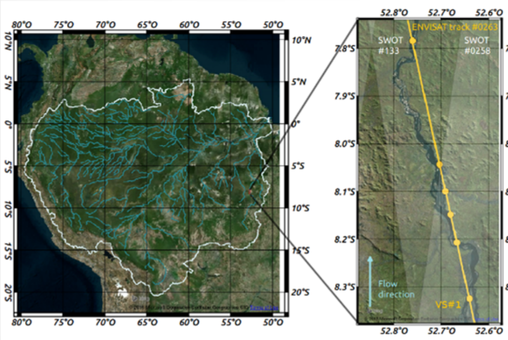




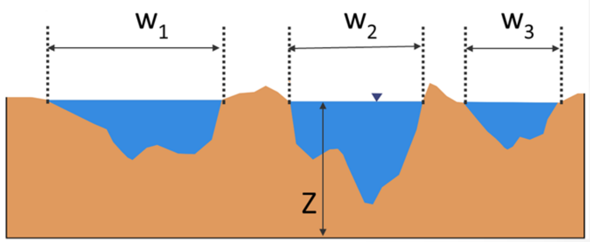
DassFLow1D (Brisset et al. 2018), see https://www.math.univ-toulouse.fr/DassFlow/rivers.html

HiVDI (Larnier et al. 2019) see next talk by Larnier et al.

Effective braided flow model in a «satellite reference »



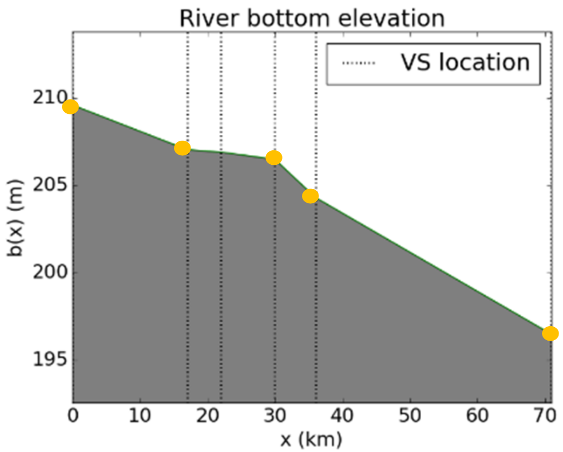
Schematic cross sectional view of a multichannel river flow

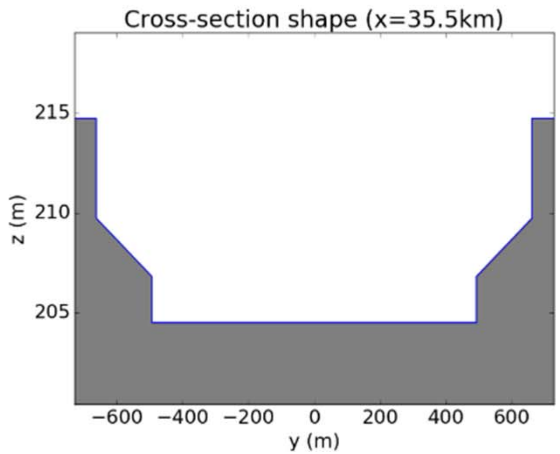


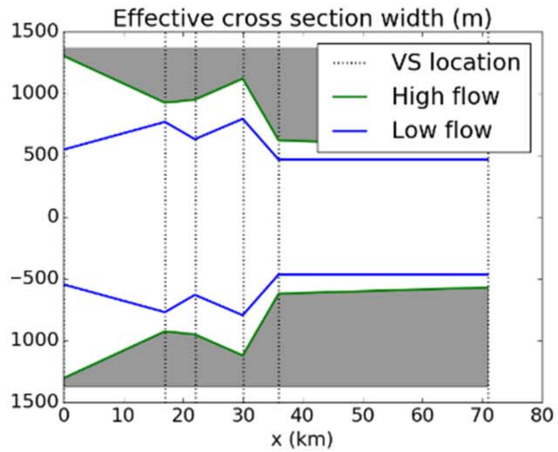
Effective hydraulic model from multisat. data: 1D single thread channel

Effective bottom elevation from altimetric rating curves (Paris et al. 2016)

Effective 1D cross section from low and high flow JERS images







Effective braided flow model in a « satellite reference »
Model calibration

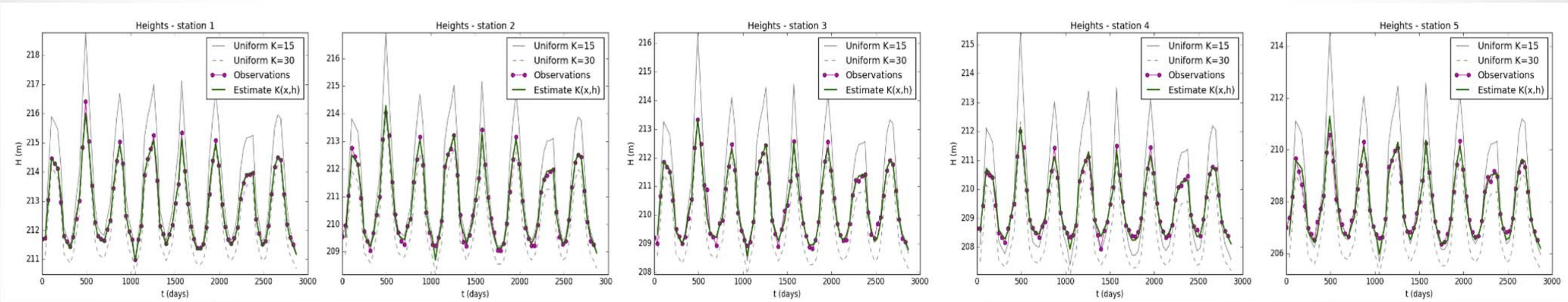
- Power law resistance/friction equation: $K(x,h) = \alpha(x)h^{\beta(x)}$

Observations and hypothesis for calibration

- $Z_{obs}(t)$ at (6VS * 75 passes), $Q(t)$ upstream (MGB model (Paiva et al. 2013),
- Hypothesis: no lateral fluxes, consistent spatialization of friction law by reach

Power roughness calibration (VDA with reduced control vector)

- Cost function $j_{obs}(c) = \frac{1}{2}\|Z_{obs} - Z(c)\|_N^2$ minimized wrt $c = (\alpha_i, \beta_i)_{i\in[1..5]}$

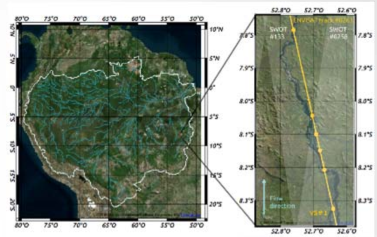


→ **Accurate reproduction of flow lines (incl. braided reaches)**
→ $K(x,h) = \alpha(x)h^{\beta(x)}$ **richer than usual constant roughness coefficients, enables K variation with (modeled)** $h(x,t)$

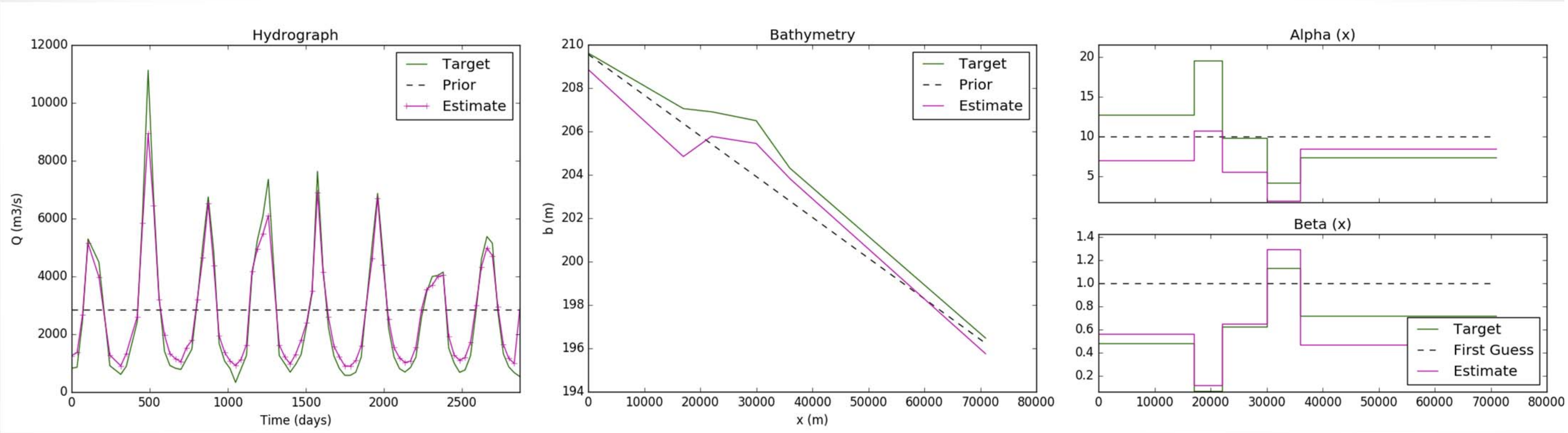
(Garambois et al., subm.)

Estimation of the "triplet" $(Q(t), K(x,h), b(x))$

Assimilation of ENVISAT observations



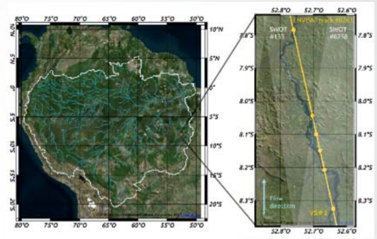
- Given: $Z_{obs}(t)$ at 6 ENVISAT VS (75 passes), observed low-high flow width
- Unknown: $Q(t),\ K(x,h) = \alpha(x)h^{\beta(x)},\ b(x)$, (unknown downstream BC)
- **Strong constrains**: "sparse" spatialization on 5 reaches of roughness and piecewise linear bathymetry



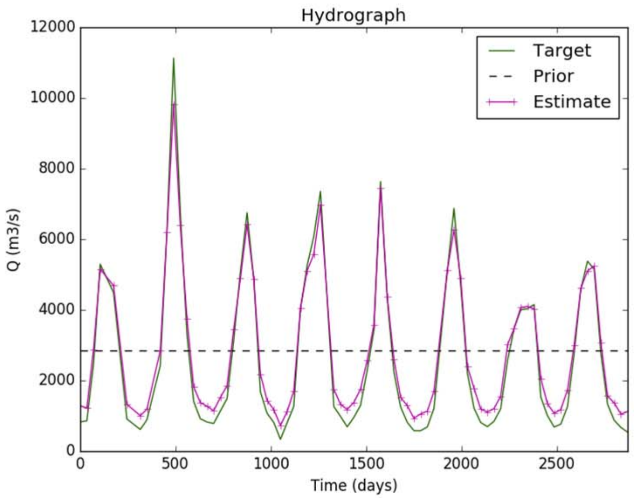
→ **Adapted Bathymetry-friction complexity+scaling enables to benefit from sparse obs.**
→ **Robust discharge inference along with effective spatial controls**
→ **Good "prior" required, sensitivity investigated (not presented)**
(cf. Tuozzollo et al. 2019 GRL, Larnier et al. 2019)

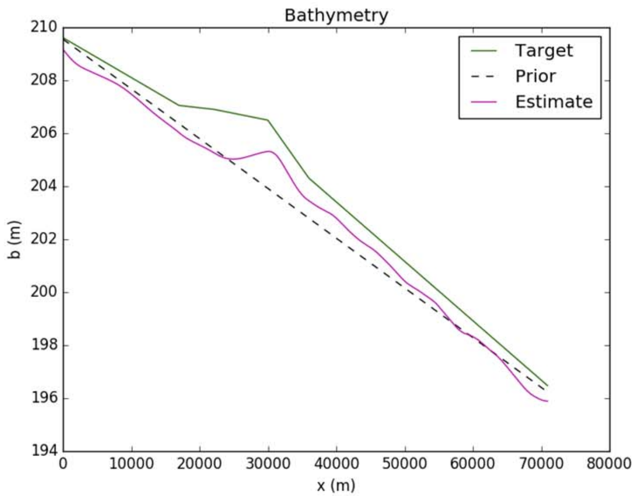
(Garambois et al., subm.)

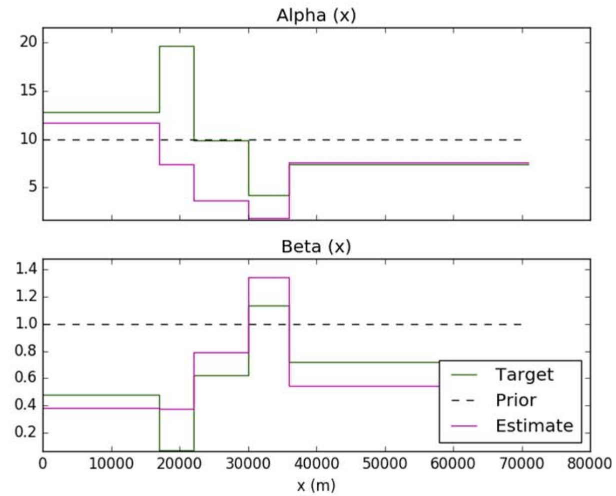
Estimation of the "triplet" $(Q(t), K(x,h), b(x))$
Assimilation of SWOT-like observations



- Given: $Z_{obs}(t)$ on two SWOT swaths (day 1 & 19 per cycle), observed low-high flow width
- Unknown: $Q(t),\ K(x,h) = \alpha(x)h^{\beta(x)},\ b(x)$, (unknown downstream BC)
- **Hypothesis/regularizations**:
  - dense bathymetry at obs scale (200m) + weak constrain on the sought bathymetry curvature (Larnier et al. 2019)
  - sparse spatialization of roughness on 5 reaches







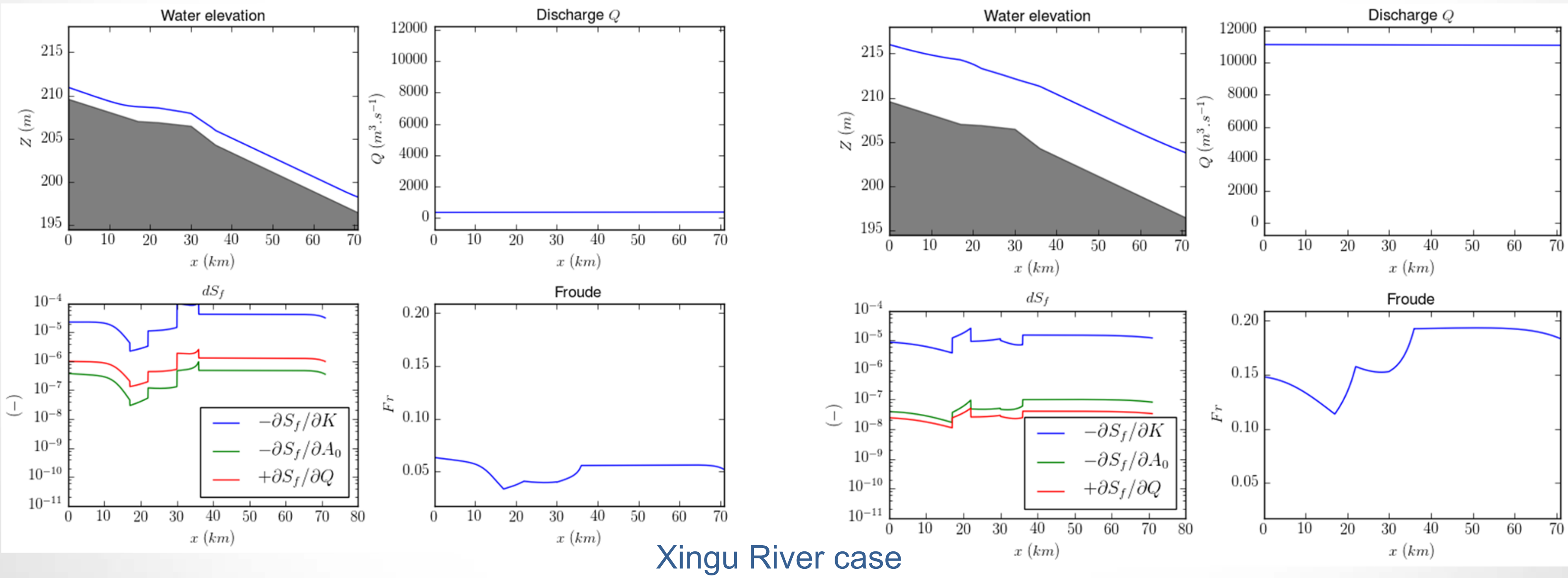
→ **Robust discharge inference along with effective spatial controls**
→ **Dense bathymetry estimated with friction laws at "low resolution"**
→ **Good "prior" required, sensitivity investigated (not presented)**
(cf. Tuozzollo et al. 2019 GRL, Larnier et al. 2019)

(Garambois et al., subm.)

Spatio-temporal sensitivity of the friction term
Numerical investigation on the calibrated model (forward run)

$$dS_f = \partial_K S_f dK + \partial_{A_0} S_f dA_0 + \partial_Q S_f dQ - d\phi(h)$$

Low flow **High flow**



Xingu River case

→ **Friction param. is 10 to 1000 times more sensitive than bathymetry-discharge** (coherent with SVD results on the Garonne River in Garambois and Monnier (2015))

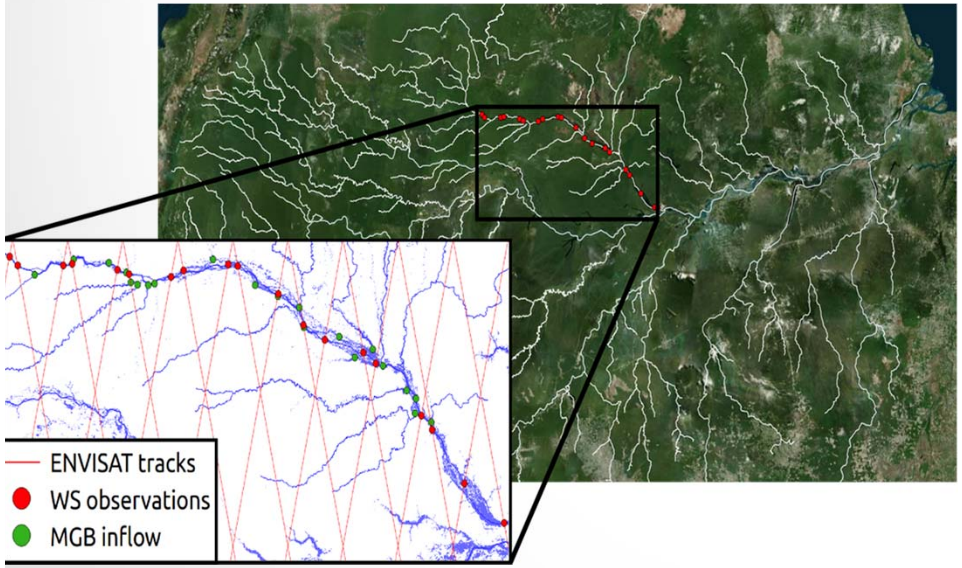
→ **Influences of bottom Slope break clearly visible at low flow, of width contraction at high flows; consistent with the findings of Montazem et al. (2019) from WS signature (curvature) analysis**

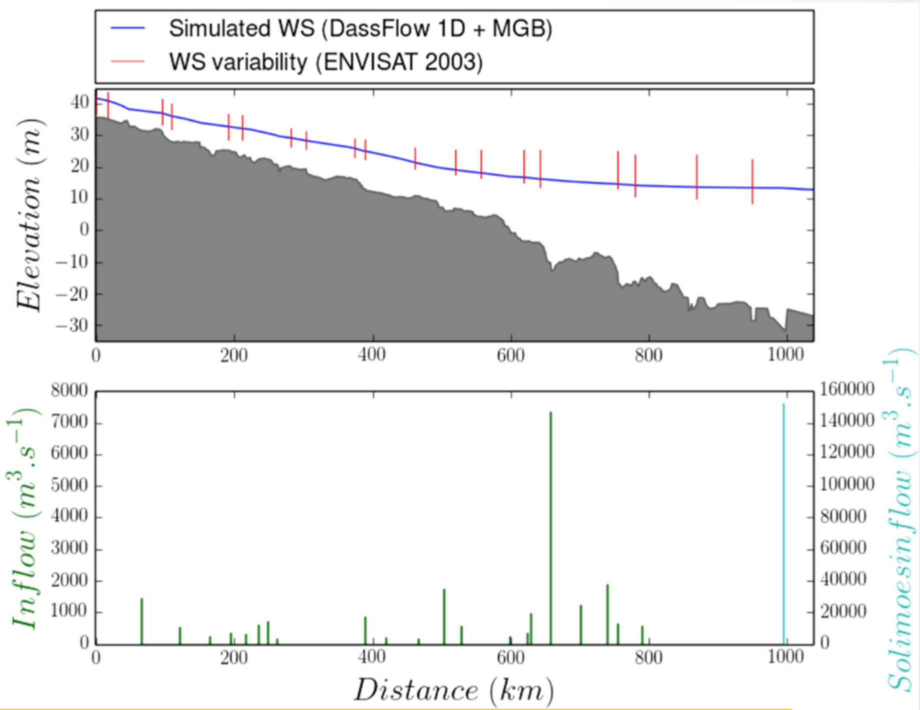
(Garambois et al., subm.)

Large scale hydraulic model with hydrological forcings
(1000km, 10years), multisatellite data

Obs: Landsat derived water masks (Pekel (2016), altimetry, in situ “GPS” flow lines and ADCP velocity profiles (Moreira et al. CPRM)

Model: DassFlow1D (HiVDI chain) + lateral inflows computed from MGB (Paiva et al. 2013) distributed hydrological model

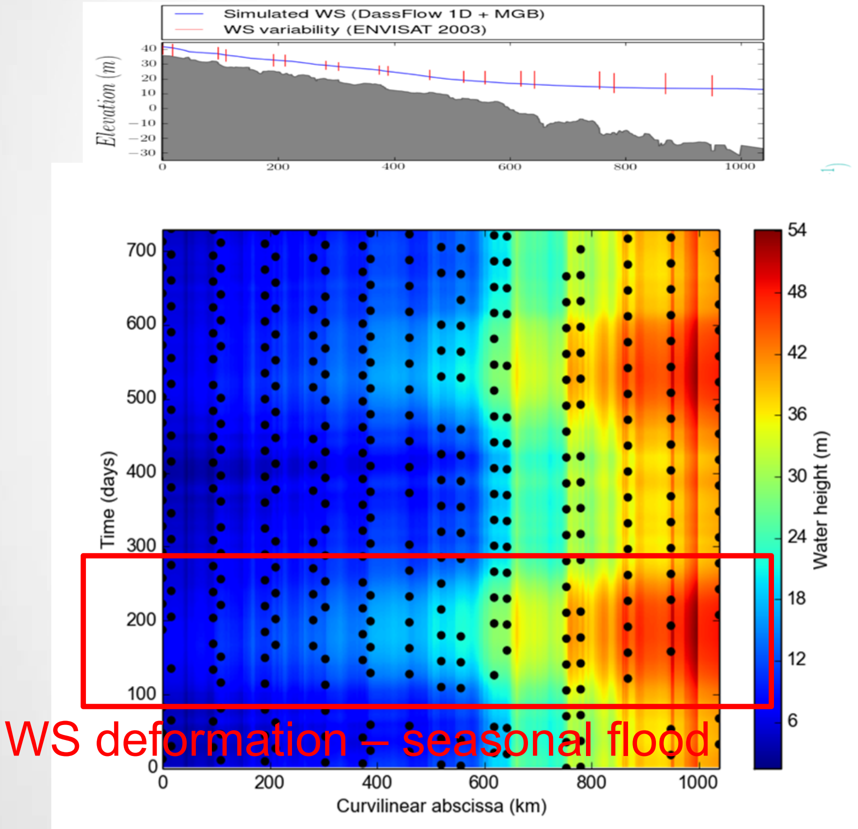




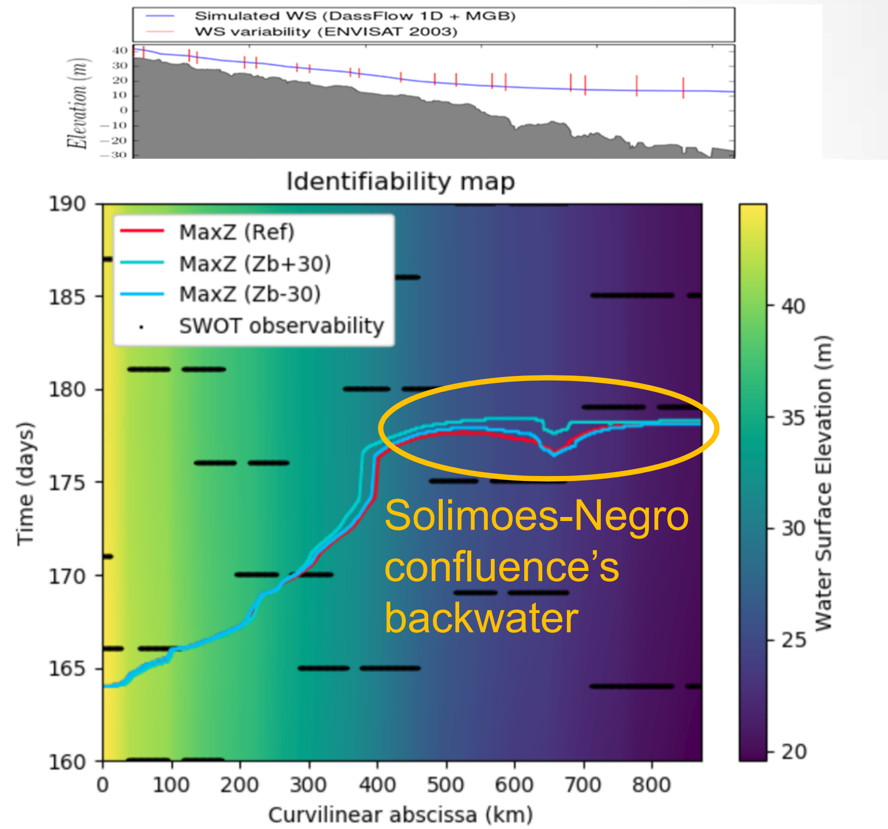
→ **Hydraulic model built from multisatellite data**
→ **Adapted roughness-bathymetry complexity, calibration on ENVISAT obs as previously, inferences from synthetic SWOT (not presented)**

Pujol et al. (in prep.)

Hydraulic visibility
Depicting flood wave propagation at large scales with satellites?



Seasonal deformation of WS – tropical hydrological regime; model calibration on historical altimetry (black dots)



SWOT observability (black) vs simulated flow depth and max Z propagation (Pujol et al.) – « identifiability map » following Brisset (2018)

Ongoing analysis of transient hydraulic signatures and multiple inflows inferences with uncertain bathy-friction - refined model at large x-t scales

Pujol et al. (in prep.)

Conclusions

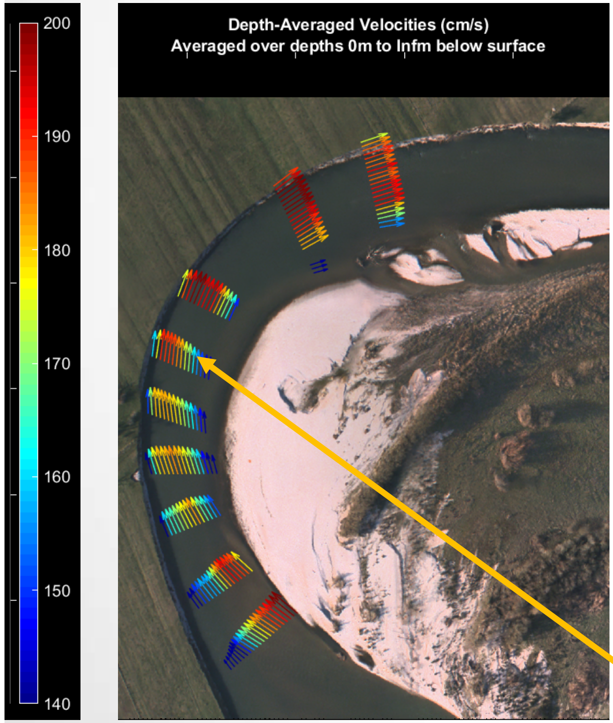
Wavelet-based segmentation method for depicting Hydraulic controls from WS signatures from fine to large scales; filtering tool for noisy 1D SWOT obs (~RiverObs). (Montazem et al.)

Adaptations and applications of HiVDI (0,5D-1D hydraulics + assimilation, IMT-ICUBE)

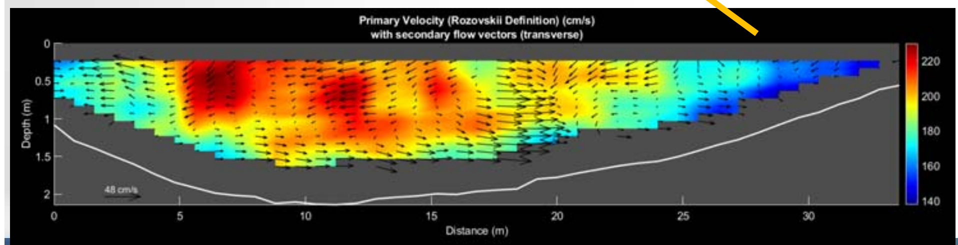
- Friction law K(h) ~ effective modeling of multichannel flows
- Friction spatialized by "reach" to be coherent with the observation grid **and** with the (rather large) meaningful scale of this parameter in the 1D Manning-Strickler equation.
  (see upscaling by Rodriguez et al.)
- Spatially distributed lateral flows: fine hydraulics + hydrological model at large scale
- Braided River discharge inferences (unknown bathymetry-friction) from WS obs.: Robust and accurate temporal signature retrieved on obs. windows if good prior available (biais remains, see talk by Larnier et al.). Coherence between sparse observations and model grid ensured through « scaled » hydraulic constrains.

DassFLow1D (Brisset et al. 2018), see https://www.math.univ-toulouse.fr/DassFlow/rivers.html
HiVDI incl. prior estimation from databases (Larnier et al. 2019) (IMT-ICUBE)
Hydraulic visibility (Garambois et al. (2017), Montazem et al. (2019)), ***Identifiability maps*** (Brisset et al. 2018)

Thank you for your attention!



« Inbank River flows complexities »,
(Left) Moselle River Bend, crédit Piasny et al. (Icube-LIVE)
(Right), Negro Solimoes confluence (crédit Gualtieri)



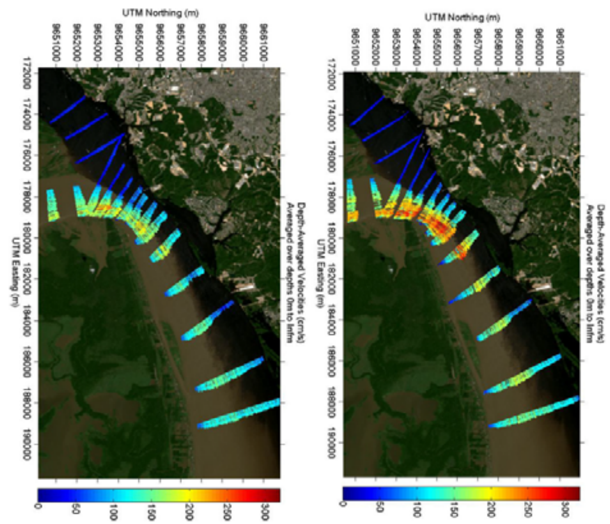


Fig. 3. Depth-averaged velocities of ADCP transects collected about the confluence of Negro and Solimões Rivers on 30–31 October 2014 (left) and on 29–30 April 2015 (right) during FS–CNS1 and FS–CNS2, respectively (Trevethan et al., 2016).

References

HiVDI algorithm & fundamentals - Inverse problem analysis:

- K. Larnier, J. Monnier, P.-A. Garambois, J. Verley. "River discharge and bathymetry estimations from swot altimetry measurements". *(submitted)*.
- P. Brisset, J. Monnier, P.-A. Garambois, H. Roux. (2018) "On the assimilation of altimetric data in 1D Saint–Venant river flow models". *Advances in Water Ressources*
- P.-A. Garambois, J. Monnier, *(2015) "*Inference of effective river properties from remotely sensed observations of water surface". *Advances in Water Ressources*

Estimations from Air SWOT data (Wilamette River):

- Tuozzolo, S, Lind, G, Overstreet, B, Mangano, J, Fonstad, M, Hagemann, M, Frasson, R.P.M, Larnier, K, Garambois, P.-A., Monnier, J., Durand, M. "Estimating river discharge with swath altimetry: A proof of concept using AirSWOT observations" GRL

Hydraulic observables – filtering method, reaches

- A. Montazem, P.-A. Garambois, S. Calmant, P. Finaud-Guyot, J. Monnier, D. Medeiros-Moreira. (2019) Wavelet-based river segmentation using hydraulic control-preserving water surface elevation profile properties. *GRL*
- A. Montazem, P.-A. Garambois, S. Calmant, K. Larnier, J. Monnier. "A hydraulic based automated wavelet denoising method for depicting flow lines from remotely sensed (SWOT) distributed measurements". (*To be submitted)*

Inferences from historical altimetry and SWOT:

- P.-A. Garambois, S. Calmant, H. Roux, A. Paris, A., Monnier, J., P. Finaud-Guyot, A. Montazem, J. Santos Da Silva. (2017) "Hydraulic visibility: Using satellite altimetry to parameterize a hydraulic model of an ungauged reach of a braided river". *Hydrological processes*,
- P.-A. Garambois, K. Larnier, A. Montazem, P. Finaud-Guyot, J. Monnier, S. Calmant. Estimation of ungauged braided river discharge and spatially distributed hydraulic controls from historical altimetry and SWOT observations. *(submitted)*

Hydraulics-hydrology coupling with multisatelilte observations

- L. Pujol, P.-A. Garambois, P. Finaud-Guyot, K. Larnier, J. Monnier, S. Biancamaria, S. Calmant. Hydraulic modeling of 1000km of the Rio Negro with hydrological forcings using existing satellilte altimetry and water masks (in preparation)