Pattern-aware flash flood modeling with a 2D hydraulic-hydrological model and multi-source variational data assimilation

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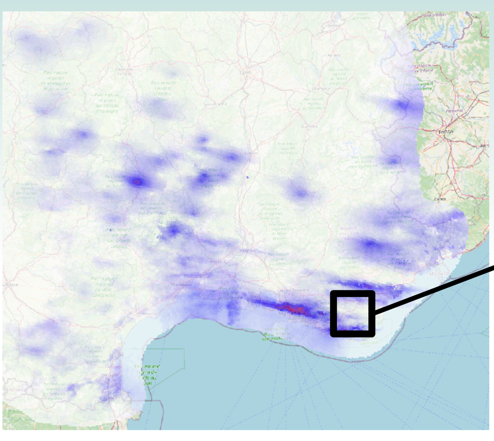
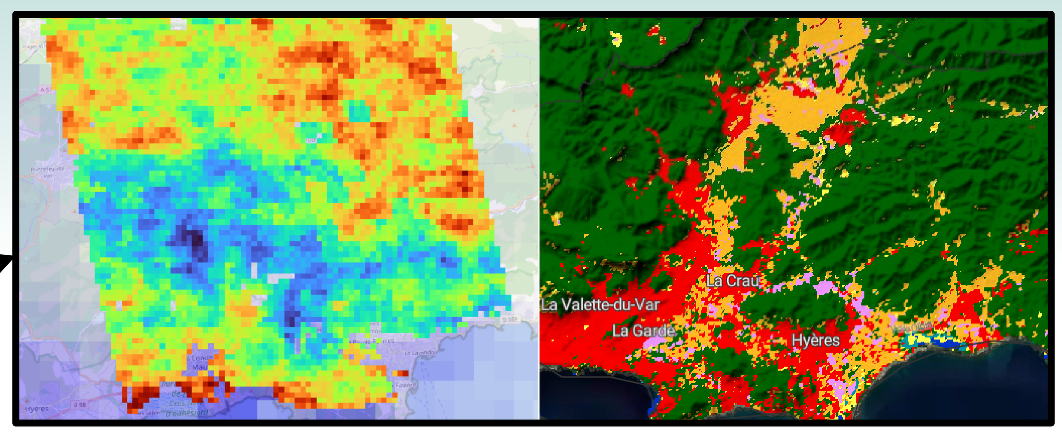
Context: accrued observability of fine-scale data informing on flash flood genesis

High resolution data products from global databases



ANTILOPE J+1
reanalysis rain product
Spatial resolution : 1km² tiles
Time step : 15min



Excerpt from ISRIC database
soil composition data :
clay content over 250x250m tiles

Land cover from Copernicus
Global Land Cover (2015)

Wealth of information from global databases

- High resolution rain data products (in space and time)
- Global estimates of soil occupation, soil composition, soil moisture
- Global DEM and local high resolution LiDar data

=> an opportunity to model fine-scale, accurate flood genesis phenomenons with distributed parameters and states over large scale catchments at high-resolution

Scientific challenges

- Accurately modeling multi-scale non-linear phenomenons in hydraulic-hydrological rainfall-runoff models
- Inferring/Calibrating distributed hydraulic parameters from the partial observation of their mixed signatures

Goal of this work

- Upgrading the DassHydro modeling platform with infiltration terms needed to model fine-scale rainfall-runoff
- Integrating relevant observations of model states and parameters in modeling approach
- Implementing a regionalization scheme for distributed parameters, integrated to the variational data assimilation methods

Hydraulic-hydrological model : DassFlow2D

2D shallow-water equations with infiltration source terms

$$\frac{\partial}{\partial t}\mathbf{U} + \frac{\partial}{\partial x}\mathbf{F}(\mathbf{U}) + \frac{\partial}{\partial y}\mathbf{G}(\mathbf{U}) = \mathbf{S}_g(\mathbf{U}) + \mathbf{S}_f(\mathbf{U}) + \mathbf{S}_{hy}(\mathbf{U})$$

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

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

SCS-CN approach : empirical net rainfall

$$r - i = r_n = \frac{(R - \lambda S(CN))^2}{(R + (1-\lambda)S(CN)}$$

Green-Ampt approach : conceptual soil column

$$i = K_s\left[1 + \frac{(\theta_s - \theta_i)\Psi_f + h}{I}\right]$$

Variational Data Assimilation method

- Multi-objective cost function : $J(\boldsymbol{\theta}) = J_{obs}(\boldsymbol{\theta}) + \alpha J_{reg}(\boldsymbol{\theta})$

$$J_{obs}(\boldsymbol{\theta}) = ||h_{obs} - h||^2_{\mathcal{O}_h} + ||Q_{obs} - Q||^2_{\mathcal{O}_Q}$$

- Control vector (differentiable regionalization operator) :

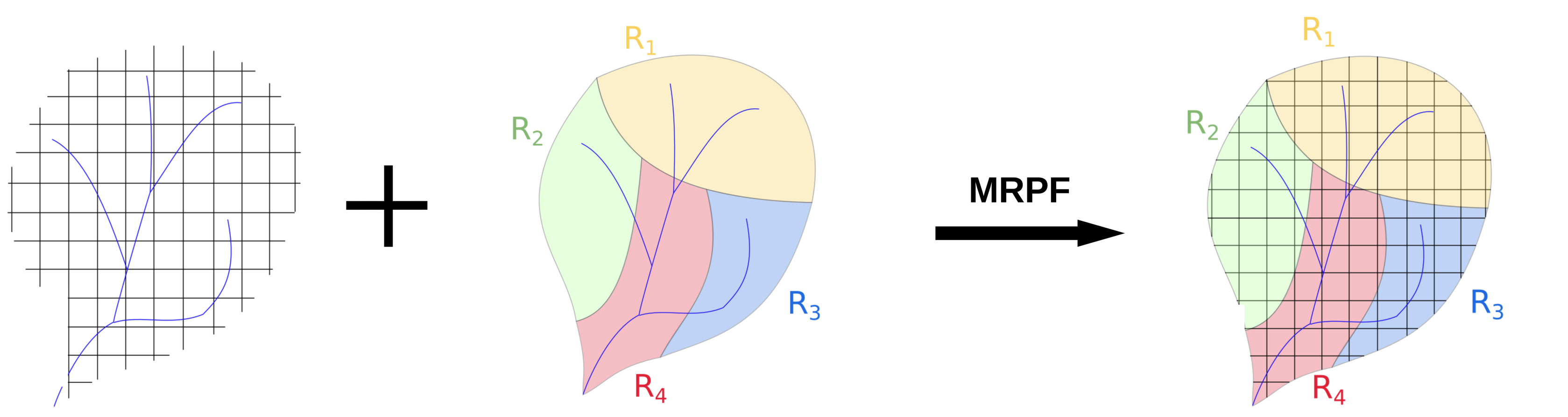
$$\boldsymbol{\theta} = (K_s(x,y), \Delta\theta(x,y)) \xrightarrow{\text{MRPF}} \boldsymbol{\theta} = (\kappa_{1..6}(R))$$

- Adjoint model obtained through automatic differentiation of the forward model
- Optimization problem : $\boldsymbol{\theta}^* = \underset{\boldsymbol{\theta}}{\mathrm{argmin}} J(\boldsymbol{\theta})$

Solving the ill-posed high-dimensional inverse problem from spatially sparse observations : Multi-scale Regional Mapping Function (MRPF)

MRPF : implicit infiltration parameter regionalization based on a priori knowledge of inverse problem solutions :

- Green-Ampt infiltration parameters are calculated from pedologic data using pedotransfer functions
- Pedotransfer coefficients are regionalized, hence reducing the number of sought parameters and enforcing spatial coherence of infiltration parameters within a region, integrating a priori knowledge of spatial variability provided by pedologic data



High resolution pedologic data (clay and sand soil composition) allowing pedotransfer-based parameter estimation

A priori regionalisation based on
(i) hydrological catchments
(ii) location of in situ stations
(iii) soil properties homogeneity

High-resolution model with enforced spatial coherence of distributed parameters

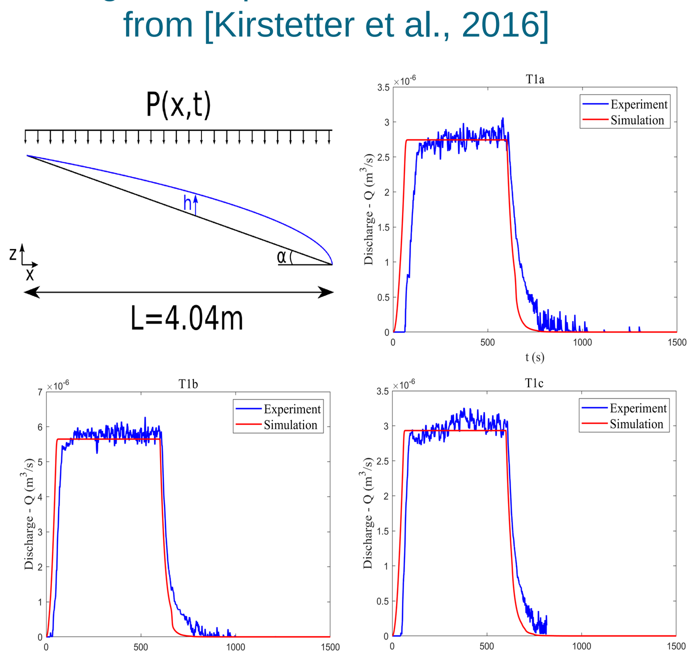
Integrating data from global databases : Fortran-Python wrapping upgrade of DassFlow2D

- Python module upgraded to import and preprocess raster data to DassFlow mesh (e.g. ANTILOPE J+1)
- Exports in HDF5 format for easy sharing
- MPI reading and interfacing for large data sets

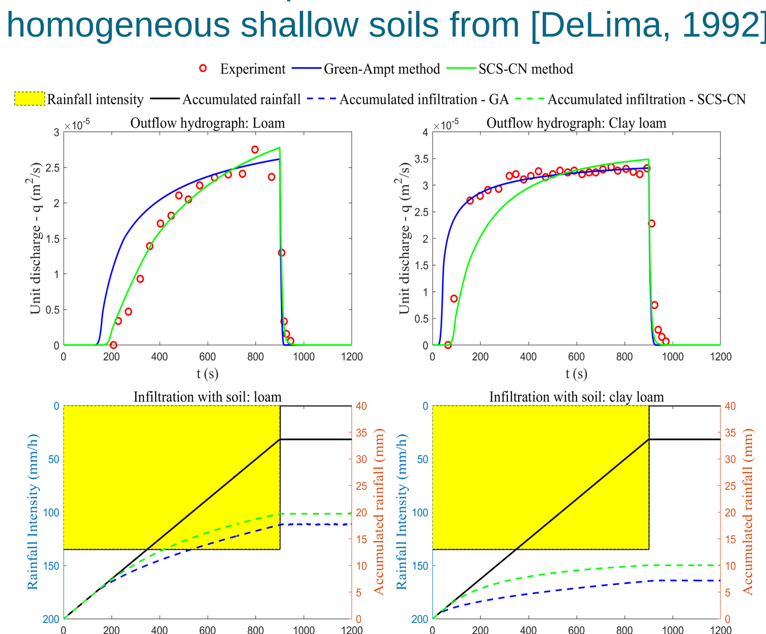
Numerical results

Validation of the source terms

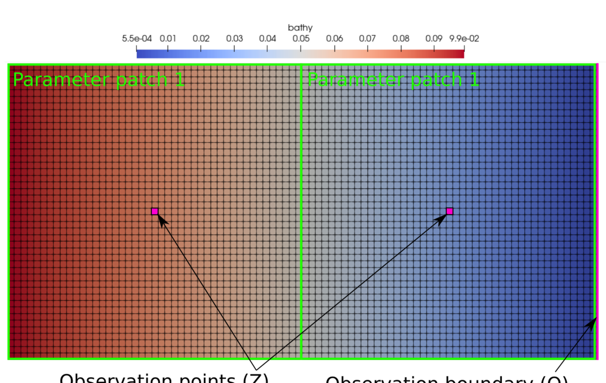
Validation of rainfall source term against experimental bench data from [Kirstetter et al., 2016]



Validation of infiltration source terms based on experimental bench data from homogeneous shallow soils from [DeLima, 1992]



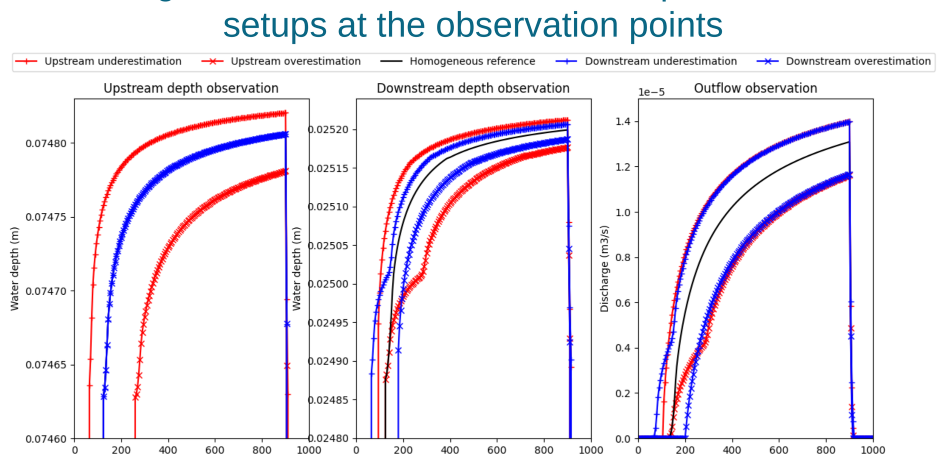
Twin experiments and hydraulic signature analysis

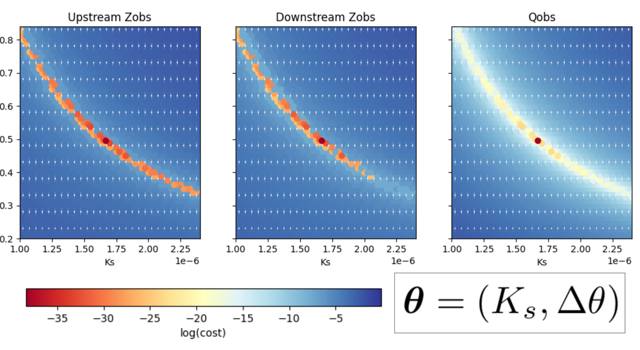


Twin experiment setup :

- 4m long channel
- 2 WSE observation points
- 1 BC flow observation
- 2 patches of Ks

Signature of distributed infiltration parameter setups at the observation points

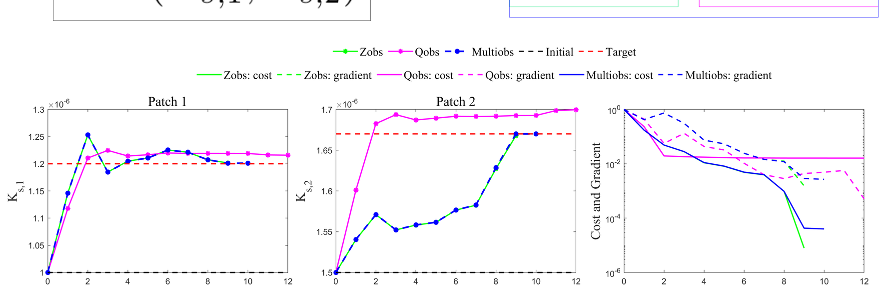




$$\boldsymbol{\theta} = (K_s, \Delta\theta)$$

Sampling of the cost function parts in the parameter space : equifinality between initial water content and infiltration

$$\boldsymbol{\theta} = (K_{s,1}, K_{s,2}) \qquad J_{obs}(\boldsymbol{\theta}) = ||h_{obs} - h||^2_{\mathcal{O}_h} + ||Q_{obs} - Q||^2_{\mathcal{O}_Q}$$

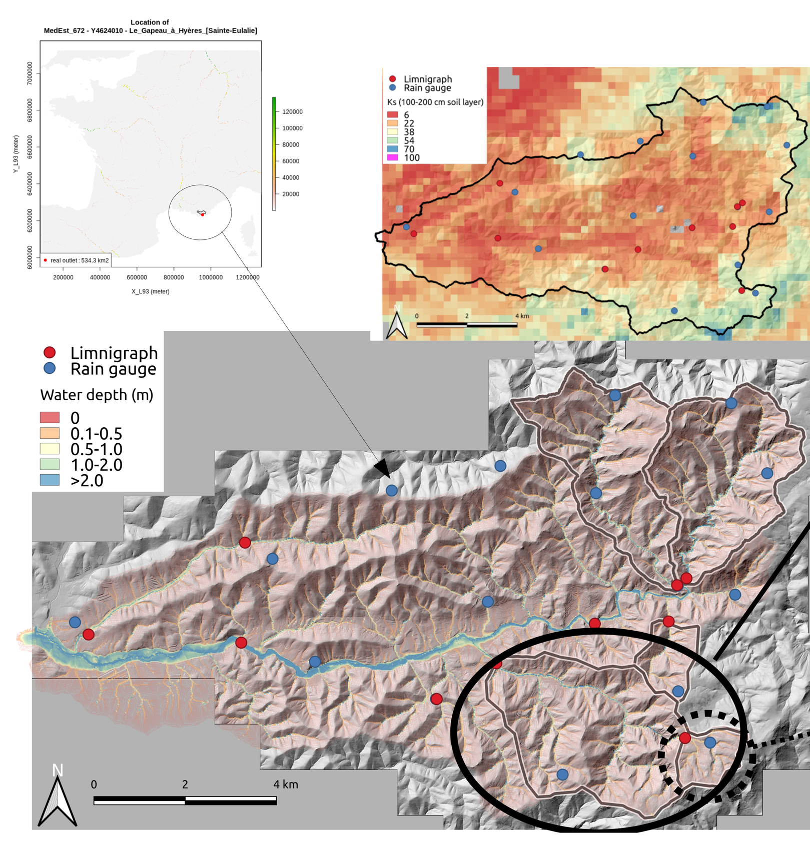


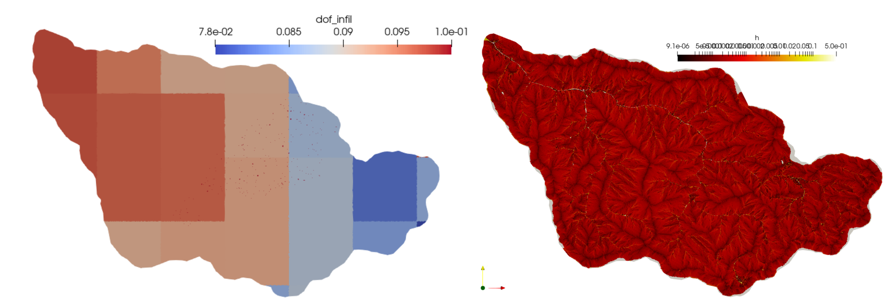
Inference of distributed parameters using water depth and downstream discharge observations

Different parameters have similar effects on observed hydraulic signatures at certain space-time scales.

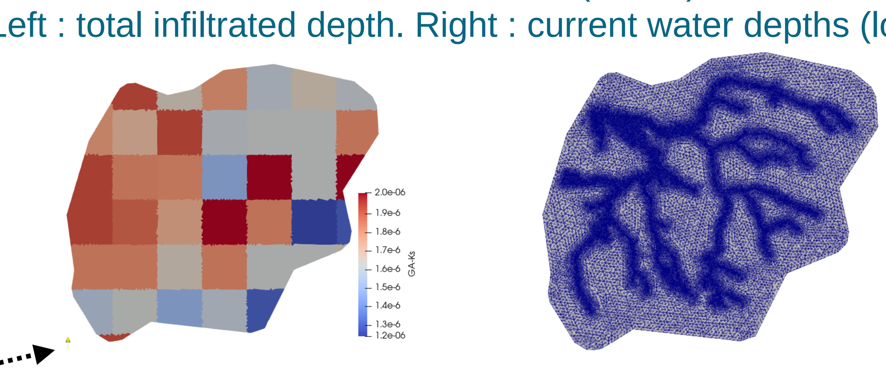
Signatures of distributed parameters may not reflect their distributed character, leading to potential issues of signature attribution and spatial equifinality.

Large scale modeling of flash floods : the Réal-Collobrier catchment

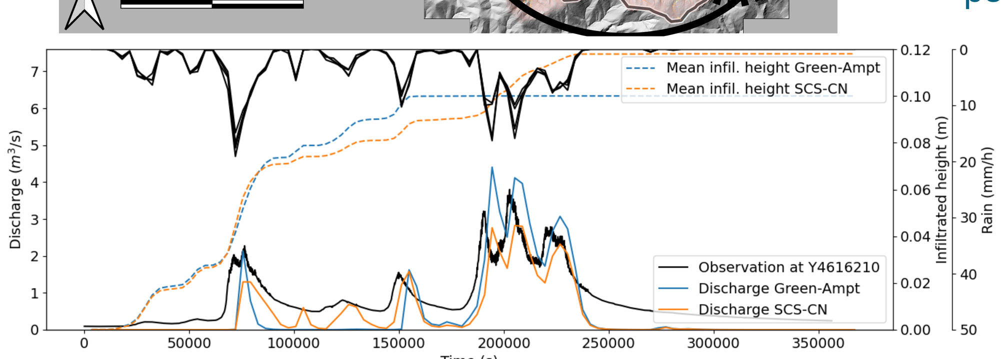




Malière sub-catchment (11km²)
Left : total infiltrated depth. Right : current water depths (log)



Rimbaud subcatchment (>1km²). Left : Ks parameter from pedotransfer function. Right : Mesh from Cartino2D



Fair results are obtained from uncalibrated estimates of distributed infiltration parameters and ANTILOPE rain. A maximum infiltrated depth is defined for the Green-Ampt infiltration.

Modeled outflows (full lines) and averaged infiltrated depth (dotted lines) at the outlet of the Rimbaud subcatchment. Blue : Green-Ampt, Orange : SCS-CN

Pattern-aware inferences

- MPR is fully implemented and differentiable, adjoint model is obtained.
- Next steps include calibration of distributed parameters and comparison to "simpler" approaches through performance at gauges, initialisation of hydrological states in the hydraulic model through remote-sensed data (e.g. from SMAP) or from hydrological models (e.g. SMASH from the DassHydro toolchain).

Other current studies with DassFlow :

- Application on urban flash floods on the Riviera-Palmeraie catchment in Abidjan : challenging assimilation problem given high spatial and temporal variability of hydrodynamic phenomenons and less observations sources (no satellite since events are under 5h, less developped in situ station network). Planned leveraging of observed surface velocity fields from optical analysis of multi-source videos.
- Multi-scale modeling of large scale river networks and selected high-resolution flooding areas (based on [Pujol, 2022]). Planned leveraging of both satellite data, in situ stations and surface velocities in multi-source assimilation approach.

Conférence SHF
« Prévision des crues et des inondations – Avancées, valorisation et perspectives »

28-30 novembre 2023 - Toulouse
Catégorie « Jeunes »

Main references related to hydraulic-hydrological modeling. On equifinality issues : [Garambois-Monnier, AWR'15], [Larnier-Monnier-Garambois et al., IPSE'20]. On identifiability capabilities : [Brisset-Monnier-Garambois et al., AWR'18]. On infiltration implementation [Ni et al., HydProc'20]. On pedotrasnfer functions : [Cosby et al., WRR'84],[Cooper et al., HESS'21]. On complex flows investigations - applications : [Garambois et al. Hydro. Proc'17], [Garambois et al. JoH'20], [Pujol et al., JoH'20].