Assessing parsimonious hydrological model structures with distributed adjoint-based calibration in SMASH Python-Fortran platform on large sample of French catchments and flash floods

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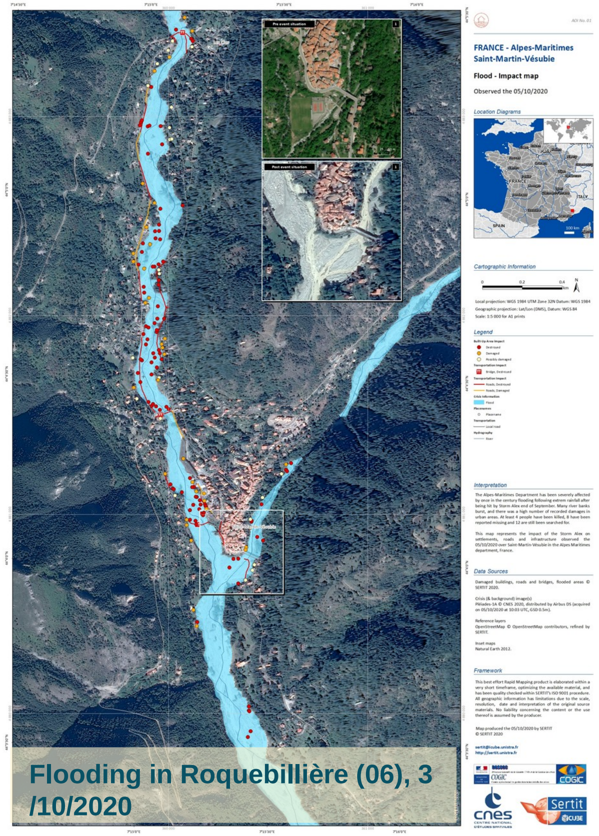
Context : upgrade French Flash flood forecasting chain – Vigicrues Flash

Key challenge : accurate flood forecasting (location, magnitude and timing of runoff), on gauged and ungauged catchments.

Approach : High resolution spatially distributed hydrodynamic modeling with multisource data fusion (in situ and satellite data)

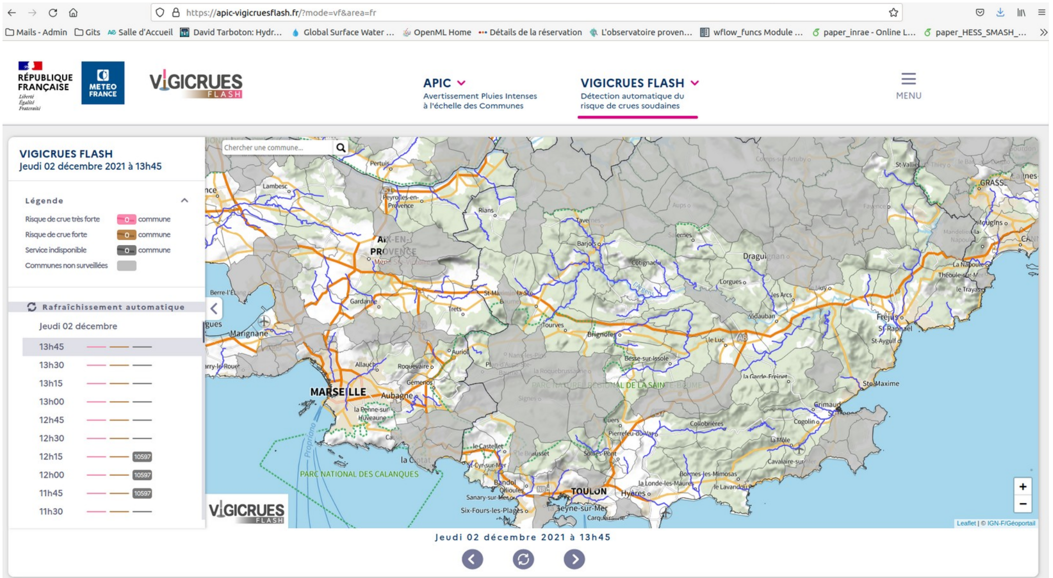

Gardon d'Alès (Gard) 8-9/09/2002


Nartuby (Var), 14/06/2010



Flooding in Roquebillière (06), 3 /10/2020

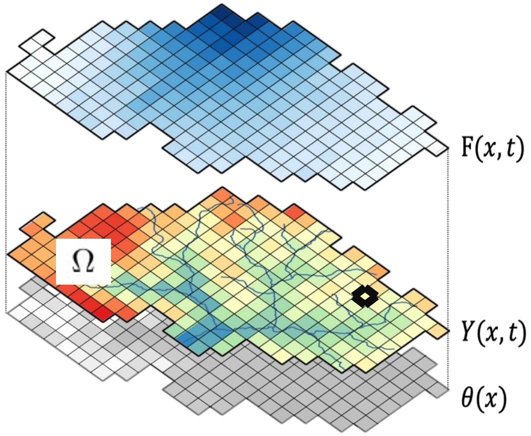
Vigicrues Flash national platform
INRAE – SCHAPI (Javelle et al. 2019)



SMASH Platform

Spatially distributed **M**odelling and **AS**similation for **H**ydrology

- Flexible hydrological data asssimilation plateform:
  - Spatially distributed, multiscale
  - Hydrological operators of various complexity available for simulating physical processes (snow, interception, infiltration, subsurface & surface flows, …)
  - Variational data assimilation (VDA) algorithm adapted to **high dimensional inverse problems**:
    - Calibration and regionalization
    - Multi-source data integration for state/output correction
  - Pyhton wrapping of fortran source code that is automatically differentiable (TAPENADE engine – Hascoet et al. (2013))



Forward hydrological model: $Q\left(x,t\right)=\mathcal{M}\left[\boldsymbol{P}\left(x,t'\right),\boldsymbol{E}\left(x,t'\right),\boldsymbol{h}\left(x,0\right),\boldsymbol{\theta}\left(x\right),t\right]\ \forall x\in\Omega, t'\in\left[0,t\right]$

Objective function: $J(\boldsymbol{\theta})=J_{obs}(\boldsymbol{\theta})+\alpha J_{reg}(\boldsymbol{\theta})$

Calibration inverse problem: $\hat{\boldsymbol{\theta}}=\underset{\boldsymbol{\theta}_{min}\leq\boldsymbol{\theta}\leq\boldsymbol{\theta}_{max}}{\operatorname{argmin}} J\left(\boldsymbol{\theta}\right)$

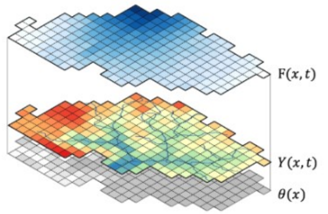
Optimization : VDA algorithm (Jay-Allemand et al. 2019, 2022) : $\boldsymbol{\theta}\left(x\right)$ optimized with LBFGS-B descent algorithm,

$\nabla_{\boldsymbol{\theta}}J$ computed with numerical adjoint model

$\boldsymbol{\theta}^{*}$ uniform first guess - Michel (1991) algo

Large sample assessment of a parsimonious structure

(Colleoni et al., tb submitted to HESS)

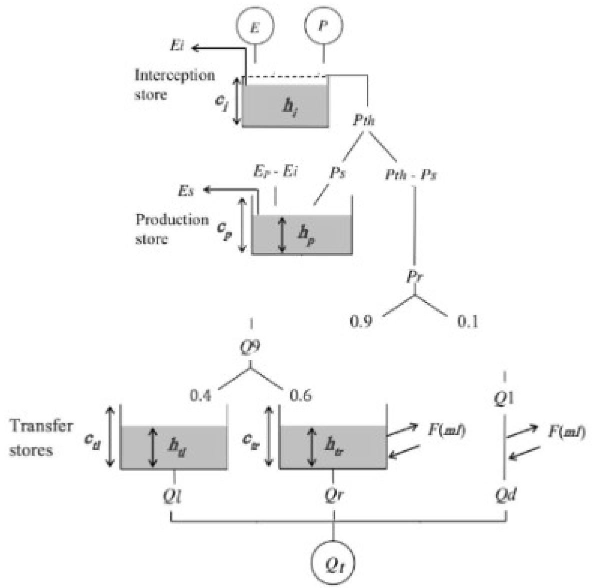


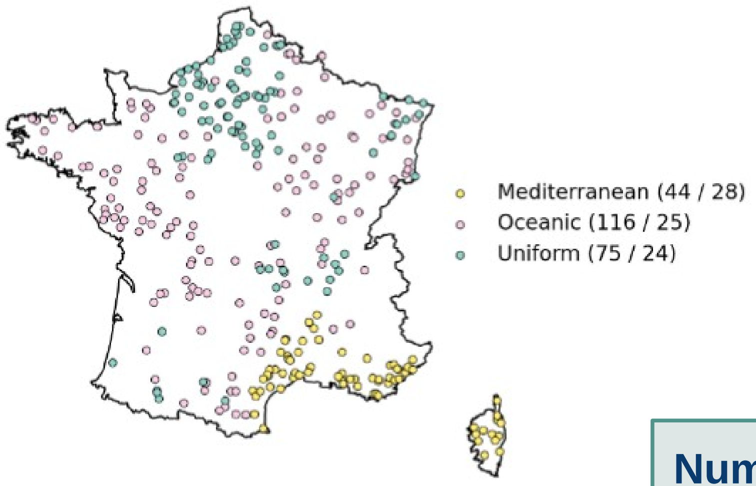
GR-like structure at pixel scale,
(VIC production also, not shown)
+ simple routing model

Large sample : 312 gauges
- 235 downstream non nested
- 77 upstream

Forcing data (Meteo France):
- Radar rainfall reanalysis, Antilope J+1 (dt=1h, dx 1km2)
- SAFRAN Evapotranspiration (dt=1j , dx = 8km desag.)

Calibration/validation data (Banque Hydro) :
- Hourly discharge time series





Control vector, six 2D fields:

$$\boldsymbol{\theta}(x) \equiv (c_i(x), c_p(x), c_{tr}(x), c_r(x), ml(x), c_{tl}(x))^T$$

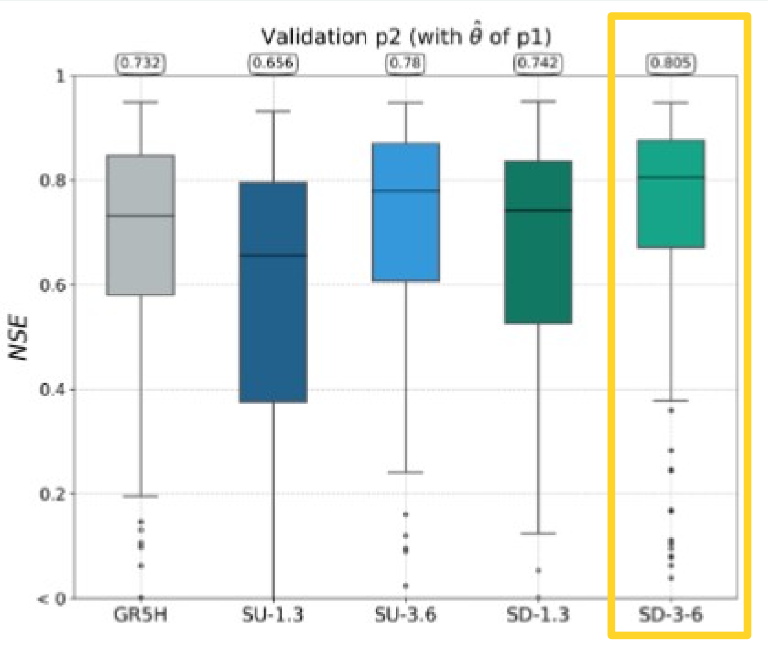
Numerical experiment design :

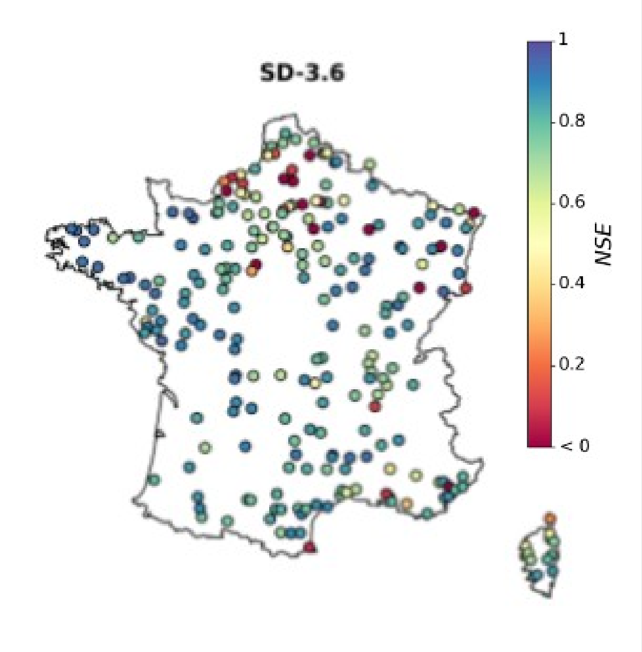
- VDA calibration with $J_{obs} = NSE$
- Temporal validation : Split sample test
- Spatio-temporal validation at upstream gages
- Analysis: regimes groups, flood signatures, global sensitivity analysis

Large sample assessment of a parsimonious structure

Temporal validation results

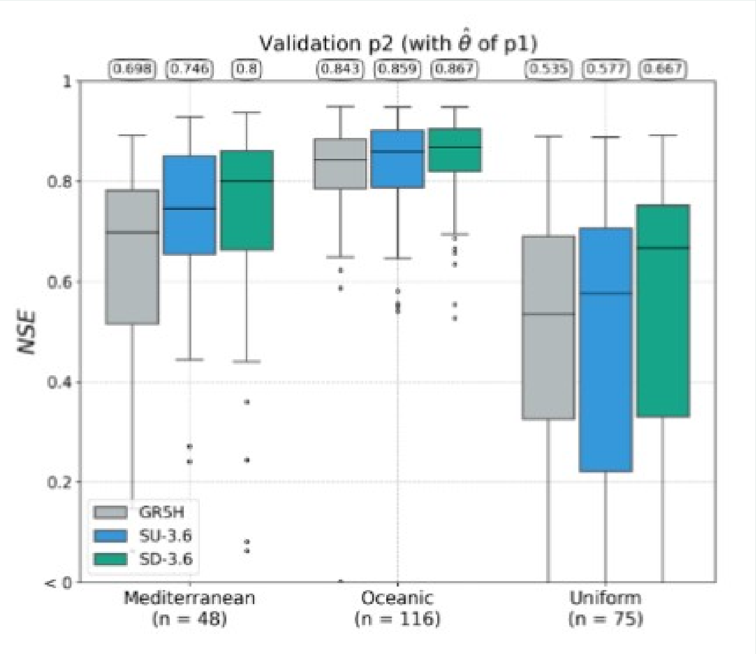
Global performance





Distributed (underconstrained) calibration remains relatively robust in validation on the tested sample

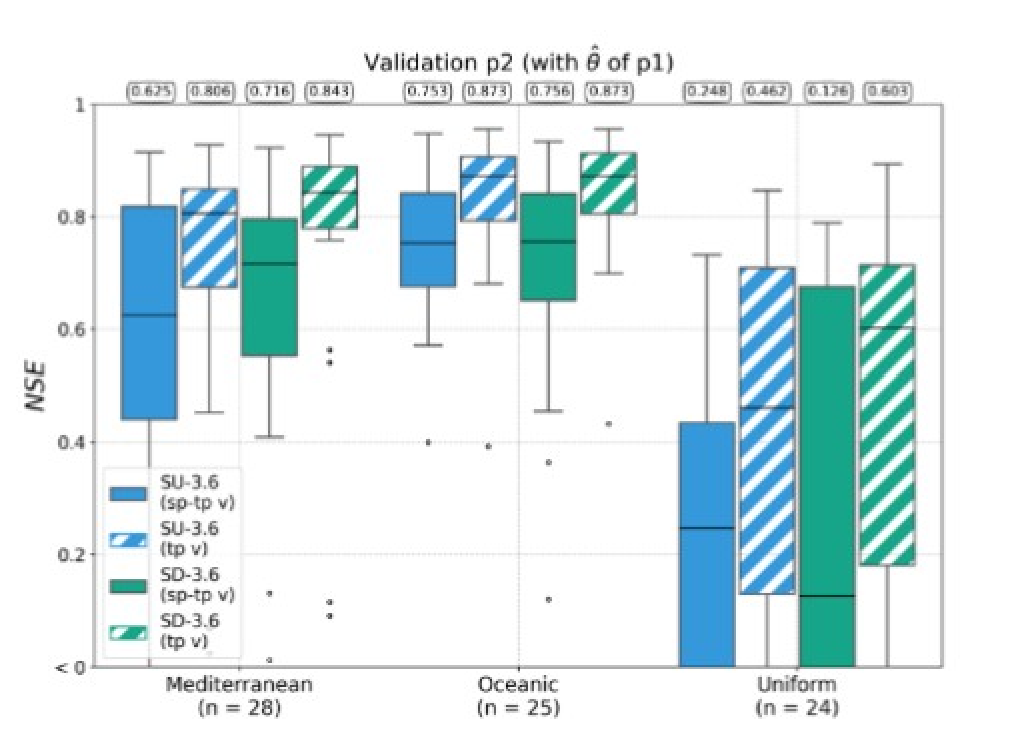
Performance by regime



Improvements needed vs significant hydrogeological influence (esp. Uniform group)

Large sample assessment of a parsimonious structure

Spatio-temporal validation = “ungauged case”

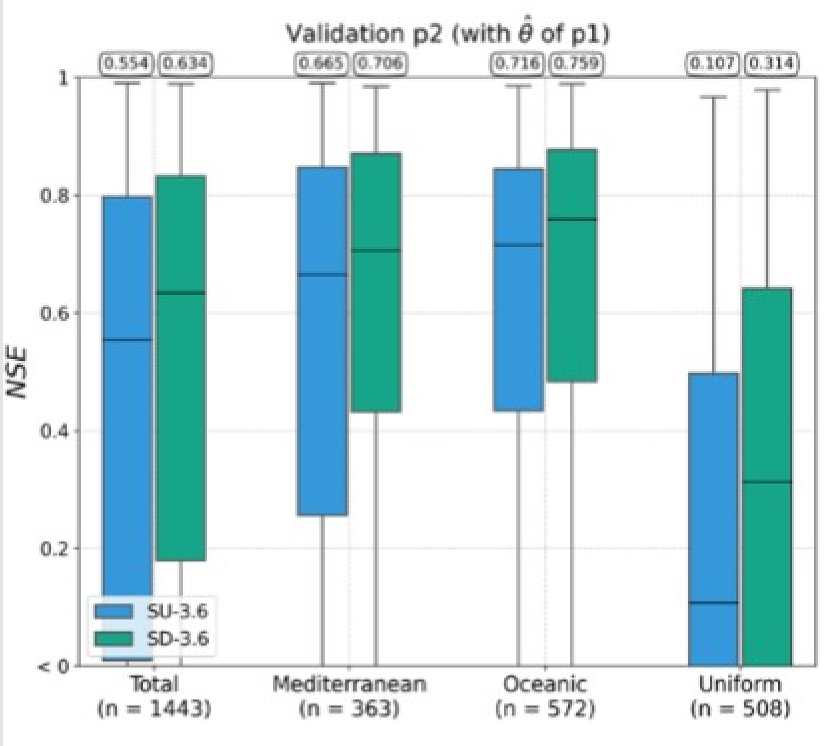


Dashed boxes : “highest reachable” efficiency, temporal validation of a local calibrations at upstream gauges

Large sample assessment of a parsimonious structure

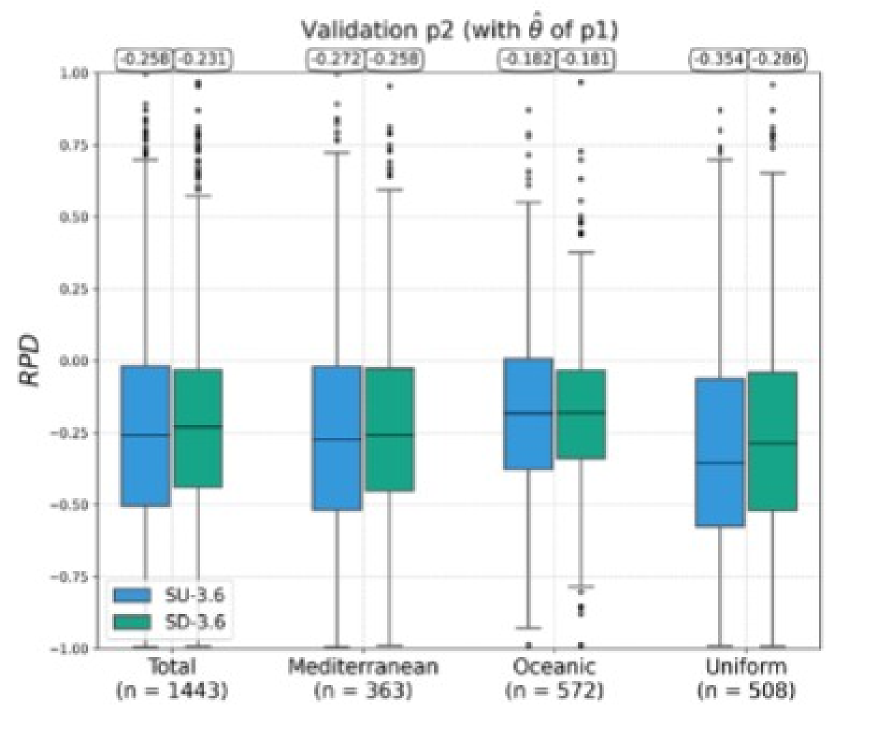
Event signatures

Performance (NSE) at flood event scale



Segmentation algorithm (Huynh et al., in prep)

Simulated peak flows accuracy



$$RPD = \frac{Q_{p,s}\left(t_{p,s}\right)}{Q_{p,o}\left(t_{p,o}\right)} - 1$$

Slight biais in validation can stem from different hydrological information between learning and validation periods (not shown)

Large sample assessment of a parsimonious structure

Regional parametric sensitivity analysis (10k parameter sets sample by catchment)

Sensitivity over the tested sample

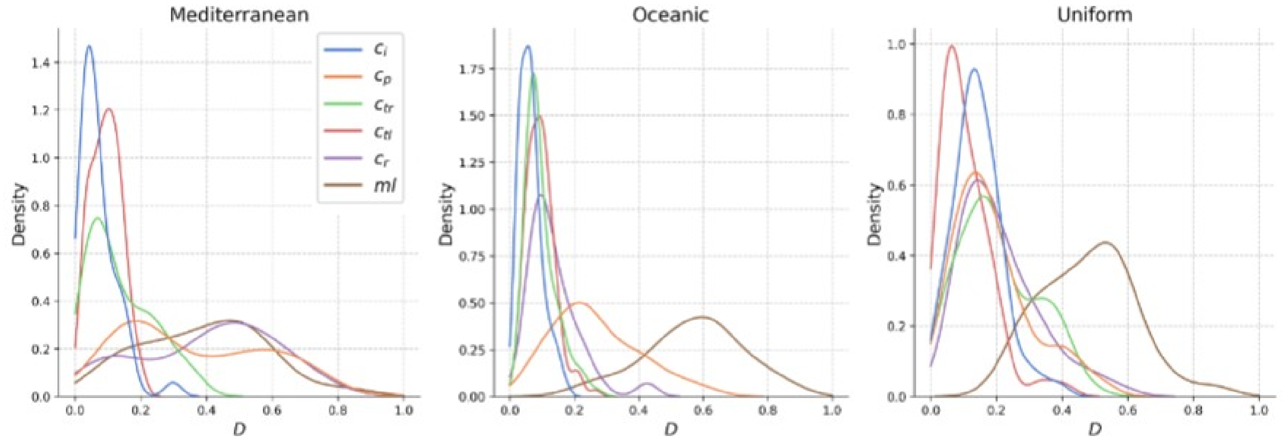


Figure 9. Parametric sensitivity of SMASH model variant S3.6 over period P2 with spatially uniform parameters sampled in previous calibration ranges, 10 000 parameter sets by catchment and NSE threshold determined by catchment such as partinoning simulations into 10 % and 90 % behavioural and non behavioural simulations denoted B and $\bar{B}$. density over catchment groups, of Kolmogorov-Smirnoff sensitivity (D) measure between the cumulative distribution curves of B and $\bar{B}$ of each catchment.

Global sensitivity ranks

Regime	c_i	c_p	c_{tr}	c_{tl}	c_r	ml
Mediterranean	6	3	4	5	1	2
Oceanic	6	2	5	4	3	1
Uniform	5	4	3	6	2	1

Table 5. Parameters sensitivity ranking for each catchment group for SMASH model variant S3.6 over period P2. For each parameters sensitivity distribution the rank has been calculated by sorting in ascending order the distribution mean value. Rank 1 is the most sensitive parameter and rank 6 the less in terms of distribution mean value.

Conclusions and perspectives

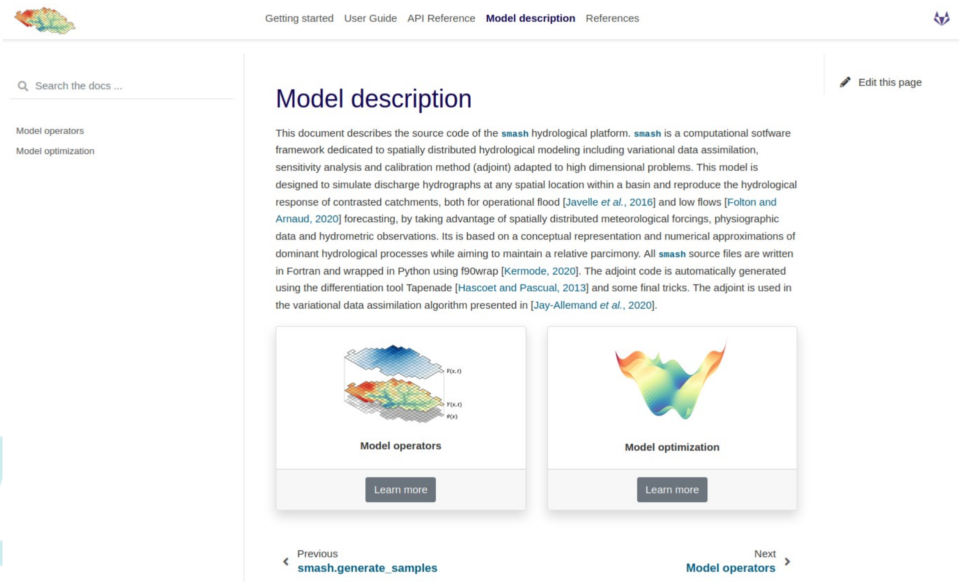
6-parameters GR-like (and VIC-like not shown) structure with spatially distributed calibration:

- **High performance in calibration** (not shown), median NSE = 0.878
- **Robustness in temporal and spatio-temporal validation** esp. for Mediterranean and Oceanic groups
- Accurate flood signatures obtained in validation
- Higher sensitivity to non conservative « groundwater exchange parameter » and produciton parameters

- **New versatile computational platform in python-fortran (open source release this year with user/dev. friendly doc and tutorials,** Colleoni et al. In prep): flexible high resolution hydrological modeling with VDA, ML…

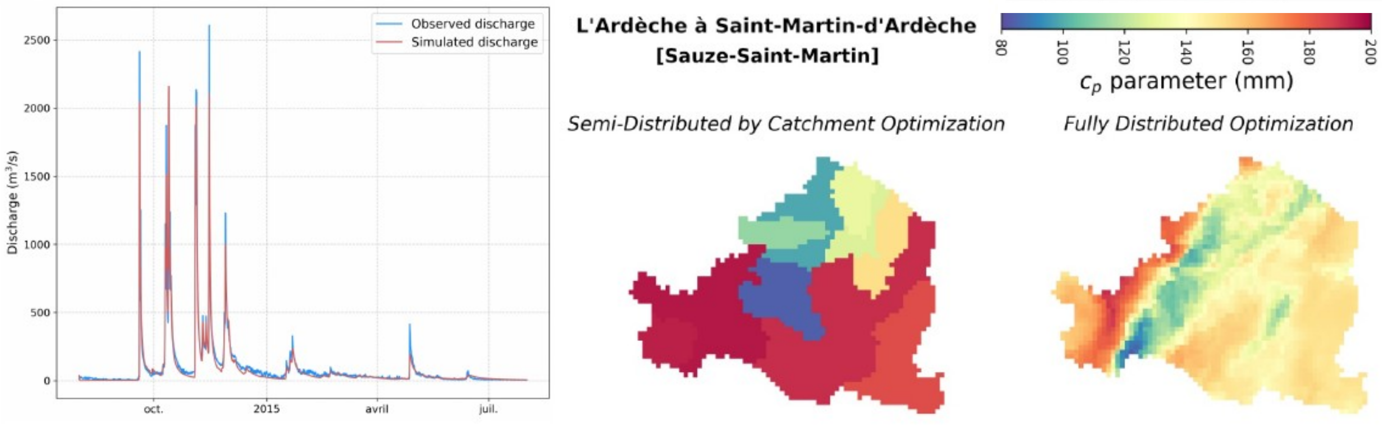
Work perspectives : add state of the art operators/models, uscaling/regionalization scheme (Samaniego et. al 2010) with higher dim. « hyperparameters », physiographic regularizations, coupling with multi-D hydraulic model with VDA (Pujol et al. 2022, GMD), direct use of worldwide and regional datasets/CM-RCM, QPF ensembles, hybrid approaches

« Semi-automatic » Sphinx documentation



Advanced computations with compact python scripts

```python
import smash

# Model Object Creation
model = smash.Model(configuration="configuration_Ardeche.txt", verbose=1)

# Uniform Optimization (prior)
model.optimize(solver="sbs", obj_fun="nse", method="u", inplace=True)

# Semi-Distributed by Catchment Optimization
model_sdc = model.optimize(solver="l-bfgs-b", obj_fun="nse", method="sdc")

# Fully Distributed Optimization
model_d = model.optimize(solver="l-bfgs-b", obj_fun="nse", method="d")

# Save results to hdf5 file
model_d.to_hdf5("res_optimization_Ardeche.hdf5")
```



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