Geomorphological alteration of urban rivers assessed by hydrological modelling

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Abstract

Urbanization alters the geomorphological attributes of rivers by increasing peak flows and reducing sediment inputs due to surface sealing and efficient stormwater systems. Attribution of geomorphological changes to urbanization has been mostly done using purely statistical tools under a regional analysis framework, which does not explicitly account for the hydrological processes by which urbanization controls river morphology. Using a process-based hourly hydrological model, we aimed to relate the observed geomorphological changes in three French rivers to the historical urbanization of their catchments over the period 1959-2018. Firstly, we applied the hydrological model to generate an hourly streamflow time series from climatic inputs by accounting for the changes in catchment imperviousness, which we estimated from historical land-cover databases. Secondly, we exploited the obtained streamflow time series to analyze the temporal evolution of the flow competence, i.e. its ability to transport sediments, with regard to the increased imperviousness of the catchments. Results show that urbanization significantly increased flow competence on the urbanized rivers, but the impact and its trend were variable from one catchment to another. This demonstrates the role of urbanization in increasing the channel instability that led to the general incision and widening observed on these rivers over the past three to four decades. Our approach shows promise in projecting the impact of changing land-use and climate on channel geomorphology.

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Context

The Mérantaise and the Morbras are two rivers located within the Seine river catchment (Fig. 1) and drain catchments of 20 km² and 51 km² of area, respectively. These two catchments underwent considerable urbanization during the late 20th century (Fig. 2). This urbanization is suspected to be the cause of the observed incision and widening of the beds of the two rivers, which exceeded 1 m of incision and 4 m of widening over the period 1964/1980 to 2015 (Tab. 1 and Fig. 3).

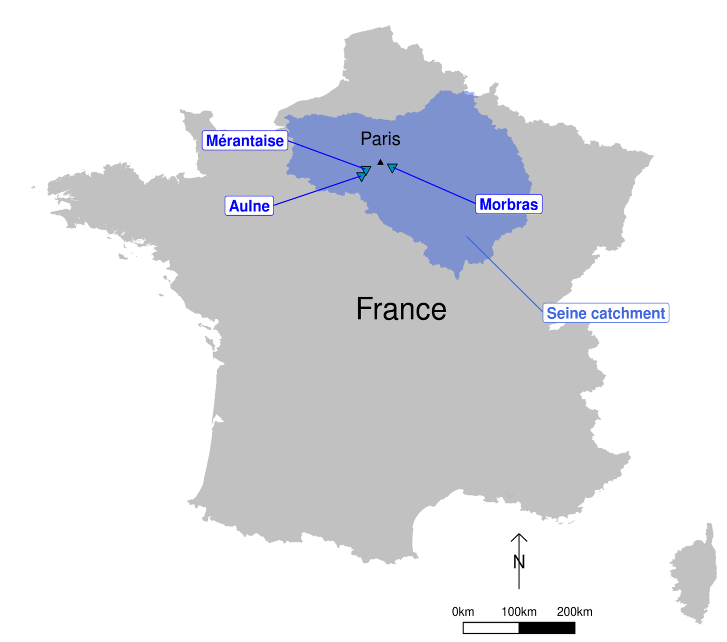

Fig. 1. Catchment location.

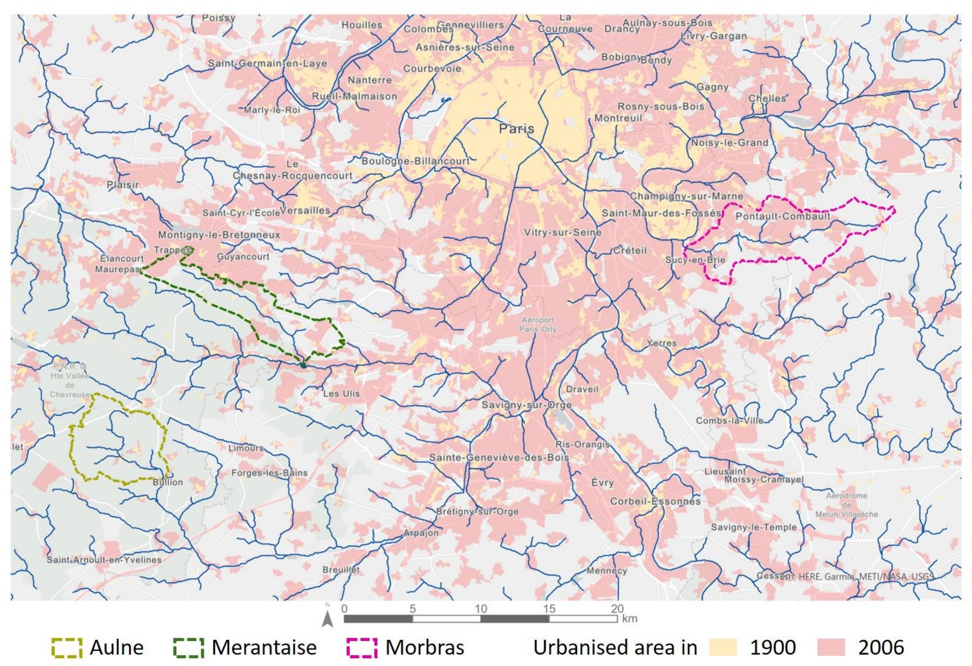

Fig. 2. Historical urbanization of the catchments.

Fig. 3 and Tab. 1. Incision and widening of the Mérantaise and Morbras river beds.

River	2015 X-sections compared to…	Incision (m)		Widening (m)	
		Mean	Max	Mean	Max
Mérantaise	1980 X-sections	0.41	1.26	1.31	4.91
Morbras	1964 X-sections	0.39	1.05	0.75	3.10

Objective

Our objective is to provide a hydrology-based evidence for the role of urbanization in the geomorphological alteration of the Mérantaise and Morbras river beds. As a control case, we included the rural Aulne catchment (34 km², Fig. 1), for which no significant geomorphological change was observed.

To do so, we used the hydrological model MU5H (Saadi et al., 2021, Fig. 4) which explicitly accounts for the effect of urbanization on the rainfall-streamflow relationship. The model was chosen based on its performances over 273 urbanized French and US catchments (Saadi et al. 2021).

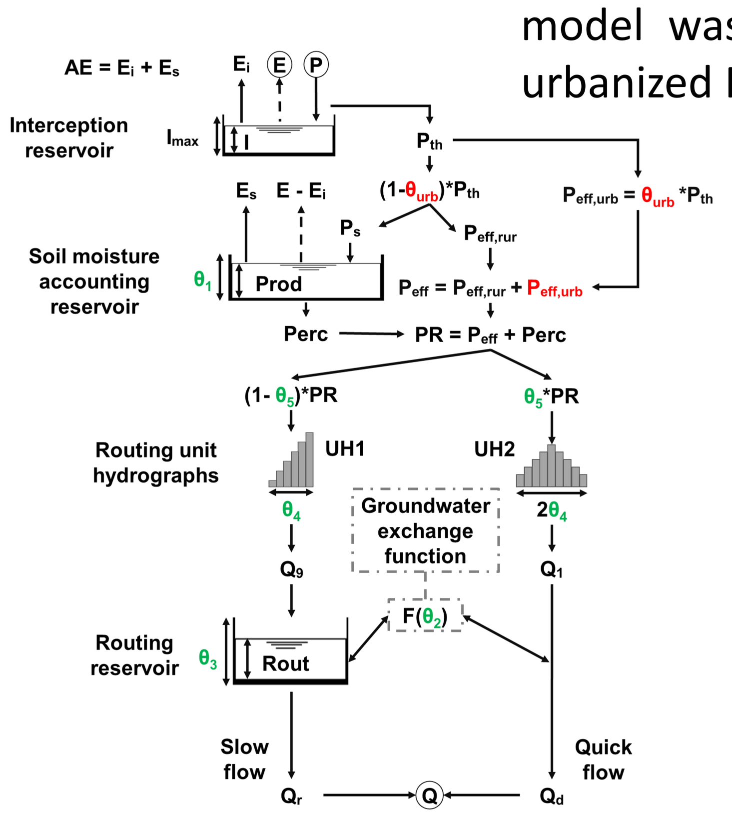

Fig. 4. MU5H model structure. In green are numerically calibrated parameters.

P: Precipitations; **E**: Potential evapotranspiration; **PR**: Net precipitation from rural ($P_{eff,rur}$) and urbanized ($P_{eff,urb}$) surfaces; **Q**: Streamflow

I_{max}, θ_1, θ_3: Reservoir capacities (mm)
θ_2: Potential exchange parameter (mm)
θ_4: Base time of unit hydrographs (h)
θ_5: Quick-flow/slow-flow split parameter (-)
θ_{urb}: Proportion of impervious surfaces (-)

Methodology

1. Data requirements

Tab. 2. Required data for the model runs and calibration.

Required data	Source	Time period
Precipitation	SAFRAN (hourly, 8 km)	**1959-2018**
Potential evapotranspiration		
Land cover	Aerial photographs by LGP + CORINE database	**1900-2015** (Mérantaise; Jugie et al., 2018) **1949-2015** (Morbras) **1990-2015** (Aulne)
Discharge	LGP + INRAE + CD94	**2007-2018** (Morbras) **2011-2018** (Aulne, Mérantaise)

2. Model calibration

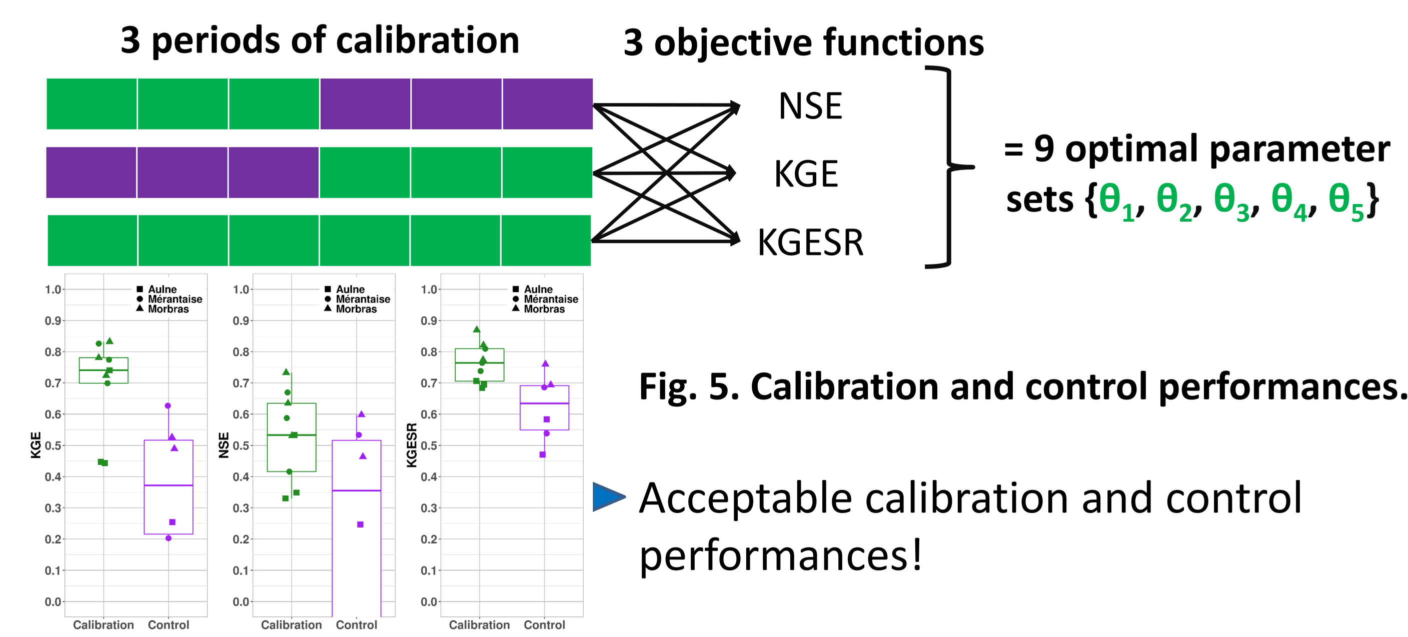

Fig. 5. Calibration and control performances.

▶ Acceptable calibration and control performances!

3. Long-term streamflow time series (1959-2018)

Each of the 9 optimal parameter sets $\{\theta_1, \theta_2, \theta_3, \theta_4, \theta_5\}$ +

1. Actual evolution of the catchment
θ_{urb} = Observed yearly TIA

2. Catchment response if there were no urbanization (nonurbanized, TIA = 0%)
$\theta_{urb} = 0\%$

4. Change in flow competence due to urbanization

For each simulation (1 to 9), **an event is defined when the discharge exceeds the critical discharge Q_{cr}(mm/h)**, above which **sediment transport occurs**:

1. Q_{cr} is estimated from the nonurbanized simulation using (Pfaundler et al., 2011):

$$Q_{cr} = 0.6 \cdot \frac{1}{N} \cdot \sum_{y} Q_{d,max,y}(\theta_{urb} = 0)$$

N: number of years (1959-2018)
$Q_{d,max,y}$(mm/h): max daily discharge for year y

2. Total competent flow (TCF_{ev}, mm/h) for the observed and simulated discharge:

$$TCF_{ev} = \sum_{h \in ev} \max(Q_h - Q_{cr}, 0) / \quad Q \in \{Q_{obs}, Q_{sim,TIA\ obs}, Q_{sim,TIA=0}\}$$

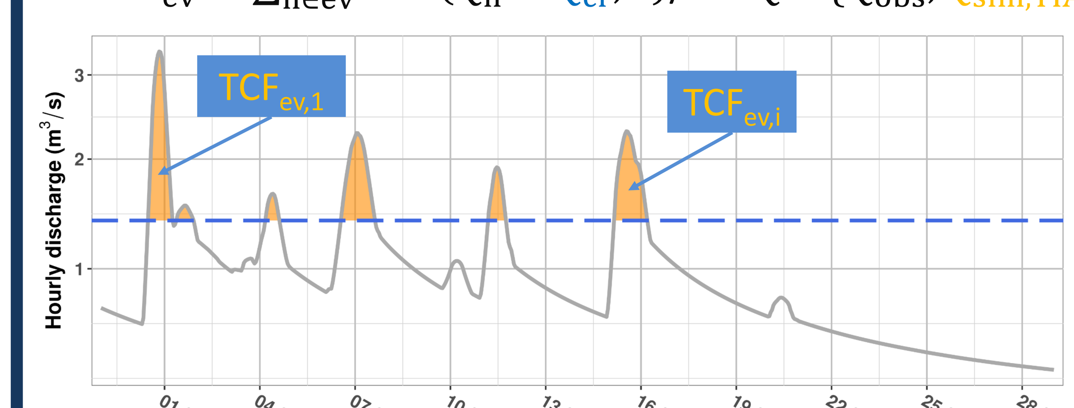

Fig. 6. Illustration of TCF_{ev}.
For each year y and month m, with N_{my} the number of years with events in the month m:

$$TCF_{ev,y} = \sum_{ev \in y} TCF_{ev}$$

$$TCF_{ev,m} = \frac{1}{N_{my}} \sum_{ev \in m} TCF_{ev}$$

3. Relative change in TCF_{ev} due to urbanization, smoothed over a window of 5 years:

$$\Delta_{rel}TCF_{ev,y}\ (\%) = 100 \frac{\sum_{y-2}^{y+2} TCF_{ev,y}(\theta_{urb} = \text{Obs. TIA}) - \sum_{y-2}^{y+2} TCF_{ev,y}(\theta_{urb} = 0\%)}{\sum_{y-2}^{y+2} TCF_{ev,y}(\theta_{urb} = 0\%)}$$

Results

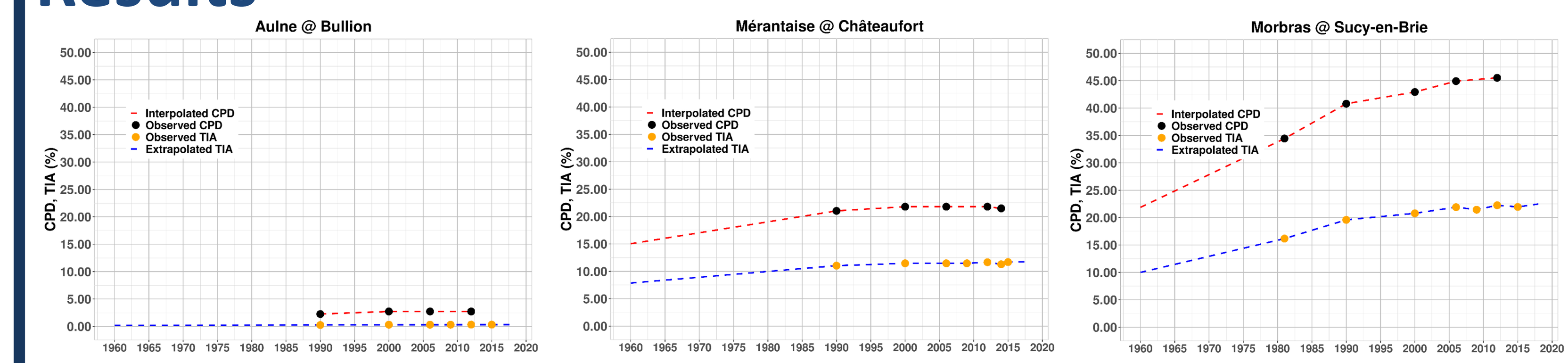

Fig. 7. Evolution of catchment percent developed (CPD) and total impervious area (TIA).

▶ The Aulne illustrates the case of near-nonurbanized situation. The Morbras catchment had a stronger gradient of urbanization, compared to the Mérantaise.

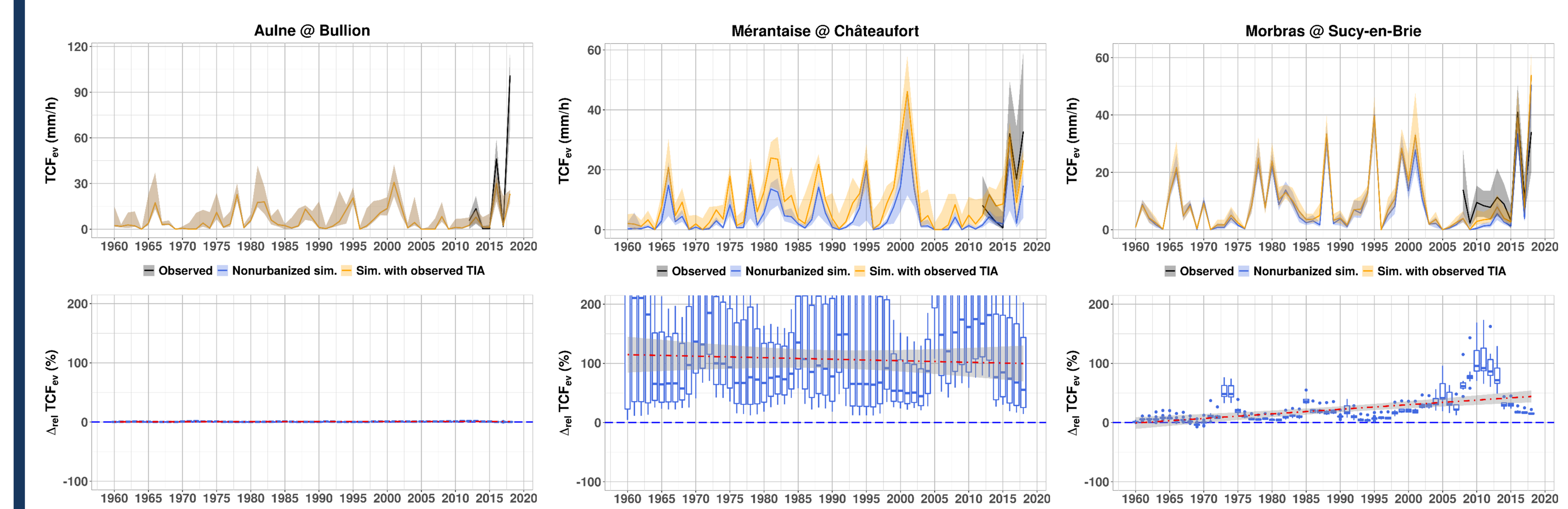

Fig. 8. Yearly evolution of total competent flow TCF_{ev}.

▶ No change on the Aulne catchment. Increased TCF_{ev} for the Mérantaise and Morbras catchments, with two differences: the trend is more significant on the Morbras ($p < 0.001$) compared to the Mérantaise, especially from the 1990s on; but the relative changes are higher on the Mérantaise.

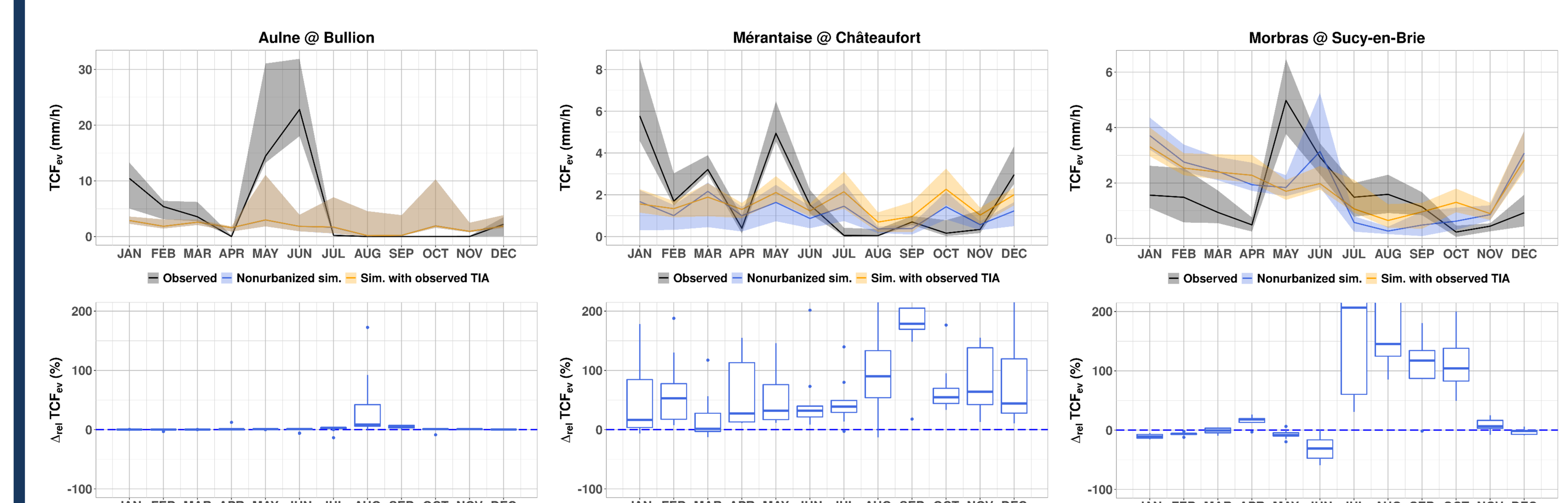

Fig. 9. Monthly evolution of total competent flow TCF_{ev}.

▶ Urbanization effect on TCF_{ev} is stronger during summer and fall, especially for the Morbras.

Conclusion and perspectives

- Using a simple hydrological model (MU5H), we attempted to establish a hydrology-based evidence of the role of urbanization in altering the geomorphology of the Mérantaise and Morbras rivers.
- Urbanization increased TCF_{ev} for the Morbras (up to +100%) and the Mérantaise (up to +300%), in line with the incision and widening magnitudes. Also, a significant trend was detected on the Morbras.
- The effect of urbanization was more important during summer and fall, especially for the Morbras.

➢ How does the effect of urbanization compare to that of climate change?

References Saadi et al. (2021). J. Hydrol. 599, 126394. https://doi.org/10.1016/j.jhydrol.2021.126394 Jugie et al. (2018). J. Hydrol. 563, 418–434. https://doi.org/10.1016/j.jhydrol.2018.06.019 Pfaundler et al. (2011). Méthodes d'analyse et d'appréciation des cours d'eau. Hydrologie – régime d'écoulement niveau R (région). Office fédéral de l'environnement, Berne. L'environnement pratique n° 1107: 113 p.