Pilot Region: the upper Durance catchment. Understanding trends in hydrologic regimes

Antony Bard, Benjamin Renard, M. Lang

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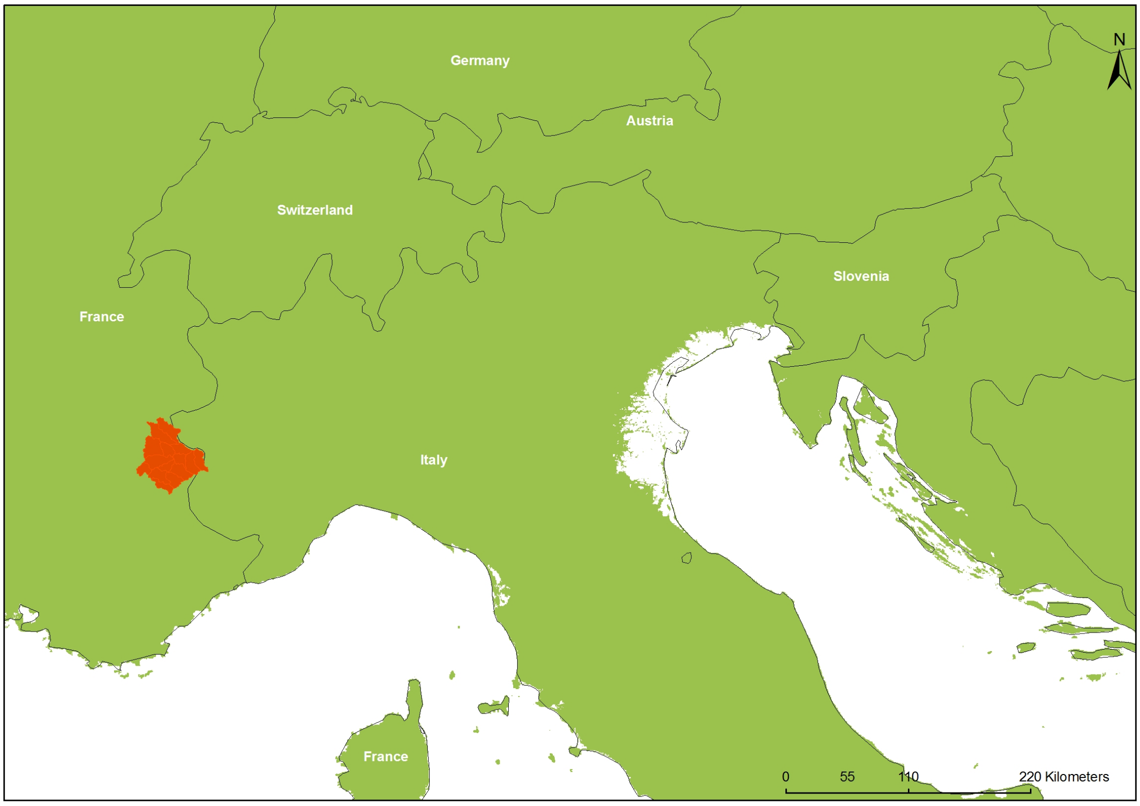
Understanding trends in hydrologic regimes



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Contents

I. Abstract

The work carried out by AdaptAlp partners allowed gathering a hydrologic dataset aimed at detecting climate-related trends in the hydrologic regime of Alpine catchments [see AdaptAlp report, *Bard et al.*, 2011, for more details]. The analysis of the series from this dataset revealed significant trends affecting certain aspects of Alpine hydrologic regimes [e.g. decreasing severity of winter droughts, earliness of snowmelt-related flows, increasing runoff for glacier regimes, see *Bard et al.*, 2011]. The aim of this study was to evaluate whether these trends correspond to the expected response of the catchments to the evolution of climate forcings for a few catchments located in the Upper Durance region. The strategy used to achieve this objective was to simulate the streamflow response to observed climate forcings using the hydrologic model SIM, and to compare the trends detected in observed and simulated streamflow.

Results from this analysis revealed a lack of consistency between trends affecting observed and simulated streamflow, suggesting that non-climatic factors play a role in the evolution of observed streamflow. However, this conclusion should be qualified for at least two reasons: (i) Non-homogeneities in the forcing data may dampen or exacerbate "genuine" trends caused by the evolution of forcings; (ii) Although the standard Nash-Sutcliffe efficiency measure suggests an overall good performance of the hydrologic model, further analyses revealed stronger deficiencies for specific aspects of the hydrologic regimes (e.g. high/low flow).

Although the results of this study are somehow inconclusive, they illustrate the difficulty to disentangle the roles of various possible causes of change in hydrologic series.

II. Introduction

II.1. Trends in hydrologic regimes of the Alps

Climate change is expected to have significant impact in mountain regions, both due to increasing temperatures and changing precipitation patterns [*IPCC*, 2007]. However, detecting its impact based on historical series is a challenging task, which needs to be decomposed into several steps:

(i) **Trend detection**: the objective is to demonstrate that the studied variable has changed (in a statistical sense), without attempting to explain the cause of that change.

(ii) **Trend understanding**: the objective is to assess the plausibility of various causes of the change, and in particular, to assess whether the change can be considered as the response of the catchment to climate forcings. This is particularly important in hydrology, since causes of change in the hydrologic regime are numerous: measurement non-homogeneities, soil use, direct influence (dams, water withdrawal, etc.), climate forcings, etc.

(iii) **Attribution to anthropogenic climate change**: the objective is to demonstrate that the detected change is caused by anthropogenic forcings, and cannot result from the sole natural forcings. According to IPCC, attribution studies are carried out by "*demonstrating that the detected change is consistent with computer model simulations of the climate change 'signal' that is calculated to occur in response to anthropogenic forcing; and demonstrating that the detected change is not consistent with alternative, physically plausible explanations of recent climate change that exclude important anthropogenic forcings*".

The work carried out by AdaptAlp partners allowed gathering a hydrologic dataset aimed at detecting climate-related trends in the hydrologic regime of Alpine catchments [see AdaptAlp report, *Bard et al.*, 2011, for more details]. The analysis of the series from this dataset revealed significant trends affecting certain aspects of Alpine hydrologic regimes [e.g. decreasing severity of winter droughts, earliness of snowmelt-related flows, increasing runoff for glacier regimes, see *Bard et al.*, 2011]. Given that the hydrologic stations in the AdaptAlp dataset control undisturbed catchments and were thoroughly quality-checked, those changes are more likely climate-related than due to measurement issues or direct influences. However, this analysis did not aim at explaining the cause(s) of the changes, but rather focused on point *(i)* above. In particular, it did not establish a formal link between the detected trends and climate change/variability.

II.2. Objective and analysis strategy

The objective of the study described in this report is to evaluate whether the trends detected in observed hydrologic regimes correspond to the expected response of the catchments to the evolution of climate forcings (e.g., temperature, precipitation – see point *(ii)* above) for a few catchments located in the Upper Durance region. To this aim, a hydrologic model is used to simulate streamflow using observed series of forcings. The important point in this analysis is that the hydrologic model is stationary: consequently, any trend detected on the simulated streamflow can only be explained by the evolution of atmospheric forcings.

The analysis is therefore based on the comparison of trends detected in observed and simulated streamflow. Consistency suggests that observed trends originate from the evolution in forcings. Conversely, inconsistent trends suggest that the sole evolution of forcings cannot explain the evolution of observed streamflow.

Note that the analysis carried out in this report does not attempt to explore point *(iii)* above. Performing an attribution study for streamflow variables remains a challenge, especially at the scale of the catchment studied herein, due to the chain of models involved and the scale inconsistencies between the different models.

II.3. Outline of the report

This report is organized as follows. Section III describes the studied catchments and the data used in the analysis. Section IV describes the methodology, including the hydrologic model and the trend detection method. Results are presented in Section V, with concluding remarks in Section VI.

III. Data

III.1. Catchments

The Durance River is a tributary to the Rhône River flowing in South-East France (Figure 1). Its total length is 324 km for a total catchment size of 14 225 km². Its source is located in the Alps at an elevation of about 2 390 m. The upstream Durance is a torrential river (see illustration in Figure 2) with typical snowmelt regime, with high flows in spring/summer and winter low flows. When moving downstream (see illustration in Figure 3), the hydrologic regime becomes more influenced by autumn and winter rainfall.

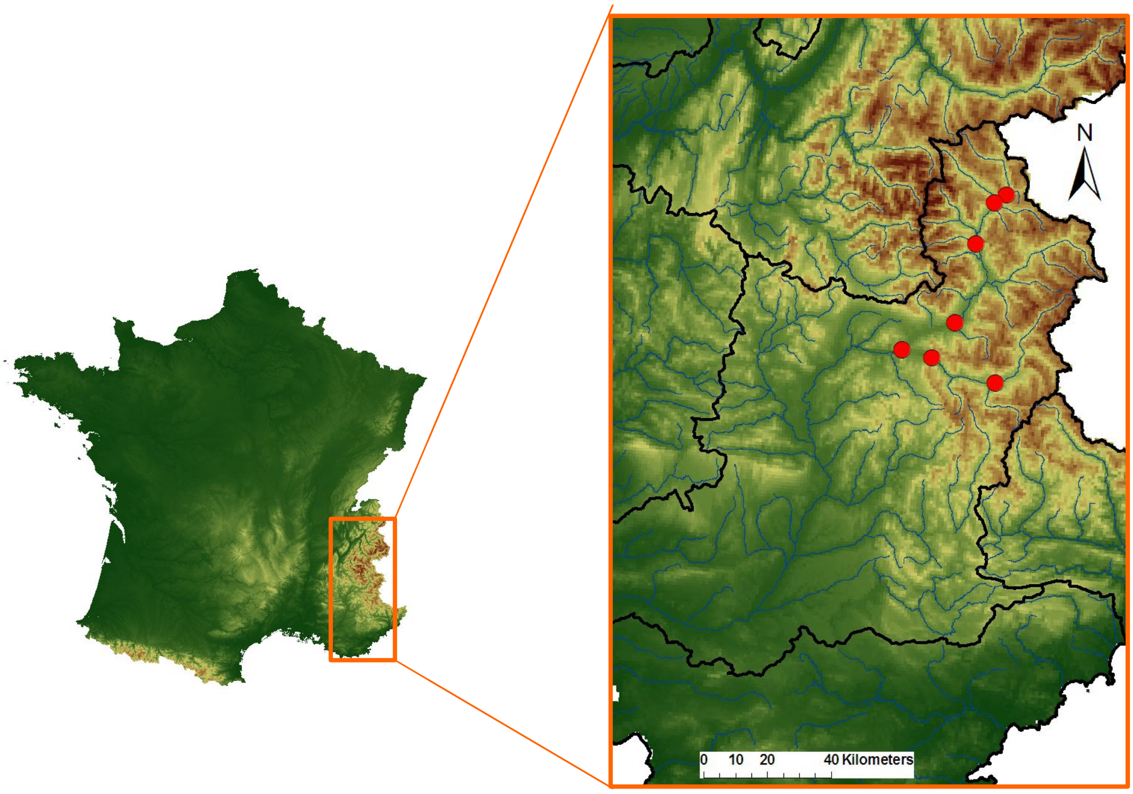

Figure 1. Location of the Durance catchment and hydrologic stations used in this study.

Figure 2. The Durance river near Embrun. Photography by Fr.Latreille.

Figure 3. The Durance river (right) at its confluence with the Rhône River

The durance river is significantly impacted by anthropogenic activities. In particular, the Serre-Ponçon Lake (Figure 4) is a large artificial lake created by a dam at the confluence of the Durance and the Ubaye rivers. Consequently, the Durance River is significantly influenced by the dam operation downstream the lake. This study will therefore focus on the Upper Durance, located upstream the Serre-Ponçon Lake.

Figure 4. The Serre-Ponçon Lake. Photography by Sylvain 05.

III.2. Hydrologic data

III.2.1 Runoff data

Data from seven stations located in the Upper Durance (see Figure 1) are used in this study. Table 1 describes the properties of these stations. Long series of more than 45 years are available, with 1961-2005 as common period of record. Note that the station Durance@Espinasses is located just downstream the Serre-Ponçon Lake. However, data for this station do not correspond to the observed streamflow, but rather to the reconstructed streamflow, i.e. the streamflow that should be observed in the absence of the dam operation.

ID	X_UTM (m)	Y_UTM (m)	River@Station	Catchment Area (km²)	Station elevation (m)	First year of record	Last year of record	Effective length of record (year)
Station 1	316476	4976388	Durance@Val des Prés	210	1351	1951	2008	48
Station 2	312843	4973772	Durance@Briançon	548	1187	1956	2008	47
Station 3	306893	4961030	Durance@Argentière la Bessée	984	950	1911	2008	60
Station 4	300359	4936248	Durance@Embrun	2170	787	1961	2008	45
Station 5	312994	4917222	Ubaye@Barcelonette	549	1132	1905	2008	93
Station 6	293201	4925143	Ubaye@Lauzet	946	790	1961	2008	46
Station 7	283684	4927718	Durance@Espinasses	3580	652	1949	2008	58

Table 1. Properties of hydrologic stations and associated catchments.

III.2.2 Forcing data

Forcing data are extracted from the SAFRAN database (Météo France). This database is based on a reanalysis of atmospheric forcings, combining ground observations and analysis data from a meteorological model. Hourly values interpolated on a 8x8 km grid are available over the period 1958-2008 [see *Vidal et al.*, 2010 for details]. The variables in the dataset are liquid and solid precipitation, air temperature, specific humidity, wind speed, visible and infrared radiations.

IV. Methodology

IV.1. Hydrologic model

This SIM model, developed by Météo France and Mines ParisTech [*Habets et al.*, 2008], is used in this study. SIM stands for Safran-Isba-Modcou, which are the three sub-components of the model:

- SAFRAN is the forcing dataset described in section III.2.2
- ISBA is a land surface model describing water and energy fluxes between the soil and the atmosphere [*Noilhan and Planton*, 1989; *Boone et al.*, 1999].
- MODCOU is a distributed hydrologic model simulating surface runoff and exchanges with groundwater aquifers [*Ledoux et al.*, 1989].

In this study, two modified versions of the SIM model are used. These modifications were proposed and are described by *Lafaysse et al.* [2010; 2011] in order to improve the efficiency of the model in the Alpine region. The simulated streamflow series were directly provided by *Lafaysse* [2010].

IV.2. Hydrologic indices

The trend analysis is based on hydrologic indices extracted from the daily streamflow series and describing winter low flows and spring snowmelt-related high flows (see [*Bard et al.*, 2011] for a more detailed description, and Figure 5 for an illustration):

- Low flow indices:
  - Annual minimum (*Amin*).
  - Annual drought duration (*Dur*), equal to the number of days below a low-flow threshold (taken as the 15%-quantile of the flow duration curve).
  - Annual volume deficit (*Vol*) (with respect to the low-flow threshold).

- Drought start (*start*), defined as the date at which the volume deficit reaches 10% of the annual volume deficit.
- Drought center (*center*), defined similarly with a percentage of 50%.
- Drought end (*end*), defined similarly with a percentage of 90%.

- Snowmelt-related high flows:
    - Annual maximum (*Amax*) of the estimated baseflow. The baseflow is estimated using the base flow separation (BFS) method proposed by *Tallaksen* [2004].
    - Annual volume (*Vol*) of the estimated baseflow.
    - Snowmelt start (*start*), defined as the date at which the baseflow volume reaches 10% of the annual volume.
    - Snowmelt center (*center*), defined similarly with a percentage of 50%.
    - Snowmelt end (*end*), defined similarly with a percentage of 90%.
    - Snowmelt duration (*Dur*), equal to the difference between the variables *end* and *start*.
- Other indices:
    - Annual mean flow (*Amean*)
    - Base flow index (BFI), defined as the ratio between the annual baseflow volume and the annual total volume.

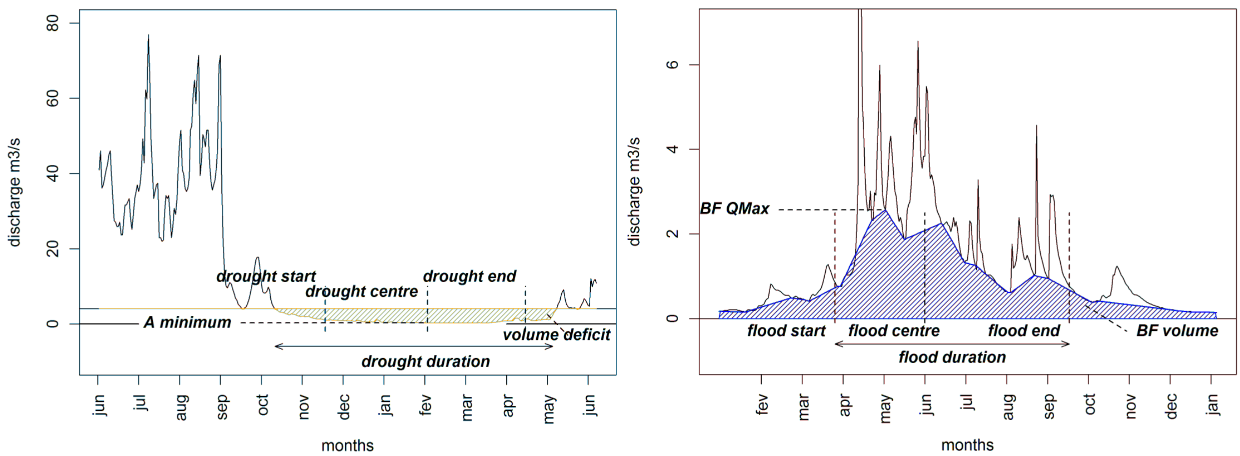

Figure 5. Definition of low and high flow variables.

IV.3. Statistical tests

The trend detection analysis is performed by applying statistical tests to the time series of hydrologic indices defined in previous section IV.1.

The Mann-Kendall trend test [*Mann*, 1945; *Kendall*, 1975] is used for at-site trend detection. This test was selected because it is distribution-free, i.e. it does not require making any distributional assumption. However, this test does assume independent data, which may not be the case for some of the studied indices (especially low-flow indices). Consequently, the "modified" Mann-Kendall test proposed by *Hamed and Rao* [1998] is implemented.

Moreover, in the context of detecting climate-related trends, one would expect that catchments with similar behavior, and located in the same climatic region, should respond in a similar way to an evolution of climate forcings. Consequently, the regional consistency of trends is studied by applying a specific test proposed by *Renard et al.* [2008]. In a nutshell, this test attempts to detect a common trend for a set of stations located in the same hydro-climatic region, but will not detect trends that are not consistent across the region. In this study, all seven hydrologic stations are considered to belong to the same hydro-climatic region.

V. Results

V.1. Streamflow simulations

The first step of the analysis is to evaluate the efficiency of the SIM model to simulate streamflow that are consistent with observations. Figure 6 provides an illustration of the SIM-generated streamflow compared with observations, for a restricted period of one particular station. Overall, the fit seems acceptable, despite some discrepancies during high flow and recession periods. Such discrepancies are commonly observed in hydrologic modeling.

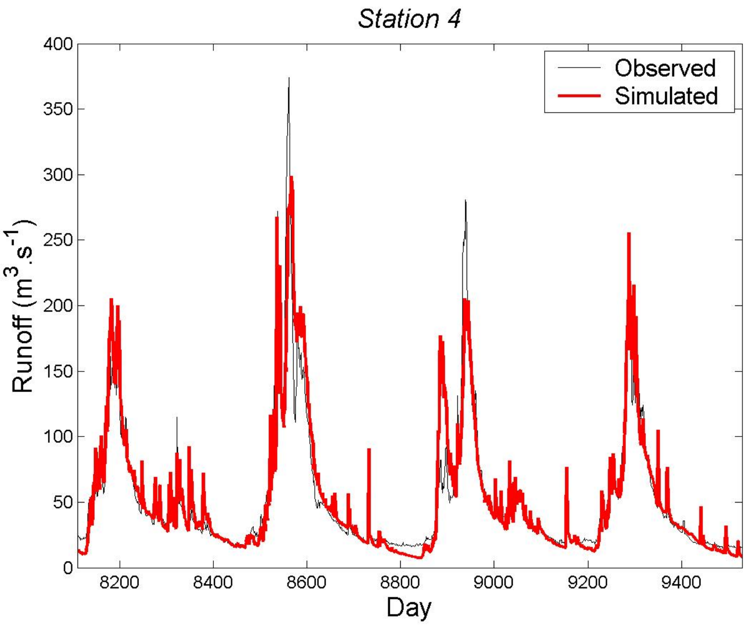

Figure 6. Illustration of SIM-generated runoff vs. observed runoff.

A more systematic evaluation is carried out by computing the Nash-Sutcliffe (NS) efficiency [*Nash and Sutcliffe*, 1970] on all seven series and for the two versions of the SIM model. Results shown in Table 2 suggest an acceptable fit, with NS values around 0.8. Station 1 is a notable exception, with NS values of 0.31-0.37 suggesting that the model has difficulty to reproduce the observations. Moreover, Table 2 also suggests that the second version of the model is more efficient. Consequently, only this second version is used in the remainder of this report.

	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7
Effective length of record (years)	45.8	46.6	39.8	46.4	46.9	46.6	47.0
Nash-Sutcliffe (model 1)	0.31	0.70	0.79	0.82	0.67	0.77	0.82
Nash-Sutcliffe (model 2)	0.37	0.76	0.83	0.86	0.73	0.82	0.86

Table 2. Efficiency of two versions of the SIM model, as measured by the Nash-Sutcliffe index.

V.2. Trend detection

Table 3 shows the results of the at-site trend analysis, for all hydrologic indices and for both simulated (top) and observed (bottom) streamflow. The following observations can be made:

- Several significant trends are detected for regime and high flow variables in observed streamflow. In particular, the high flow trend is a signal detected elsewhere in the Alps, and corresponds to increasing earliness and duration of snowmelt-related flows [e.g. decreasing severity of winter droughts, earliness of snowmelt-related flows, increasing runoff for glacier regimes, see *Bard et al.*, 2011]. However, those trends are not detected on simulated streamflow. This means that, according to the hydrologic model, the sole evolution of forcings cannot explain the trends detected in observed streamflow.
- Regarding low flow variables, several significant trends are detected in both observed and simulated streamflow, but the stations where the trends are detected do not match (with the exception of the downward trend in variable “drought end” for station 2).

Simulated streamflow	Regime		Low Flow						High Flow					
	Amean	BFI	start	center	end	AMin	Vol	Dur	start	center	end	AMax	Vol	Dur
Station 1	1	1	1	-1	-0.05	0.1	-0.1	-0.05	-1	-1	-1	1	1	1
Station 2	-1	1	-1	-1	-0.05	1	-1	-0.1	-1	-1	-1	1	1	-1
Station 3	-1	1	-1	-1	-0.05	1	-1	-1	-1	-1	1	-1	-1	1
Station 4	-1	1	-1	-1	-0.1	1	-1	-1	-1	-1	1	1	-1	1
Station 5	1	1	1	-1	-1	1	-1	-1	-1	-1	1	1	1	1
Station 6	1	1	-1	-1	-0.1	1	-1	-1	-1	-1	1	1	1	0.1
Station 7	-1	1	-1	-1	-1	1	-1	-1	-1	-1	1	-1	1	1

Observed streamflow	Regime		Low Flow						High Flow					
	Amean	BFI	start	center	end	AMin	Vol	Dur	start	center	end	AMax	Vol	Dur
Station 1	-0.01	1	-0.1	-1	-1	-1	1	1	-0.1	-0.1	1	-1	-0.1	0.1
Station 2	-0.01	1	-1	-0.05	-0.1	-1	1	1	-0.01	-1	0.1	-1	-0.1	0.01
Station 3	-1	1	-1	-1	-1	-1	-1	-1	-1	-1	1	-1	-1	1
Station 4	-1	1	-1	-1	-1	-1	-1	-1	-1	-1	1	-1	-1	0.1
Station 5	-1	1	-1	-1	-1	0.1	-1	-1	-1	-1	1	1	-1	1
Station 6	1	1	1	1	-1	1	-1	-1	-1	1	0.1	-1	1	0.05
Station 7	-1	0.1	1	1	-1	1	-1	-1	-1	-1	0.1	1	1	0.05

Table 3. Comparison of trends detected for simulated (top) and observed (bottom) streamflow, on the period 1961-2005. Colored cells represent significant trends at 10% error level (blue = upward, red = downward). The numbers give the significativity: -1=non-significant downward trend; -*p*=significant downward trend with error level *p*; 1=non-significant upward trend; *p* = significant upward trend with error level *p*.

Table 4 shows the results of the regional test and confirms the preceding observations: regionally consistent trends are detected on observed streamflow for regime and high flow variables, but are not detected on simulated streamflow. Conversely, a downward trend is detected on simulated streamflow for the variable "drought end", but this trend is not significant for observed streamflow.

	Regime		Low Flow						High Flow					
	Amean	BFI	start	center	end	AMin	Vol	Dur	start	center	end	AMax	Vol	Dur
Simulated	1	1	-1	-1	-0.1	1	-1	-1	-1	-1	1	1	1	1
Observed	-0.1	1	-1	-1	-1	-1	1	1	-0.05	-1	1	-1	-0.1	0.05

Table 4. Comparison of regional trends detected for simulated and observed streamflow, on the period 1961-2005. Legend is identical to Table 3.

V.3. Discussion

Overall, the results of at-site and regional trend analyses show a lack of consistency between the trends affecting observed and simulated streamflow. Several interpretations are possible:

(i) This lack of consistency may suggest that the observed streamflow does not solely result from the stationary transformation of forcing climatic variables by the catchment. Indeed, it is not impossible that non-climatic factors, ignored by the hydrologic model, impact on observed streamflow. Such factors may be measurement non-homogeneities, soil use change, direct anthropogenic influences, etc. Although data are related to undisturbed catchments and were thoroughly quality-checked, it is unfortunately not possible to definitely exclude the existence of such non-climatic factors.

(ii) Forcing data from the SAFRAN database (see section III.2.2) may not be homogenous. Indeed, this database makes use of ground observations series, which are not homogenized and whose availability varies in time. This may result in a lack of homogeneity in the input variables used by the hydrologic model. In turn, this lack of homogeneity may dampen or exacerbate "genuine" trends caused by the evolution of climate forcings.

(iii) Lastly, the ability of the hydrologic model to reproduce the transformation of forcings into streamflow may not be as good as the Nash-Sutcliffe efficiency suggests.

The latter point can be illustrated by considering Figure 7, which attempts to evaluate the efficiency of the hydrologic model using other diagnostics than the Nash-Sutcliffe measure. This figure shows that although the model accurately and precisely reproduces the annual mean flow, stronger discrepancies are observed for other hydrologic indices. This is problematic since the trend analysis is based on those poorly-reproduced indices.

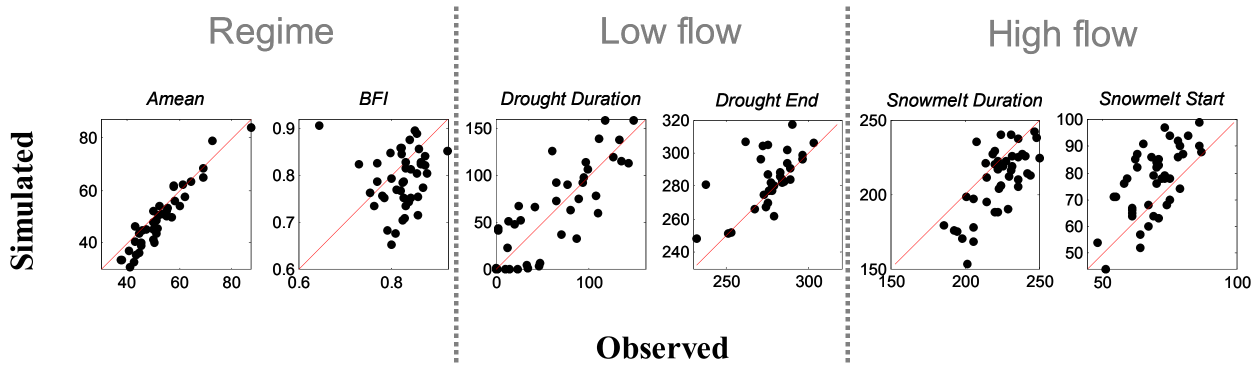

Figure 7. Comparison of selected hydrologic indices computed for observed and simulated streamflow.

VI. Conclusions

The aim of this study was to evaluate whether the trends detected in observed hydrologic regimes correspond to the expected response of the catchments to the evolution of climate forcings. This was achieved by using a hydrologic model to simulate the streamflow response to observed climate forcings, and comparing the trends detected in observed and simulated streamflow.

Unfortunately, the results are somehow inconclusive: the lack of consistency between trends affecting observed and simulated streamflow suggests that non-climatic factors play a role in the evolution of observed streamflow, but possible biases due to non-homogeneities of the forcing data and/or lack of efficiency of the hydrologic model cannot be excluded.

These results illustrate the difficulty to disentangle the roles of various possible causes of change in hydrologic series. Further insights could be gained by using alternative datasets for observed forcings, or alternative hydrologic models. This might shed light on the relative role of data non-homogeneities and model inadequacies.

VII. Acknowledgment

We wish to thank Matthieu Lafaysse for providing the simulated streamflow series. Data owners (Electricité de France and the French Ministry Minister of Ecology, Sustainable Development, Transport and Housing through the HYDRO database) are gratefully acknowledged for providing us with the data and discussing their quality.

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