Over 100 years of climatic and hydrologic variability of a Mediterranean and mountainous watershed: the Durance River

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Abstract This paper presents a methodology to build long climatic and hydrologic time-series, based on the downscaling of large-scale climatic data and local observations. This method has been applied on the Durance watershed, on which long historical daily streamflow series have been recently brought to light. These long series allow a validation of the reconstruction method, which show very promising performances on both calibration and validation periods. Finally, 22 1900–2010 streamflow series have been built and used to illustrate the hydrological variability on the Durance watershed over the last century.

Key words hydrological variability; historical time-series; streamflow reconstruction; analogues method; Alps

INTRODUCTION

Improving the understanding of mountain watersheds hydrological variability is a great scientific issue, for both researchers and water resources managers. This paper presents a methodology to build long climatic (air temperature and precipitation) and hydrologic time-series, based on large-scale climatic data and local observations. This methodology has just been applied to the case study of the Durance watershed (14 000 km^2), situated in the French Alps, which is characterized by a variety of hydrological processes (from snowy to Mediterranean regimes) and a wide range of anthropogenic influences (hydropower, irrigation, industries, drinking water, etc.).

A sample of long historical series of daily streamflows beginning in the early 20th century, which have recently been found, is also presented. Then, these series allow us: (1) to validate our reconstruction methodology of hydrometeorological time-series, and (2) to better understand the temporal and spatial hydrological variability of the Durance River over the last century.

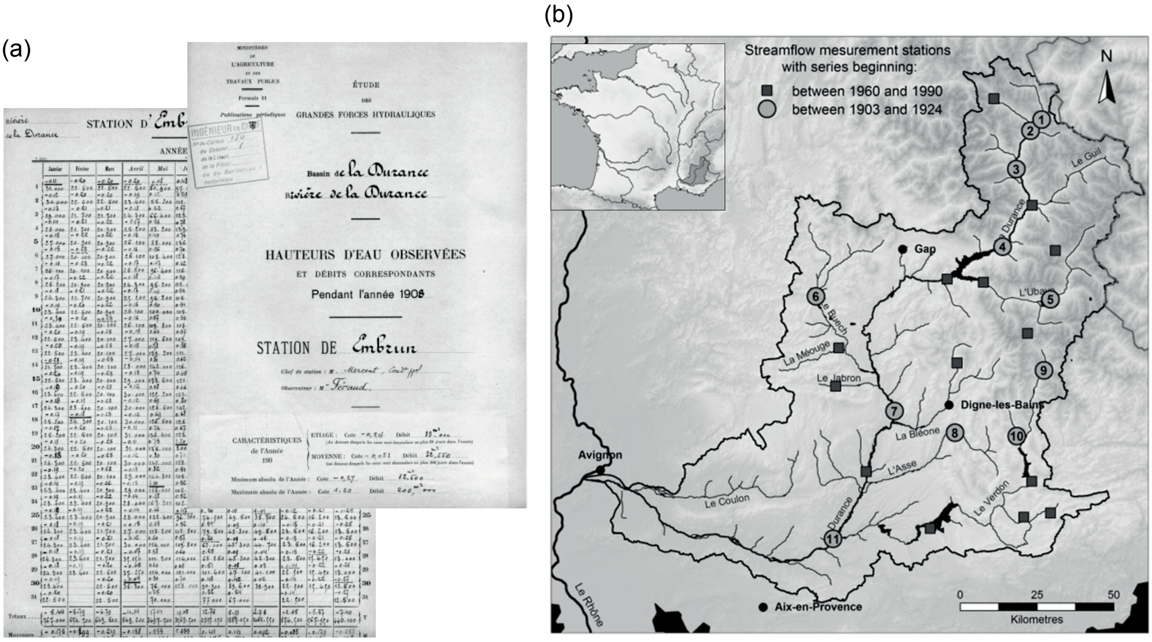

Fig. 1 (a) Historical data sample and (b) map of the long streamflow series collected for the Durance watershed.

Table 1 Characteristics of the long streamflow series collected for the Durance watershed.

No.	River	Station	Area (Km²)	Alt. (m)	Start	End	Length (years)
1	Durance	Val-des-Près - La Vachette	210	1352	1917	2011	95
2	Durance	Briançon	548	1187	1904	2011	108
3*	Durance	L'Argentière-La-Bessée	984	950	1910	2011	102
4	Durance	Embrun – La Clapière	2170	787	1904	2011	108
5	Ubaye	Barcelonnette	549	1132	1904	2011	108
6	Buech	Serres – Les Chambons	771	657	1906	2011	106
7*	Durance	Oraison l'Escale	6760	415	1924	2011	88
8	Asse	Clue de Chabrieres	375	605	1908	2011	104
9	Verdon	Colmars	158	1230	1903	2011	109
10	Issole	Saint-Andre-Les-Alpes – Mourefrey	137	931	1904	2011	108
11*	Durance	Pont de Mirabeau / Jouques-Cadarache	11700	247	1918	2011	94

*Stations whose number is marked with a star will not be used in the following study.

Long time-series of daily streamflows on the durance watershed

In order to improve knowledge on the hydrological variability of the Durance River watershed, the first source of information explored would be streamflow measurements over time. With the aim of extending our database of historical daily streamflow series, a search in various sources of hydrological archives was carried out in association with an historian. This work allowed the discovery of several 100-year-old daily streamflow series, kept in the form of hand-written annual tables, as shown in Fig. 1(a). If some of these series were still available and used in a digital form, most of them could be considered as "new" data. These new series have been digitized and 11 historical series beginning between 1904 and 1924 are now available on the Durance watershed. These series are presented in Table 1 and localized in Fig. 1(b). On the same figure another set of 14 streamflow stations beginning between 1960 and 1990 are also shown.

In parallel with the search for data itself, information on the methods used to construct these series have been looked for (such as instrumentation, gauging, rating curves, etc.). This type of information is useful to assess data quality and homogeneity over time (Kuentz *et al.*, 2012).

RECONSTRUCTION OF STREAMFLOW SERIES: THE ANATEM METHOD

Three steps to obtain daily streamflow series

As streamflow is an integrator of a wide range of global and local hydrometeorological processes and variables, such as precipitation, air temperature, watershed configuration or river layout, it is difficult to make a direct reconstruction of this variable. Climatic variables such as precipitation and air temperature have more regional patterns and are generally easier to model.

The streamflow reconstruction method presented here is hence composed of three steps: (1) reconstruction of climatic variable time-series, by the method detailed below, (2) rainfall–runoff calibration on a common period of streamflow and climatic data availability, (3) reconstruction of streamflow series using reconstructed climatic series as inputs for hydrological models.

Reconstruction of climatic series: a combination of two classical methods

Usually, reconstructions of climatic variables are based on the use of observed (control) series. A reconstruction model is built with calibration on a common period of available data on the target series. Generally, the models used are multiple linear models between variables (for precipitation series), or monthly ranges between inter-annual regimes (for air temperature series).

The analogues method (Obled *et al.*, 2002) is traditionally used to produce climatic series for weather forecasts or for climate projections downscaling (Bourqui *et al.*, 2011). This method is based on a classical hypothesis of meteorology saying that similar atmospheric pressure fields generate similar local climatic variables. Starting from this hypothesis, the method builds a climatic series on a period A by using observed data available at the same point on a period B. It uses geopotential fields data that must be available daily during both periods A and B. For each day of the period A, called target day, similar days in terms of geopotential fields, called analogue days, are found in period B. The observed data of theses analogue days are directly used as the target day value. In order to take into account the uncertainty of this reconstruction, an ensemble of analogue days is selected for each target day (50 in our case).

To build a climatic series on period A, the ANATEM method combines these two methods: the linear model based on a local control series and the analogues ensembles. As a simplification it could be said that the model is the control series model corrected and dressed by the uncertainty of analogues ensembles. The error made by the control series model on each analogue day is then transferred to the target day.

A simplified formulation of the ANATEM model is given by formula (1) for air temperature and formula (2) for precipitation. Note that formula (2) is only a theoretical formula, since it does not exclude the possibility of dividing by zero. In our application, some numerical treatments are made to avoid this problem.

$$\left[\hat{T}_d^k\right]_{k=1\ldots n} = CS_d + \left[T_{ANA_d^k} - CS_{ANA_d^k}\right]_{k=1\ldots n} \tag{1}$$

$$\left[\hat{\mathrm{P}}_{\mathrm{d}}^{\mathrm{k}}\right]_{\mathrm{k}=1..\mathrm{n}} = \mathrm{CS}_{\mathrm{d}} \cdot \left[\frac{\mathrm{P}_{\mathrm{ANA_d^k}}}{\mathrm{CS}_{\mathrm{ANA_d^k}}}\right]_{\mathrm{k}=1..\mathrm{n}} \tag{2}$$

where d is the considered day, k is the rank of the analogue day, n is the number of searched analogue days (50 in our application), $\hat{T}$ and $\hat{P}$ are the estimated values, T_{ANA} and P_{ANA} are the air temperature and precipitation values of the analogue days, CS is the value of the control series, and CS_{ANA} are the control series values for the analogue days.

The control series can be local or regional series, or other variables such as, for air temperature reconstruction, the thickness of the atmosphere layer between the 700 and 1000 hPa geopotentials.

STREAMFLOW RECONSTRUCTION ASSESSMENT ON THE DURANCE

Data and model

For this application, various types of data are needed. Climatic series are the 1 km × 1 km precipitation and air temperature extracted from the climatic reanalysis by Gottardi (2012), on the 1948–2010 observation period (B). Climatic series used for simulations at a given streamflow station are the mean daily areal precipitation and air temperatures over the watersheds.

As presented in the first part, historical daily streamflow data are available on both observation and reconstruction periods for eight stations. To improve our analyses, another sample of 14 stations with streamflow series starting between 1960 and 1990 has also been used.

Geopotential fields are taken from the 20th Century Reanalysis by the NOAA (Compo *et al.*, 2011): an archive of 700 and 1000 hPa geopotential fields is available from 1871 to 2010. As control series, two long climatic series have been used: a daily observed precipitation series at Gap, available from 1883 to the present, and a daily series of atmosphere thickness between the 700 and 1000 hPa geopotentials, extracted from the 20CR NOAA re-analysis (Compo *et al.*, 2011).

The ANATEM method is then used to reconstruct precipitation and air temperature on the 1 January 1899 to 31 December 2010 period. fifty continuous climatic time series are randomly generated from the 50 analogue ensembles, available every day.

The streamflow reconstruction is made by a conceptual rainfall–runoff model (MORDOR model developed at Électricité De France by Garçon (1996) and applied worldwide), forced by precipitation and air temperature reconstruction. On a sample of 22 watersheds, rainfall–runoff models were calibrated on the 1980–1994 period, using the Kling-Gupta Efficiency (KGE, Gupta *et al*., 2009) criterion (equation (3)) as the objective function.

$$KGE = \sqrt{(1-R)^2 + (1-\alpha)^2 + (1-\beta)^2} \tag{3}$$

where R is the coefficient of correlation, α is the bias of variance and β is the bias of mean.

Rainfall–runoff model performances on the calibration period are rather satisfactory with a mean KGE of 0.86 (mean Nash-Sutcliffe Efficiency of 0.78) at a daily time-step.

One simulation example: the Barcelonnette station on the Ubaye River

In order to give an illustration of the simulation results, the complete process previously described have been applied to the Barcelonnette station on the Ubaye River. For this station, the historical streamflow record began in 1904 and the data availability is very good, since only 3 years are completely missing.

As detailed before, the first part of the simulation process is to simulate climatic series, which will then be used as input for the hydrological model to produce streamflow series. The annual aggregations of the daily series obtained by these steps are shown in Fig. 2. As the ANATEM method produce ensembles, for each simulated hydrometeorological variable (air temperature, precipitation and streamflow), 50 simulated series are available and plotted on the figure.

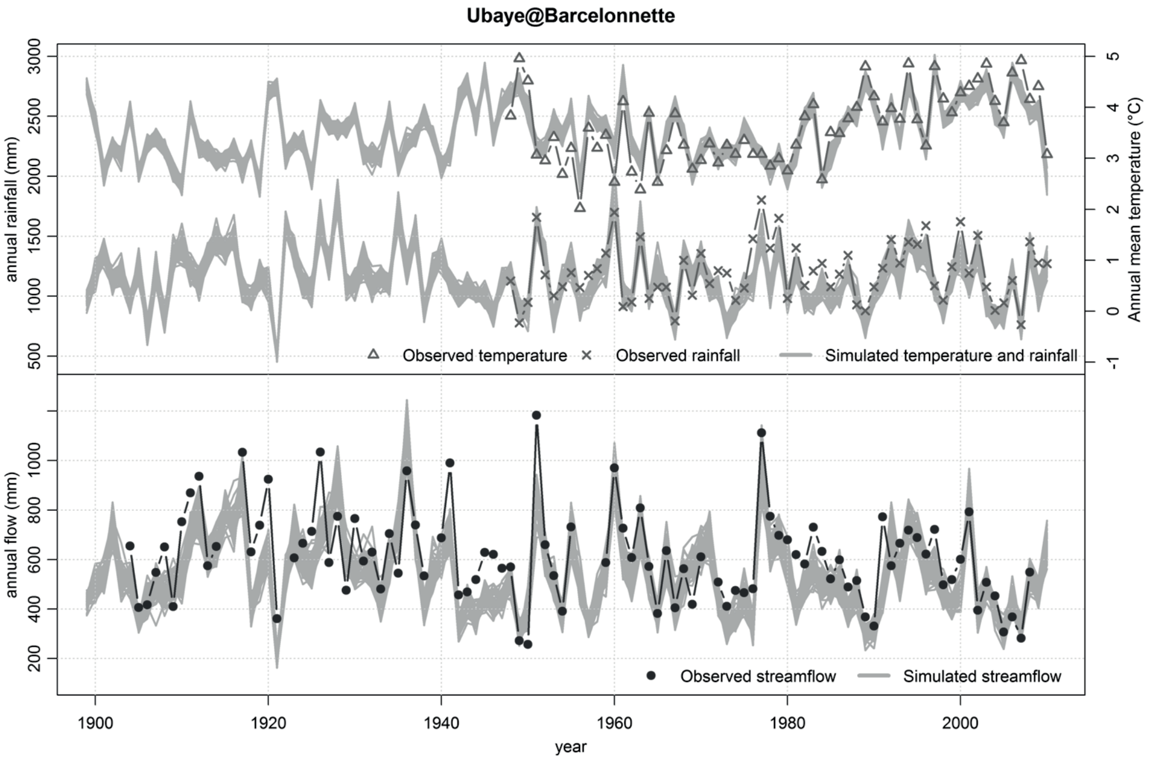

Fig. 2 Climatic and hydrologic simulated and observed annual series for the Barcelonnette station on the Ubaye River.

Figure 2 shows a good reconstruction for the two climatic variables. The interannual variability is well represented, as well as historical dry, wet, cold or warm years. Since air temperature has a lower spatio-temporal variability than precipitation, the spread of reconstructed series is narrower and appears to be more reliable for the air temperature than for the precipitation.

Streamflow simulations, only based on climatic reconstructions, are also quite good, with a good reconstruction of historical low-flow (1921, end of 1940s) or high-flow periods (mid 1910s, 1935–1936). Simulations appear to be better during the last period (1948–2010), where climatic reconstructions are probably better, and streamflow series is known to be more homogeneous.

Simulation performance

The simulation process has been applied to our sample of 22 streamflow stations. The evaluation of reconstructed series has been done in a deterministic mode, based only on the mean daily reconstructed series. Then, these reconstructed series are compared to observed ones, for which the availability period depends on each station. The simulation performance is evaluated in terms of correlation, bias, KGE and NSE (Table 2) for daily, monthly and annual time-steps.

On the A (historical) and B (observation) periods, Table 2 shows rather good performances in terms of correlation and KGE, i.e. a good representation of the variability at different time-steps. However, NSE values are poor to moderate due to a strong mean and variance bias, even worse during the A period.

As an example, the Barcelonnette station on the Ubaye River shows good performances with correlation coefficients (resp. NSE) ranging from 0.77 to 0.90 (resp. 0.42 to 0.80) on the A+B period. However, other stations, e.g. the Clue de Chabrières station on the Asse River, show lower performances with correlation coefficients (resp. NSE) ranging from 0.64 to 0.76 (resp. –0.30 to 0.40) on the A+B period. In this case, this could be explained by the relative lower quality of the streamflow measurements at this very unstable station, and by a more rainfall-influenced hydrological regime.

These results show a strong mean and variance bias, which are not due to biases on the climatic reconstructions, but due to rainfall–runoff model transposition on a very large time period. Sensitivity analyses to the rainfall–runoff model calibration time period have shown that the reconstructed streamflow series are rather sensitive to the selected periods (as shown by Coron *et al*., 2012). In fact, the correlation coefficients are rather stable, but the simulated water balance could be significantly biased. This difficulty with respect to the long-term water balance of reconstructed streamflow series on a 100 years range is a major issue and has to be put into perspective with climate impact studies, usually using rainfall–runoff models also calibrated on short time periods.

In conclusion, Table 2 shows promising results for the reconstruction method at different time-steps. This performance on a daily to monthly time-step shows that the reconstruction method is able to provide hydrological time-series useful for a wide range of management and water resources applications.

Table 2 Performance criteria of streamflow simulations at three time-steps: mean values and standard deviations on a sample of 8 and 22 stations.

Period	A Period: 1900–1947 (8 stations)			B Period: 1948–2010 (22 stations)		
Time-step	Daily	Monthly	Annual	Daily	Monthly	Annual
R	0.78 (± 0.10)	0.85 (± 0.07)	0.66 (± 0.12)	0.78 (± 0.09)	0.86 (± 0.06)	0.78 (± 0.15)
α	0.80 (± 0.15)	0.82 (± 0.12)	0.88 (± 0.18)	0.78 (± 0.11)	0.81 (± 0.11)	0.88 (± 0.13)
β	0.82 (± 0.12)	0.82 (± 0.12)	0.83 (± 0.12)	0.90 (± 0.18)	0.90 (± 0.18)	0.90 (± 0.18)
KGE	0.64 (± 0.18)	0.70 (± 0.16)	0.56 (± 0.15)	0.63 (± 0.15)	0.69 (± 0.14)	0.66 (± 0.16)
NSE	0.58 (± 0.16)	0.66 (± 0.17)	-0.22 (± 0.78)	0.59 (± 0.15)	0.69 (± 0.13)	0.19 (± 0.66)

R, coefficient of correlation; α, bias of variance; β bias of mean; KGE, Kling-Gupta Eff., NSE, Nash-Sutcliffe Eff.

HYDROLOGICAL VARIABILITY OVER 100 YEARS

The previous sections allowed presentation and evaluation of a new method to reconstruct streamflow series on long historical periods. Finally, 22 long streamflow series have been built on the 1900 to 2010 period using this method. In Fig. 4 the annual streamflow anomaly of these series (ratio between annual streamflow and interannual mean streamflow) is presented. This figure shows a rather pronounced consistency of the hydrological variability within the Durance watershed during the last century, despite the wide range of snowy- to rainfall-influenced regimes. The interannual variability on the Durance watershed is quite important, with annual streamflow varying from almost 50% to 300% of their mean value. Some well-known extreme events, e.g. the 1921 and late 1940s droughts, or the 1935–1936 floods, clearly appear.

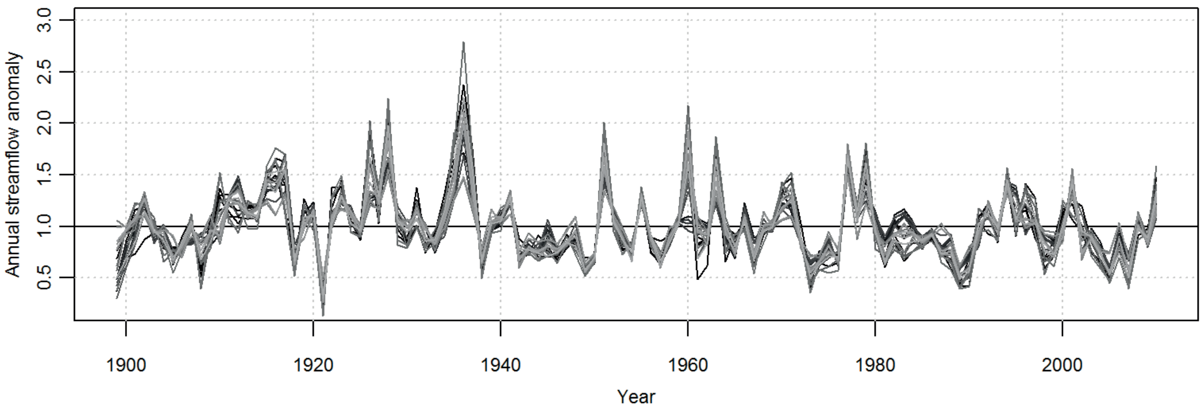

Fig. 4 Annual simulated streamflow anomaly (annual streamflow divided by the mean interannual streamflow) on 22 stations in the Durance watershed.

CONCLUSIONS

This paper presents a simple but efficient method (ANATEM) to reconstruct climatic and hydrologic time-series over the last 100 years. This method is based on an analogue search in geopotential fields, a modern climatic archive, long-term regional observations and a rainfall–runoff model. The ANATEM method has been applied to reconstruct streamflow series of 22 watersheds within the Durance watershed during the 1900–2010 period.

Recent research in historical hydrological archives allowed us to unearth long streamflow time-series (from the beginning of the 20th century) that allowed us to validate the ANATEM method. The mean correlation coefficient between observed and reconstructed time-series was rather high (from 0.6 to 0.9 for different aggregation time periods). However, streamflow reconstructions are significantly biased, due to rainfall–runoff model transposition difficulties over such a long period.

Finally, the 22 1900–2010 reconstructed streamflow series allowed characterisation of the Durance watershed's hydrological variability over the last century. These streamflow series highlight the high temporal variability of hydrometeorological processes on a long term basis, that should be taken into account in future management and water resources applications.

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