Antony, 21 April 2016

Dr Ralf Merz
c/o Editorial Office
Journal of Hydrology

__Revised version of paper__

Dear Dr Merz,

Please find attached the revised version of the paper entitled “Climate elasticity of streamflow revisited – an elasticity index based on long-term hydrometeorological records”.

We would like to apologize for the time needed to produce this revised version after we submitted our answer to the reviewers’ comments. Although the comments were very positive, there was one comment which did require running additional tests, and we must say that we had a hard time… finding the time

We submit below the answers to the questions raised by the reviewers and the action taken by us, as well as a revised version. With these changes and the additions made on request of reviewers, we believe that the paper is now much clearer and ready for publication in HESS.

Looking forward to hearing from you, I remain

Yours sincerely

Vazken Andréassian

Irstea
1, rue Pierre-Gilles de Gennes
CS 100 30
92761 Antony cedex
FRANCE
Tél.: (33) 1.40.96.62.58

vazken.andreassian@irstea.fr

ANSWER TO REVIEWERS (in blue) AND ACTIONS TAKEN IN THE FINAL VERSION (in red)

- **REVIEW BY ALBERTO VIGLIONE**

We thank Alberto Viglione (AV) for his detailed review and relevant comments, which we will take into account in the revised version of the paper. We give here a rapid answer to the points raised:

a. Concerning the use of the Turc-Mezentsev (T-M) formula:

AV underlines that because the T-M formula does explicitly include the effect of both P and PE, the result that we find (bivariate regression better than monovariate) is obvious. Let us clarify what was our aim with this exercise:

1. First of all we wanted an objective way to define how empirical elasticity should be computed;
2. But since there is no absolute reference, we needed a relative reference which would at the same time “behave as a real catchment” and allow for an explicit computation of elasticity. This is why we chose the T-M formula. Let’s also add that it is the most widely used formula in elasticity-related literature, so that it seemed natural to use it;
3. The fact that the T-M formula imposes a distinct and well-defined elasticity for Q vs PE and Q vs P reflects the “hydrological good sense”. Thus, even if our synthetic experiment had an expected outcome, it does however provide a way to quantify what we gain by using the bivariate approach

As a partial conclusion, we do argue that indeed, using the T-M formula as the theoretical reference is a ‘strong’ assumption which explains that a bivariate solution to elasticity is better that a monovariate one. However, beyond reflecting the “hydrological good sense”, it also reflects the visual impression from the graphs that we present in supplement. Moreover, we believe that the T-M formula’s assumptions are likely to be shared by most hydrologists, and that the T-M formula is both extremely simple and widely-used, which should turn our demonstration acceptable to many of our readers.

b. Concerning the advantage of using GLS regression:

As you mentioned it, GLS is needed in theory because the M-years anomalies are calculated with moving windows, which results in the strong correlation between the points. Our test with the synthetic data shows that it is indeed the best solution (but there is no revolution when comparing with OLS).

c. Concerning the claim that the empirical elasticity framework is “model free”:

We do agree that this is not entirely true, because a linear model… is a model. By “model free”, we wanted to underline the distinction which exists with most of the elasticity literature which deals with simulated data (i.e. before this linear model step, there is a full hydrological model). We will precise it in the revised version.

The sentence on the “model-free” nature of our approach now reads:
“the empirical elasticity assessment advocated in this paper can provide an estimate of the impact of climate change on hydrology that is almost model-free (except for the assumption of linearity, of course) and allows ‘digging’ into past observations to predict the impact of future changes.”

Detailed comments:

- Page 3646, line 24: “indicates the difference or change” from what? I guess from the long term mean value (p.s., the Authors define the for their analyses at page 3652).

Changed to:
“the operator Δ indicates the difference between the dated and the average value”

- Page 3652, line 17: there is a typo in “to compute the relative rather than the relative elasticity”.

Done:
“to compute the absolute rather than the relative elasticity”.

- Pages 3653-3654, Section 3.3.2: I would suggest to add literature references for the bootstrap significance test for GLS.

We added the following reference:
Efron, B. and R.J .Tibshirani. 1994. An introduction to the bootstrap. CRC press.

- Page 3657, Section 4.2: it is unclear how the Turc-Mezentsev formula has been fitted to the data. Has the parameter n been calibrated? If so how? And what values have been obtained for n (how different from 2.5)?

We mention in section 3.2 that we use a fixed reference value for *n* : “Here, we followed Le Moine et al. [2007] and used a fixed value n=2.5.”

- Page 3657, lines 10-12: actually I cannot see, in Figure 8, a link between the two elasticities even for the elasticity to precipitation. What I see is that the Turc-Mezentsev formula implies bounds at -1 and +1 for the elasticities.

We changed the sentence, which now reads: « we can see that the link between the two measurements on a catchment-by-catchment basis is extremely weak for precipitation and even more for potential evaporation. »

- Caption of Table 5. “Univariate” should be bivariate.

Done

- Figure 6: it would be better to use consistent scales for (a)-(b) and for (c)-(d).

Done.

- **Anonymous Reviewer #2**

We thank Reviewer 2 (hereafter R2) for his detailed review and relevant comments, which we will take into account in the revised version of the paper. We give here a rapid answer to the points raised:

1 log-likelihood for the GLS model

We will take R2’s recommendation and move the description to the Appendix.
The description was transferred to the Appendix (it is now appendix 1).

2 preference of GLS over OLS :

As R2 noticed, we did assume that if residual auto-correlation violates the assumption of iid variables, it could affect the precision of the estimate. Obviously, in our results, the difference between GLS and OLS results is very small (see Figure 7, b and d). We will comment further this point in the revised version.

3 possible use of the Fu formula to complement the observations of the Turc-Mezentsev formula

We did not have an occasion to look in detail at the Fu formula, which does look extremely similar to the Turc-Mezentsev formula, and does respect the same boundary conditions, while not being analytically identical. We plotted both formulas and their own partial derivatives in the Q/P vs P/E0 nondimensional space (see attached file) and we could verify that both formulas are numerically equivalent provided we use the following relationship between Fu’s parameter m_Fu and Turc-Mezentsev parameter n_TM:

m_Fu = ln(2)/ln(2-2^(-1/n_TM))

We have not been yet able to identify the reason for this surprising result from the description given by Zhang et al. (2004). The maths seem perfectly fine. We noticed that Fu (1981) cites Mezentsev, and we wonder whether he did notice that the expression he reached was numerically equivalent to that of Mezentsev (unfortunately, none of us can read Chinese)?

4 While I find the overview of the figures provided in the appendix very insightful, I would welcome if some of the results of the individual catchments could be presented in a tabular format. As a minimum output I could imagine information on: catchment name; coordinates; elevation; elasticity and longterm mean annual P, Q, Epot.

We will add the information to the supplement
The list of catchments was added as appendix

References

Fu, B. (1981), On the calculation of the evaporation from land surface, Atmospherica Sinica, 5, 23-31.
Zhang, L.; Hickel, K.; Dawes, W. R.; Chiew, F. H. S.; Western, A. W. & Briggs, P. R. A rational function approach for estimating mean annual evapotranspiration. Water Resources Research, 2004, 40, W02502.

As far as the remark on why we check the normality of the residuals (while assessing the significance of the parameters using a bootstrap approach), we believe that it is fundamental that any statistical model based on a given set of assumptions be verified against those assumptions first. The core assumption of our model is that the residuals from the regression model follow a normal distribution. This is why we are testing it. We believe that any compromise on this point could jeopardize our method. Hydrologists often neglect to check fundamental statistical assumptions although it is extremely simple to do, which leads to unexpected and inconsistent results. The reviewer is right in pointing out the connection between the normality assumption and the significance of the model parameters. We chose a bootstrap method to estimate this significance because certain models we tested failed the normality tests. In this case, we could not apply the standard approach and had to rely on the bootstrap to give valid results.

MINOR COMMENTS: p. 3654, l. 20f: “Note for the”: It would be more consistent to place this in section 3.3.2 Table 4,5: please provide a “full name” for sigma, not just SD (I assume this standard deviation) Table 5, caption: Change from “Univariate” to “Bivariate”
Done

- **Francis Chiew**

We thank Francis Chiew (FC) for his detailed review and relevant comments, which we will take into account in the revised version of the paper. We give here a rapid answer to the main comments:

1. We agree that it is natural to have much larger variations in the real world than in the model world, and we are not overly surprised by the lack of clear correlation between the empirical and the model elasticity (see Fig. 8).
2. We agree that introducing seasonality to the too simple water balance formula is a good idea, it could perhaps improve the link between theoretical and empirical elasticity.
3. We agree that OLS and GLS are neither strictly empirical nor distribution-free. But these are probably the simplest models available to describe the elasticity of streamflow, at least much simpler than the available alternatives. And in comparison with the methods of Fu et al. (2007) - which we will discuss in the revised version of the paper - there are no numerical instabilities at the origin.

We introduce the reference to the work of Fu et al (2007) in section 1.2 as follows: "Fu et al (2007) mentioned this issue and proposed to transform the "single parameter precipitation elasticity of streamflow index" into a "two parameter climate elasticity index" which would be function of both precipitation and temperature, in order to account for both effects simultaneously."

- **Tim McVicar**

We thank Tim McVicar for his comments. We have been careless with the words we used: we used "potential evapotranspiration" with the meaning given to it by Thonrthwaite (1948) "the maximum that evaporation can reach and depends only on the climate", which is equivalent to the "atmospheric evaporative demand" (AED). While we were interested in identifying the elasticity of streamflow to AED, we have used the expression "Potential Evapotranspiration" and "Reference Evapotranspiration" interchangeably (while we should not have). We will correct this in the revised version of the paper.

As far as the different AED formulations are concerned, we used two different ones: the empirical formulation of Oudin (which is based on radiation and temperature) and the Penman-Monteith reference evapotranspiration. We did not see any notable difference, this is why only presented one the results obtained with the most common formula (PM). We will do a last test with Penman's formulation.

We remade the computations using for Potential Evaporation the Penman-Shuttleworth formula instead of the Penman-Monteith formula. Results changed little, but were they changed, it was in the right direction. Thus, we decided to modify the paper to include only the results obtained with the new formula.

Section 2 now reads:

"*As far as potential evaporation data is concerned, we used the Penman-Shutlleworth equation (Shuttleworth, 2013). Note that tests implemented with the classical Penman-Monteith reference evapotranspiration equation showed little difference (they can be found in the discussion version of this paper), but we preferred to switch to the Penman-Sutlleworth potential evapotranspiration formula because Donohue et al (2010) suggested that it was the most appropriate form of ETp when considering a changing climate.*"

Climate elasticity of streamflow revisited – an elasticity index based on long-term hydrometeorological records

Vazken Andréassian[1], Laurent Coron[1,2], Julien Lerat[3], Nicolas Le Moine[4]
[1] Irstea, Hydrosystems and Bioprocesses Research Unit (HBAN), Antony, France
[2] *now at* EDF-DTG, Toulouse, France
[3] Bureau of Meteorology, Canberra, Australia
[4] UPMC, Paris, France

Abstract

We present a new method to derive the empirical (i.e., data-based) elasticity of streamflow to precipitation and potential evaporation. This method, which uses long-term hydrometeorological records, is tested on a set of 519 French catchments.
We compare a total of five different ways to compute elasticity: the reference method first proposed by Sankarasubramanian et al. (2001) and four alternatives differing in the type of regression model chosen (OLS or GLS, univariate or bivariate). We show that the bivariate GLS and OLS regressions ~~is~~ provide the most robust solution, because ~~it~~ they account~~s~~ for the co-variation of precipitation and potential evaporation anomalies. We also compare empirical elasticity estimates with theoretical estimates derived analytically from the Turc-Mezentsev formula.
Empirical elasticity offers a powerful means to test the extrapolation capacity of those hydrological models that are to be used to predict the impact of climatic changes.

1. Introduction

1.1 About hydrological elasticity

In a context of growing uncertainty on water resources due to climate change, simple tools able to provide robust estimates of this impact are essential to support policy and planning decisions. Streamflow elasticity is one such tool: it describes the sensitivity of the changes in streamflow related to changes in a climate variable (Schaake and Liu, 1989). $\varepsilon_{Q/X}$, the elasticity of streamflow *Q* to a climate variable *X* is defined by the following equation:

$$\Delta Q / \overline{Q} = \varepsilon_{Q/X} \Delta X / \overline{X} \qquad \textbf{Eq. 1}$$

where $\overline{Q}$ and $\overline{X}$ are the long-term average value of streamflow and the climatic variable, respectively, and the operator Δ indicates the difference ~~or change~~between the dated and the average value. $\varepsilon_{Q/X}$ is nondimensional [% / %], because it is a ratio between two relative (and thus already nondimensional) quantities. One can also define elasticity as the ratio between two absolute quantities and, provided both quantities are expressed in the same unit (for example, $mm.yr^{-1}$ for streamflow, precipitation or potential evaporation), it would still be a nondimensional ratio [$mm.yr^{-1}$ / $mm.yr^{-1}$]. We will name this absolute elasticity $e_{Q/X}$, defined as:

$$\Delta Q = e_{Q/X} \Delta X \qquad \textbf{Eq. 2}$$

Table 1~~Table 1~~ summarizes the notations used in this paper.

1.2 Past studies on elasticity in hydrology

▪ Theoretical (model-based) studies

Most of the studies on elasticity are *theoretical*, in the sense that they are based on flows simulated by a hydrological model fed with different inputs. There are many examples of such theoretical studies. Nemec and Schaake (1982) used the Sacramento model, Vogel et al. (1999) used the linear regression coefficients of annual streamflow models, Sankarasubramanian et al. (2001) used the abcd model, Niemann and Eltahir (2005) used a purpose-built model and Chiew (2006) used the SIMHYD and AWBM models. The most widely used model in elasticity studies is the long-term water balance formula first proposed by Turc & Mezentsev (Mezentsev, 1955; Turc, 1954) (see section 3.2). This formula (sometimes improperly confused with Budyko's formula) was used in elasticity studies by Dooge (1992), Arora (2002), Sankarasubramanian et al. (2001), Yang et al. (2008), Potter and Zhang (2009), Yang and Yang (2011), Donohue et al. (2011) and Yang et al. (2014), among others.

▪ Empirical (data-based) studies

Only a few of the published elasticity studies are *empirical*. By *empirical*, we mean that they use measured data (for different sub-periods) to evaluate the climate elasticity of streamflow. To our knowledge, *Sankarasubramanian et al.* (2001) were the first to publish a method based on the median of annual flow anomalies to compute elasticity, later used by Chiew (2006). Potter et al. (2010) analyzed concomitant reductions of precipitation and streamflow in the Murray-Darling basin over three major historic droughts, and Potter et al. (2011) suggested computing elasticity as a multiple linear regression linking annual transformed streamflow values to annual precipitation and temperature anomalies.

- **Difference between theoretical (model-based) and empirical (data-based) elasticity assessments**

To clarify the differences existing between theoretical and empirical elasticity computing approaches, we have listed the key characteristics of both methods in Table 2Table 2. The most important problem stems from the co-variation of potential evaporation (or temperature) and precipitation: Fu et al. (2007a) mentioned this issue and proposed to transform the "single parameter precipitation elasticity of streamflow index" into a "two parameter climate elasticity index" which would be function of both precipitation and temperature, in order to account for both effects simultaneously. Recently, Chiew et al. (2013) underline that "because of the inverse correlation between rainfall and temperature, any effect from the residual temperature on streamflow is much less apparent than the direct effect of (the much more variable) rainfall." Note that the use of model simulations to compute streamflow elasticity circumvents this problem.

However, there remains what we consider to be a major disadvantage: since all hydrological models are a simplification of reality, using them to predict changes requires some type of initial validation on empirical (observed) data. Indeed, we have recently compared (see Fig. 9a in Coron et al., 2014) the ability of three models of increasing complexity to reproduce the variations in water balance equilibrium over 10-year-long periods and shown that all three models tested had a tendency to underestimate observed changes.

In this paper, we will focus on identifying the most robust approach to compute empirical elasticity. Then we will compare the results obtained by this method with the theoretical elasticity of the Turc-Mezentsev water balance formula. This comparison will only aim at illustrating the difference between the two approaches, since there is no reason to consider one or the other as the "true" reference.

1.3 Scope of the paper

In this paper, we test four alternative approaches to compute the empirical streamflow elasticity, which we compare over a large catchment set to the approach first suggested by Sankarasubramanian et al. (2001). In section 2, we present the data set of 519 French catchments on which this study is based. Section 3 gives a short overview on the possible graphical representations of catchment elasticity and the methods used to quantify empirical elasticity. Section 4 presents a preliminary selection of the formulas, focusing on the distinction between univariate and bivariate methods. Then section 5 presents a regional analysis of streamflow elasticity to precipitation and potential evaporation over France. Last, the conclusion identifies a few perspectives for further work.

2. Catchment dataset

Figure 1 presents the 519 catchments analyzed for these studies.

Long series of continuous daily streamflow and precipitation were available over the 1976–2006 period. The data set encompasses a variety of climatic conditions (oceanic, Mediterranean, continental, mountainous). Precipitation data was provided by Météo France as a gridded product, based on a countrywide interpolation of rain gage data (SAFRAN product). As far as potential evaporation data is concerned, we used the Penman-~~Monteith~~ Shutlleworth equation (Shuttleworth, 1993) [~~*Allen et al.*, 1998~~] ~~in this paper~~. Note that tests implemented with the classical Penman-Monteith *reference* evapotranspiration equation showed little difference (they can be found in the discussion version of this paper), but we preferred to switch to the Penman-Sutlleworth *potential* evapotranspiration formula because Donohue et al. (2010) suggested that it was the most appropriate form of *atmospheric evaporation demand* when considering a changing climate.

To illustrate the issues raised this paper, we will use the catchment of the River Brèze at Meyrueis. This 36-km² catchment located in the south of France has a good quality stream-gaging station and a long observation series.

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3. A review of methods to assess streamflow elasticity

3.1 Graphical assessment of elasticity

Nemec and Schaake (1982) introduced the classical sensitivity plots showing the changes in streamflow (or in some streamflow-based characteristics) as a function of percent change in precipitation (Figure 2Figure 2). Their approach consisted in assessing streamflow elasticity over the whole modeling period by gradually changing the model inputs individually. If the hydrological model behavior is free from thresholds or strong hysteresis effects, this method produces a set of parallel curves such as those shown in Figure 2Figure 2.

Wolock and McCabe (1999) used a similar graph (Figure 3Figure 3), but replaced the percent changes with the absolute changes (plotting $e_{Q/X}$ instead of $\varepsilon_{Q/X}$): in this paper, we will follow their example, but replace the model-based results with observations.

The graphs used herein describe *empirical elasticity*: they are based on hydrological data only and require a sub-sampling of long-term records, i.e., distinguishing a number of sub-periods. Therefore, a point is apparent for each of these sub-periods. Figure 4 presents an example in which ΔQ is plotted as a function of either ΔP or Δ$E_0$$E_P$.

To represent the co-variations of ΔQ with both ΔP or Δ$E_0$$E_P$ simultaneously, we need either a three-dimensional graph or a graph based on isolines (see Fu et al., 2007b). Figure 4 c presents an example using a color code. This graph is particularly useful because the values of ΔP and ΔE_0 ΔE_P are often correlated (Chiew et al., 2013), which may make the two-dimensional representations misleading.

The graphical representation of empirical elasticity shown in Figure 4 allows looking at data without formulating an arbitrary modeling choice. The only convention lies in the duration of the sub-periods. Here, we chose a duration of 10 years in order to obtain contrasted yet representative periods. Figure 5 illustrates the changes induced by a change in this duration. It is reassuring to see that similar trends are observed for a wide range of period lengths. The relationship between the different variables does not remain absolutely identical, however, and there is clearly a trade-off between a longer duration, which ensures that the relationships are close to their

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long-term value, and a lower number of points, which reduces the confidence in the trend displayed by the plot.

3.2 Reference method for theoretical elasticity assessment: the Turc-Mezentsev formula

Most of previous studies used a model-based definition of elasticity, and several of them used the Turc-Mezentsev formula (Mezentsev, 1955; Turc, 1954). The interested reader can refer to *Lebecherel et al.* (2013) for an historical review on this formula, which is given by:

$$Q = \Psi(P, E_P) = P - \frac{P}{\left(1 + \left(\frac{P}{E_P}\right)^n\right)^{\frac{1}{n}}} = P - \left(P^{-n} + E_P^{-n}\right)^{\frac{-1}{n}} \qquad \textbf{Eq. 3}$$

with *Q* – long-term mean average flow (mm/yr), *P* – long-term mean average precipitation (mm/yr), ~~E_0~~ E_P – long-term mean average potential evaporation (mm/yr). *n* is the only free parameter of the formula. Here, we followed *Le Moine et al.* (2007) and used a fixed value *n*=2.5.

Partial derivatives of the Turc-Mezentsev formula are easily computed, they are given in Eq. 4~~Eq. 4~~ and Eq. 5~~Eq. 5~~. They allow computing the theoretical value of the precipitation and potential evaporation elasticity directly for each catchment.

$$\frac{\partial Q}{\partial E_P} = \Psi'_P(P, E_P) = -\left(1 + \left(\frac{E_P}{P}\right)^n\right)^{-\frac{n+1}{n}} \qquad \textbf{Eq. 4}$$

$$\frac{\partial Q}{\partial P} = \Psi'_{E_P}(P, E_P) = 1 - \left(1 + \left(\frac{P}{E_P}\right)^n\right)^{-\frac{n+1}{n}} \qquad \textbf{Eq. 5}$$

3.3 Alternative methods for empirical streamflow elasticity assessment

We will now focus on data-based methods assessing empirical elasticity. Long-term series of streamflow and catchment climate are required. Before introducing the methods compared in this paper, let us introduce the notation $\Delta X_i^{(M)} = X_i^{(M)} - X^{(LT)}$ denoting the departure (anomaly) of a variable X computed over a period of M years starting from year i versus the long-term average $X^{(LT)}$ computed over the entire period.

Five methods will be compared in this paper, all listed in Table 3.

- **Nonparametric method**

This method computes an annual time-series of relative streamflow anomalies (i.e., differences with the long-term mean) and then uses the median of these values as an elasticity estimator:

$$\begin{cases} e^{(M)}{}_{Q/P} = median\left(\dfrac{\Delta Q_i^{(M)}}{\Delta P_i^{(M)}}\right) \\ e^{(M)}{}_{Q/E_P} = median\left(\dfrac{\Delta Q_i^{(M)}}{\Delta E_{P_i}{}^{(M)}}\right) \end{cases} \quad \textbf{Eq. 6}$$

This method is similar to the one advocated by *Sankarasubramanian et al.* (2001) except that they used it to compute the relative rather than the ~~relative~~ absolute elasticity (see Table 1~~Table 1~~). In addition, *Sankarasubramanian et al.* (2001) applied the method to yearly data only, whereas we used sub-periods ranging from 1 to 25 years in this study.

- **Regression methods quantifying precipitation and potential evaporation elasticities (OLS or GLS estimates) *independently***

These methods compute elasticity as either an ordinary least-square (OLS) or generalized least-square (GLS) solution (Johnston, 1972) of the regression models detailed in Table 4~~Table 4~~. See Appendix 1 for a quick description of the method used to perform the GLS regression.

- **Methods quantifying precipitation and potential evaporation elasticities (OLS or GLS estimates) *simultaneously***

These methods (OLS or GLS) quantify precipitation and potential evaporation elasticities *simultaneously* by looking for the GLS solution of a regression model with the same statistical assumptions as above (see Table 5~~Table 5~~).

The strength of the bivariate method obviously lies in the fact that it accounts for the cross-correlation of ΔP and ~~ΔE_0~~ ΔE_P values. The method used for inferring the parameter values and their significance was identical to the method described above. Note that for the sake of consistency with the GLS models, the uncertainty in the OLS parameters was assessed with the bootstrap approach (Efron and Tibshirani, 1994).

4. Selection of the best method to compute empirical streamflow elasticity

4.1 Assessing the capacity of the five methods to compute the empirical elasticity of a synthetic data set

As a first step to compare the merits of the different regression models presented in the previous section, the elasticity estimation was conducted with synthetic streamflow data generated from the Turc-Mezentsev formula, where the parameter n was set at 2.5 (Le Moine et al., 2007). The advantage of using synthetic flow here is that we know the exact (i.e., analytical) solution for elasticity, and this will help identify~~ies~~ the drawbacks of some of the methods compared.

For this test, the observed streamflow anomalies $\Delta Q_i^{(M)}$ were replaced by the estimates $\Delta \tilde{Q}_i^{(M)} = \Psi\left(P_i^{(M)}, E_{P_i}^{(M)}\right) - \Psi\left(P^{(LT)}, E_P^{(LT)}\right)$ where Ψ is given in Equation 3. The empirical elasticity values were subsequently compared with the exact values $\Psi'_P\left(P^{(LT)}, E_P^{(LT)}\right)$ and $\Psi'_{E_P}\left(P^{(LT)}, E_P^{(LT)}\right)$ given in Equations 4 and 5, respectively. The performance of each regression model was judged according to the absolute bias B and root mean square error (RMSE) R:

$$B_X^{(M)} = \left| \sum_{k=1}^{N} \left[e_{Q_i/X_i}^{(M)} - \Psi'_x\left(P_i^{(LT)}, E_{Pi}^{(LT)}\right) \right] \right| \quad \textbf{Eq. 7~~10~~}$$

$$R_X^{(M)} = \sqrt{\sum_{i=1}^{N} \left[e_{Q_i/X_i}^{(M)} - \Psi'_x\left(P_i^{(LT)}, E_{P^i}^{(LT)}\right) \right]^2} \quad \textbf{Eq. 8~~11~~}$$

where *X* is the climate variable (P or ~~E_0~~E_P), $e_{Q_i/X_i}^{(M)}$ is the corresponding empirical elasticity value computed for catchment *i* using sub-periods of *M* years, and *N*=519 is the number of catchments.

The performance of the five alternative methods is presented in Figure 6Figure 6, which shows the absolute bias and the root mean square error on the elasticity for precipitation and potential evaporation, respectively.

The four plots in Figure 6Figure 6 clearly indicate the superiority of the two bivariate models (OLS-2 and GLS-2) over the three univariate models (NP, OLS-1 and GLS-1), with bias and RMSE on both types of elasticity that are lower by several orders of magnitude. This first result suggests that the estimation of empirical elasticity is greatly improved when conducted simultaneously on rainfall and potential evaporation.

Figure 6Figure 6 also shows that the duration of the sub-periods can slightly affect the performance of the regression model. The largest impact can be seen in the bias on the elasticity to potential evaporation (Figure 6.a) where the optimal duration of 20 years provides a better performance compared to the other durations. The 20-year duration seems to be the best choice for both types of elasticity, for all regression models, and both bias and RMSE. The only noticeable exception is the bias on elasticity to rainfall (Figure 6.b) for the GLS-2 model where the best elasticity values are obtained for sub-periods of 10 years. This could indicate that the optimal duration may not be identical for the estimation of elasticity to rainfall and potential evaporation.

This study based on synthetic data shows the clear superiority of the methods based on bivariate regressions (OLS2 and GLS2): the Non-Parametric method (NP) and the univariate regressions (OLS1 and GLS1) are clearly unable to compute streamflow elasticity robustly. Because the NP method is the reference method (suggested by (Sankarasubramanian et al., 2001)), Figure 7Figure 7(a,c) compares the empirical elasticity values given by the NP method and the GLS2 method: the differences are very large. On the other hand, Figure 7Figure 7(b,d) shows that there is little difference between the estimates given by OLS2 and GLS2. However, for statistical reasons (presented in the aAppendix 2) we consider that the GLS solution should probably be preferred.

Having decided on the best method to compute empirical elasticity, we can now compare model elasticities with the GLS estimates based on measured streamflow.

4.2 Coherence of data-based and model-based elasticity estimates

We now wish to compare the *empirical* elasticity computed with the GLS2 method (the recommended one) with the *theoretical* elasticity derived analytically from the Turc-Mezentsev formula (see Eq. 3~~Eq. 3~~). While in the previous test we used synthetic data, we now use the actual (measured) streamflow. This means that contrary to the preceding test, we do not have any "reference": since neither the data-based nor the model-based elasticity can be considered "true," we can only assess the coherence between the two computations.

The scatterplots illustrated in Figure 8~~Figure 8~~ compare the elasticity values obtained by the multivariate regression (GLS2) method and the model-based approach: we can see that the link between the two measurements on a catchment-by-catchment basis ~~remains acceptable~~prpis extremely weak for precipitation… and even more~~, but very weak~~ for potential evaporation.

The fact that empirical and theoretical elasticities differ is in itself noteworthy and would require further analysis. At this point, we cannot draw any further conclusion from this comparison: as widely used as it is, the Turc-Mezentsev relationship remains a theoretical model and cannot be considered superior to the data-based elasticity assessment.

5. Results: Regional elasticity analysis over France

Henceforth, we only consider the empirical elasticity estimates given by the GLS2 method. Figure 9~~Figure 9~~ illustrates the results: each of the 519 gaging stations of the data set are shown, but the points for which the elasticity coefficient is not significantly different from zero are indicated with a cross only. For the other points, the color code gives the elasticity value.

From the maps, it is difficult to identify physical reasons for the spatial variations in elasticity values. The Massif central highlands seem to show a slightly higher occurrence of high-intensity elasticities, both to P and ~~E_0~~E_P, and the Paris Basin lowlands a slightly lower occurrence. This tendency could perhaps be related to the absence/presence of large groundwater aquifers, but more detailed comparative studies are needed to draw a firm conclusion.

A few outliers appear, which is common when using a large data set: one catchment shows a negative elasticity to precipitation and five catchments show a positive elasticity to potential evaporation. We checked each of the plots individually and verified that this was in fact due to a very limited span of streamflow anomaly ΔQ, which made the regression rather meaningless.

To conclude this countrywide analysis of elasticity, we tested a possible relation between catchment size and elasticity values. Figure 10~~Figure 10~~ speaks for itself: over the range of catchment areas covered by this study, no trend could be identified with catchment area.

6. Conclusion

6.1 Synthesis

In this paper, we identified an improved method to assess the empirical elasticity of streamflow to precipitation and potential evaporation. This method (GLS2), which uses long-term hydrometeorological records, was tested on a set of 519 French catchments.

We started with a synthetic data set and compared this improved method with the reference nonparametric method and with several univariate and bivariate alternatives: we obtained results with a much lower bias and RMSE, this difference being clearly due to the fact that the improved method was able to account for the covariation of precipitation and potential evaporation anomalies.

We then compared the improved empirical elasticity estimate with the theoretical estimates derived analytically from the Turc-Mezentsev formula. Empirical and theoretical estimates weakly correlated: the link between the two measurements on a catchment-by-catchment basis is weak for precipitation, and very weak for potential evaporation.

6.2 Limits and perspectives

As a simple method characterizing the sensitivity of streamflow to climatic changes, the identification of empirical elasticity seems promising. Indeed, the empirical elasticity assessment advocated in this paper can provide a ~~"model-free"~~n estimate of the impact of climate change on hydrology that is *almost* model-free~~,~~ (except for the assumption of linearity, of course) and allows ~~looking~~ digging into *past*

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observations to predict the impact of *future* changes. Another perspective can also be seen for studies involving hydrological models for climate change assessment: empirical elasticity could provide a very useful benchmark against which to test the predictions of complex hydrological models (see e.g. how the extrapolation capacity of several hydrological models was assessed in Coron et al. (2014)).

Naturally, the elasticity assessment has its limits: there is no guarantee for its ability to extrapolate to the most extreme climatic changes (i.e., to changes that are far from those observed over historical records). The formula chosen to compute potential evaporation is also a concern. In this paper, we used the Penman-Shutlleworth equation (Shuttleworth, 1993) ~~Penman-Monteith equation (Allen et al., 1998)~~. We also repeated this study with the Oudin et al. (2005) formula (a formula widely used in France), and the Penman-Monteith equation (Allen et al., 1998), which did not yield significant differences. This result was expected because the catchments considered here are energy-limited with few cases where actual evaporation reaches its potential value. However, for other climates (i.e., drier environments), additional work would be required to further test the sensitivity of streamflow elasticity to the potential evaporation formula.

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Appendix 1 – GLS regression

Mis en forme : Retrait : Gauche : 0 cm

The parameters of the GLS regression were inferred by maximizing the log-likelihood function associated with this model:

$$L\left(\left\{\Delta Q_i^{(M)}\right\},\left\{\Delta X_i^{(M)}\right\} \mid e_{Q/X}^{(M)},\sigma,\alpha\right)= -\frac{k}{2}\log(2\pi)-k\log(\sigma)-\frac{1}{2}\log(1-\alpha^2) -\frac{1}{2\sigma^2}\left(\left(1-\alpha^2\right)\omega_1^{\,2}+\sum_{i=2}^{k}\left(\omega_i-\alpha\omega_{i-1}\right)^2\right)$$

Eq. 997

where k is the number of sub-periods. The optimization was performed with the Nelder-Mead algorithm (Nelder and Mead, 1965) using the ordinary least-square solution (OLS) as a starting point (i.e., the solution of the same regression model with $\alpha = 0$). The validity of the model assumptions was checked (see Appendix) by computing the Shapiro-Wilks test (with an expected *p*-value greater than 0.05) and Durbin-Watson statistic (with an expected value greater than 1) from the series of innovations $\hat{\delta}_i$:.

$\hat{\delta}_i = \hat{\omega}_i - \alpha\hat{\omega}_{i-1}$ if $i > 1$ and $\hat{\delta}_1 = \hat{\omega}_1$ **Eq. 10108**

$\hat{\omega}_i = \Delta Q_i^{(M)} - e_{Q/X}^{(M)}\Delta X_i^{(M)}$ **Eq. 11119**

Unlike the OLS solution, the distribution of the elasticity values obtained with this approach does not have a closed form. As a result, the significance of the regression's coefficients was assessed with a bootstrap approach as follows:

a. The GLS model was fit with the maximum likelihood approach first. This allowed computing the series of innovations δ_i.

b. The innovations $\{\delta_i\}_{i=2,..,n}$ were resampled with replacement to form a new series of bootstrapped innovations $\{\delta^*{}_i\}_{i=2,...,n}$. The first innovation δ_1^* of this series was set to ω_1.

c. The bootstrapped innovations were used to generate a new series of bootstrapped observations $\Delta Q_i^{(M)*} = e_{Q/X}^{(M)}\Delta X_i + \sum_{i=1}^{n}\delta_i^*\alpha^i$.

d. Finally the GLS model was fit with the maximum likelihood approach using the bootstrapped observations leading to new values of the GLS parameters.

Steps (c) and (d) were repeated 1000 times and the 2.5% and 97.5% percentiles of the GLS parameters were derived from the empirical distribution formed with the

1000 parameter samples. A parameter was considered as significantly different from zero if both the 2.5% and 97.5% percentiles were either strictly positive or negative.

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Appendix 2 - Validity of statistical assumptions underlying the regression models

Mis en forme : Retrait : Gauche : 0 cm

This section reviews the validity of the statistical assumptions underlying the OLS2 and GLS2 regression models described in section 3.3.

- Figure 11~~Figure 11~~.a shows that the GLS2 model has the highest proportion of catchments where the normality assumption cannot be rejected based on the Shapiro-Wilks test. However, the difference with the other models remains limited, with this proportion varying from 50% for OLS2 with 10-year sub-periods to 63% for GLS2 with 20-year sub-periods. Overall, a significant proportion of catchments still fail the test, whatever regression model is considered, which suggests that additional assumptions could be tested for the distribution of the innovations.
- Figure 11~~Figure 11~~.b reveals that a high level of autocorrelation is present in the innovations of the OLS2 model with only 5% (with 10-year sub-periods) and only 27% (with 20-year sub-periods) of the catchments reaching a satisfactory Durbin-Watson statistic value. This was an expected result. Logically, this proportion is much higher for the GLS2 models, reaching 89% for 10-year sub-periods and 84% for 20-year sub-periods. Here also a small proportion of the catchments fail the test, even with regression models embedding an explicit autocorrelation treatment. This result suggests that the residuals may require higher-order autoregressive models.

Overall, the results illustrated in Figure 11~~Figure 11~~ indicate that the GLS2 model is the most satisfactory regression model from a statistical point of view. The difference introduced by the length of the averaging period (10 or 20 years) is very limited.

Appendix 3 – Main caracteristics of the catchment dataset

Catchment code	e_{Q/E_p}	$e_{Q/P}$	Altitude of the outlet (m a.s.l.)	Area (km²)	River Name
A1050310	-0.74	0.58	282	238	L' Ill à Altkirch
A1080330	-0.58	0.54	242	668	L' Ill à Didenheim
A1152010	-0.42	0.48	256	288	La Largue à Illfurth
A2023030	-0.58	0.54	432	44	La Petite Fecht à Stosswihr
A2073010	-0.38	0.86	303	31	Le Strengbach à Ribeauvillé
A2122010	0.05	0.68	326	118	La Weiss à Kaysersberg [Fréland-Gare]
A2332110	-0.52	0.69	262	107	La Lièpvrette à Lièpvre
A2512010	-1.25	0.91	221	42	L' Andlau à Andlau
A2612010	-0.60	0.71	161	57	L' Ehn à Niedernai
A2732010	-1.31	1.08	267	224	La Bruche à Russ [Wisches]
A2842010	0.04	1.01	169	167	La Mossig à Soultz-les-Bains
A3151010	-0.22	0.66	146	280	La Moder à Schweighouse-sur-Moder [amont]
A3301010	-0.37	0.52	144	622	La Moder à Schweighouse-sur-Moder [aval]
A3422010	-0.57	0.45	196	184	La Zorn à Saverne [Schinderthal]
A3472010	0.23	0.80	147	684	La Zorn à Waltenheim-sur-Zorn
A3712010	-0.84	0.41	176	192	La Sauer à Goersdorf [Liebfrauenthal]
A3832010	-0.59	0.78	124	204	Le Seltzbach à Niederroedern
A3902010	-0.64	0.38	173	275	La Lauter à Wissembourg [Weiler]
A4050620	-0.98	1.73	439	152	La Moselle à Rupt-sur-Moselle
A4142010	-0.58	1.11	407	184	La Moselotte à Vagney [Zainvillers]
A4173010	-0.61	0.98	455	65	La Cleurie à Cleurie
A4200630	-0.71	0.99	372	627	La Moselle à Saint-Nabord [Noirgueux]
A4250640	-0.88	0.90	325	1218	La Moselle à Épinal
A5261010	-0.72	0.74	265	383	Le Madon à Mirecourt
A5431010	-0.31	0.77	225	948	Le Madon à Pulligny
A5730610	-0.38	0.88	200	3346	La Moselle à Toul
A6051020	-0.51	0.59	339	371	La Meurthe à Saint-Dié
A6151030	-0.70	0.51	282	727	La Meurthe à Raon-l'Étape
A6571110	-0.18	0.81	220	560	La Vezouze à Lunéville
A6731220	-0.45	0.75	234	498	La Mortagne à Gerbéviller
A6761010	-0.52	0.96	211	2294	La Meurthe à Damelevières
A6953010	-0.18	1.32	198	85	L' Amézule à Lay-Saint-Christophe
A7010610	-0.54	0.90	184	6835	La Moselle à Custines
A7122010	-0.16	0.73	187	228	L' Esch à Jezainville
A7642010	-0.41	0.41	200	150	La Petite Seille à Château-Salins
A7821010	-0.22	0.71	180	928	La Seille à Nomeny
A7881010	-0.16	0.67	164	1274	La Seille à Metz
A8431010	0.06	1.17	167	1241	L' Orne à Rosselange
A9942010	-0.39	0.72	191	1150	La Nied à Bouzonville

B0220010	-0.18	0.65	300	368	La Meuse à Goncourt
B1092010	-1.02	0.40	291	401	Le Mouzon à Circourt-sur-Mouzon [Villars]
B2220010	-0.46	0.75	216	2543	La Meuse à Saint-Mihiel
B3150020	-0.59	0.84	162	3915	La Meuse à Stenay
B4631010	-0.26	0.74	159	1978	La Chiers à Carignan
B5322010	0.00	0.77	153	125	La Vence à la Francheville
D0206010	0.06	0.79	133	115	La Solre à Ferrière-la-Grande
E1766010	-0.15	0.26	37	88	La Rhonelle à Aulnoy-lez-Valenciennes
E1827020	-0.31	0.99	15	241	L' Hogneau à Thivencelle
E3346010	-0.35	0.45	26	132	La Marque à Bouvines
E3511210	-1.45	0.81	83	87	La Lys à Lugy
E4035710	0.12	0.79	19	392	L' Aa à Wizernes
E5300210	-0.90	0.73	26	103	La Liane à Wirwignes
E5400310	-0.08	0.44	6	917	La Canche à Brimeux
E5406510	-0.08	0.55	24	345	La Ternoise à Hesdin
E5505720	0.06	0.36	12	792	L' Authie à Dompierre-sur-Authie
E6470910	0.08	0.34	4	5643	La Somme à Abbeville [Epagne-Epagnette]
G1003010	-0.58	0.69	15	255	L' Yères à Touffreville-sur-Eu
H0100010	-0.57	0.67	249	373	La Seine à Nod-sur-Seine
H0100020	-1.07	0.87	180	686	La Seine à Plaines-Saint-Lange
H0400010	-0.24	0.66	149	2340	La Seine à Bar-sur-Seine
H0400020	-0.13	0.60	139	2392	La Seine à Courtenot
H0503010	-0.09	0.64	109	249	L' Hozain à Buchères [Courgerennes]
H1051020	-0.29	0.66	185	690	L' Aube [partielle] à Longchamp-sur-Aujon [Outre Aube]
H1333010	1.62	1.87	137	22	La Laine à Soulaines-Dhuys
H1513210	-0.38	0.72	86	171	La Barbuise à Pouan-les-Vallées
H1603010	-0.21	0.46	78	366	La Superbe à Saint-Saturnin
H1932020	0.04	0.43	63	281	La Voulzie à Jutigny
H2062010	-0.61	0.29	161	264	Le Beuvron à Ouagne [Champmoreau]
H2073110	-1.00	0.40	170	87	Le Sauzay à Corvol-l'Orgueilleux
H2083110	-0.32	0.52	150	192	La Druyes à Surgy
H2322010	-0.49	0.47	312	267	Le Serein à Bierre-lès-Semur
H2342010	-0.35	0.51	129	1116	Le Serein à Chablis
H2412010	-0.20	0.58	205	478	L' Armançon à Quincy-le-Vicomte
H2513110	-0.43	0.75	88	133	Le Tholon à Champvallon
H3102010	-0.39	0.49	187	152	L' Ouanne à Toucy
H3122010	-0.46	0.46	133	559	L' Ouanne à Charny
H3201010	-0.38	0.64	78	2302	Le Loing à Châlette-sur-Loing
H3613010	-0.14	0.22	86	162	Le Lunain à Paley
H3623010	-0.15	0.23	105	104	L' Orvanne à Blennes
H4022020	-0.20	0.19	56	851	L' Essonne à Guigneville-sur-Essonne [La Mothe]
H4223110	-0.16	0.43	80	152	La Remarde à Saint-Cyr-sous-Dourdan
H4243010	-0.18	0.55	54	231	L' Yvette à Villebon-sur-Yvette
H5062010	-0.14	0.76	206	618	Le Rognon à Doulaincourt-Saucourt
H5142610	-0.39	0.79	170	114	La Chée à Villotte-devant-Louppy [Villote devant Loupy]

H5172010	-0.23	0.78	95	2109	La Saulx à Vitry-en-Perthois
H5732010	-0.06	0.84	62	769	Le Grand Morin à Pommeuse
H6102010	-0.63	0.73	222	283	L' Aire à Beausite [Amblaincourt]
H6122010	-0.56	0.97	154	629	L' Aire à Varennes-en-Argonne
H6162010	-0.40	0.92	117	957	L' Aire à Chevières
H6201010	-0.44	0.78	100	2242	L' Aisne à Mouron
H6221010	-0.48	0.84	77	2888	L' Aisne à Givry
H6313020	-0.19	0.27	59	810	La Suippe à Orainville
H6423010	-0.05	0.58	58	300	L' Ardres à Fismes
H6531011	-0.23	0.57	33	7810	L' Aisne à Trosly-Breuil [Hérant]
H7021010	-0.09	0.59	160	320	L' Oise à Hirson
H7033010	-0.95	0.90	140	256	Le Thon à Origny-en-Thiérache
H7041010	-0.27	0.85	101	860	L' Oise à Monceau-sur-Oise
H7061010	-0.35	0.80	70	1193	L' Oise à Origny-Sainte-Benoite
H7162010	-0.17	0.85	51	1637	La Serre à Pont à Bucy
H7401010	-0.21	0.57	35	4320	L' Oise à Sempigny
H7423710	-0.24	0.36	33	280	L' Aronde à Clairoix
H7611012	-0.14	0.60	26	13484	L' Oise à Pont-Sainte-Maxence [Sarron]
H7713010	-0.52	0.31	89	214	Le Petit Thérain à Saint-Omer-en-Chaussée
H7742010	-0.82	0.68	61	755	Le Thérain à Beauvais
H7742020	-0.25	0.42	33	1210	Le Thérain à Maysel
H7833520	0.05	0.09	32	58	L' Ysieux à Viarmes [Giez]
H7853010	-0.23	0.22	37	102	Le Sausseron à Nesles-la-Vallée
H8012010	-0.66	0.63	87	247	L' Epte à Gournay-en-Bray
H8043310	0.02	-0.01	40	99	L' Aubette de Magny à Ambleville
H8212010	-0.45	0.53	53	377	L' Andelle à Vascoeuil
H9202010	0.15	0.44	119	477	L' Avre à Acon
H9222010	0.12	0.35	78	872	L' Avre à Muzy
H9331010	0.08	0.28	24	4561	L' Eure à Cailly-sur-Eure
H9402030	-0.15	0.26	47	1029	L' Iton à Normanville
H9501010	-0.13	0.11	13	5891	L' Eure à Louviers
I0113010	-0.17	0.51	166	82	Le Guiel à Montreuil-l'Argillé
I0122010	-0.20	0.47	127	251	La Charentonne à Ferrières-Saint-Hilaire
I1203010	-0.38	0.46	32	173	La Calonne aux Authieux-sur-Calonne
I2001010	-0.41	0.57	90	88	La Dives à Saint-Lambert-sur-Dive
I2021010	-0.37	0.37	53	283	La Dives à Beaumais
I2213610	-0.07	0.52	6	57	L' Ancre à Cricqueville-en-Auge
I3131010	-0.23	0.64	106	1019	L' Orne à Rabodanges
I4032010	-0.76	0.63	8	256	La Seulles à Tierceville
I5053010	1.15	0.24	76	116	La Souleuvre à Carville
I7222020	0.47	1.62	18	141	La Soulles à Saint-Pierre-de-Coutances
I7913610	-0.27	0.70	9	73	Le Thar à Jullouville
J0014010	-1.09	0.44	111	65	Le Nançon à Lécousse [Pont aux Anes]
J0144010	-0.76	0.54	58	82	La Loysance à Saint-Ouen-la-Rouërie
J0323010	-0.42	0.39	19	62	Le Guyoult à Epiniac
J1103010	-0.82	0.61	32	103	L' Arguenon à Jugon-les-Lacs
J1114010	-0.54	0.22	41	113	La Rosette à Mégrit

J1313010	-0.77	0.72	40	244	Le Gouessant à Andel
J1513010	-0.87	0.81	103	135	Le Gouët à Saint-Julien
J1813010	-0.68	0.57	17	342	Le Leff à Quemper-Guézennec
J2233010	-0.74	0.62	94	265	Le Léguer à Belle-Isle-en-Terre
J2603010	-0.48	0.54	26	44	Le Jarlot à Plougonven
J2605410	-0.56	0.51	27	42	Le Tromorgant à Plougonven
J2723010	-0.66	0.74	13	142	La Penze à Taulé [Penhoat]
J3024010	-0.12	0.76	33	45	Le Guillec à Trézilidé
J3205710	-0.13	0.91	39	24	L' Aber Wrac'h au Drennec
J3213020	-0.56	0.81	47	27	L' Aber-Benoit à Plabennec [Loc Maria]
J3323020	-0.36	0.66	20	95	L' Aber Ildut à Brélès [Keringar]
J3601810	-2.25	1.21	97	117	L' Aulne à Scrignac [Le Goask]
J3713010	-0.82	0.65	91	258	L' Hyères à Trébrivan [Pont Neuf]
J3834010	-0.11	0.77	26	140	La Douffine à Saint-Ségal [Kerbriant]
J4214510	-0.88	0.62	128	7	Le Langelin à Briec [Pont D 72]
J4224010	-0.52	0.64	22	108	Le Jet à Ergué-Gabéric
J4313010	-0.25	0.95	20	181	Le Steir à Guengat [Ty Planche]
J4514010	-0.39	0.66	20	21	Le Moros à Concarneau [Pont D 22]
J4614010	-0.72	0.65	36	72	Le Ster Goz à Bannalec [Pont Meya]
J4742010	-0.33	0.74	23	576	L' Éllé à Arzano [Pont Ty Nadan]
J4803010	-1.29	1.14	100	102	L' Isole à Scaër [Stang Boudilin]
J4902010	-0.06	0.90	7	832	La Laïta à Quimperlé [ancienne]
J5102210	-0.54	0.54	24	299	Le Scorff à Plouay [Pont Kerlo]
J5613010	-0.53	0.52	44	316	L' Evel à Guénin
J5704810	-0.73	0.50	46	46	Le Coët-Organ à Quistinic [Kerdec]
J6213010	-0.51	1.05	25	182	Le Loch à Brech
J7083110	-0.40	0.62	44	152	Le Chevré à la Bouëxière [Le Drugeon]
J7483010	-0.32	0.75	17	809	La Seiche à Bruz [Carcé]
J7633010	-0.24	0.89	24	406	Le Semnon à Bain-de-Bretagne [Rochereuil]
J7824010	-0.26	0.76	15	112	L' Aron à Grand-Fougeray [La Bernardais]
J7973010	-0.20	0.90	27	40	Le Canut Sud à Saint-Just [La rivière Colombel]
J8002310	-1.58	1.12	178	29	L' Oust à Saint-Martin-des-Prés [La Ville Rouault]
J8363110	-0.44	0.79	35	301	L' Yvel à Loyat [Pont D 129]
J8433010	-0.49	0.72	49	135	La Claie à Saint-Jean-Brévelay
J8602410	-0.38	0.57	69	28	L' Aff à Paimpont [Pont du Secret]
J8632410	-0.37	0.68	14	343	L' Aff à Quelneuc [La rivière]
J8813010	-0.42	0.90	26	161	L' Arz à Molac [Le Qinquizio]
J9300610	-0.10	0.54	1	10148	La Vilaine à Rieux
K0010010	0.42	1.48	1116	60	La Loire à Usclades-et-Rieutord [Rieutord]
K0403010	-0.07	1.02	936	138	Le Lignon du Velay au Chambon-sur-Lignon
K0454010	-0.19	0.79	596	217	La Dunières à Sainte-Sigolène [Vaubarlet]
K0523010	-1.02	0.38	706	347	L' Ance du Nord à Saint-Julien-d'Ance [Laprat]
K0567520	-0.48	0.86	653	129	La Semène à Saint-Didier-en-Velay [Le Crouzet]
K0567530	-0.07	0.36	811	58	La Semène à Jonzieux
K0624510	-0.28	0.56	432	105	Le Bonson à Saint-Marcellin-en-Forez [Le Bled]
K0663310	-0.84	1.07	583	61	La Coise à Larajasse [Le Nézel]
K0673310	-0.15	1.05	436	181	La Coise à Saint-Médard-en-Forez [Moulin Brûlé]

K0724510	-0.53	0.65	342	13	Le Chanasson à Civens [La rivière]
K0733220	-1.58	0.63	817	60	Le Lignon de Chalmazel à Chalmazel [Chevelières]
K0773220	-1.15	0.74	333	662	Le Lignon de Chalmazel à Poncins [2]
K0813020	-1.84	1.58	378	197	L' Aix à Saint-Germain-Laval
K0974010	-0.38	0.84	364	86	Le Gand à Neaux
K0983010	-0.47	0.84	293	435	Le Rhins à Saint-Cyr-de-Favières [Pont Mordon]
K1084010	-1.58	0.71	357	23	La Teyssonne à Changy [La Noaillerie]
K1173210	5.89	2.39	241	593	L' Arconce à Montceaux-l'Étoile
K1284810	-0.63	0.78	318	135	La Selle à la Celle-en-Morvan [Polroy]
K1321810	-1.25	0.49	268	1792	L' Arroux à Étang-sur-Arroux [Pont du Tacot]
K1503010	-1.69	0.47	361	157	La Besbre à Châtel-Montagne
K1524010	-0.99	0.69	314	121	Le Barbenan au Breuil
K1724210	-1.05	0.80	212	114	La Dragne à Vandenesse
K1753110	-0.91	0.25	200	333	L' Alène à Cercy-la-Tour [Coueron]
K1914510	-0.62	0.63	196	115	L' Ixeure à la Fermeté
K1954010	-0.68	0.64	207	226	La Nièvre d'Arzembouy à Poiseux [Poisson]
K2064010	-0.86	1.28	910	66	Le Langouyrou à Langogne
K2123010	-0.66	0.89	1124	125	Le Chapeauroux à Châteauneuf-de-Randon [Hermet]
K2233020	-0.35	1.37	634	231	L' Ance du Sud à Monistrol-d'Allier [Pouzas]
K2514010	-0.08	1.13	768	156	L' Allanche à Joursac [Pont du Vernet]
K2523010	-0.06	0.93	710	322	L' Alagnon à Joursac [Le Vialard]
K2834010	-0.38	0.83	836	71	La Dolore à Saint-Bonnet-le-Chastel [Moulin Neuf]
K2871910	-1.12	0.56	412	795	La Dore à Saint-Gervais-sous-Meymont [Maison du Parc / Giroux-Dore]
K2884010	-2.87	0.74	403	73	La Faye à Olliergues [Giroux-Faye]
K2944010	-1.66	0.65	335	72	Le Couzon à Courpière [Le Salet]
K3206010	-3.04	-0.31	784	8	La source-de-chez-Pierre à Ceyssat
K3222010	-0.70	0.68	666	360	La Sioule à Pontgibaud
K3264010	-0.57	0.70	538	111	La Saunade à Pontaumur
K3292020	-0.74	0.65	502	1300	La Sioule à Saint-Priest-des-Champs [Fades-Besserve]
K4094010	-0.50	0.41	153	478	Le Nohain à Saint-Martin-sur-Nohain [Villiers]
K4443010	-0.30	0.59	79	165	L' Ardoux à Lailly-en-Val
K4873110	-0.01	0.56	82	263	La Brenne à Villedômer [Bas-Villaumay]
K5090910	-0.21	0.69	321	526	Le Cher à Chambonchard
K5183010	-0.41	0.54	329	861	La Tardes à Évaux-les-Bains
K6334010	-0.54	0.01	180	79	La Nère à Aubigny-sur-Nère
K6402510	-0.80	0.06	102	1240	La Sauldre à Salbris
K6492510	-0.85	0.30	73	2297	La Sauldre à Selles-sur-Cher
K7312610	-0.90	0.65	82	1707	L' Indre à Saint-Cyran-du-Jambot
K7414010	-0.47	0.60	99	109	La Tourmente à Villeloin-Coulangé [Coulangé]
K7424010	-0.30	0.51	97	78	L' Olivet à Beaumont-Village [1]
K7514010	-0.20	0.69	66	128	L' Échandon à Saint-Branchs
L0010610	-1.15	0.68	749	64	La Vienne à Peyrelevade [Servières]
L0010620	-1.43	0.68	740	77	La Vienne à Peyrelevade [La Rigole du Diable]
L0093010	-0.27	0.96	301	188	La Combade à Masléon

L0314010	-0.95	0.71	313	131	La Vige à Saint-Martin-Sainte-Catherine
L0563010	-0.77	0.72	218	605	La Briance à Condat-sur-Vienne [Chambon Veyrinas]
L0624010	-0.45	0.76	230	153	L' Aixette à Aixe-sur-Vienne
L0813010	-0.59	0.76	214	298	La Glane à Saint-Junien [Le Dérot]
L4033010	-0.53	0.84	448	190	La Rozeille à Moutier-Rozeille [Aubusson]
L4220710	-0.67	0.60	215	1235	La Creuse à Fresselines
L4321710	-0.62	0.49	272	561	La Petite Creuse à Genouillac
L4411710	-0.59	0.57	218	853	La Petite Creuse à Fresselines [Puy Rageaud]
L4530710	-0.73	0.54	187	2427	La Creuse à Éguzon-Chantôme
L4653010	-0.63	0.60	124	438	La Bouzanne à Velles [Forges]
L5034010	-1.37	0.52	324	129	L' Ardour à Folles [Forgefer]
L5101810	-0.64	0.59	297	568	La Gartempe à Folles [Bessines]
L5134010	-0.57	1.00	200	175	La Semme à Droux
L5223020	-0.44	0.75	178	286	Le Vincou à Bellac [2]
L5323010	-0.39	0.65	171	232	La Brame à Oradour-Saint-Genest
L5623010	-0.72	1.01	183	188	La Benaize à Jouac
L6202030	-0.56	0.48	58	886	La Claise au Grand-Pressigny [Étableau 2]
M0050620	-0.08	0.71	124	909	La Sarthe à Saint-Céneri-le-Gérei [Moulin du Désert]
M0250610	-0.13	0.73	48	2713	La Sarthe à Neuville-sur-Sarthe [Montreuil]
M0361510	-0.15	0.43	102	833	L' Huisne à Nogent-le-Rotrou [Pont de bois]
M0500610	0.03	0.55	38	5452	La Sarthe à Spay [amont]
M0680610	-0.16	0.64	21	7523	La Sarthe à Saint-Denis-d'Anjou [Beffes]
M1034020	0.05	0.71	126	267	L' Ozanne à Trizay-lès-Bonneval [Prémoteux]
M1041610	-0.11	0.89	118	1080	Le Loir à Saint-Maur-sur-le-Loir
M1214010	-0.13	0.33	121	87	Le Couëtron à Souday [Glatigny]
M3253110	-0.79	0.97	94	185	L' Aron à Moulay
M3313010	-1.12	0.69	115	121	L' Ernée à Ernée
M3323010	-0.66	0.76	67	376	L' Ernée à Andouillé [Les Vaugeois]
M3340910	-0.25	0.88	45	2908	La Mayenne à l' Huisserie [Bonne]
M3423010	-0.24	0.78	50	404	La Jouanne à Forcé
M3504010	-0.55	0.83	51	234	Le Vicoin à Nuillé-sur-Vicoin
M3600910	-0.26	0.96	27	3935	La Mayenne à Château-Gontier
M3630910	-0.08	0.87	20	4166	La Mayenne à Chambellay
M3774010	-0.60	0.76	43	77	Le Chéran à la Boissière
M5102010	-0.23	0.87	46	259	Le Layon à Saint-Georges-sur-Layon
M5222010	-0.26	0.79	20	927	Le Layon à Saint-Lambert-du-Lattay [Pont de Bézigon]
M6014010	-0.14	0.78	70	38	Le Beuvron à Andrezé [Tuvache]
M6333020	-0.32	0.67	6	463	L' Erdre à Nort-sur-Erdre [Moulin de Vault]
M7112410	-0.54	0.63	50	872	La Sèvre Nantaise à Tiffauges [La Moulinette]
M7453010	-0.67	0.60	19	595	La Maine à Remouillé
M8205020	-0.02	1.11	6	139	L' Ognon aux Sorinières [Villeneuve]
N0113010	0.29	0.89	28	33	Le Falleron à Falleron
N3001610	-0.30	0.69	65	131	Le Grand Lay à Saint-Prouant [Monsireigne]
N3024010	-0.52	0.52	42	121	Le Louing à Chantonnay [St-Philbert du Pont

					Charrault]
O0015310	1.36	1.32	558	36	Le Maudan à Fos
O0105110	-2.23	-0.18	2154	5	La Neste de Cap de Long à Aragnouet [Les Edelweiss]
O0126210	-1.31	0.90	1070	67	La Neste de Rioumajou à Tramezaïgues [Maison Blanche]
O0362510	-0.82	0.62	472	385	Le Salat à Soueix-Rogalle [Kercabanac]
O0384010	-1.10	0.52	501	170	L' Arac à Soulan [Freychet]
O0502520	-1.18	0.61	386	1159	Le Salat à Saint-Lizier [Saint Girons]
O0525010	0.02	1.16	441	14	La Gouarège à Cazavet [Aliou]
O0592510	-0.45	0.72	270	1579	Le Salat à Roquefort-sur-Garonne
O0744030	-0.84	0.86	290	220	L' Arize au Mas-d'Azil
O1115010	-0.79	0.93	1239	24	L' Artigue à Auzat [Cibelle]
O1432930	-0.71	0.39	521	134	L' Hers à Bélesta [source de Fontestorbes]
O1442910	-0.81	0.73	417	191	L' Hers Vif au Peyrat
O1484310	-1.10	1.01	507	68	La Touyre à Lavelanet [2]
O1494330	-1.03	0.96	387	95	La Touyre à Léran
O1584610	-0.44	0.69	306	136	Le Douctouyre à Vira [Engraviès]
O1634010	-0.35	0.65	239	197	La Vixiège à Belpech
O2344010	-0.50	0.71	122	524	Le Girou à Cépet
O2725010	-0.17	0.61	191	36	La Lauze à Sémézies-Cachan [Faget-Abbatial]
O3006710	-0.59	0.83	1026	10	La Goudech à Saint-Maurice-de-Ventalon [La Cépède]
O3011010	-0.43	0.73	927	65	Le Tarn au Pont-de-Montvert [Fontchalettes]
O3035210	1.48	0.88	611	26	Le Briançon aux Bondons [Cocures]
O3064010	-0.51	1.68	554	132	Le Tarnon à Florac
O3084320	1.00	1.13	556	126	La Mimente à Florac
O3165010	-0.59	1.64	708	34	La Brèze à Meyrueis
O3194010	0.34	1.45	704	98	La Jonte à Meyrueis [aval]
O3364010	-0.74	0.77	446	428	La Dourbie à Nant [Pont de Gardies]
O3401010	-0.27	0.98	355	2143	Le Tarn à Millau [2]
O3424010	-1.23	0.49	343	169	Le Cernon à Saint-Georges-de-Luzençon [aval]
O3454310	0.02	0.45	340	112	La Muze à Montjaux [Saint-Hippolyte]
O4194310	-0.23	0.40	357	207	Le Gijou à Vabre [Rocalé]
O4704030	-0.61	0.63	427	71	Le Dadou à Paulinet [Saint-Jean-de-Jeanne]
O5042510	-0.95	0.34	578	300	L' Aveyron à Palmas [Pont de Manson]
O5055010	-0.56	0.47	584	108	Le Serre à Coussergues [Resuenhe]
O5092520	-1.22	0.46	533	584	L' Aveyron à Onet-le-Château [Rodez]
O5192520	-0.80	0.51	276	1060	L' Aveyron à Villefranche-de-Rouergue [Recoules]
O5224010	-0.29	0.74	276	208	L' Alzou à Villefranche-de-Rouergue [barrage Cabal]
O5284310	-0.94	0.59	317	104	La Serène à Saint-André-de-Najac [Canabral]
O5292510	-0.75	0.56	163	1604	L' Aveyron à Laguépie [1]
O5312910	-0.24	0.94	730	139	Le Viaur à Arques
O5344010	-0.11	0.84	814	57	Le Vioulou à Salles-Curan [Trébons-Bas]
O5424010	-1.13	0.42	352	161	Le Céor à Centrès [Estrebaldie]
O5464310	-1.23	0.43	363	176	Le Giffou à Saint-Just-sur-Viaur [La Fabrèguerie]
O5534010	-0.80	0.95	245	223	Le Lézert à Saint-Julien-du-Puy [Port de la Besse]

O5685010	-0.43	0.35	139	181	La Bonnette à Saint-Antonin-Noble-Val
O5754020	-0.53	0.60	125	310	La Vère à Bruniquel [La Gauterie]
O6125010	-0.08	0.90	143	62	La Petite Barguelonne à Montcuq
O6134010	-0.30	0.75	74	453	La Barguelonne à Valence [Fourquet]
O6793310	-0.16	0.58	58	834	La Gélise à Mézin [Courbian]
O6804630	-0.43	0.87	245	9	L' Osse à Castex [Mielan]
O7011510	-0.85	0.90	813	187	Le Lot à Sainte-Hélène
O7015810	-0.57	-0.64	981	33	L' Esclancide à Pelouse [Les Salces]
O7041510	-1.22	0.71	667	468	Le Lot à Balsièges [Bramonas]
O7085010	-0.56	-0.52	663	83	Le Coulagnet à Marvejols
O7101510	-0.94	0.64	525	1158	Le Lot à Banassac [La Mothe]
O7131510	-0.70	0.54	388	1633	Le Lot à Lassouts [Castelnau]
O7145220	0.62	0.91	439	53	La Boralde de Saint-Chély à Castelnau-de-Mandailles
O7234010	-0.46	0.81	948	117	La Rimeize à Rimeize
O7245010	-0.08	0.83	947	65	Le Chapouillet à Rimeize [Chassignoles]
O7265010	-0.60	0.67	921	78	La Limagnole à Fontans [Saint-Alban]
O7444010	-0.78	1.13	924	286	Le Bès à Saint-Juéry
O7502510	-0.43	0.70	704	1795	La Truyère à Neuvéglise [Grandval]
O7635010	-1.08	0.87	645	109	La Bromme à Brommat
O7874010	-1.22	0.33	236	545	Le Dourdou à Conques
O8113510	-0.11	0.59	183	681	Le Célé à Figeac [Merlançon]
O8133520	-0.62	1.20	142	1246	Le Célé à Orniac [Les Amis du Célé]
O8255010	-0.92	0.80	103	119	Le Vert à Labastide-du-Vert [Les Campagnes]
O8394310	-0.64	0.45	87	220	La Lémance à Cuzorn
O9196210	-0.07	0.42	53	10	La Cadanne à Pondaurat
P0010010	-2.40	0.65	786	89	La Dordogne à Saint-Sauves-d'Auvergne
P0115010	-0.30	0.89	905	21	La Burande à la Tour-d'Auvergne
P0115020	-0.50	0.94	569	85	La Burande [ou ru de Burons] à Singles
P0212510	-0.84	0.68	954	40	La Rhue à Égliseneuve-d'Entraigues
P0364010	-0.63	0.95	709	169	La Santoire à Condat [Roche-Pointue]
P0885010	-1.74	0.61	377	117	Le Mars à Bassignac [Vendes]
P0924010	-0.96	0.64	631	79	La Triouzoune à Saint-Angel
P1114010	-0.48	0.61	566	81	La Luzège à Maussac [Pont de Maussac]
P1154010	-1.11	0.83	452	250	La Luzège à Lamazière-Basse [Pont de Bouyges]
P1502510	-0.52	1.02	419	455	La Maronne à Pleaux [Enchanet]
P1772910	-1.07	0.72	559	349	La Cère à Sansac-de-Marmiesse
P2114010	-2.05	0.67	131	63	La Sourdoire à la Chapelle-aux-Saints
P2184310	-0.68	0.67	114	191	La Tourmente à Saint-Denis-lès-Martel
P2484010	-0.48	0.41	77	573	Le Céou à Saint-Cybranet
P3001010	-1.48	0.74	773	42	La Vézère à Saint-Merd-les-Oussines [Maisonnial]
P3021010	-0.99	0.95	675	138	La Vézère à Bugeat
P3234010	-1.57	0.56	153	104	La Loyre à Voutezac [Pont de l'Aumonerie]
P3245010	-1.03	0.47	123	52	Le Mayne à Saint-Cyr-la-Roche
P3352510	-0.86	0.37	478	164	La Corrèze à Corrèze [Pont de Neupont]
P3502510	-1.06	0.72	224	354	La Corrèze à Tulle [Pont des soldats]
P3614010	-0.47	0.67	546	42	La Montane à Eyrein [Pont du Geai]

P3922510	-0.42	0.81	103	954	La Corrèze à Brive-la-Gaillarde [Le Prieur]
P4015010	-1.38	0.75	133	58	La Couze à Chasteaux [Le Soulier]
P4271010	-0.56	0.66	56	3657	La Vézère à Campagne
P5404010	-0.27	0.65	36	74	L' Eyraud à la Force [Bitarel]
P6081510	-0.85	0.75	137	448	L' Isle à Corgnac-sur-l'Isle
P6134010	-0.54	0.56	154	197	La Loue à Saint-Médard-d'Excideuil
P7001510	-0.80	0.78	91	1859	L' Isle à Bassilac [Charrieras]
P7181510	0.26	0.49	36	3342	L' Isle à Saint-Laurent-des-Hommes [Bénévent]
P7261510	-0.59	0.50	7	3757	L' Isle à Abzac
P8012510	-0.98	1.04	160	140	La Dronne à Saint-Pardoux-la-Rivière [Le Manet]
P8215010	-0.59	0.45	113	40	La Belle à Mareuil
P8312520	-0.66	1.12	37	1912	La Dronne à Bonnes
Q0115710	-1.15	1.52	505	32	L' Oussouet à Trébons
Q0214010	-1.81	0.91	337	78	L' Échez à Louey
Q0280030	-1.75	0.90	167	876	L' Adour à Estirac
Q0664010	-0.28	0.38	141	207	Le Bouès à Juillac
Q1094010	-0.27	1.24	92	426	Le Larcis à Lannux
Q1100010	-0.35	0.91	80	2921	L' Adour à Aire-sur-l'Adour [2]
Q2593310	-0.64	1.07	26	2478	La Midouze à Campagne
Q3120010	-0.33	0.83	6	7707	L' Adour à Saint-Vincent-de-Paul
Q3464010	-0.90	0.96	6	1144	Le Luy à Saint-Pandelon
Q7322510	-3.30	0.85	123	498	Le Saison à Mauléon-Licharre
Q8032510	-0.75	0.77	43	246	La Bidouze à Aïcirits-Camou-Suhast [Saint-Palais]
Q8345910	-0.33	0.75	37	17	Le Mendialçu à Hasparren
Q9164610	-1.89	1.09	149	157	La Nive des Aldudes à Saint-Étienne-de-Baïgorry
R1132510	-1.23	1.34	217	139	La Tardoire à Maisonnais-sur-Tardoire
R1264001	-0.25	0.42	106	293	Le Bandiat à Feuillade
S2224610	-0.42	0.59	41	113	Le Grand Arriou à Moustey [Biganon]
S2235610	-0.29	0.40	35	42	Le Bouron à Belin-Béliet [Moulin du Moine]
S2242510	-0.52	0.70	14	1678	L' Eyre à Salles
S4214010	-1.13	0.34	21	77	Le Magescq à Magescq
S5144010	-1.90	1.37	31	142	La Nivelle à Saint-Pée-sur-Nivelle
U0104010	-0.92	0.86	306	64	Le Coney à Xertigny
U0444310	-0.72	1.41	243	225	La Semouse à Saint-Loup-sur-Semouse
U0474010	-0.57	0.79	209	1028	La Lanterne à Fleurey-lès-Faverney
U0610010	-0.48	0.96	195	3761	La Saône à Ray-sur-Saône
U0635010	-0.18	0.64	200	146	La Gourgeonne à Tincey-et-Pontrebeau
U0724010	-0.92	0.93	200	385	Le Salon à Denèvre
U0924010	-0.48	0.89	232	397	La Vingeanne à Saint-Maurice-sur-Vingeanne
U0924020	-0.55	0.89	198	609	La Vingeanne à Oisilly
U1004010	-1.64	0.42	388	71	L' Ognon à Servance [Fourguenons]
U1025010	-0.89	0.43	445	32	Le Rahin à Plancher-Bas
U1054010	-0.38	0.60	229	1259	L' Ognon à Beaumotte-Aubertans
U1074010	-0.64	0.64	200	1755	L' Ognon à Chevigney-sur-l'Ognon
U1084010	-0.34	0.68	186	2071	L' Ognon à Pesmes
U1109010	-0.52	0.91	291	56	La Venelle à Selongey
U1204010	-0.60	0.87	273	230	La Tille à Crécey-sur-Tille

U1224010	-0.28	0.66	223	845	La Tille à Arceau [Arcelot]
U1224020	-0.44	0.50	202	882	La Tille à Cessey-sur-Tille
U1235020	-0.66	0.94	194	271	La Norges à Genlis
U1420010	-0.39	0.79	173	11693	La Saône à Pagny-la-Ville [Lechatelet]
U2002010	-0.46	0.70	938	33	Le Doubs à Mouthe
U2012010	-0.24	0.50	855	170	Le Doubs à Labergement-Sainte-Marie
U2022010	-0.27	0.45	824	382	Le Doubs à la Cluse-et-Mijoux [Pontarlier amont]
U2122010	-0.51	0.68	506	1159	Le Doubs à Goumois
U2142010	-0.44	0.67	414	1306	Le Doubs à Glère [Courclavon]
U2215020	-0.62	0.77	394	590	Le Dessoubre à Saint-Hippolyte
U2222010	0.02	0.84	334	2236	Le Doubs à Mathay
U2305210	-1.28	1.10	474	9	Le Saint-Nicolas à Rougemont-le-Château
U2345020	-1.07	0.20	468	30	La Savoureuse à Giromagny
U2345030	-0.87	0.49	358	144	La Savoureuse à Belfort
U2356610	0.00	0.21	323	43	Le Rupt à Dung
U2425260	-0.20	0.16	275	541	Le Cusancin à Baume-les-Dames
U2512010	-0.13	0.87	241	4658	Le Doubs à Besançon
U2542010	-0.49	0.78	201	5169	Le Doubs à Rochefort-sur-Nenon
U2604030	-0.69	1.84	359	291	La Loue à Vuillafans
U2615820	-0.28	0.53	437	210	Le Lison [source] à Nans-sous-Sainte-Anne
U2615830	0.08	0.50	325	284	Le Lison à Myon
U2616410	-0.10	0.42	629	15	Le Verneau à Nans-sous-Sainte-Anne
U2624010	-0.28	1.10	275	1068	La Loue à Chenecey-Buillon
U2634010	-0.28	0.98	236	1264	La Loue à Champagne-sur-Loue
U2722010	-0.32	0.81	180	7346	Le Doubs à Neublans-Abergement
U3205210	-1.26	0.70	368	31	La Grosne à Trades [Les Chambosses]
U3214010	-1.65	0.57	243	334	La Grosne à Jalogny [Cluny]
U3225010	0.87	0.78	214	271	La Guye à Sigy-le-Châtel [Corcelles]
U3424010	-0.26	0.36	176	938	La Seille à Saint-Usuge
U4014010	-0.10	0.49	240	84	La Reyssouze à Montagnat
U4204010	-0.53	0.65	255	41	La Veyle à Lent
U4235010	-0.77	0.71	215	93	Le Renon à Neuville-les-Dames
U4505010	-0.92	0.61	310	55	L' Ardières à Beaujeu
U4624010	-0.77	0.62	211	337	L' Azergues à Châtillon
V0144010	0.03	0.98	606	332	Le Giffre à Taninges [Pressy]
V0205010	-3.49	0.20	458	28	Le Bronze à Bonneville [Thuet]
V0245610	-0.32	0.32	436	47	L' Aire à Saint-Julien-en-Genevois [Thairy]
V0325010	-2.93	0.70	707	171	La Dranse de Morzine à Seytroux [Pont de Couvaloup]
V1015010	-0.88	0.36	851	76	La Valserine à Lélex [Niaizet]
V1015030	-1.63	0.69	579	110	La Valserine à Chézery-Forens [Chézery]
V1015810	-1.32	1.13	401	182	La Semine à Châtillon-en-Michaille [Coz]
V1214010	-7.26	0.89	528	224	Le Fier à Dingy-Saint-Clair
V1235210	-7.92	0.38	469	25	L' Ire à Doussard
V1235610	-3.62	0.24	456	93	L' Eau Morte à Doussard
V1237410	-1.61	0.31	465	30	Le Laudon à Saint-Jorioz
V1264010	-2.70	0.93	316	1286	Le Fier à Vallières

V1414010	-0.26	0.20	382	158	Le Seran à Belmont-Luthézieu [Bavosière]
V1425010	-3.11	2.23	249	41	Le Groin à Artemare [Cerveyrieu]
V1504010	-1.53	0.55	433	94	Le Guiers Mort à Saint-Laurent-du-Pont
V1774010	-0.14	0.68	204	696	La Bourbre à Tignieu-Jameyzieu
V2024010	-1.28	0.60	793	101	La Saine à Foncine-le-Bas
V2035010	-0.33	0.19	819	95	La Lemme à Fort-du-Plasne [Pont-de-Lemme]
V2202010	-0.83	0.82	458	734	L' Ain à Marigny [Chalain]
V2206010	-0.43	0.79	499	51	Le Hérisson à Doucier
V2414010	-2.25	0.83	442	203	La Bienne à Saint-Claude [Chenavier]
V2444020	-0.36	0.94	323	593	La Bienne à Jeurre
V2814020	-0.31	0.37	272	331	Le Suran à Neuville-sur-Ain [La Planche]
V2924010	-0.33	0.64	293	210	L' Albarine à Saint-Rambert-en-Bugey
V2934010	0.01	0.43	242	290	L' Albarine à Saint-Denis-en-Bugey [Pont Saint Denis]
V4144010	-0.20	0.64	309	454	L' Eyrieux à Beauvène [Pont de Chervil]
V4214010	-0.66	0.63	542	189	La Drôme à Luc-en-Diois
V4225010	-1.70	0.76	564	227	Le Bez à Châtillon-en-Diois
V4275010	-0.97	0.56	329	101	La Gervanne à Beaufort-sur-Gervanne
V4414010	-0.43	0.62	276	192	Le Roubion à Soyans
V5045810	-1.20	1.26	638	63	Le Borne à Saint-Laurent-les-Bains [Pont de Nicoulaud]
V6035010	0.42	0.65	338	157	Le Toulourenc à Malaucène [Veaux]
V6052010	-0.94	0.71	194	587	L' Ouvèze à Vaison-la-Romaine
V7124010	0.27	1.28	148	244	Le Gardon de Mialet à Générargues [Roucan]
W0000010	-1.37	0.32	1851	46	L' Isère à Val-d'Isère
W0224010	1.06	1.01	652	333	Le Doron de Bozel à la Perrière [Vignotan]
W2222010	0.50	1.17	750	984	Le Drac à Corps [Le Sautet]
W2335210	-0.23	0.85	948	70	La Roizonne à la Valette [La Rochette]
W2405010	0.54	0.88	885	51	La Jonche à la Mure
W2714010	-0.04	0.66	1088	223	La Romanche à Mizoën [Chambon amont]
W3315010	-0.72	0.23	962	74	Le Meaudret à Méaudre
W3335210	-1.49	0.59	707	37	L' Adouin à Saint-Martin-en-Vercors [Tourtre]
X0010010	0.98	1.44	1363	206	La Durance à Val-des-Prés [Les Alberts]
X0100010	-1.39	0.83	1190	548	La Durance à Briançon [aval]
X0310010	-1.88	0.60	784	2283	La Durance à Embrun [La Clapière]
X0434010	1.46	1.03	1136	542	L' Ubaye à Barcelonnette [Abattoir]
X0454010	1.26	1.27	806	943	L' Ubaye au Lauzet-Ubaye [Roche Rousse]
X0500010	-1.03	0.93	756	3580	La Durance à Espinasses [Serre-Ponçon]
X1034020	-0.14	1.14	674	731	Le Buech à Serres [Les Chambons]
X1225010	-0.01	0.85	829	165	Le Bes à la Javie [Esclangon-Péroure]
X2114010	0.97	0.94	943	138	L' Issole à Saint-André-les-Alpes [Mourefrey]
Y0115410	-1.50	0.96	101	16	La Massane à Argelès-sur-Mer [Mas d'en Tourens]
Y0255020	-0.14	0.65	197	49	L' Ample à Reynès [Le Vila]
Y0325010	0.38	0.78	160	32	La Canterrane à Terrats [Moulin d'en Canterrane]
Y0624020	-0.31	0.02	246	218	L' Agly à Saint-Paul-de-Fenouillet [Clue de la Fou]
Y1225010	0.25	0.07	346	66	Le Lauquet à Greffeil
Y1325010	-0.10	0.46	128	142	Le Treboul à Villepinte

Y1415020	-0.09	0.33	94	242	L' Orbiel à Bouilhonnac [Villedubert]
Y1416210	-0.67	0.84	109	85	La Clamoux à Malves-en-Minervois
Y2015010	0.63	1.21	198	155	L' Arre au Vigan [La Terrisse]
Y2102010	-0.73	0.87	139	916	L' Hérault à Laroque
Y2214010	-0.37	1.06	160	181	La Lergue à Lodève
Y3204010	0.49	1.25	40	116	Le Lez à Montferrier-sur-Lez [Lavalette]
Y4002010	-0.32	0.46	252	50	L' Arc à Pourrières
Y4022010	-0.06	0.56	174	297	L' Arc à Meyreuil [Pont de Bayeux]
Y4214010	-0.46	0.19	96	205	La Touloubre à la Barben [La Savonnière]
Y4604020	0.52	0.55	81	184	Le Gapeau à Solliès-Pont
Y4624010	-0.03	0.83	12	536	Le Gapeau à Hyères [Sainte-Eulalie]
Y5005210	0.47	0.40	254	146	Le Cauron à Bras [Pont de l'Avocade]
Y5032010	-0.74	0.64	183	505	L' Argens à Châteauvert
Y5105010	3.33	1.35	181	203	Le Caramy à Vins-sur-Caramy [Les Marcounious]
Y5106610	1.22	0.86	189	228	L' Issole à Cabasse [Pont des Fées]
Y5202010	-0.73	0.72	42	1651	L' Argens aux Arcs
Y5215020	-0.34	0.92	46	229	L' Aille à Vidauban [Le Baou]
Y5235010	-0.58	0.78	151	194	La Nartuby à Trans-en-Provence
Y5235030	-0.13	0.61	235	149	La Nartuby à Châteaudouble [Rebouillon]
Y5312010	-0.95	0.69	8	2514	L' Argens à Roquebrune-sur-Argens
Y5505410	-3.86	0.72	7	48	Le Grenouiller à Saint-Raphaël [Agay]
Y5615010	-0.11	0.94	133	206	Le Loup à Tourrettes-sur-Loup [Les Vallettes]
Y5615020	-0.06	0.79	192	153	Le Loup à Gourdon [Loup amont]
Y6432010	-0.60	0.96	188	1829	Le Var à Malaussène [La Mescla]
Y6434010	0.19	1.04	140	443	L' Estéron au Broc [La Clave]
Y6624010	-0.16	1.31	280	453	La Roya à Breil-sur-Roya

Mis en forme : Anglais (Royaume-Uni)

Table 1. Summary of the elasticity notations used in this paper (*X* being precipitation *P* or potential evaporation ~~E_0~~E_P)

Notation	Definition	Formula
$\varepsilon_{Q/X}$	*Relative streamflow elasticity – percent* change of streamflow *Q* by *percent* change of climate variable *X*	$\frac{\Delta Q}{\overline{Q}} = \varepsilon_{Q/X} \frac{\Delta X}{\overline{X}}$
$e_{Q/X}$	*Absolute streamflow elasticity – mm* change of streamflow *Q* by *mm* change of climate variable *X*	$\Delta Q = e_{Q/X} . \Delta X$

Table 2. Comparison of the theoretical and empirical elasticity assessment methods

	Theoretical (model-based) elasticity assessment	**Empirical (data-based) elasticity assessment**
Co-variations of different climatic variables	The modeling approach distinguishes between the impact of different climatic variables (by keeping part of the forcing constant while modifying the other part).	Problem: the changes in observed climatic variables can be correlated (e.g., ΔP negatively correlated with ΔT when the driest years are also the warmest), which makes it more difficult to attribute streamflow changes to one or the other variable
Data requirements	No need for long concomitant series of observed streamflow and climatic variables (only what is needed for model calibration)	Long concomitant series of observed streamflow and climatic variables are required
Extrapolation capacity	Extrapolates to extreme climatic changes (i.e., to changes that have not been observed over historical records)	Can only deal with the changes that have been observed in the available historical record.

Table 3. Regression models used to assess empirical elasticity

Notation	Definition	Inputs	Number of parameters
NP	Nonparametric regression	$\Delta P_i^{(M)}$ or $\Delta E_{P_i}^{(M)}$	0
OLS1	Ordinary least squares using a single climate input	$\Delta P_i^{(M)}$ or $\Delta E_{P_i}^{(M)}$ ~~$\Delta E_{0_i}^{(M)}$~~	1
OLS2	Ordinary least squares using two climate inputs	$\Delta P_i^{(M)}$ and $\Delta E_{P_i}^{(M)}$ ~~$\Delta E_{0_i}^{(M)}$~~	2
GLS1	Generalized least squares using a single climate input	$\Delta P_i^{(M)}$ or $\Delta E_{P_i}^{(M)}$ ~~$\Delta E_{0_i}^{(M)}$~~	3
GLS2	Generalized least squares using two climate inputs	$\Delta P_i^{(M)}$ and $\Delta E_{P_i}^{(M)}$ ~~$\Delta E_{0_i}^{(M)}$~~	4

Table 4. Univariate regression models for empirical elasticity assessment

$\Delta Q_i^{(M)} = e^{(M)}{}_{Q/X} . \Delta X_i^{(M)} + \omega_i$		**Eq. 12**
OLS	$\omega_i \sim N(0,\sigma)$	
GLS	$\begin{cases} \omega_i = \alpha \omega_{i-1} + \delta_i \\ \delta_i \sim N(0,\sigma) \\ \omega_i \sim N(0, \sigma\sqrt{1-\alpha^2}) \end{cases}$	
$\Delta Q_i^{(M)}$: streamflow anomaly over *M* years, considered as the explained variable $\Delta X_i^{(M)}$: rainfall or potential evaporation anomaly for the same sub-period, considered as the explanatory variable $e_{Q/X}^{(M)}$: streamflow elasticity (equal to the regression slope) ω_i: regression residual α: parameter of the first-order autoregressive process (AR1) δ_i: innovation of the autoregressive process σ: standard deviation *M*: number of years over which the long-term streamflow, precipitation and evaporation average is computed		

Table 5. ~~Univariate~~ Bivariate regression models for empirical elasticity assessment

$\Delta Q_i^{(M)} = e_{Q/P}^{(M)}.\Delta P_i^{(M)} + e_{Q/Ep}^{(M)}.\Delta E_{P_i}^{(M)} + \omega_i$		**Eq. 13**
OLS	$\omega_i \sim N(0,\sigma)$	
GLS	$\begin{cases} \omega_i = \alpha\omega_{i-1} + \delta_i \\ \delta_i \sim N(0,\sigma) \\ \omega_i \sim N(0,\sigma\sqrt{1-\alpha^2}) \end{cases}$	

$\Delta Q_i^{(M)}$: streamflow anomaly over *M* years, considered as the explained variable

$\Delta X_i^{(M)}$: rainfall or potential evaporation anomaly for the same sub-period, considered as the explanatory variable

$e_{Q/X}^{(M)}$: streamflow elasticity (equal to the regression slope)

ω_i: regression residual

α: parameter of the first-order autoregressive process (AR1)

δ_i: innovation of the autoregressive process

σ: standard deviation

M: number of years over which the long-term streamflow, precipitation and evaporation average is computed

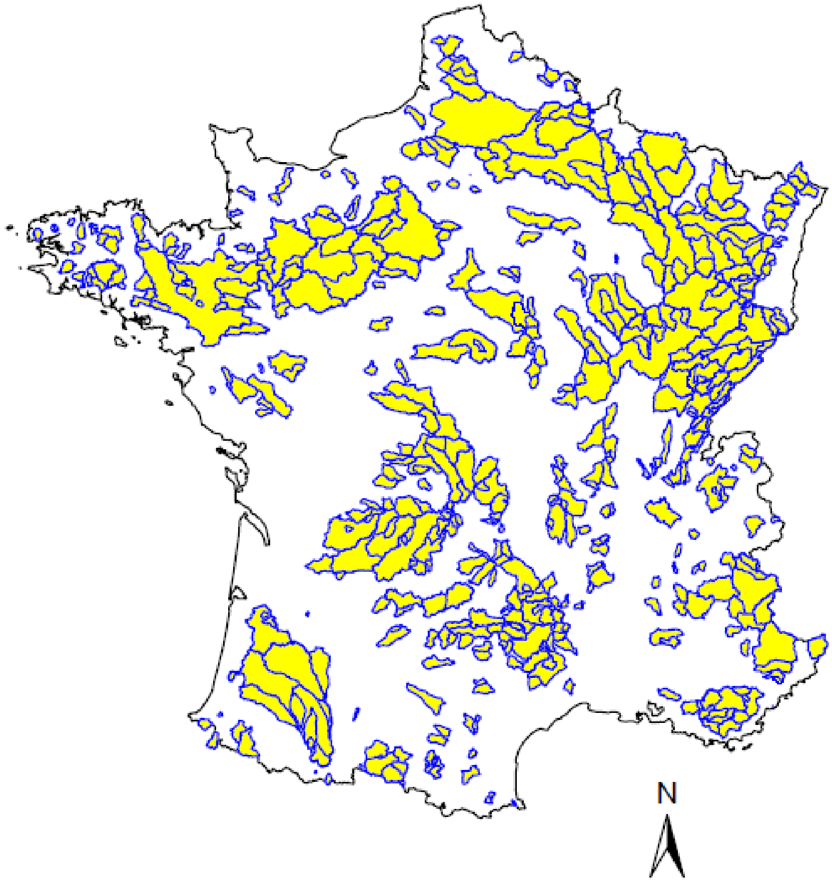

Figure 1. Location of the 519 French catchments analyzed in this study

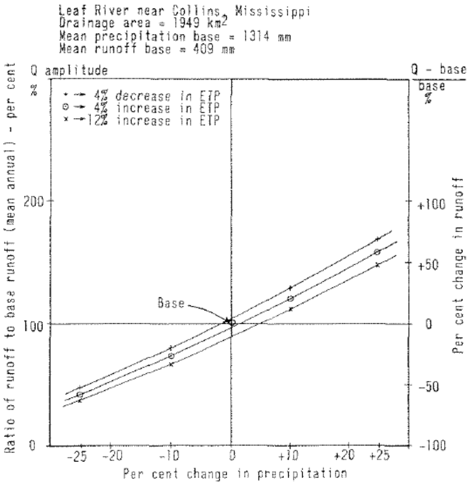

Figure 2. Yield change graph proposed by Nemec and Schaake (1982) to illustrate the hydrological elasticity analysis

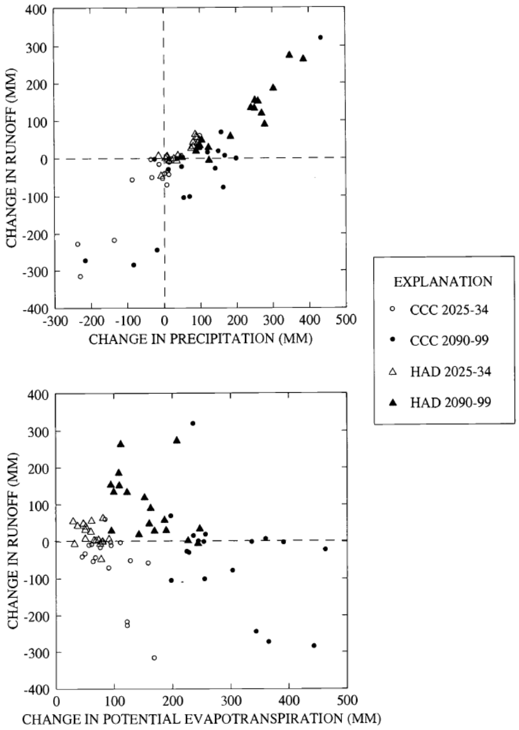

Figure 3. Elasticity graphs proposed by Wolock and McCabe (1999)

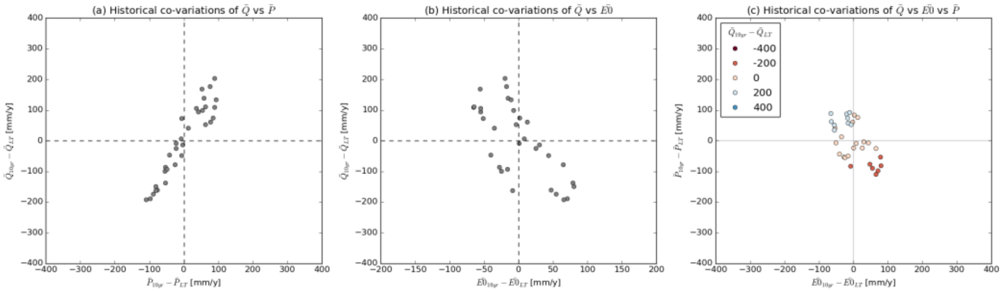

Figure 4. Streamflow elasticity graphs for an empirical (data-based) assessment for the Brèze catchment at Meyrueis (code: O3165010): (a) ΔQ vs ΔP, (b) ΔQ vs ΔE_P, (c) ΔQ (color-coded) vs ΔP and ΔE_P

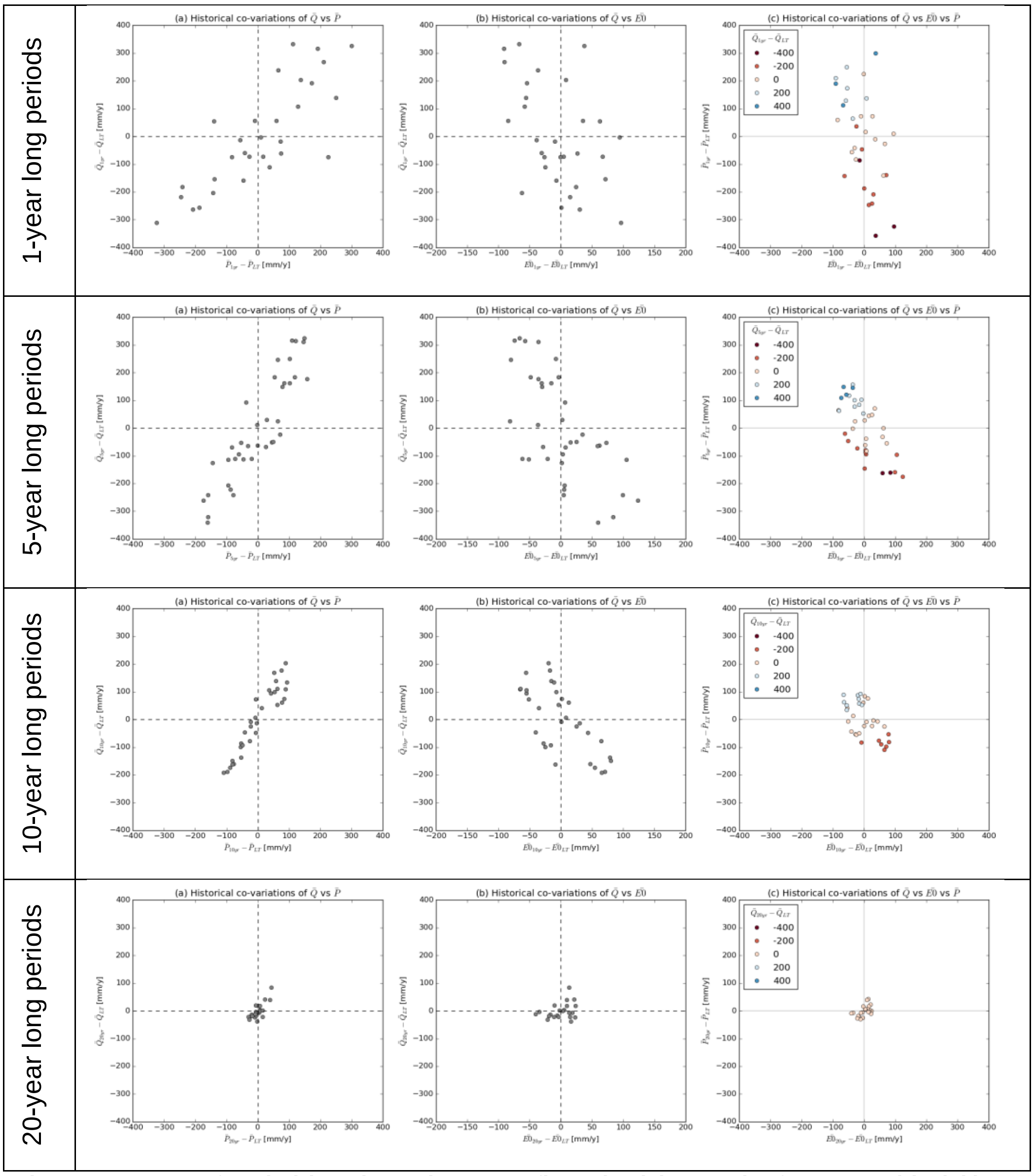

Figure 5. Impact of period length on the streamflow elasticity graphs for an empirical (data-based) assessment. The graphs present from left to right ΔQ vs ΔP, ΔQ vs ΔE_p, ΔQ (in colors) vs ΔP and ΔE_p. LT stands for Long Term (entire period).

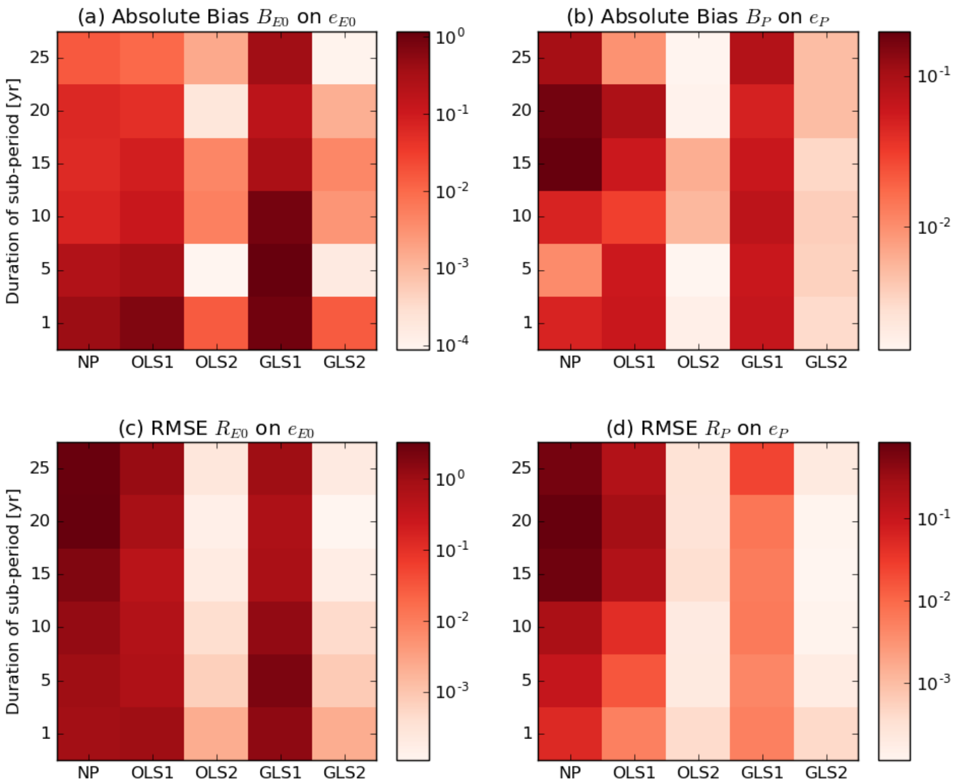

Figure 6: Performance of the five models proposed to compute empirical elasticity, tested on synthetic data generated with the Turc-Mezentsev model.

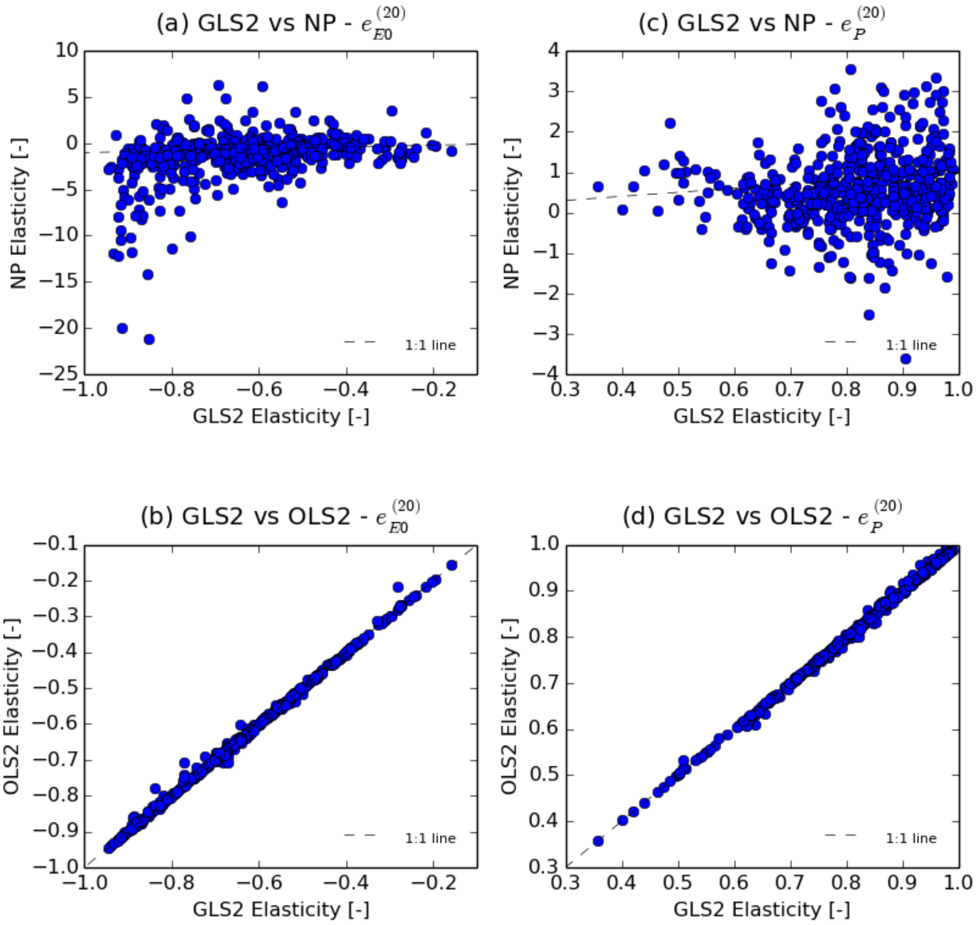

Figure 7: Comparison of elasticity estimates obtained with the GLS2, OLS2 and NP methods using synthetic flow data and 20-year sub-periods.

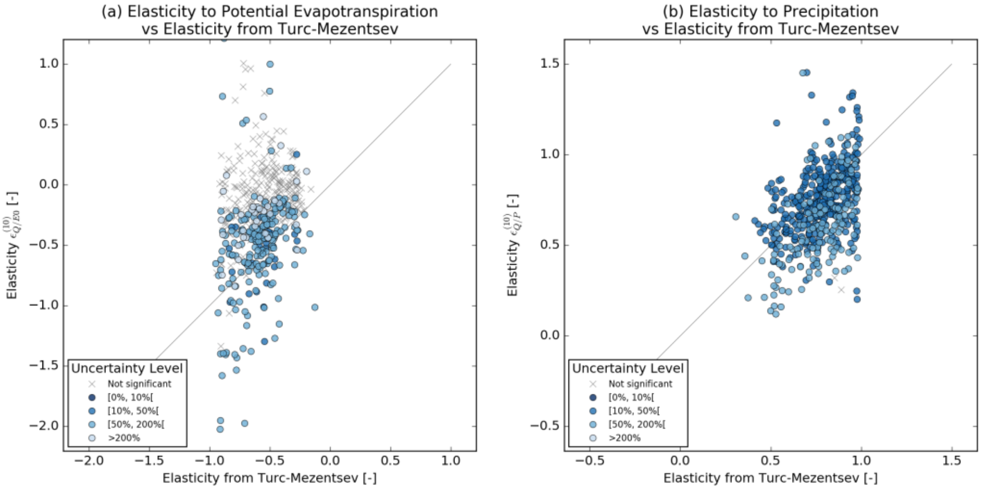

Figure 8. Comparison of the data-based and model-based elasticities; streamflow elasticity to potential evaporation (a) and precipitation (b).

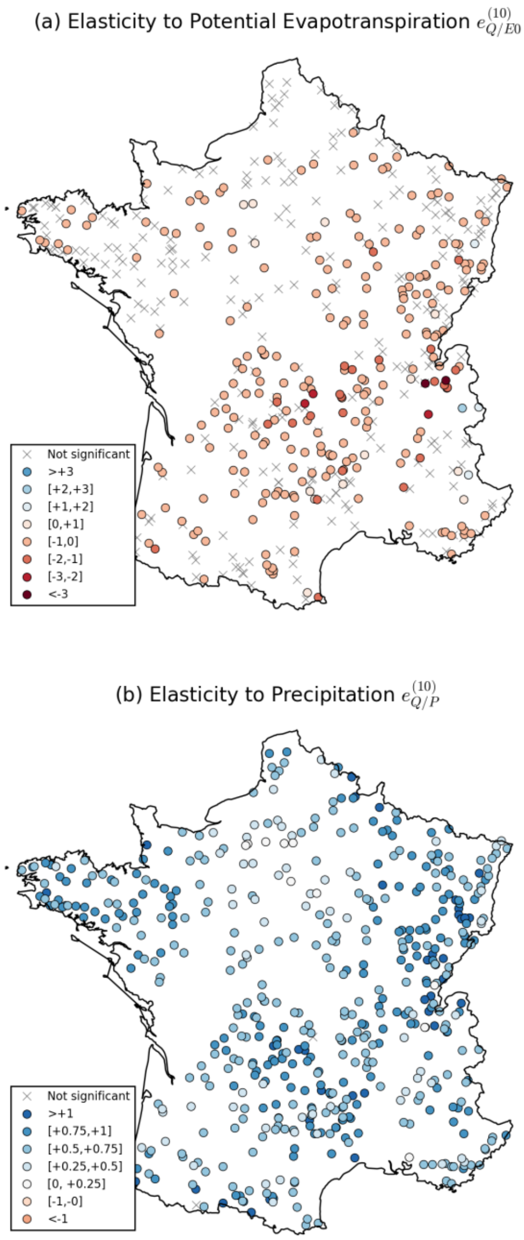

Figure 9. Regional analysis of (a) streamflow elasticity to precipitation and (b) streamflow elasticity to potential evaporation. Elasticity values were obtained by the GLS2 regression method using 20-year sub-periods. Each dot represents a catchment outlet, the color represents the elasticity value. Those catchments where the linear correlation was found to be nonsignificant are indicated with a cross.

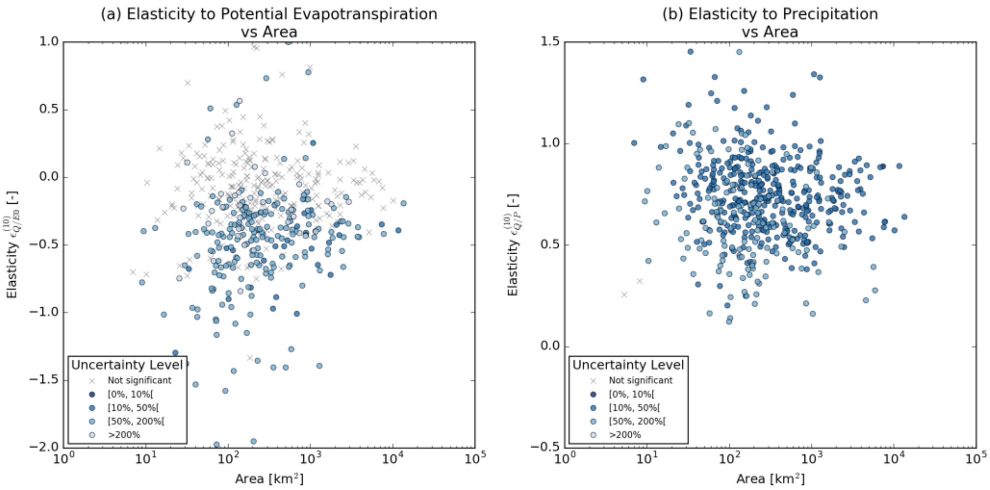

Figure 10. Elasticity values vs catchment area: (a) streamflow elasticity to potential evaporation and (b) streamflow elasticity to precipitation. Elasticity values were obtained by the GLS2 regression method with 20-year sub-periods.

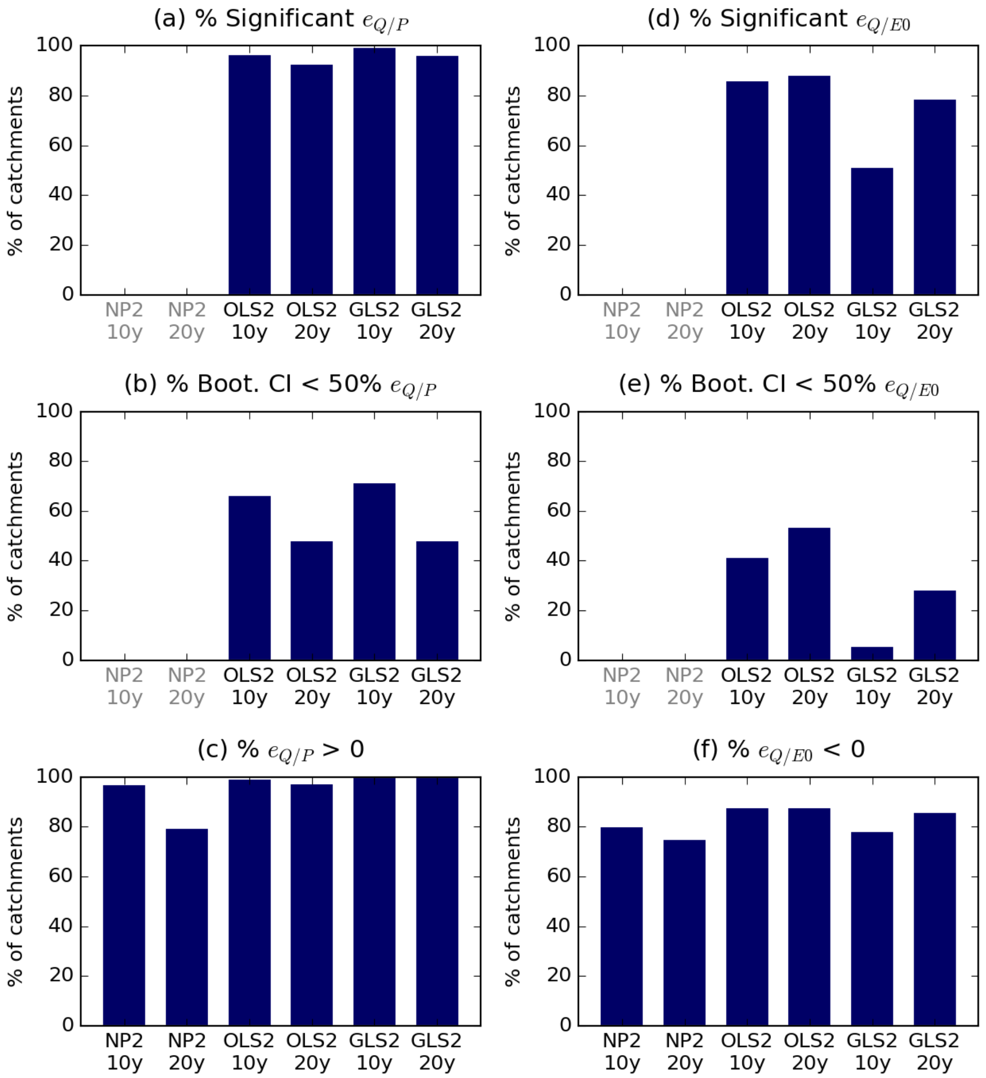

Figure 11. Proportion of catchments having a positive outcome for (a) the Shapiro-Wilks normality test and (b) the Durbin-Watson test on autocorrelation of innovations

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