Hydrol. Earth Syst. Sci. Discuss., 10, 3103–3142, 2013
www.hydrol-earth-syst-sci-discuss.net/10/3103/2013/
doi:10.5194/hessd-10-3103-2013

Hydrology and Earth System Sciences
Open Access
Discussions

Non-stationary flood frequency analysis in continental Spanish rivers, using climate and reservoir indices as external covariates

J. López and F. Francés

Research Institute of Water and Environmental Engineering, Universitat Politècnica de València, Spain

Received: 31 January 2013 – Accepted: 8 February 2013 – Published: 12 March 2013

Correspondence to: J. López (jeslpede@posgrado.upv.es) and
F. Francés (ffrances@hma.upv.es)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Recent evidences of the impact of persistent modes of regional climate variability, coupled with the intensification of human activities, have led hydrologists to study flood regime without applying the hypothesis of stationarity. In this study, a framework for flood frequency analysis is developed on the basis of a tool that enables us to address the modelling of non-stationary time series, namely, the "generalized additive models for location, scale and shape" (GAMLSS). Two approaches to non-stationary modelling in GAMLSS were applied to the annual maximum flood records of 20 continental Spanish rivers. The results of the first approach, in which the parameters of the selected distributions were modeled as a function of time only, show the presence of clear non-stationarities in the flood regime. In a second approach, the parameters of the distributions are modeled as functions of climate indices (Arctic Oscillation, North Atlantic Oscillation, Mediterranean Oscillation and the Western Mediterranean Oscillation) and a reservoir index that is proposed in this paper. The results when incorporating external covariates in the study highlight the important role of interannual variability in low-frequency climate forcings when modelling the flood regime in continental Spanish rivers. Also, with this approach is possible to properly introduce the impact on the flood regime of intensified reservoir regulation strategies and to be used as predictive tools. Application of non-stationary analysis shows that the differences between the quantiles obtained and their stationary equivalents may be important over long periods of time.

1 Introduction

One of the greatest challenges facing the Hydrology is to gain a better understanding of flood regimes. To do this, flood frequency analysis (FFA) is most commonly used by engineers and hydrologists worldwide and basically consists of estimating flood peak quantiles for a set of non-exceedance probabilities. The validity of the results in the application of FFA is theoretically subject to the hypothesis that the series are independent and identically distributed (Stedinger et al., 1993; Khaliq et al., 2006). The hypothesis of stationarity has been a cornerstone in FFA and has conditioned flood study under the assumption that time series are free of trends and abrupt changes (Salas, 1992). In fact, all water-related infrastructures were and are currently designed assuming a stationary world. In recent decades the evidence of natural variation in the climatic system, as well as the potential influence of human activity on climate change or in directly changing the hydrologic cycle (NRC, 1998), have made the hypothesis of stationarity widely questioned. With this point in mind, several researchers have begun exploring the validity of this hypothesis in flood regimes in regions around the world (Douglas et al., 2000; Franks, 2002; Mudelsee et al., 2003; Milly et al., 2005; Villarini et al., 2009a; Wilson et al., 2010). These studies have revealed clear violations of the assumption of stationarity, which is consistent with studies that indicate an acceleration in the hydrologic cycle (Allen and Smith, 1996; Held and Soden, 2006) and the impact it has on the frequency of extreme events (Milly et al., 2002; Blösch and Montanari, 2010).

Focusing on the Iberian Peninsula, a lack of stationarity in some components of the hydrologic cycle has been demonstrated in several recent studies (De Luis et al., 2009; Gonzalez et al., 2009; López-Moreno et al., 2010, 2011; Lorenzo-Lacruz et al., 2011). These results have detected the presence of trends, and their conclusions suggest an important link between the variability exhibited in hydroclimatic variables and the main low-frequency climate forcings affecting southern Europe. However, little research has examined the presence or absence of stationarity in flood regimes of Iberian Peninsula rivers, with the exception of Silva et al. (2012) and López and Francés (2013). Results in these studies show the teleconnection between the observed changes in flood regimes and anomalies in the indices that describe the temporal evolution of low-frequency atmospheric circulation patterns. It is inevitable that climate forcings are pointed to as potential modulators of the frequency and magnitude of floods in the Iberian Peninsula, given that the peninsula is located in a region exposed to disturbances from both the Atlantic Ocean and the Mediterranean Sea. Other factors in addition to low-frequency climate variability that may influence the magnitude and frequency of river floods are linked to human activities, such as changes in land use, deforestation, dam construction, etc. With respect to continental Spain, one of the human activities that may have a considerable impact on flood frequency is the high degree of regulation of major rivers, which is the result of the construction of numerous dams in the twentieth century – the number of large dams growing from 58 in 1900 to 1195 in 2000 and with a total storage capacity of 56 500 hm^3 (Berga-Casafont, 2003). Therefore, the effect of intensifying the strategies of regulation by dams in time must be considered when modelling floods in most of the continental Spanish rivers.

Advances in the field of synoptic climatology have shown that ocean-atmosphere interactions are not chaotic or random, and that it is possible to identify patterns of low-frequency variability that are semi-stationary. These observations have helped overcome the difficulties encountered in studying the relationship between climate variability and hydrological variables. In the last decade, due to the definition of various climate indices that describe the evolution of atmospheric circulation patterns on a macro-scale, the analysis of the influence of low-frequency climate forcings on changes experienced by hydrological variables has been intensified. Studies in various regions of the world have shown the important influence of phenomena such as ENSO (El Niño-South Oscillation) on interannual and interdecadal hydrological variables (Waylen and Poveda, 2002; Philips et al., 2003; Xu et al., 2004; Jin et al., 2005; Zhang et al., 2007). In Europe, the North Atlantic Oscillation (NAO) has been shown to be the main source of low-frequency variability in the flow regime in several major rivers (Shorthouse and Arnell, 1997; Rîmbu et al., 2002; Markovic et al., 2009; Massei et al., 2010). The influence of the NAO on rivers of Spain has also been established in recent years by various researchers (Trigo et al., 2004; Gámiz-Fortis et al., 2008; Morán et al., 2010a,b; Lorenzo-Lacruz et al., 2011; López and Francés, 2013) and this has demonstrated the possibility of incorporating climate indices in FFA.

Recently, Milly et al. (2008) stated the stationarity hypothesis must be abandoned and that “stationarity is dead” and “should not be revived”. The authors called for innovative thinking and methods to provide estimates of hydrologic indicators that would be both reliable and useful for water management. Non-stationary modelling of floods in the Iberian Peninsula has not been previously studied. However, in the light of current knowledge, it is now necessary to study floods with a non-stationary point of view. The river basins of continental Spain are sites of broad interest for addressing this study in light of the importance of low-frequency atmospheric circulation patterns as flood generation mechanisms (López and Francés, 2013).

In the literature various methodologies to the probabilistic modelling of flood frequency in a non-stationary context have been proposed. Khaliq et al. (2006) presented a review of most of them including the incorporation of trends in the parameters of the distributions, the incorporation of trends in statistical moments, the quantile regression method and the local likelihood method. Studies of FFA under non-stationary conditions have mostly assumed trends in time (Olsen et al., 1998; McNeil and Saladin, 2000; Stedinger and Crainiceanu, 2001; Strupczewski et al., 2001; Renard et al., 2006; Yi et al., 2006; Leclerc and Ouarda, 2007; Delgado et al., 2010). The time-varying models provide useful tools for reconstructing the behaviour of flood frequency. However, the adoption of predictions from a model that is time dependent is not entirely correct: trends can change in the short and long-term because of climate variability and the intensification of human activities. For this reason, in the last decade some researchers have explored the possibility of incorporating climate indices as external forcings into models for FFA, assuming linear and nonlinear dependences (Katz et al., 2002; Sankarasubramanian and Lall, 2003; El Aldouni et al., 2007; Kwon et al., 2008; Aissoui-Fqayeh et al., 2009; Ouarda and El-Aldouni, 2011). The results have shown the feasibility of incorporating climate indices as covariates in the models, and so enabling the models to better describe changes in flood regimes over time by incorporating explanatory variables. On the contrary, few studies have included the impact of anthropogenic activities in the modelling of flood frequency. One example is the study made by Villarini et al. (2009b) that incorporated a population index to describe the impact of land use changes in an urban watershed. Problems that have confronted the implementation of non-stationary FFA are linked to the selection of the model and the complexity involved in estimating parameters. In general, non-stationary models have a larger number of parameters than stationary ones, and so the question of parsimony becomes an important point.

The aim of this paper is to address the non-stationary modelling of river floods in continental Spain and demonstrate that the incorporation of climate forcings (through various climate indices) and human activity (using a specific index for the presence of reservoirs) may result in appropriate covariates to describe changes in the frequency and magnitude of floods. In addition, we will show the differences over time in estimated quantiles considering and excluding non-stationarity in order to analyze the importance of considering non-stationary models. It has been observed that the main patterns of low-frequency atmospheric variability affecting Europe are correlated in their principal variability components; and so in order to address the question of parsimony in the models, we propose to use empirical orthogonal functions analysis (EOFs) to identify the principal components (PCs) that contain the greatest variance of climate indices. These PCs will be used as the external forcing covariates, reducing the number of model parameters. To incorporate these external covariates we have used the "generalized additive models for location, scale and shape" (GAMLSS) as proposed by Rigby and Stasinopoulos (2005). GAMLSS was successfully used by Villarini et al. (2009b, 2010a,b, 2011) in hydrological studies.

2 Case study

The Iberian Peninsula is surrounded by two huge and contrasting masses of water (the Atlantic Ocean and the Mediterranean Sea), which coupled with a complex geography ensures a marked irregularity in the spatial and temporal distribution of precipitation (Rodríguez-Puebla et al., 2001; Trigo et al., 2004). This irregularity in rainfall is directly transferred to the flow and flow regime in the Iberian rivers (Benito et al., 2008).

Figure 1 shows the location of 20 gauging stations selected for this study within the continental Spain, which occupies approximately 84 % of the Iberian Peninsula. It is important to note that given the crucial impact of reservoirs in the flood regime of major rivers, sites were selected with natural as well as altered regimes.

2.1 Flood data

The series of annual maximum daily flows from 20 gauging stations cover the period 1950–2007. Table 1 shows the main characteristics. The stations are distributed throughout continental Spain, 8 are in natural regimes and 12 have upstream reservoirs which potentially can affect their flood regime (altered regime). It is important to note that the selection of annual maximum daily flows was carried out for hydrological years, running from 1 October to 30 September of the following year. The hydrometric time series and reservoir information were obtained from the database of the Centro de Estudios Hidrográficos del CEDEX (http://hercules.cedex.es/general/default.htm).

2.2 Reservoir index (RI)

As an indicator of the impact of regulation strategies following the construction of dams on flood regimes in rivers of continental Spain, a dimensionless reservoir index (RI) is proposed:

$$\mathrm{RI} = \sum_{i=1}^{N} \left(\frac{A_i}{A_\mathrm{T}}\right) \cdot \left(\frac{C_i}{C_\mathrm{T}}\right) \qquad (1)$$

where N is the number of reservoir upstream of gauging station, A_i is the catchment area of each reservoir, A_T is the catchment area of the gauge station, C_i is the total capacity of each reservoir, and C_T is the mean annual runoff at the gauging station. Table 2 shows the maximum (i.e. nowadays) values obtained for the RI at sites under an altered regime, where the different degrees of alteration for each site are obvious:

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀◀ ▶▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

from a light alteration in station 2015, 5029, 8032 and 9002 to a strong one in stations 4014 and 5047. Similarly, Fig. 2 shows two examples of the time evolution of RI for two study sites compared with the annual floods series. This figure shows the lesser dam impact of the altered flood regime for flow gauge station 2015 (interior peninsular), while flow gauge station 7006 (Mediterranean coast) shows a high degree of alteration of the flood regime after dam construction in the late 50's.

2.3 Flood generation mechanisms in continental Spanish rivers

According to previous studies, floods in the western part of the Iberian Peninsula are closely linked to changes in winter precipitation (Capel, 1981; Benito et al., 1996; Rodrigo et al., 2000). Winter precipitation is mostly advective, which is the result of the entry of frontal systems that generate persistent and heavy rainfall. These rainfalls are associated with low pressure areas in the Atlantic that send moist air across the peninsula, highlighting the impact that atmospheric circulation patterns such as the AO and the NAO can have on flood generation. On the other hand, the generation of floods in the eastern peninsular is linked to the development of mesoscale convective systems (Llasat and Puigcerver, 1994) that produce heavy rainfall during the late summer and early autumn. Benito et al. (2008) mention that these systems mainly affect the Mediterranean coast, with no significant effects on the Iberian central plateau. However, the flood regime in the Mediterranean facade is not so simple. Other factors affect flood regimes, such as the complexity of the orography, melting snow process in Pyrenean rivers in the north-eastern part of the peninsula (Beguería et al., 2003), and the high degree of dam regulation. The influence of air masses from the Atlantic entering from a southwest-northeast direction also affects river basins in the northeast of the peninsula, where behaviour similar to the western basins is seen with major floods during the winter months. This area facilitates the entry of air masses and acts as a moisture corridor towards the Pyrenees, where these flows are reactivated and generate orographic precipitation. In the basins of the Cantabrian coast (northwestern peninsular) air flows from the north and northwest have an important influence, while rainfall in the interior of the Iberian Peninsula generated by these flows makes a smaller contribution.

2.4 Climate indices

The teleconnection between the flood regime and climate indices that characterizes low-frequency climate variability has recently been the subject of study worldwide. Previous studies in continental Spain have shown links in the time evolution of flow and rainfall regimes with the evolution of low-frequency circulation patterns (Trigo et al., 2004; López-Bustins et al., 2008; Morán et al., 2010a; Lorenzo-Lacruz et al., 2011). Our attention is focused on four climatic indices: North Atlantic Oscillation index (http://www.cru.uea.ac.uk/); Arctic Oscillation index (http://www.cpc.noaa.gov); Mediterranean Oscillation index (http://www.cru.uea.ac.uk/); and Western Mediterranean Oscillation index (http://www.ub.edu/gc/English/wemo.htm). These indices were selected to incorporate climate forcings in non-stationary modelling of the flood frequency in continental Spanish rivers and so obtain potential predictive variables.

Actually, climate indices for the winter period (December to February) were used as external covariates in the non-stationary models. This particularity was taken because in these months it was observed the greatest influence of low-frequency atmospheric circulations patterns on the variability of river flood regimes in continental Spain (Trigo et al., 2004; Lorenzo-Lacruz et al., 2011; López and Francés, 2013). To satisfy the principle of parsimony, we propose a prior EOFs analysis. EOFs analysis is usually undertaken with two objectives; finding spatial patterns and reducing the dimensionality of a set of variables that reveal multicollinearity. With the latter objective it was decided to use this analysis because previous results had shown a high degree of correlation with climatic indices that describe the behaviour of macroscale atmospheric circulation patterns. EOFs analysis showed that the first two components account for 93 % of the total variance of the four indices, and so it was decided to retain the two first PCs as explanatory covariates of the selected distribution parameters. The retained principal components show that the first component (PC1 – 66 %) explains the temporal evolution of the winter indices NAO, AO and MO; while the second component (PC2 – 27 %) is clearly linked to the evolution of winter WeMO.

The modelling period was 1950–2007 – which is the common period for flood records and the climatic indices.

3 Methodology

Modelling of time series for which the stationarity hypothesis can no longer be taken for granted requires a modelling framework in which the parameters of the selected distributions can vary as a function of explanatory variables. As mentioned in the introduction, in this paper we use the generalized additive models for location, scale and shape called GAMLSS and proposed by Rigby and Stasinopoulos (2005). In GAMLSS the response random variable Y (annual maximum peak discharges in this work) has a parametric cumulative distribution function and its parameters can be modeled as function of selected covariates, in this case: time (t_i), climate indices (AO$_i$, MO$_i$, NAO$_i$ and WeMO$_i$) and reservoir index (RI$_i$). Therefore, three different models were used for the analysis of flood frequency in the study sites: model 0, 1 and 2. We first consider the stationary model (model 0), in which the distributions parameters are independent on covariates: all the parameters are constants. After then, we address the time-varying model (model 1), where the distribution parameters can vary as function of time only. Finally, model 2 incorporates external covariates, where the distribution parameters can vary as function of climate and reservoir indices.

A GAMLSS model assumes that independent observations y_i for $i = 1, 2, 3, \ldots, n$ have distribution function $F_Y\left(y_i|\boldsymbol{\theta}_i\right)$ where $\boldsymbol{\theta}_i = \left(\boldsymbol{\theta}_{i1}, \boldsymbol{\theta}_{i2}, \ldots, \boldsymbol{\theta}_{ip}\right)$ is a vector of p distribution parameters accounting for location, scale and shape. Ordinarily, p is less or equal to four, since, one, two, three and four parameter distributions guarantee enough flexibility for most applications in Hydrology. The distribution parameters are related to covariates by monotonic link functions $g_k(\cdot)$ for $k = 1, 2, \ldots, p$ where the parameters were modeled through proper link functions. In this work only identity and logarithm link functions worked properly (Table 3). GAMLSS involves several models; in particular we use the semi-parametric additive formulation:

$$g_k(\boldsymbol{\theta}_k) = \boldsymbol{\Phi}_k\boldsymbol{\beta}_k + \sum_{j=1}^{m} h_{jk}(\boldsymbol{x}_{jk}) \tag{2}$$

where $\boldsymbol{\theta}_k$ is a vector of length n, $\boldsymbol{\Phi}_k$ is a matrix of explanatory variables (i.e. covariates) of order $n \times m$, $\boldsymbol{\beta}_k$ is a parameter vector of length m, $h_{jk}(\cdot)$ represents the functional dependence of the distribution parameters on explanatory variables $\boldsymbol{x}_{jk}$. This dependence can be linear or smooth through smoothing terms. In this study the smooth dependence is based on cubic spline functions. The addition of smoothing terms in the Eq. (2) has many advantages, such as identifying non-linear dependence in modelling the parameters of the parametric distribution on explanatory variables. This dependence can be linear or smooth through cubic splines functions.

When smooth dependence is incorporated to describe the relation between distribution parameters and selected covariates, this dependence tends to increase the complexity of the model. In order to avoid the over-fitting of models, the degrees of freedom of the cubic splines are optimized using the Akaike Information Criterion (AIC) and the Schwarz Bayesian Criterion (SBC). For an exhaustive discussion, reader can consult Rigby and Stasinopoulos (2005) and Stasinopoulos and Rigby (2007). With these criteria, final models are provided with a balance between accuracy and complexity. It is worth noting that in none of the cases, the degrees of freedom in the cubic spline were greater than ln(n). This is achieved because increased model complexity is linked to the extraction of information from the data. On the opposite, as degrees of freedom tend to zero, the cubic spline tends to a straight line. Therefore, the linear trend is included as a limiting case in represent the dependence of distribution parameters on covariates. If there are no additive terms in any of the distribution parameters, we have a model of the form:

$$g_k(\boldsymbol{\theta}_k) = \boldsymbol{\Phi}_k\boldsymbol{\beta}_k \tag{3}$$

This is the parametric linear model, where $\mathbf{\Phi}_k \boldsymbol{\beta}_k$ is a combination of linear estimators. In case that all the distribution parameters are independent of the covariates, then for $\boldsymbol{\theta}_k$ the model simplifies to a stationary model with constants parameters $g_k(\boldsymbol{\theta}_k) =$ constant.

Once we define the functional dependence between distribution parameters and each selected covariates and the effective degrees of freedom for the cubic spline, we select the distribution function $F_Y\left(y_i|\boldsymbol{\theta}_i\right)$ according to the largest value of the maximum likelihood. In this paper, we selected five widely used distribution functions in modelling streamflow data (Table 3): Gumbel (GU); Lognormal (LNO); Weibull (WEI); Gamma (GA); and Generalized Gamma (GG). The first four have two parameters and the last one have three parameters. For a more comprehensive discussion on theory, model fitting, and selection, the reader is referred to Rigby and Stasinopoulos (2005), Stasinopoulos and Rigby (2007) and Villarini et al. (2009b).

In the absence of a statistic to evaluate the goodness of fit of the selected models as a whole, verification was made in accordance with the recommendations of Rigby and Stasinopoulos (2005) by analyzing the normality and independence of the residuals of each model. The first four statistical moments of the residuals and the Filliben correlation coefficients were examined, and a visual inspection of diagnostic plots of the residuals (residuals vs. response, qq-plots and worm plots) was made. This action ensures that the selected models can adequately explore the systematic part, the remaining (residual) information being white noise (random signal). All of the calculations were performed on the platform R (R Development Core Team, 2008), using the freely available gamlss package.

4 Results

4.1 GAMLSS implementation

This section presents the fitted non-stationary models (models 1 and 2) for the 20 study sites. Table 4 summarizes the selected distributions as well as the type of dependence of distribution parameters as a function of time for model 1. Table 5 summarizes the selected distributions, the significant covariates for each parameter and the type of dependence of distributions parameters as a function of external covariates. First of all, it can be seen in both tables that the GG and LNO distributions offer the best overall results in modelling the flood frequency in continental Spanish rivers. And second, the observed results show that the incorporation of time trends and external forcings can affect behaviour of the mean and variance of the distributions.

Model 1 shows that in most sites (80 %) the parameter θ_1 presents time dependence and this dependence is generally via non-parametric smoothing functions. The parameter θ_2 is independent of the time trends in most models (55 %); however, there are also seven cases with linear dependence and only two cases with smooth dependence. For the sites in which the best fitted model was the GG distribution, the parameter θ_3 is time independent in all cases.

For non-stationary models with incorporated external covariates (model 2), the high significance of PC1 is obvious as the explanatory covariate in the parameters of the selected distributions. It can also be seen in Table 5 that the PC1 is presented as a significant covariate in parameter θ_1 in 18 sites, while only 3 sites are presented as significant covariates for parameter θ_2. These results are due to the strong influence that the AO, MO, and NAO configurations exert in modulating the hydroclimate in much of the Iberian Peninsula. A weak statistical significance is observed with PC2, which is presented as an explanatory covariate in 8 sites for the θ_1 parameter and 4 sites for the θ_2 parameter. The lesser significance of PC2 is explained by the lesser influence of WeMO in modulating flood regimes – with its influence limited to the basins on the north of the Iberian Peninsula. In a similar way to the results obtained in model 1, the parameter θ_3 of the GG distribution is independent of climate and reservoir indices. In other words, it seems skewness coefficient and other high order dimensionless moments are low sensible to climate and regulation variations.

Figure 3 top panels show, with an example at station 2015 in the Duero basin, the strong correlation between the AO, MO, and NAO winter climate indices and annual maximum peak discharges (top left panel), as well as with the PC1 (top panel right), where patterns of correlation are particularly evident in the central and western peninsular basins. As representative of northern basins, Fig. 3 lower panels show the strong correlation between the WeMO winter index and annual maximum peak discharges at station 1427 (lower left panel). In this station, a high degree of correlation is also observed with the PC2, which mainly captures the variability of this climate index (lower right panel).

Concerning the result in the 12 study sites under altered regimen, RI is a significant covariate in 6 of them, which have high values of RI. For model 2 the dependence of parameter θ_1 with respect to the climatic and human activity indices is general and usually linear, giving more parsimonious models. In opposition, parameter θ_2 is independent with respect to external forcing in most sites (70 %).

Figure 4 and Table 6 summarize the quality of fit of model 2 at nine representative study sites, which is carried out by inspecting the residual plots and calculating the first four moments of the distribution of the residuals. The results do not indicate significant deviations from normality in the residuals: for 58 data, the critical value of the Filliben's coefficient is 0.979. This result supports the inference that the models fit the data adequately. Similar conclusion was obtained for model 1.

4.2 Results with non-stationary approaches: models 1 and 2

Figure 5 shows the estimated median and the 2.5th and 97.5th percentiles in nine representative sites. The median was selected as a proxy of the observations, also represented in the figure. The results obtained with non-stationary models assuming time dependence only (model 1) show the presence of a pattern of decreasing trends in most of the study sites, these trends being identifiable during the post-1960 period. Model 1 adequately describes the changes in annual maximum flood peaks; however, time-trend models are unable to identify subsequent changes (as can be observed in the stations 1734, 2002, 2015 and 8032). These sites reveal that the increased frequency of floods in western rivers after 1995 is ignored by time-trend models. Moreover, results for sites 4014, 5004, 5047 and 7006 show the effects of intensified regulation by reservoirs in southern basins. These sites clearly show the presence of steeply decreasing trends, and indicate abrupt changes in the series during the 1960's and 70's not reproduced by model 1.

Figure 5 also shows the results obtained in modelling flood frequency under non-stationary conditions while incorporating external forcings (model 2). The improvement after incorporating external covariates in the description of the changes in the flood series is obvious and corroborated with AIC and SBC criteria. It can be seen that model 2 captures more adequately the dispersion of flood values, and shows the potential of climate and reservoir indices to modulate the frequency and magnitude of floods. As in the time-trend models, the modelling for model 2 shows the presence of trends in the flood frequency. In the western basins of the continental Spain the results of flood frequency show the presence of an increasing trend during the period 1950–1970, then a strong downward tendency is observed between 1970–1995, and finally an increasing trend is seen during the period 1995–2005. This pattern can also be observed in mountain basins near the Mediterranean coast in the east of the continental Spain. The presence of reservoirs has clearly impacted on flood frequency in southwestern river basins (4014, 5004 and 5047), as a steep decrease shows in the frequency and magnitude of floods. In addition, the results exhibit higher decrease than the observed in sites under natural regime and sites that have only been slightly altered.

The modelling of flood frequency in Mediterranean basins, and particularly those near the coast and the Pyrenees, reveals a weak or null influence for atmospheric circulation patterns. Figure 5 shows how model 2 does not adequately describe flood behaviour for station 9018. These results clearly show that floods in these basins are linked to mechanisms independent of those used in this study. This station is in a Pyrenean basin that experiences a bimodal flow regime with a strong influence of snowmelt processes in flood generation – a factor not considered in this study. The flood modelling in basins located in the southern Mediterranean shows the potential reservoir index (RI) as a covariate that explains changes caused by regulation strategies at these sites, as the flood magnitude has obviously diminished considerably over the past 40 yr. Incorporating RI enables us to characterize changes in the distribution median, and enables us to see this effect in the model – as can be seen at stations 4014, 5004, 5047 and 7006 in Fig. 5.

By analyzing the results of the modelling in the non-stationary scenario with model 2 and the stationary scenario with model 0 in the two cases presented in Fig. 6, it is possible to observe that the median is underestimated in the stationary model for low values of PC1, while the model overestimates the median for the high values of PC1. These results are very important because when applying the models for estimating flood designs this could lead to major problems if we continue simplifying reality with stationary models. It is clear that peak floods are linked to low values of PC1, while smaller floods are clearly linked to high values. The flood series for station 5004 (Fig. 6 left panel) shows that the impact of reservoirs complicates the identification of the relationship with PC1. However, the incorporation of RI enables us to identify the impact of regulatory strategies and address the more complex relationship.

4.3 Comparison between stationary and non-stationary models

The study of floods in operational Hydrology aims to estimate flood events for a given probability of excess that is defined a priori in order to obtain flooding maps, design protective measures or flood risk management plans. Legislation on flood risk in Europe is based on the FFA for estimating floods associated with various return periods such as 50, 100 and 500 yr (Benito et al., 2004).

Figure 7 shows the results of FFA in stationary conditions (model 0) and non-stationary conditions (models 1 and 2), for an exceedance probability of 0.01 (i.e.

return period of 100 yr). Estimates are presented for 9 of the 20 study sites, which are representative of natural regimes, low altered regime, as well as those that are substantially altered. The graphs highlight the problems of assuming stationarity in estimating flood events. It can be seen that non-stationarity models indicate the existence of periods in which flood frequency experienced significant increases. We can generally speak of a similar pattern of increases in flood frequency during the periods 1960–1975 and 1995–2005. A clear decrease in flood frequency can be seen during the period 1975–1995. Sites with a high altered regime show that the construction of dams caused a decrease in the frequency of floods – especially evident at stations 4014, 5004, 5047 and 7006.

The results suggest that for an event-based design assuming a stationary model can lead to two major problems: assuming a risk greater than that which is contemplated; or over-sizing the structural and non-structural measures. An FFA of station 2015 shows that the peak flood for an annual probability of excess of 0.01 during the 58 yr of the registration period has ranged from a maximum value of 1899 $\mathrm{m^3\,s^{-1}}$ in 1968 to a low of 223 $\mathrm{m^3\,s^{-1}}$ in 1988. These values demonstrate that broad inferences drawn from flood events under non-stationary conditions may show dramatic changes. It should be mentioned that the maximum value recorded is clearly much higher than the value of 989 $\mathrm{m^3\,s^{-1}}$ estimated for stationary conditions. Similar behaviour can be observed in all study sites. These results reinforce our questioning of the hypothesis of stationarity and lead us to suggest the imminent need for an FFA that can take this dynamic behaviour into account. An important point is that in the context of non-stationarity, the term “return period” loses meaning, as the probabilities of excess change from year to year. Therefore, new definitions should be created that assume the hypothesis of non-stationarity.

4.4 Non-stationary models as predictive tools

Returning to the inference of flood events, models with time-trends (model 1) show certain problems. These problems can be seen in Fig. 8, in which the behaviour inferred with the model clearly captures the overall variability; however, the interannual variability is inadequately explained. Trends for all the studied sites are persistent and no changes are detected. These results lead us to suppose that the assumption of these trends in the series could lead to errors. Two study cases (stations 2015 – low altered regime and 5004 – high altered regime) were selected to observe this effect and the models were fitted for the period 1950–1990. Then, we used the model as a predictive tool for the period 1991–2007. The results shown in the left panel of Fig. 8 highlight the difficulties in making predictions beyond the range of values used in the fitting process with model 1. It is evident that the time-trend models validate erroneously, in this case resulting in flood underestimation. A better performance is observed in model 2 (right panel Fig. 8), where changes in the frequency of floods at the two sites are more adequately captured. Unquestionably, the incorporation of climate indices helps the models capture the changes in the frequency of floods in the fitting and in the validation periods.

5 Conclusions

The flood frequency analysis under non-stationary conditions in 20 rivers in continental Spain between 1950 and 2007 was the main objective of the present study. This statistical modelling was conducted using GAMLSS models, which have the flexibility to deal with non-stationary probabilistic modelling, as well as the ability to model the dependence of distribution parameters with respect to external covariates (climate and reservoir indices).

Violations of the assumption of stationarity in the flood series in rivers of continental Spain are obvious and this conclusion is consistent with those obtained in recent studies of the precipitation regimes at different scales in the Iberian Peninsula (Norrant and Douguédroit, 2005; De Luis et al., 2009; López-Moreno et al., 2010; Río et al., 2010; Rodríguez-Puebla and Nieto, 2010) as well as in monthly flow regimes (Morán-Tejeda et al., 2011; Lorenzo-Lacruz et al., 2012). Our results show that changes and trends in flood regime are clearly linked to low-frequency climate forcings and the effects of the intensification of dam regulatory strategies over the last 50 yr.

Although several mechanisms may be responsible for generating floods in Spanish rivers, this work shows that outside the Mediterranean coast in many basins the origin of floods is linked to winter precipitation, which is the product of the arrival of air from the Atlantic front. This can be seen in the highly negative correlation between the values of the winter climate indices of the AO, MO and NAO and the magnitude of floods. A less obvious relationship was observed with WeMO, which revealed a significant link with the magnitude of floods in the northern peninsular basins. In these basins, the origin of the floods is influenced by air masses from the Atlantic and moist flows from the north. For Mediterranean basins it is clear that the low-frequency atmospheric circulations patterns used in the study did not govern the flood regime. This is explained by a significant influence of other factors in the generation of runoff (more complex geography, mesoscale convective events, high degree of regulation, snowmelt, etc.). These factors are independent of macroscale climate forcings.

The non-stationary modelling approaches used in GAMLSS showed that temporal trends and external forcings mostly affect the mean of the distributions, with much less effect on variance. In the modelling of time-dependent parameters, the results showed that there is a non-linear dependency through parametric smoothing formulations. It can be seen that the models that involve non-parametric cubic spline formulations are more flexible and tend to better reproduce the dispersion of floods. However, the types of models that provide a good fit and flexibility are highly sensitive to changes in the evolution of predictive variables. Therefore, they should be used with caution because there is a tendency to over-parameterise when optimising the degree of freedom of the model.

The implementation of EOFs analysis prior to the incorporation of climatic indices enabled us to identify multicollinearity, and so obtain more parsimonious models. These findings also affect the dependence of the distributions parameters with respect to the PCs. Our previous analyses using directly winter indices as external covariates in the models exhibit nonlinear dependencies, while that assuming the PC's the dependence of the parameters are linear in most cases.

The FFA results with the models under non-stationary conditions show that for an annual maximum peak discharge with 0.01 annual exceedance probability (corresponding to the return period of 100 yr under stationary conditions) the variations obtained are dramatic, with extended periods in which the flood quantile values are much higher than the estimates under stationary conditions. These results have far-reaching effects in hydrological practice and are evidence that the traditional stationary simplification we have assumed in the study of flood frequency may lead us to assume greater risks in hydraulic design than intended. This raises the need to use alternative models for assuming the dynamics of nature instead of the classic FFA. However, assuming non-stationary modelling means redefining the concept of the return period, which makes sense in stationary modelling, but does not make sense in non-stationary modelling where probability changes annually.

The application of non-stationary models shows that models incorporating the effect of climate and reservoirs in a simple manner as explanatory covariates (model 2), can better describe non-stationarities in the frequency and magnitude in river floods in continental Spain than just time-trend models (model 1). Moreover, the use of models as predictive tools shows that only non-stationary models with the incorporation of additional covariates can be considered – it can be seen that when trends change, the changes that occur after the fitting period are ignored in non-stationary models without external forcings. However, although the potential of climatic indices as descriptive variables of climatic variations in flood series appears obvious, at present there are no long-term predictions for all the climate indices employed in this study.

Acknowledgements. This work has been supported by CONACYT of Mexico and the Spanish research project Floodmed (CGL2008-06474-C02-02/BTE). We acknowledge D. Stasinopoulos, R. Rigby, and C. Akantziliotou for making the GAMLSS package freely available in R. We would also like to thank J. Smith and G. Villarini for the fruitful meetings held with the second author during his stay at Princeton University.

References

Aissoui-Fqayeh, I., El Aldouni, S., Ouarda, T., and Hilaire, A.: Dévelopment du modèle log-normal non-stationnaire et comparision avec le modèle GEV non-stationnaire, Hydrolog. Sci. J., 54, 1141–1156, 2009.

Allen, R. and Smith, L. A.: Monte Carlo SSA: detecting irregular oscillations in the presence of cloured noise, J. Climatol., 9, 3373–3404, 1996.

Beguería, S., López-Moreno, A., Lorente, A., Seeger, M., and García-Ruiz, J.: Assessing the effect of climate oscillations and land-use changes on streamflow in the central Spanish Pyrenees, Ambio, 32, 283–286, 2003.

Benito, G., Machado, M., and Pérez-González, A.: Climate change and flood sensitivity in Spain, edited by: Branson, J., Brown, A. G., and Gregory, K. J., London, 1996.

Benito, G., Lang, M., Barriendos, M., Llasat, M. C., Francés, F., Ouarda, T., Thorndycraft, V. R., Enzel, Y., Bardossy, A., Coeur, D., and Bobée, B.: Use of systematic, palaeoflood and historical data for the improvement of flood risk estimation, Review of Scientific Methods, Natural Hazard, 31, 623–643, 2004.

Benito, G., Thorndycraft, V. R., Rico, M., Sánchez-Moya, Y., and Sopeña, A.: Palaeoflood and floodplain records from Spain: evidence for long-term climate variability and environmental changes, Geomorphology, 101, 68–77, 2008.

Berga-Casafont, L.: Presas y Embases en la España del Siglo XX, Revista de Obras Públicas, 37–40, 2003.

Blösch, G. and Montanari, A.: Climate change impacts – throwing the dice?, Hydrol. Process., 381, 374–381, 2010.

Capel, J.: Los climas en España, Oikos-Tau, Barcelona, 1981.

De Luis, M., González-Hidalgo, J. C., Longares, L. A., and Štepánek, P.: Seasonal precipitation trends in the Mediterranean Iberian Peninsula in second half of 20th century, Int. J. Climatol., 29, 1312–1323, 2009.

Delgado, J. M., Apel, H., and Merz, B.: Flood trends and variability in the Mekong river, Hydrol. Earth Syst. Sci., 14, 407–418, doi:10.5194/hess-14-407-2010, 2010.

Douglas, E., Vogel, R., and Kroll, C.: Trends in floods and low flows in the United States: impact of spatial correlation, J. Hydrol., 240, 90–105, 2000.

El Aldouni, S., Ouarda, T., Zhang, X., Roy, R., and Bobeé, B.: Generalized maximum likelihood estimators for the nonstationary generalized extreme value model, Water Resour. Res., 43, 1–13, 2007.

Franks, S. W.: Identification of a change in climate state using regional flood data, Hydrol. Earth Syst. Sci., 6, 11–16, doi:10.5194/hess-6-11-2002, 2002.

Gámiz-Fortis, S., Pozo-Vázquez, D., Trigo, R. M., and Castro-Díez, Y.: Quantifying the predictability of winter river flow in Iberia. Part II: Seasonal predictability, J. Climate, 21, 2484–2502, 2008.

Gonzalez, J. C., Lopez-Bustins, J.-A., Štepánek, P., Martin-Vide, J., and de Luis, M.: Monthly precipitation trends on the Mediterranean fringe of the Iberian Peninsula during the second-half of the twentieth century (1951–2000), Int. J. Climatol., 29, 1415–1429, 2009.

Held, I. and Soden, B.: Robust responses of the hydrological cycle to global warming, J. Climate, 19, 5686–5699, 2006.

Jin, Y. H., Kawamura, A., Jinno, K., and Berndtsson, R.: Quantitative relationship between SOI and observed precipitation in southern Korea and Japan by nonparametric approaches, J. Hydrol., 301, 54–65, 2005.

Katz, R. W., Parlange, M. B., and Naveau, P.: Statistics of extremes in hydrology, Adv. Water Resour., 25, 1287–1304, 2002.

Khaliq, M. N., Ouarda, T. B. M. J., Ondo, J. C., Gachon, P., and Bobée, B.: Frequency analysis of a sequence of dependent and/or non-stationary hydro-meteorological observations: a review, J. Hydrol., 329, 534–552, 2006.

Kwon, H.-H., Brown, C., and Lall, U.: Climate informed flood frequency analysis and prediction in Montana using hierarchical Bayesian modeling, Geophys. Res. Lett., 35, 1–6, 2008.

Leclerc, M. and Ouarda, T.: Non-stationary regional flood frequency analysis at ungauged sites, J. Hydrol., 343, 254–265, 2007.

Llasat, M. and Puigcerver, M.: Meteorological factors associated with floods in the north-eastern part of the Iberian Peninsula, Nat. Hazards, 9, 81–93, 1994.

López, J. and Francés, F.: Assessing teleconnections between climatic indices and floods in continental Spanish Rivers, in revision, 2013.

López-Bustins, J. A., Martin, V., J., and Sanchez, L. A.: Iberia winter rainfall trends based upon changes in teleconnection and circulation patterns, Global Planet. Change, 63, 171–176, 2008.

López-Moreno, J. I., Beguería, S., and García-Ruíz, J.: Trends on high flows in the central Spanish Pyrenees: response to climatic factors or to land-use change change?, Hydrolog. Sci. J., 51, 1039–1050, 2010.

López-Moreno, J. I., Vicente-Serrano, S. M., Moran-Tejeda, E., Zabalza, J., Lorenzo-Lacruz, J., and García-Ruiz, J. M.: Impact of climate evolution and land use changes on water yield in the ebro basin, Hydrol. Earth Syst. Sci., 15, 311–322, doi:10.5194/hess-15-311-2011, 2011.

Lorenzo-Lacruz, J., Vicente-Serrano, S. M., López-Moreno, J. I., González-Hidalgo, J. C., and Morán-Tejeda, E.: The response of Iberian rivers to the North Atlantic Oscillation, Hydrol. Earth Syst. Sci., 15, 2581–2597, doi:10.5194/hess-15-2581-2011, 2011.

Lorenzo-Lacruz, J., Vicente-Serrano, J., López, J., Morán, T., and Zabalza, J.: Recent trends in Iberian streamflows (1945–2005), J. Hydrol., 414–415, 463–475, 2012.

Markovic, D., Koch, M., and Lange, H.: Long-term variations of hydrological and climate time series from the German part of the Elbe River Basin, Hydrol. Process., 43, 1–28, 2009.

Massei, N., Laignel, B., Deloffre, J., Mesquita, J., Motelay, A., Lafite, R., and Durand, A.: Long-term hydrological changes of the Seine River flow (France) and their relation to the North Atlantic Oscillation over the period 1950–2008, Int. J. Climatol., 30, 2146–2154, 2010.

McNeil, A. and Saladin, T.: Developing Scenarios for Future Extreme Losses Using the POT Method, London, 2000.

Milly, P. C. D., Wetherald, R. T., Dunne, K., and Delworth, T. L.: Increasing risk of great floods in a changing climate, Nature, 415, 514–571, 2002.

Milly, P. C. D., Dunne, K., and Vecchia, A.: Global pattern of trends in streamflow and water availability in a changing climate, Nature, 438, 347–350, 2005.

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., and Stouffer, R. J.: Stationarity is dead: whiter water management?, Science, 319, 573–574, 2008.

Morán, T. E., López, M. I., Ceballos, B. A., and Vicente, S. S.: Influence of the North Atlantic Oscillation on the streamflows of the Duero basin (Spain): spatial variability and response times, Geophys. Res. Abstr., EGU2010-13616, EGU General Assembly 2010, Vienna, Austria, 2010a.

Morán, T. E., Moreno, L. M., Ceballos, B. A., and Vicente-Serrano, S. M.: Evaluating Duero's basin (Spain) response to the NAO phases: spatial and seasonal variability, Hydrol. Process., 25, 1–14, 2010b.

Morán, T. E., López-Moreno, J., Ceballos-Barbancho, A., and Vicente-Serrano, S.: River regimes and recent hydrological changes in the Duero basin (Spain), J. Hydrol., 404, 241–258, 2011.

Mudelsee, M., Borngen, M., and Tetzlaff, G.: No upward trends in the occurrence of extreme floods in central Europe, Nature, 425, 166–169, 2003.

Norrant, C. and Douguédroit, A.: Monthly and daily precipitation trends in the Mediterranean (1950–2000), Theor. Appl. Climatol., 83, 89–106, 2005.

NRC: Decade-to-Century-Scale Climate Variability and Change: a Science Strategy, Panel on Climate Variability on Decade-to Century Time Scales, National Academy Press, Washington DC, 1998.

Olsen, J. R., Lambert, J. H., and Haimes, Y. Y.: Risk of extreme events under nonstationary conditions, Risk Anal., 18, 497–510, 1998.

Ouarda, T. and El-Aldouni, S.: Bayesian nonstationarity frequency analysis of hydrological variables, J. Am. Water Resour. As., 47, 496–505, 2011.

Philips, I., McGregor, G., Wilson, C., Bower, D., and Hannah, D.: Regional climate and atmospheric circulation controls on the discharge of two British rivers, 1974–1997, Theor. Appl. Climatol., 76, 141–164, 2003.

Renard, B., Lang, M., and Bois, P.: Statistical analysis of extreme events in a non-stationary context via a Bayesian framework: case study with peak-over-threshold data, Stoch. Env. Res. Risk A., 21, 97–112, 2006.

Rigby, R. A. and Stasinopoulos, D. M.: Generalized additive models for location, scale and shape, J. Roy. Stat. Soc. C-App., 54, 507–554, 2005.

Rîmbu, N., Boroneanţ, C., Buţă, C., and Dima, M.: Decadal variability of the Danube river flow in the lower basin and its relation with the North Atlantic Oscillation, Int. J. Climatol., 22, 1169–1179, 2002.

Río, S. D., Herrero, L., Fraile, R., and Penas, A.: Spatial distribution of recent rainfall trends in Spain (1961–2006), Int. J. Climatol., 31, 1–12, 2010.

Rodrigo, F. S., Esteban-Parra, M. J., Pozo-Vázquez, D., and Castro-Díez, Y.: Rainfall variability in southern Spain on decadal to centennial time scales, Int. J. Climatol., 20, 721–732, 2000.

Rodríguez-Puebla, C. and Nieto, S.: Trends of precipitation over the Iberian Peninsula and the North Atlantic Oscillation under climate change conditions, Int. J. Climatol., 30, 1807–1815, 2010.

Rodríguez-Puebla, C., Encinas, A. H., and Sáenz, J.: Winter precipitation over the Iberian peninsula and its relationship to circulation indices, Hydrol. Earth Syst. Sci., 5, 233–244, doi:10.5194/hess-5-233-2001, 2001.

Salas, J. D.: Analysis and modelling of hydrologic time series, in: Handbook of Hydrology, edited by: Maidment, D., McGraw-Hill, New York, 25, 19.11–19.72, 1992.

Sankarasubramanian, A. and Lall, U.: Flood quantiles in a changing climate: seasonal forecasts and causal relations, Water Resour. Res., 39, 4.1–4.12, 2003.

Shorthouse, J. and Arnell, N.: Spatial and temporal variability on European river flows and the North Atlantic Oscillation, FRIEND '97-regional hydrology: concepts and models for sustainablewater resource management, IAHS, 246, 77–85, 1997.

Silva, A. T., Portela, M. M., and Naghettini, M.: Nonstationarities in the occurrence rates of flood events in Portuguese watersheds, Hydrol. Earth Syst. Sci., 16, 241–254, doi:10.5194/hess-16-241-2012, 2012.

Stasinopoulos, D. M. and Rigby, R. A.: Generalized additive models for location scale and shape (GAMLSS), J. Stat. Softw., 23, p. 7, 2007.

Stedinger, J. R. and Crainiceanu, C. M.: Climate Variability and Flood Risk Assessment, Risk-Based Decision making in Water Resources IX, American Society of Civil Engineers, California, United States, 77–86, 2001.

Stedinger, J. R., Vogel, R. M., and Foufoula, G. E.: Frequency analysis of extreme events, in: Handbook of Hydrology, edited by: Hill, M., McGraw-Hill, New York, 18.11–18.65, 1993.

Strupczewski, W. G., Singh, V. P., and Mitosek, H. T.: Non-stationary approach to at-site flood frequency modelling, III. Flood analysis of Polish rivers, J. Hydrol., 248, 152–167, 2001.

Trigo, R., Pozo-Vázquez, D., Osborn, T., Castro-Díez, Y., Gámiz-Fortis, S., and Esteban-Parra, M.: North Atlantic oscillation influence on precipitation, river flow and water resources in the Iberian Peninsula, Int. J. Climatol., 24, 925–944, 2004.

Villarini, G., Serinaldi, F., Smith, J. A., and Krajewski, W. F.: On the stationarity of annual flood peaks in the continental United States during the 20th century, Water Resour. Res., 45, 1–17, 2009a.

Villarini, G., Smith, J. A., Serinaldi, F., Bales, J., Bates, P. D., and Krajewski, W. F.: Flood frequency analysis for nonstationary annual peak records in an urban drainage basin, Adv. Water Resour., 32, 1255–1266, 2009b.

Villarini, G., Smith, J. A., and Napolitano, F.: Nonstationary modeling of a long record of rainfall and temperature over Rome, Adv. Water Resour., 33, 1256–1267, 2010a.

Villarini, G., Vecchi, G. A., and Smith, J. A.: Modeling the dependence of tropical storm counts in the North Atlantic Basin on climate indices, Mon. Weather Rev., 138, 2681–2705, 2010b.

Villarini, G., Smith, J. A., Serinaldi, F., Ntelekos, A. A., and Schwarz, U.: Analyses of extreme flooding in Austria over the period 1951–2006, Int. J. Climatol., 32, 1–17, 2011.

Waylen, P. and Poveda, G.: El Niño–Southern Oscillation and aspects of western South American hydro-climatology, Hydrol. Process., 16, 1247–1260, 2002.

Wilson, D., Hisdal, H., and Lawrence, D.: Has streamflow changed in the Nordic countries? – Recent trends and comparisons to hydrological projections, J. Hydrol., 394, 334–346, 2010.

Xu, Z., Takeuchi, K., and Ishidaira, H.: Correlation between El Niño–Southern Oscillation (ENSO) and precipitation in South-east Asia and the Pacific region, Hydrol. Process., 18, 107–123, 2004.

Yi, H., Bardossy, A., and Brommundt, J.: Non-stationarity flood frequency analysis southern Germany, in: Proceedings of the 7 th International Conference on HydroScience and Engineering, Philadelphia, USA, 10–13 September, 2006.

Zhang, Q., Xu, C.-Y., Jiang, T., and Wu, Y.: Possible influence of ENSO on annual maximum streamflow of the Yangtze River, China, J. Hydrol., 333, 265–274, 2007.

Table 1. Analyzed flow gauge stations (* indicate stations with upstream dams).

Station	Basin area (km^2)	Maximum annual peak (m^3 s^{-1})	C.V.	Station	Basin area (km^2)	Maximum annual peak (m^3 s^{-1})	C.V.
1427	712	900	0.744	5047*	6162	596	0.952
1734	558	500	0.682	7006*	7111	345	0.628
2002*	1500	414	0.890	7029*	14 894	259	0.825
2015*	12 740	764	0.819	8032*	984	585	0.886
2046	770	235	0.851	8090	829	291	0.929
2052*	252	176	0.969	9002*	25 194	4950	0.411
3005	3253	658	0.770	9018	238	391	0.514
4014*	34 771	3830	1.321	9071	943	320	0.459
5004*	16 166	2278	1.141	9096*	7796	3318	1.232
5029*	1111	242	0.830	9111	2384	1304	0.838

C.V.: coefficient of variation.

Table 2. Maximum reservoir index (RI) in the flow gauge stations under altered regime.

Station	RI	Station	RI
2002	**0.276**	5047	**0.991**
2015	0.014	7006	**0.360**
2052	0.058	7029	**0.465**
4014	**0.517**	8032	0.013
5004	**0.329**	9002	0.009
5029	0.019	9096	0.129

Table 3. Summary of the probability density function considered to model the annual maximum peak discharge and the link functions used in the study.

	Probability density function	Link functions $g(\cdot)$		
		θ_1	θ_2	θ_3
Gumbel	$f_y\left(y\|\theta_1,\theta_1\right) = \frac{1}{\theta_2}\exp\left\{\left(\frac{y-\theta_1}{\theta_2}\right) - \exp\left(\frac{y-\theta_1}{\theta_2}\right)\right\}$ $-\infty < y < \infty,\ -\infty < \theta_1 < \infty,\ \theta_2 > 0$	Identity ()	ln()	–
Lognormal	$f_y\left(y\|\theta_1,\theta_2\right) = \frac{1}{\sqrt{2\pi\theta_2}}\frac{1}{y}\exp\left\{-\frac{[\log(y)-\theta_1]^2}{2\theta_2^2}\right\}$ $y > 0,\ \theta_1 > 0,\ \theta_2 > 0$	Identity ()	ln()	–
Weibull	$f_y\left(y\|\theta_1,\theta_2\right) = \frac{\theta_2 y^{\theta_2-1}}{\theta_1^{\theta_2}}\exp\left\{-\left(\frac{y}{\theta_1}\right)\right\}$ $y > 0,\ \theta_1 > 0,\ \theta_2 > 0$	ln()	ln()	–
Gamma	$f_y\left(y\|\theta_1,\theta_2\right) = \frac{1}{\left(\theta_2^2\theta_1\right)^{\frac{1}{\theta_2^2}}}\frac{\frac{1}{y^{\theta_2^2}}\exp\left[\frac{-y}{\left(\theta_2^2\theta_1\right)}\right]}{\Gamma\left(\frac{1}{\theta_2^2}\right)}$ $y > 0,\ \theta_1 > 0,\ \theta_2 > 0$	ln()	ln()	–
Generalized Gamma	$f_y\left(y\|\theta_1,\theta_2,\theta_3\right) = \frac{\|\theta_1\|y^{\theta_1\theta_3-1}}{\Gamma(\theta_3)\theta_2^{\theta_1\theta_3}}\exp\left\{-\left(\frac{y}{\theta_2}\right)^{\theta_1}\right\}$ $y > 0,\ -\infty < \theta_1 < \infty,\ \theta_2 > 0,\ \theta_2 > 0$	ln()	ln()	Identity ()

Table 4. Summary for the selected models 1: cs(·) indicates that the dependence between parameter distributions and time is via the cubic spline with the indicated degree of freedom; *t* linear dependence; and ct refers to a parameter that is independent of time.

Station	Distribution	θ_1	θ_2	θ_3	Station	Distribution	θ_1	θ_2	θ_3
1427	LNO	cs(t,2)	ct	–	5047	LNO	cs(t,2)	ct	–
1734	GA	*t*	ct	–	7006	LNO	cs(t,2)	*t*	–
2002	LNO	cs(t,2)	ct	–	7029	LNO	cs(t,3)	ct	–
2015	LNO	cs(t,1)	ct	–	8032	GG	*t*	ct	ct
2046	WEI	cs(t,2)	*t*	–	8090	GG	cs(t,2)	*t*	ct
2052	LNO	cs(t,1)	cs(t,1)	–	9002	GA	cs(t,2)	*t*	–
3005	GG	cs(t,2)	ct	ct	9018	GG	cs(t,2)	ct	ct
4014	GA	cs(t,1)	ct	–	9071	GG	cs(t,2)	ct	ct
5004	LNO	cs(t,2)	*t*	–	9096	LNO	*t*	*t*	–
5029	GA	cs(t,2)	*t*	–	9111	GG	ct	cs(t,2)	ct

Table 5. Summary for the selected models 2: cs(·) indicates the dependence between parameter distributions and external covariates is via the cubic spline with the indicated degree of freedom; the opposite linear dependence; ct refers to a parameter that is independent of the covariates.

Station	Distribution	θ_1	θ_2	θ_3	Station	Distribution	θ_1	θ_2	θ_3
1427	LNO	PC1 cs(PC2,1)	PC1 PC2	–	5047	LNO	PC1 PC2 RI	cs(PC2,2)	–
1734	GA	cs(PC1,1) CP2	PC2	–	7006	LNO	PC1 cs(RI,1)	ct	–
2002	LNO	PC1 RI	ct	–	7029	LNO	PC1 RI	ct	–
2015	LNO	PC1	ct	–	8032	GG	PC1	ct	ct
2046	WEI	cs(PC1,2)	ct	–	8090	GG	PC1	cs(PC2,1)	ct
2052	LNO	PC1	ct	–	9002	GA	PC2	ct	–
3005	GG	cs(PC1,2)	ct	ct	9018	GG	PC1 PC2	ct	ct
4014	WEI	cs(PC1,2) PC2 RI	ct	–	9071	GG	PC2	ct	ct
5004	LNO	PC1 cs(RI,1)	ct	–	9096	LNO	PC1	PC1	–
5029	GA	cs(PC1,2)	ct	–	9111	GG	PC1 cs(PC2,1)	ct	ct

Table 6. Residuals moments for the non-stationary modelling of annual maximum peak discharges using model 2 (external forcings as covariates) and Filliben coefficient.

Station	Mean	Variance	Skewness	Kurtosis	Filliben coefficient
1427	0.003	1.017	0.134	2.451	0.992
1734	−0.001	1.018	0.213	2.768	0.994
2002	0.000	1.017	−0.154	2.093	0.989
2015	0.000	1.017	0.035	2.929	0.993
2046	−0.001	1.024	−0.042	2.785	0.996
2052	0.000	1.018	0.025	2.140	0.992
3005	0.003	1.019	−0.023	3.458	0.991
4014	−0.014	1.017	0.339	2.046	0.987
5004	0.000	1.018	−0.286	2.636	0.992
5029	−0.001	1.016	0.029	2.422	0.997
5047	0.007	1.017	0.344	3.539	0.988
7006	0.000	1.017	0.326	2.520	0.991
7029	0.000	1.018	−0.374	2.772	0.989
8032	−0.002	1.018	0.013	2.537	0.995
8090	0.002	1.014	−0.004	3.009	0.993
9002	0.001	1.018	−0.184	2.644	0.995
9018	−0.002	1.017	0.007	2.174	0.994
9071	0.001	1.016	0.019	2.154	0.993
9096	0.006	1.017	−0.258	3.441	0.988
9111	0.008	1.012	−0.001	2.257	0.994

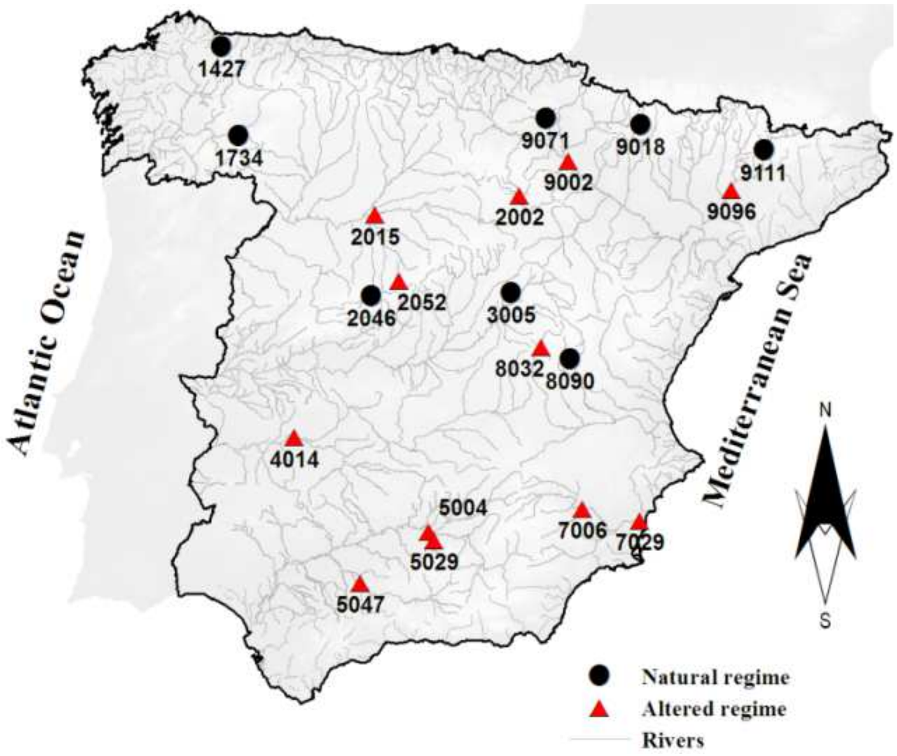

Fig. 1. Map of study region showing the spatial distribution of the selected 20 flow gauge stations in continental Spain. Circles indicate sites in natural regimes and triangles indicate sites in altered regimen.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀| |▶
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

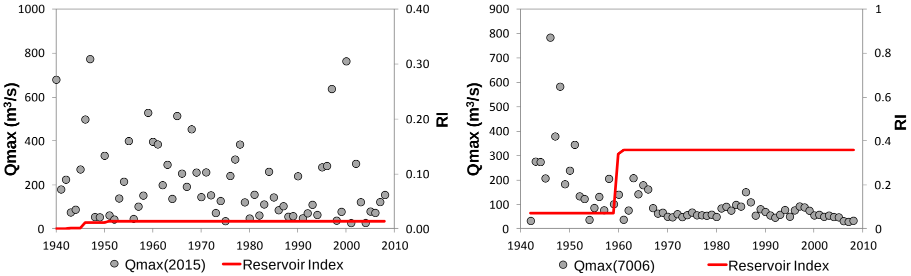

Fig. 2. Temporal evolution of the reservoir index (RI) for the flow gauge stations 2015 and 7006.

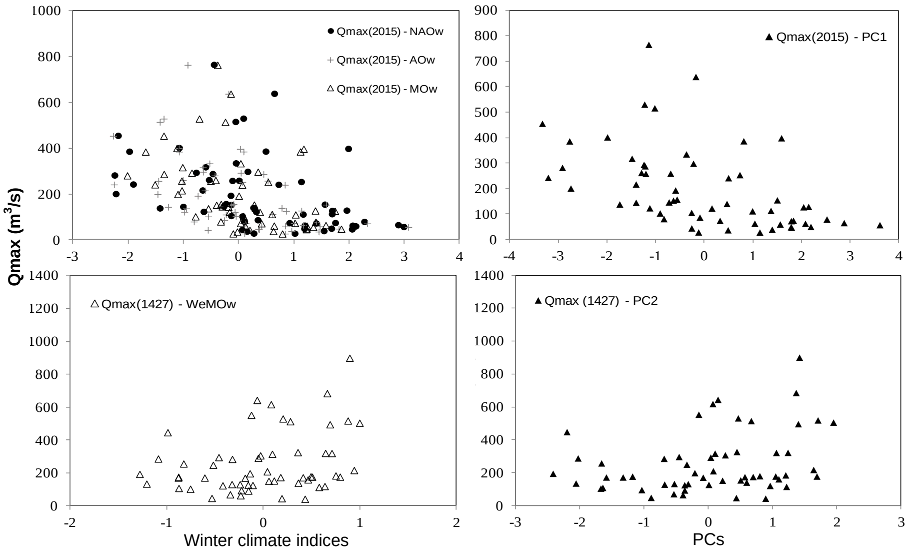

Fig. 3. Scatterplots between annual maximum peak discharges and the corresponding values of the principal components (right panel) and winter climatic indices (left panel).

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

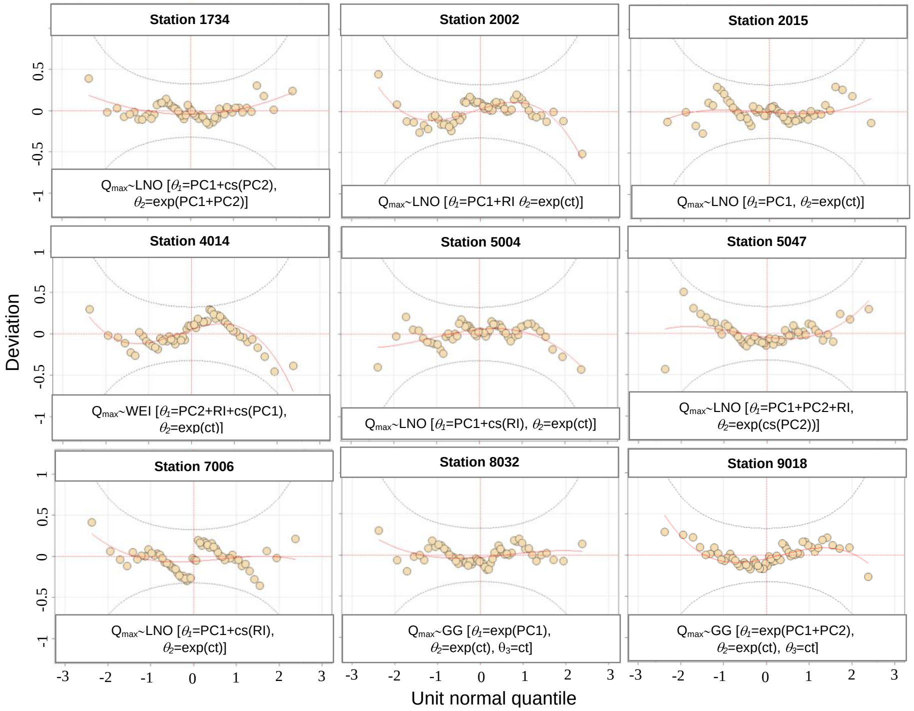

Fig. 4. Worm plots of residuals for nine representative sites of model 2. For a good fit the points should be on the red line and between the two black dotted lines.

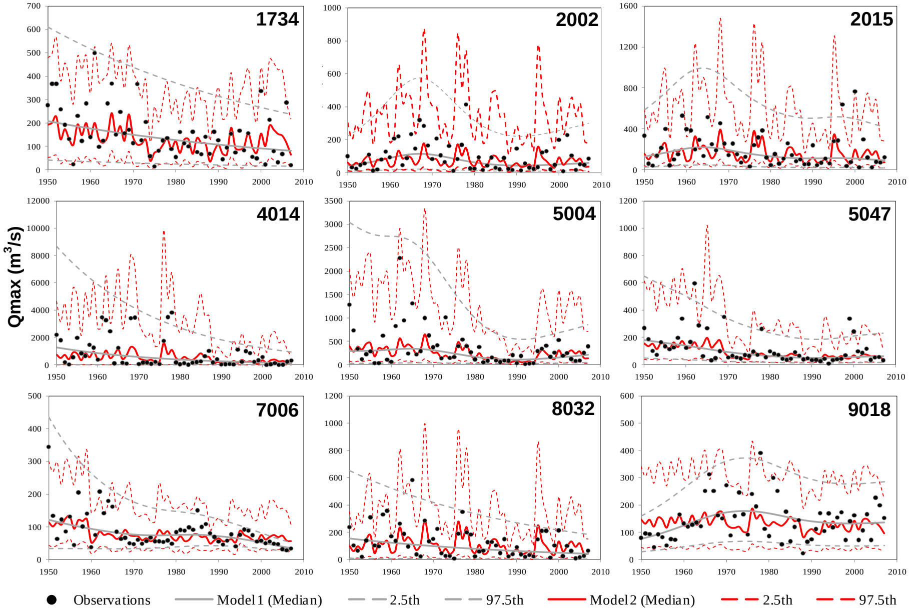

Fig. 5. Summary of the results of modelling annual maximum peak discharge in nine representative sites with models 1 and 2 under non-stationary conditions. The results show the median estimates and the 2.5th and 97.5th percentiles.

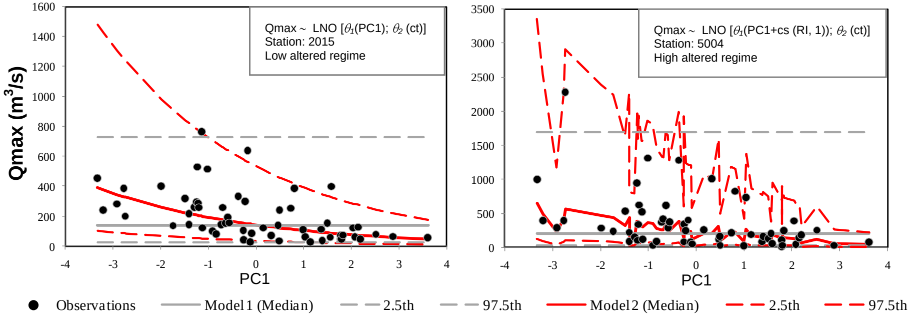

Fig. 6. Estimates of the median and the 2.5th and 97.5th percentiles for models 0 and 1; and stations 2015 (right panel) and 5004 (left panel) plotted against PC1.

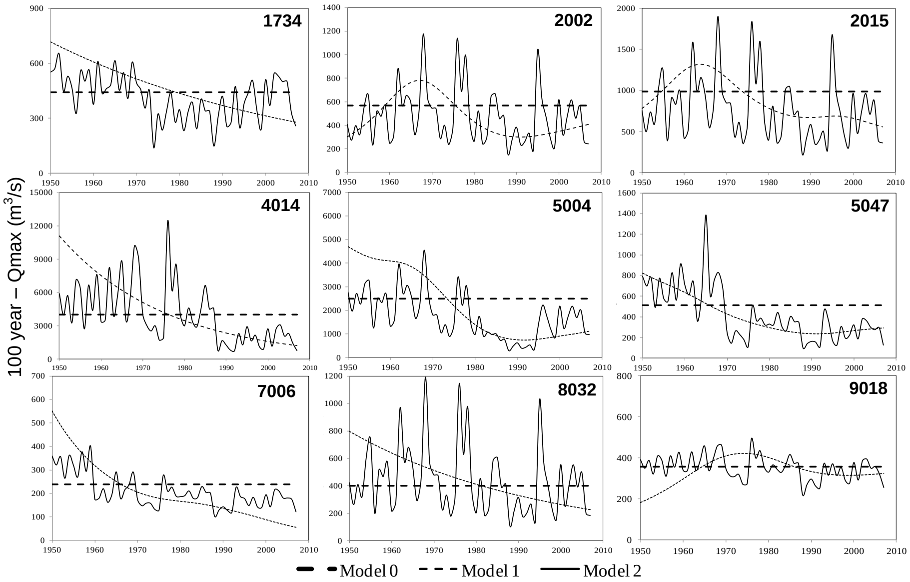

Fig. 7. Modelling of the annual maximum peak discharge with 0.01 annual exceedance probability for the period 1950–2007 based on models 0, 1 and 2.

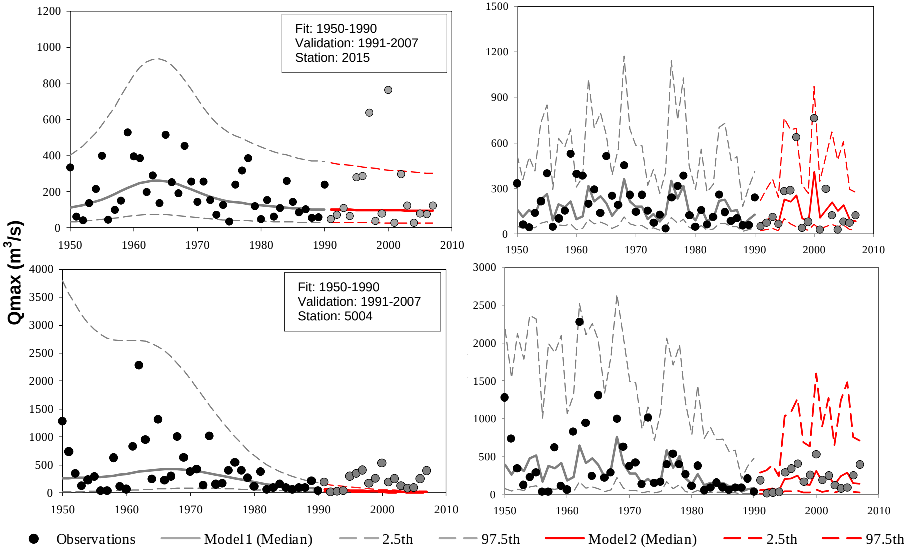

Fig. 8. Results of modelling the annual maximum peak discharges at stations 2015 (top panel) and 5004 (bottom panel) with Models 1 and 2. Only part of the information for fitting model is used (black circles). The models are then used as predictive tools (red lines) and observations not used in the fitting are shown with grey circles.

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀◀ | ▶▶
◀ | ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion