TRENDS IN RAINFALL AND STREAMFLOW SERIES: PORTUGUESE CASE STUDIES

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ABSTRACT

During the history of the Earth, numerous large-scale climate changes occurred, some of them with a cyclic nature. The majority of such changes happened in periods of hundreds, thousands or even millions of years as a result of natural causes, like small variations in Earth's orbit that change the amount of solar energy received by the planet. However, in recent decades, it has been progressively accepted by the scientific community that the emission of greenhouse gases into the atmosphere is the major driving force of the climate change that presumably is occurring since the last century and mainly since the last 50–75 years. However, if there was a change in such a recent and short period, then the time series of the hydrologic variables more directly related to the climate, as the rainfall or the temperature, should denote signs of it, in the form of trends or non-homogeneities. In the previous scope, several studies have been conducted for mainland Portugal aiming at identifying trends in long hydrological time series and at trying to understand those trends from a climate change perspective. Some of the models applied for that purpose, as well as some of the results thus achieved, are briefly summarized. In general terms, the studies showed that the analyzed time series do not show the trends that are generally pointed out as denoting signs of the climate change, possibly due to their pronounced natural variability and to the insufficient length of the recording periods. There was only one exception, the rainfall in March which, in relative terms, denotes a significant decrease over mainland Portugal, such a decrease being however very small when considered in absolute terms.

Keywords: climate change, Gumbel law, hydrologic time series, kernel technique, trend detection, Mann–Kendall test, moving average, statistical models.

1 INTRODUCTION

Ever since a long time ago, humans studied and tried to control the environment in a way to improve their living conditions. Water, as an essential element for survival, has always been of extreme concern, not only due to its scarcity but also due to its excess or surplus, mainly because of its impact on society in terms of agriculture, land use, safety and water resources [1–3].

In the past, global water balance was taken into consideration with no regard to long-term changes. Forecasts were, thus, designed according to well-established stationary models. However, the scientific community is increasingly accepting that the climate change that seems to have been occurring during the last century has effects on the temporal and spatial patterns of most of the hydrologic variables. The international body for the assessment of climate change, the Intergovernmental Panel on Climate Change, IPCC, states that 'climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer' [4, p. 126].

Nowadays, there is a consensus among the scientific community that the increase in the atmosphere temperature will intensify the hydrological cycle [5], thus amplifying the magnitude of some of the extreme hydrologic events, as well as changing the temporal and the spatial patterns of most of the hydrologic variables. It is more and more often mentioned that some regions, especially those located in the higher latitudes, will become more humid while other regions will get drier, as those around the Mediterranean Sea [6]. Also the extreme

hydrologic events – like droughts and floods – will become more frequent and intensive in some areas that will turn out to be more prone to hydrologic disasters. These results are mainly provided by general circulation models (GCM) based on scenarios of greenhouse gas concentration.

Milly *et al.* [7] argue that such climate change undermines the stationarity – a basic assumption that historically has assisted practice and research in the fields of hydrology and water resources management. Clarke [8] questions the widespread assumption of stationarity in hydrological practices and argues that the next few decades should see an increase in understanding the processes causing climate change and variability, not only for the purpose of forecasting the development of that change but also for predicting the frequency of occurrence of extreme events of a certain magnitude.

For Mainland Portugal and as far as the rainfall is concerned, although a decrease is generally pointed out, the results from different climate scenarios denote substantial differences, meaning that there is a considerable uncertainty regarding future projections [9,10]. However, at the annual level, it is almost consensual that the decrease over the full time span of records is not statistically significant [2,3,11–17], although there are some sub-periods with significant trends (either increasing or decreasing) that often alternate over time. At the monthly level, a decreasing trend in the rainfall in March, statistically significant at the 5% significance level, is almost always mentioned [2,3,11–16]. For the period from 1976 to 2002, Boken *et al.* [18] also identified a significant decrease in the precipitation during the spring season. According to these authors, from 1970s onwards, a decrease in the annual precipitation as well as of the number of wet days occurred, along with an increase in the number of dry days. Heavier or more intense rainfall events in the North as well as more drought occurrences in the South are also pointed out [10,12].

In terms of the annual surface runoff in Portugal, the models were unable to identify any pronounced trend though they suggested some changes in the temporal pattern within the year, more often with less water during spring, summer and fall. An increase in the spatial asymmetry of the water distribution may also occur as the decrease in the water availability is expected to become more pronounced towards the South [10,12]. However, sometimes there is some misperception regarding the surface runoff reduction effectively due to the climate changes and the one resulting from the increasing water usage by the modern society. Also, the difference between natural hydrological variability or cycle and trend is not always easy to establish.

While some authors choose to use GCM to analyze the effects of the climate change in mainland Portugal, other authors apply different approaches based on the analysis of long time series. This was the case of the research summarized herein, which aimed at recognizing trends in long hydrological time series, mainly by means of statistical tools, and at relating those trends to the climate change [19,20]. Essentially, only rainfall and streamflow samples were considered, which still leaves a considerable opportunity of research focused on other hydrological variables, namely temperature. It should be mentioned that the Portuguese hydrologic database comprehends a large number of monitoring points some of them with very long time series, especially rainfall series, thus enabling the trend detection based on statistical approaches.

The first studies that will be mentioned utilized monthly, quarterly and annual rainfall records at a few rain gauges. Statistical tools as well as moving average techniques and specific procedures to detect non-homogeneities were applied [11,12].

Subsequently, not only the rainfall series at a much larger number of rain gauges were studied [13,14] but also the performance of irrigation reservoirs under changing hydrologic constraints

was analyzed [21,22]. These constraints combined changes in the temporal patterns both of the inflows to the reservoirs and of the outflows (demands), in the latter case due to changes in the crop evapotranspiration. More recently, trend detection in extreme rainfall series [23] and in the within-the-year rainfall pattern were also accomplished [24]. Additionally, an exploratory analysis on the variability of flood occurrence rates in eight Portuguese watersheds to ascertain if that variability is concurrent with the principle of stationarity is also presented [25].

Some of the more relevant results thus achieved as well as the models applied are briefly mentioned. In general terms, the studies showed that, for mainland Portugal and with a few exceptions, it is still difficult to identify trends in most of the rainfall and streamflow series that can be unequivocally interpreted as signs of climate change, assumable because the hydrologic variables are much more resilient than the human perception or because the time window of the samples is still too small.

The hydrological data to which the different models were applied were acquired in the *Sistema Nacional de Informação de Recursos Hídricos*, SNIRH, online database which has high data quality standards and is the main source of Portuguese hydrological and hydrometeorological data used by researchers and practitioners of water resources engineering and science. The stream gauging stations that were analyzed are installed in rivers under natural or pristine conditions, that is, without significant regulation that could influence the watersheds responses to floods.

2 DESCRIPTION OF THE MODELS

2.1 Introduction

The results from the trend analysis applied to long hydrologic time series herein summarized were the outcome for mainland Portugal from several studies from the authors or conducted by the authors [19,20] based on different models, most of them well set in the literature. Specific relevant aspects related to the overall design of those models or with their application are briefly mentioned.

The studies were mainly focused in rainfall series – annual, seasonal and monthly rainfalls and also short duration intense rainfalls – and most of the models had statistical nature.

To ascertain the effect of the climate change in the reliability of the water supplies based on artificial reservoirs, streamflow series as well as evapotranspiration series were also included in the trend analysis although only as components of the simulation algorithm applied to detect changes in the performance of artificial reservoirs. Additionally, the records at a few stream gauging stations were also analyzed with respect to the changes in the frequency of the flood events.

2.2 Trends in monthly and seasonal rainfalls: moving averages and cumulative moving averages

One of the models more often applied, namely to rainfall data, was the **moving average technique** [26], which is a very common tool to smoothen out short-term fluctuations or to highlight longer term trends or cycles in a long temporal series.

For an annual series with length N, the moving average with length n is formed by the averages over the $N–n+1$ subsets of n consecutive years each in which the original series can be split (with $N > n$) – Fig. 1.

The length n should be large enough to ensure that the consecutive averages mirror the statistical behavior of the different subsets (as a thumb rule, n should be larger than 15 years).
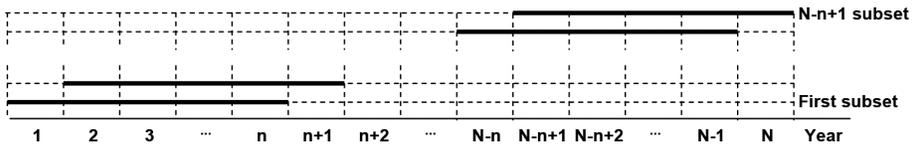
Figure 1: $N - n + 1$ subsets with constant length n resulting from the application of the moving average technique to a series with length N (adapted from [11]).
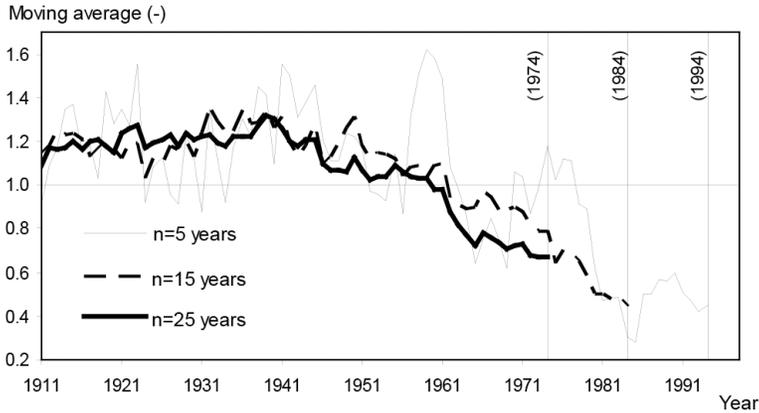

Figure 2: Moving average technique. Effect of the length n on the dimensionless moving averages. Example based on 88 years of rainfall records in March in Alter do Chão rain gauge (rain gauge number 4 of Fig. 8).

A larger n results in a decrease in the number of subsets with averages being compared and smoothes the trends. In the applications carried out, n was fixed based on a sensitivity analysis considering subsets with different lengths. Figure 2 exemplifies the effect of three different lengths n (5, 15 and 25 years) based on 88 years of the rainfall series in March (1911–1998) in a rain gauge located in the South or Portugal (Alter do Chão rain gauge – number 4 of Fig. 8). In the figure, the average of the rainfalls in each subset was made dimensionless by the division by the long-term mean rainfall in March.

Figure 2 clearly shows that as the length n increases the moving average curve becomes more regular. Also the number of subsets that define that curve decreases. However, the three moving average curves denote a similar global pattern. It should be stressed that, for very small values of n, some of the fluctuations presented by the moving average curve may be caused by spurious extreme values.

Another technique applied to the rainfall series aimed at detecting non—homogeneities based on the statistical comparison of the averages of consecutive pairs of cumulative moving averages. For this purpose, each time series with length N was split into two series, temporally contiguous, one built upon the first n elements – **anterior subset** – and the other built upon the last N-n elements – **posterior subset** [11,12]. The averages of each two paired subsets are next compared in statistical terms. The division of the original series into paired subsets is successively repeated by increasing by one the length of the anterior subset and consequently by decreasing by one the length of the posterior subset – Fig. 3 – until the
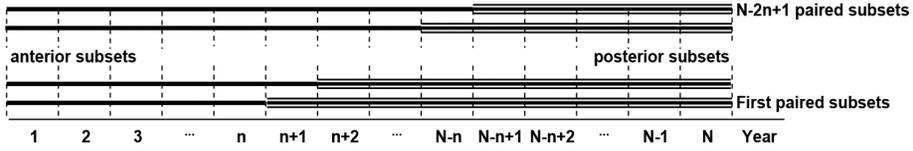
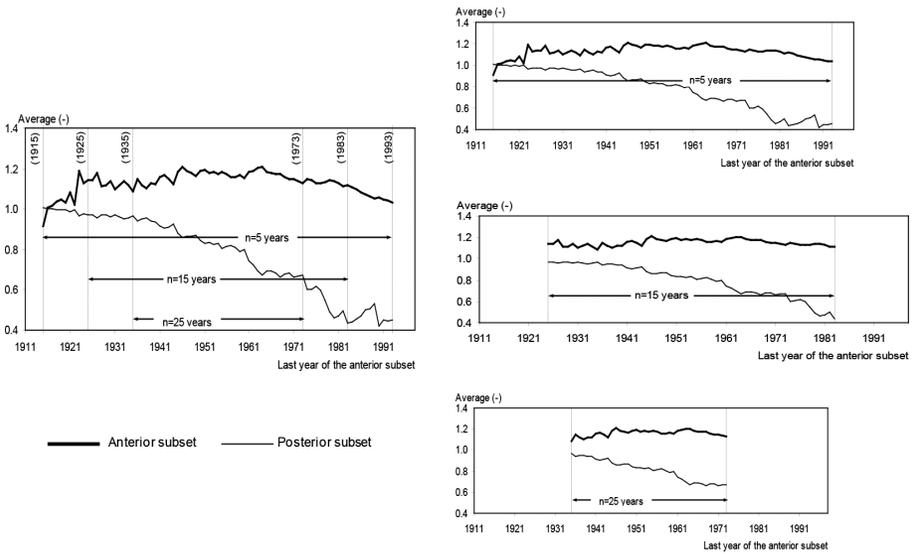Figure 3: $N - 2n + 1$ paired subsets considered in the detection of non-homogeneities (adapted from [11]).

Figure 4: Cumulative moving averages. Effect of the length *n* on the dimensionless paired anterior and posterior subsets. Example based on 88 years of rainfall records in March in Alter do Chão rain gauge (rain gauge number 4 of Fig. 8).

minimum length of *n* is reached for the posterior subset. For a series with length *N*, the total number of averages compared is twice the total number of contiguous paired subsets, that is to say, is equal to $2 \times (N - 2n + 1)$.

As in the case of the simple moving average technique, the length *n* resulted from a sensitivity analysis based on the assumption of different lengths. For the same example of Fig. 2, Fig. 4 exemplifies the comparison between the averages of each two consecutive anterior and posterior subsets. The only effect as *n* increases is a decrease in the number of points that define the curves, resulting in a 'shortening' of the two paired curves, as suggested by the figure.

The statistical comparison of the two averages of each pair of anterior/posterior subsets utilized the **Student's *t*-parametric test** and the **Mann–Whitney non-parametric test** [27,28].

The *t*-statistic to test whether two means are different can be calculated as follows [29, pp. 86-88]:

$$t_s = \frac{\left| \overline{X}_1 - \overline{X}_2 \right|}{s \sqrt{1/n_1 + 1/n_2}}, \tag{1}$$

where $\bar{X}_1$ and $\bar{X}_2$ are the two averages under comparison, n_1 and n_2 the lengths of the corresponding samples ($N = n_1 + n_2$) and s an estimator of the population standard deviation computed based on the unbiased standard deviation of the two samples, s_1 and s_2, according to:

$$s = \sqrt{\frac{(n_1 - 1)\ s_1^2 + (n_2 - 1)\ s_2^2}{n_1 + n_2 - 2}} \qquad (2)$$

For the confidence level of $\eta = 1\text{-}\alpha$, where α stands for the level of significance, the hypothesis that the two averages are not significantly different is rejected if:

$$\left| t_s \right| > t_{(1-\alpha/2)}, \qquad (3)$$

where $t_{(1-\alpha/2)}$ is the quantile $(1 - \alpha\ /\ 2)$ of the Student distribution for a number of degrees of freedom of $n_1 + n_2 - 2$.

Because the Student's t-test is a parametric test, it enforces some restrictions that should be verified prior to its application [27, pp. 217–218, 29, pp. 86–88]. A non-parametric test could overcome the need for such verification. Among this type of tests, the Mann–Whitney test was applied to each two paired anterior and posterior subsets. Let n_1 and n_2 denote the lengths of such subsets and $N = n_1 + n_2$ the length of the complete sample.

This test uses an auxiliary variable, Y, with generic element yi defined based on the original sample, X, of the xi elements ($1 \le i \le N$) according to:

$$yi = \text{number of elements of } X \text{ smaller or equal to } xi, \text{ including } xi. \qquad (4)$$

The statistic of the Mann–Whitney test, NMW, is given by [28, pp. 131–144, 30, pp. 349–350]:

$$N_{MW} = \min\left\{ n_1(N - n_1) + \frac{n_1(n_1 + 1)}{2} - \sum_{i=1}^{n_1} y_i; \sum_{i=1}^{n_1} y_i - \frac{1}{2} n_1(n_1 + 1) \right\}. \qquad (5)$$

A NMW has an asymptotic normal distribution with average $\bar{N}_{MW}$ and variance s_{MW}^2 given by

$$\bar{N}_{MW} = \frac{n_1(N - n_1)}{2}, \qquad (6)$$

$$s_{MW}^2 = \frac{n_1(N - n_1)(N + 1)}{12}. \qquad (7)$$

The hypothesis of homogeneity regarding the average is rejected for a confidence level of $\eta = 1 - \alpha$ if:

$$\left| \frac{(N_{MW} - \bar{N}_{MW})}{(s_{MW}^2)^{0.5}} \right| > \varphi^{-1}_{(1-\alpha/2)}, \qquad (8)$$

where ϕ is the cumulative distribution function of the standard normal and φ^{-1}, its inverse.

A non-homogeneity was considered to occur whenever at least one of the previous tests indicated that the two averages under comparison were statistically different. The analysis carried out showed two kinds of non-homogeneities: the sporadic ones due to a period of time (a few years, seasons or months) with extremely high or extremely low rainfall and those persisting

along time and indicating successive posterior subsets with averages consistently different from the averages of the corresponding anterior subsets, thus, denoting a trend. In other words**, a trend was considered to occur whenever persistent non-homogeneities were detected**.

2.3 Trends in monthly and annual rainfalls: the Mann–Kendall non-parametric test and the Sen slope estimator

The well-known **Mann–Kendall non-parametric test** (also named Kendall's tau test), due to Mann [31] and Kendall [32], was applied to detect trends in monthly and annual rainfall series. By applying the Sen slope estimator [33–35], the trends thus detected were additionally characterized in terms of dimensionless magnitudes.

The Mann–Kendall test is a rank-based non-parametric test for assessing the significance of a trend, and has been widely used in hydrological trend detection studies. The null hypothesis H_0 is that a sample of data $\{x_i, i = 1, 2, …, N\}$ is independent and identically distributed. The alternative hypothesis H_1 is that a monotonic trend exists in X. The statistic S of the test is defined as follows:

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \text{sgn}(x_i - x_j) \tag{9}$$

where the x_j are the sequential data values, N is the length of the data set and

$$\text{sgn}(x_i - x_j) = \begin{cases} 1 & \text{if} & x_i - x_j > 0 \\ 0 & \text{if} & x_i - x_j = 0 \\ -1 & \text{if} & x_i - x_j < 0 \end{cases} \tag{10}$$

Mann [31] and Kendall [32] have documented that when $N \geq 8$, the statistic S is approximately normally distributed with the mean, E, and the variance, V, as follows:

$$E(S) = 0, \tag{11}$$

$$V(S) = \frac{N(N-1)(2N+5) - \sum_{m=1}^{N} t_m \, m \, (m-1) \, (2\,m+5)}{18}, \tag{12}$$

where t_m is the number of ties of extent m. The standardized test statistic Z is computed by

$$Z = \begin{cases} \dfrac{S-1}{\sqrt{V(S)}} & \text{if} & S > 0 \\ 0 & \text{if} & S = 0 \\ \dfrac{S+1}{\sqrt{V(S)}} & \text{if} & S < 0 \end{cases} \tag{13}$$

The standardized statistic Z follows the standard normal distribution with mean 0 and variance 1 under the null hypothesis of no trend. A positive Z value indicates an upward trend, whereas a negative one indicates a downward trend. To test for either an upward or downward

monotone trend (a two-tailed test) at α level of significance, H_0 is rejected if the absolute value of Z is greater than $\phi^{-1}(1-a/2)$ where ϕ^{-1} has the meaning previously defined.

To estimate the true slope of an existing trend (as a change per year), the Sen's non-parametric method can be used if such trend can be assumed to be approximately linear.

To get the slope estimate Q, the slopes of all data value pairs are computed according to

$$Q_k = \frac{x_j - x_i}{j - i} \qquad i > j \text{ and } x_i \neq x_j, \tag{14}$$

where x_i is the variable being studied and i the year in which the ith observation occurs.

For a series with N values, x_i is the number of slope estimates, Q_k is $n* = N(N-1)/2$. The Sen's estimator of slope is the median of those $n*$ values of Q_k. Accordingly, if the $n*$ values of Q_k are ranked from the smallest to the largest, the Sen's estimator will be

$$Q = Q_{[(n*+1)/2]} \qquad \text{if } n* \text{ is odd} \tag{15}$$

or

$$Q = \frac{1}{2}\left(Q_{[n*/2]} + Q_{[(n*+2)/2]}\right) \qquad \text{if } n* \text{ is even.} \tag{16}$$

A $(1-a/2)$ two-sided confidence interval about the slope estimate is obtained by the non-parametric technique based on the normal distribution.

The Q estimate of the magnitude of the trends is robust even when the series X presents discordant values or outliers [34]. For univariate time series (as the one of the rainfall in a given month), the possible effect of seasonality is also eliminated.

In the three tests previously mentioned – Student, Mann–Whitney and Mann–Kendall tests – a significance level of $a = 5\%$ was adopted (non-exceedance probability of $1-a/2 = 0.975$ for bilateral or two-sided tests).

2.4 Trends in annual maximum daily rainfalls: the Gumbel law

The analysis of extreme rainfall events utilized annual maximum daily rainfall series – *Pamd* series – which were treated also by means of the moving average technique based on subsets
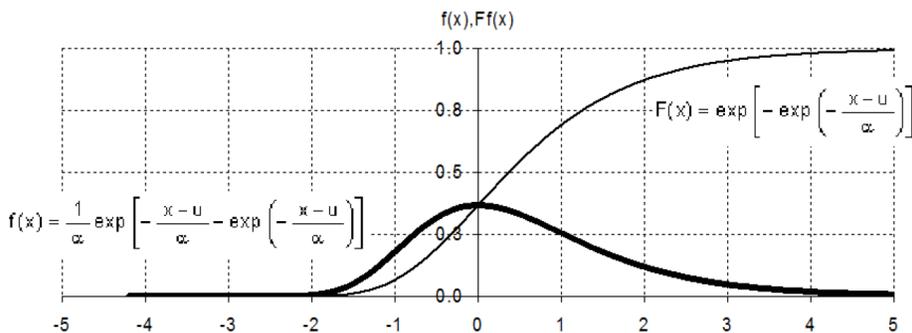

Figure 5: Gumbel probability density function, $f(x)$, and probability distribution function, $F(x)$: general equations and curves for a scale parameter of $a = 1$ ($a > 0$) and a location (mode) parameter of $u = 0$.
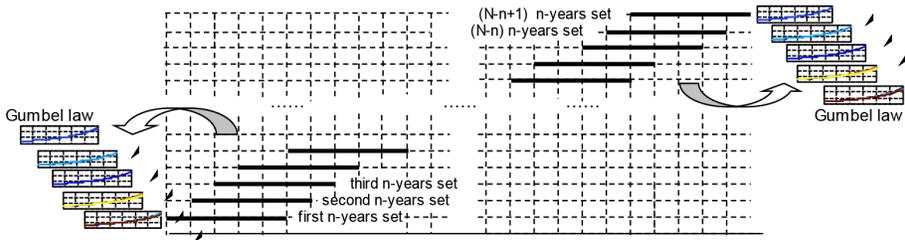
Figure 6: Gumbel law applied to the $(N - n + 1)$ consecutive set of n years of annual maximum daily rainfalls.

with length n [23]. The annual maximum daily rainfall series are built upon one value per hydrological year, the maximum rainfall amount in 24 h.

The study also included the comparison of the **probability distribution function of the Gumbel** law [36,37] obtained by considering separately each one of the N-n + 1 consecutive subsets with constant length n into which the *Pamd* series with length N was split – Figs 5 and 6. For each subset, the probability distribution function was obtained by applying the method of moments based on the Weibull plotting position formula [38].

A last study focused only on rainfall tried to ascertain changes in the within-the-year patterns as well as in the distribution of the maximums rainfalls. The study utilized the moving average technique complemented by the application of the Student and Mann–Whitney tests [24].

2.5 Performance of artificial reservoirs: simulation algorithms

Along with the rainfall analysis, the performance of artificial regulating reservoirs aiming at providing water for irrigation was also analyzed [14,21] based on hypothetical case studies located in the river sections of stream gauging stations. The models considered were more extensive and complex than those applied to rainfall data because they needed to account for the trends in both the inputs (river flows) and outputs from to hypothetical reservoirs (irrigation demands). A monthly time step was adopted. The analyzed period lasted from October 1910 to September 2004 (94 hydrological years).

As the streamflow series are generally not as long as the rainfall series, rainfall-runoff models were employed to fill the gaps and to extend the monthly flow data, namely, the soil sequential water budget [39–43] and the Temez model [43,44] To ascertain the trends in the crop water requirements, long evapotranspiration series were established based on the Thornthwaite [41,45] and on the Penman-Montheith [46,47] models. Different water supplies – in terms of volumes and guaranties/reliabilities – were considered.

To analyze the changes along time in the performance of the hypothetical irrigation regulating reservoirs, the 94 years of data were split into 94-30+1=65 consecutive subsets, each with constant length of 30 years. To analyze the performance of each hypothetical reservoir throughout each one of those subsets, computational **simulation algorithms based on the mass equation** were applied.

The simulation applied to the design of the storage capacities of artificial reservoirs is based on the replication of the reservoir exploitation during a period of time equal to the length of the inflow data time series.

The technique allows for considering the evaporation and other losses from the reservoir and, unlike other methods, it is useful in determining the performance of the reservoir,

because it allows the designer to consider restrictions on the water supply when the reservoir is depleted. The simulation can be considered as a trial-and-error method in which a guess is made about the capacity, *C*, the exploitation of the reservoir is made for this capacity, and finally performance measures are evaluated [48].

For a given time interval of several years, the simulation is performed along consecutive time periods or steps, each one with the constant duration D*t*. An initial value for the storage capacity is assumed, and the reservoir is considered to be at a given state at time zero (generally full or empty). The stored volume in each new time step is computed by applying the mass equation:

$$S_{t+1} = S_t + Q_t - D_t - E_t + P_t - L_t,$$ (17)

with the restriction:

$$0 \le S_{t+1} \le C,$$ (18)

where *C* is the capacity, S_t and S_{t+1} are the volumes stored at the beginning of time periods *t* and *t+1* (with $\Delta t = (t+1)-t$), respectively. The remaining variables represent changes in the storage volume during the *t*th time period: Q_t is the inflow volume, D_t is the target demand, E_t represents the losses by evaporation, P_t is the precipitation over the reservoir and L_t are other losses from the reservoir.

The performance measure adopted in the studies was the **reliability**, *G*. Though there is no single definition of the reliability of a reservoir, it can be considered as a measure of the dependability of the system's requirements being met [49, p. 68]. The most common definition presented in the technical literature [48, p. 13] defines the reliability, *G*, as the percentage of time units in which a specified demand is met:

$$G = \left(1 - \frac{Nr}{N}\right) \times 100,$$ (19)

where N_r is the number of periods where the supply is not able to meet the demand and restrictions on water use are made (failure in the supply) and *N* is the total number of time periods in the analysis. Then, N_r / N is the empirical probability of failure of the demand being met, and *G* is its complement (non-failure probability). It should, however, be stressed that this concept deals only with an empirical frequency. On a monthly basis, *G* represents the percentage of months with total fulfillment of the water requirements.

2.6 Non-stationarity in the occurrence rate of floods: the kernel occurrence rate estimation method applied to POT data

The last study that will be mentioned refers to an exploratory analysis on the variability of the streamflow regime in mainland Portugal watersheds, in what concerns the occurrence rate of floods, in order to ascertain if that variability is concurrent with the hypothesis of non-stationarity [25].

The study utilized mean daily streamflows at a few gauging stations. Daily rainfall records at rain gauges located in some of those watersheds were also utilized, but only with the purpose of checking whether there are significant discrepancies between peaks in rainfall and streamflow, which would eventually suggest that the behavior exhibited by the streamflows

was under a significant anthropogenic influence. Such an analysis allowed considering that the flood regime in the studied watersheds was nearly pristine.

The peaks-over-threshold (POT) sampling technique was applied to extract the dates (POT time data) and peak values (POT value data) of flood events and extreme rainfall events, respectively, from the streamflow and rainfall samples.

The peaks-over-threshold approach in hydrological frequency analysis consists of applying a sampling technique to a time series that retains the peak values that exceed a given truncation level usually called base level or threshold [50]. The selected peaks must meet the independence condition. Several criteria have been presented in the literature to verify this hypothesis [50] The criterion used for the mean daily flow series [51,52] determines that flood peaks should be separated in time by three times the time to peak and, furthermore, that the flow between two consecutive peaks should decrease below as much as two thirds of the first peak. Due to the relatively small areas of the watersheds that were analyzed, a reference time to peak of one day was adopted.

The selection of the threshold is a procedure that involves a great level of subjectivity [53]. Lang *et al*. [50] reviewed a number of systematic approaches to carry out this selection. Lang *et al*. [50] remark, however, that there is no universal and unequivocal method for selecting the threshold, and that there is no unique threshold value that must be selected but rather a range of appropriate values. The threshold adopted was set equal to seven times the long-term mean daily flow, or modulus, which according to Quintela [54] provides a lower limit to identify the flood occurrences [55].

A non-parametric method for analyzing non-stationarities in the occurrence rate $\lambda(t)$ of floods and extreme rainfall events was applied to the POT time data – the kernel occurrence rate estimation method, or kernel technique [56,57].

The kernel technique is a non-parametric method developed by Diggle [56] for smoothing point process data. For estimating the intensity of a point process such as the time-dependent occurrence rate, $\lambda(t),$ this technique may be formulated as:

$$\widehat{\lambda}(t) = h^{-1} \sum_{i=1}^{m} K\left(\frac{t - T_i}{h} \right),$$ (20)

where K is the kernel function and h is the bandwidth. The following Gaussian kernel was used [58,59]:

$$K(y) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{y^2}{2} \right).$$ (21)

To facilitate the interpretation of the results, the original units of $\widehat{\lambda}(t)$ of d^{-1} (number of occurrences above threshold per day at a given point in time, t) were multiplied by 365.25, thus indicating the number of occurrences above threshold per year, yr^{-1}.

To reduce the boundary bias near the extremes of the time interval, pseudo-data were generated outside of the observation interval, before estimating $\lambda(t)$. For that purpose, a straightforward method of reflection was used, covering the amplitude of three times h before and after the limits of the time interval. Figure 7 exemplifies the estimated occurrence rates $\lambda(t)$ in one of the studied watersheds (S6 – Ponte Juncais, see Fig. 12 and Table 2), with and without pseudo-data generation, showing the correction of the boundary bias via pseudo-data generation.

Similar to the moving average technique previously mentioned, the selection of the band-width, h, determines the bias and variance properties of the occurrence rate estimator $\hat{\lambda}(t)$ and represents a compromise between two cases: a too small h results in fewer data points that effectively contribute to the kernel estimation, which leads to a reduced bias and a high variance; on the other hand, a too large h leads to an oversmoothing of the estimator, resulting in a small variance and increased bias. Furthermore, since there is a high seasonal variability of the hydrologic regime in Portugal and, as the objective was to describe the inter-annual variability of $\hat{\lambda}(t)$, the bandwidth should be considerably higher than the year to avoid the effect of the seasonal variability.

To quantify the uncertainties associated with the occurrence rate $\hat{\lambda}(t)$, a confidence band was constructed around $\hat{\lambda}(t)$, by means of bootstrap simulations [60,61] applied to the POT data, augmented by the pseudo-data. For that purpose, a resampling estimation with replacement was repeated until 2000 estimated curves $\hat{\lambda}^*(t)$ were obtained. After that, the percentile-t type confidence band developed by Cowling *et al.* [60] and comprehensively described in [57,58,61] was applied to the 2000 $\hat{\lambda}^*(t)$ to construct a 90% bootstrap confidence band around.

Given the expected role of the North Atlantic Oscillation (NAO) in modulating rainfall and river flows in western Iberian watersheds, an additional analysis was conducted on the relationship between the floods and that index aiming at ascertaining whether or not the phase of the NAO has an influence on the occurrence rate of floods in the studied watersheds

The NAO is a prominent and recurrent pattern in climate variability of the Northern Hemisphere, which refers to a redistribution of atmospheric masses between the Arctic and the subtropical Atlantic [62]. Studies carried out by Hurrell [63] and Trigo *et al*. [64] have established links between the NAO phase and precipitation in Western Europe. There are also a number of studies on the influence of the NAO on precipitation and river flow in the western Iberian Peninsula in winter months [65–70], which have shown that when the NAO is in its negative phase, precipitation and river flows tend to be above normal.
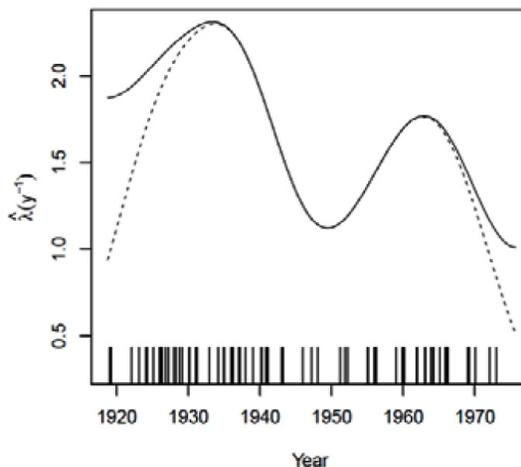

Figure 7: Estimated flood occurrence rate at S6 – Ponte Juncais (Fig. 12 and Table 2), with (solid line) and without (dashed line) pseudodata generation; flood dates (represented by vertical lines) obtained from the POT time data (adapted from [25]).

The NAO index adopted was the Iceland-Gibraltar index developed by the Climate Research Unit ([71]; http://www.cru.uea.ac.uk/cru/data/nao/), based on instrumental pressure measurements in Gibraltar and SW Iceland back to 1821. Only the standardized sea-level pressures differences from November to March were considered: NAO (NDJFM).

3 RESULTS

3.1 Trends in monthly and seasonal rainfalls: moving averages and cumulative moving averages

The moving average technique and the trend detection based on the identification of persistent non-homogeneities between consecutive pairs of anterior and posterior subsets were first applied to the rainfall series in the rain gauges 1–11 schematically located in Fig. 8 [12]. For that purpose, annual rainfall series as well as rainfall series in different seasons and months of the year were analyzed. All the series were referred to the hydrologic or water year which, in Portugal, starts on October 1st. The minimum length of each moving average was fixed at $n = 15$ years, which was also the minimum length of any anterior and posterior subsets.

The results achieved, which suggested a similar behavior in all the analyzed rain gauges, are exemplified in Figs 9 and 10, based on the rainfall records at Torre de Moncorvo (rain gauge number 10, in the North of Portugal, with $N = 117$ years of records, from 1878 to 1995) and Évora (rain gauge number 7, in the South of Portugal, with $N = 97$ years of records, from 1900 to 1996), respectively.

For each given period of time (year, season or month), the moving averages as well as the averages of the consecutive pairs of anterior and posterior subsets were made dimensionless by division by the average of the respective rainfall series in the global period of N years.
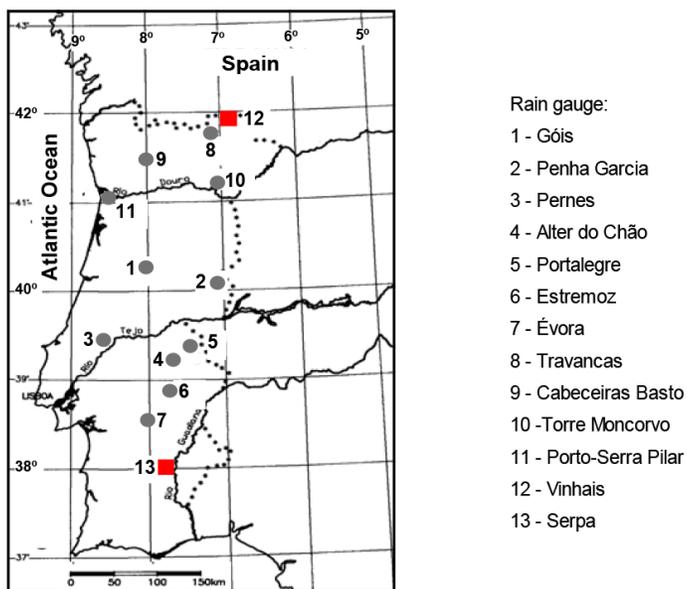

Figure 8: Location of some of the rain gauges considered in the trend analysis. The rain gauges from 1 to 11 were adopted by Portela and Quintela [12] (see Table 1), and the rain gauges 3, 12 and 13 are three of the 24 analyzed by Vaz [23] (see Fig. 12).

Each moving average was identified by the first year of the corresponding $n = 15$ years period. The averages of each pair of anterior and posterior subsets were identified by the last year of the corresponding anterior subset.

Figures 9 and 10 clearly show that the rainfall series in March at both rain gauges exhibit a downwards trend, which is also visible in the second quarter of the hydrological year, also as result from the decrease of the rainfall in March.

For rain gauges 1–11 of Fig. 8, Table 1 allows comparing the averages of the rainfall series in the recording periods and in the last 15 years analyzed by Portela and Quintela [12].

The previous table shows that the rainfall in March exhibits notorious decreases in all the rain gauges. In annual terms, the last periods of 15 years were drier than the total recording periods. However, the statistical tests applied showed that in any rain gauge the decrease in the annual rainfall was always within the natural variability of the phenomenon and, therefore, did not represent a non-homogeneity, and accordingly, a sign of the climate change.

3.2 Trends in monthly and annual rainfalls: the Mann–Kendall non-parametric test and the Sen slope estimator

To apply the Mann–Kendall test along with the Sen slope estimator 94 years of monthly and annual rainfall (from October 1910 to September 2004) in 144 Portuguese rain gauges were selected (Fig. 11) [13,14]. Some of the series had a few sporadic gaps that were filled based on linear regression analysis [27].
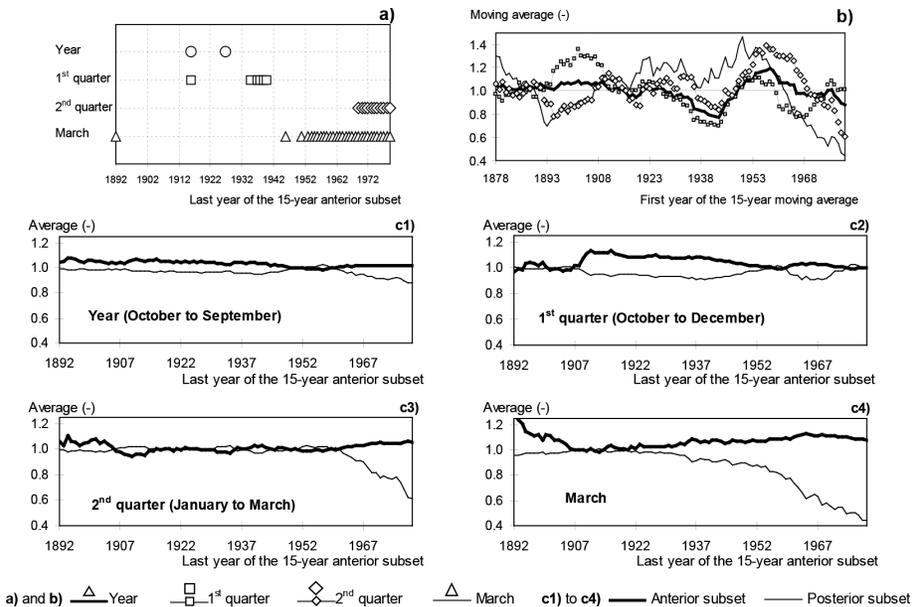
Figure 9: Torre de Moncorvo rain gauge. October 1878 to September 1995 ($N = 117$): (a) non-homogeneity occurrences; (b) dimensionless moving averages in 15-year periods and (c1)–(c4) averages of the successive pairs of anterior and posterior subsets (adapted from [12]).

Table 1: Rain gauges 1–11 of Fig. 8.

| Rain gauge | Recording period | | | | | Last 15 years | | | | |
| | Period (from October to September) | Average rainfall | | | | Period (from October to September) | Dimensionless average rainfall | | | |
		Year (mm)	1st quarter (mm)	2nd quarter (mm)	March (mm)		Year (–)	1st quarter (–)	2nd quarter (–)	March (–)
1–G6is	1917–1999	1162	404	441	132	1985–1999	0.927	1.040	0.755	0.439
2–Penha Garcia	1910–1999	803	306	289	89	1985–1999	0.976	1.123	0.800	0.368
3–Pernes	1915–1995	834	310	323	100	1981–1995	0.784	0.922	0.589	0.376
4–AlterdoChao	1911–1999	625	224	236	72	1985–1999	1.028	1.212	0.820	0.436
5–Portalegre	1910–1997	854	312	325	101	1983–1997	0.975	1.105	0.762	0.436
6–Estremoz	1911–1995	658	243	248	82	1981–1995	0.878	1.022	0.651	0.434
7–Evora	1900–1996	640	239	240	76	1982–1996	0.924	1.049	0.724	0.418
8–Travancas	1913–1999	993	345	336	101	1985–1999	0.935	1.061	0.727	0.451
9–Cabeceiras Basto	1913–1999	1505	527	562	166	1985–1999	0.982	1.173	0.775	0.394
10–Torre Moncorvo	1878–1995	563	204	173	54	1981–1995	0.882	1.012	0.614	0.442
11 –Porlo–SerraPilar	1900–1994	1187	440	4J5	127	1980–1994	0.985	1.075	0.796	0.651

Average rainfalls in the recording periods and in the last 15–year periods (adapted from [12]).
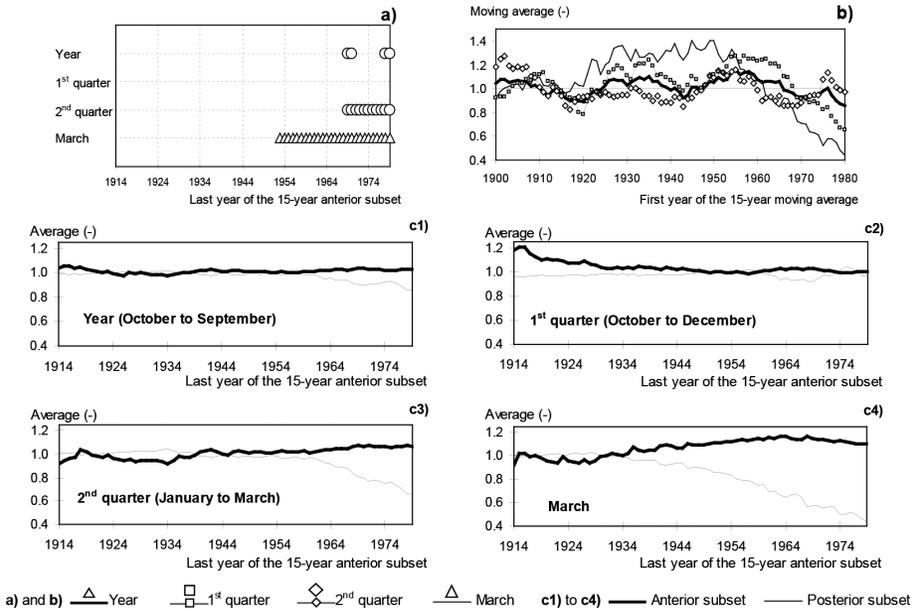
Figure 10: Évora rain gauge. October 1900 to September 1996 ($N = 97$): (a) dimensionless moving averages in 15-year periods; (b) non-homogeneity occurrences and (c1)–(c4) averages of the successive pairs of anterior and posterior subsets (adapted from [12]).

The Mann–Kendall test showed that most of the trends denoted by the 144 monthly and annual rainfall series were statistically meaningless, being explained by the natural temporal variability of the rainfall regime. Whenever the Mann–Kendall test pointed out a significant trend in a monthly or annual rainfall series, the Sen estimator was applied to quantify the magnitude of such trend.

By means of a GIS, maps with the spatial distribution (based on the Krigging interpolation method) of the Sen estimator were produced, as shown in Fig. 11 in which the dots represent the 144 rain gauges considered in the study. Any value from one of the maps in Figure 11 represents a change (increase, if positive, decrease, if negative) in the annual amount of rainfall expressed in percentage of the mean annual rainfall in the period to which the map under consideration refers.

Figure 11 clearly shows that most of the rainfall changes are spatially quite circumscript and almost neglectable. Only the rainfall in March exhibits a very pronounced and widespread downwards trend. However, it should be said that except for a small region in the North of Portugal, the rainfall in March is always smaller than 150 mm, which means that a maximum annual decrease according to the Sen estimator of about 1.3% will, in fact, represent a median decrease of the annual amount of rainfall in March of only 2 mm.

3.3 Trends in annual maximum daily rainfalls: the Gumbel law

To analyze the consequences of different recording periods in the estimates of the extreme rainfalls given by the Gumbel law, the annual maximum daily rainfall series, *Pamd*, at 24 rain
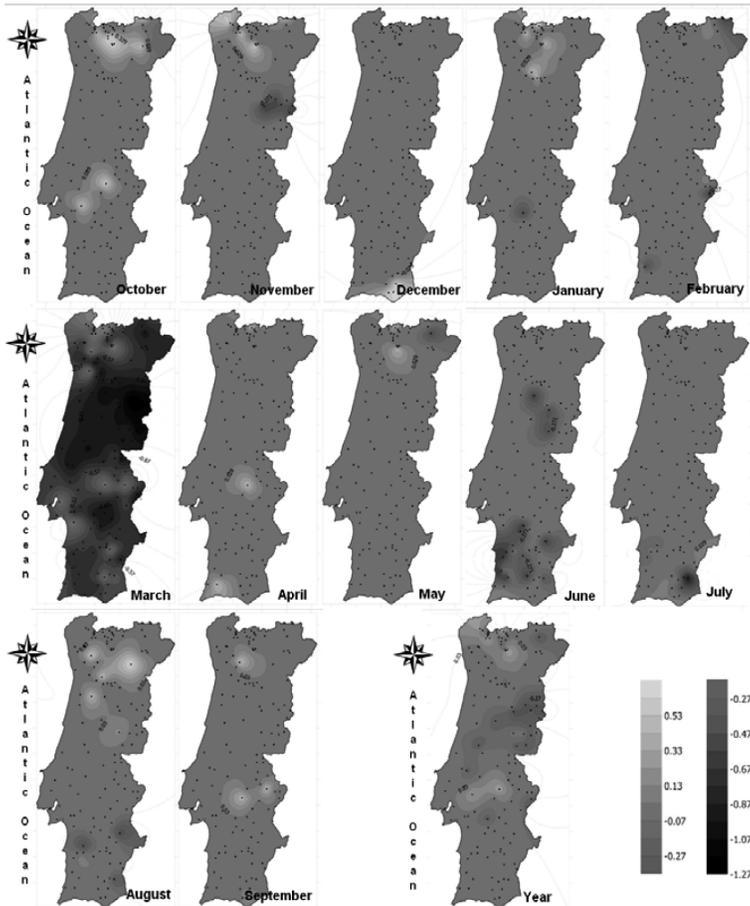
Figure 11: Trends in the monthly and annual rainfall series at 144 Portuguese rain gauges. For each interval (month or hydrological year), the scale represents the yearly variation (light gray for the increase and dark grey for the decrease) of the rainfall, expressed in percentage of the mean annual rainfall in that time interval. The dots represent the 144 rain gauges utilized in the study. The grey background of the maps stands for zero in the Sen slope scale (neither an increase nor a decrease) (adapted from [13]).

gauges geographically spread over mainland Portugal and with more than 70 years records were studied (Fig. 12) [23]

At each rain gauge, the Gumbel cumulative distribution was computed based on the *Pamd* records in each one of the successive subsets of $n = 25$ consecutive years into which the global recording period was split. The results achieved for the recording period of 70 years, from October 1931 to September 2001, are exemplified in Fig. 13, based on rain gauges numbers 3, 12 and 13 of Fig. 8 (also included in Fig. 12). For each *Pamd* sample, the total number of 25-year subsets analyzed was 70 - 25 + 1 = 46.

For the three rain gauges adopted as examples, Fig. 13 shows the Gumbel cumulative curves based on the first five and on the last five subsets of 25 years each (each subset is
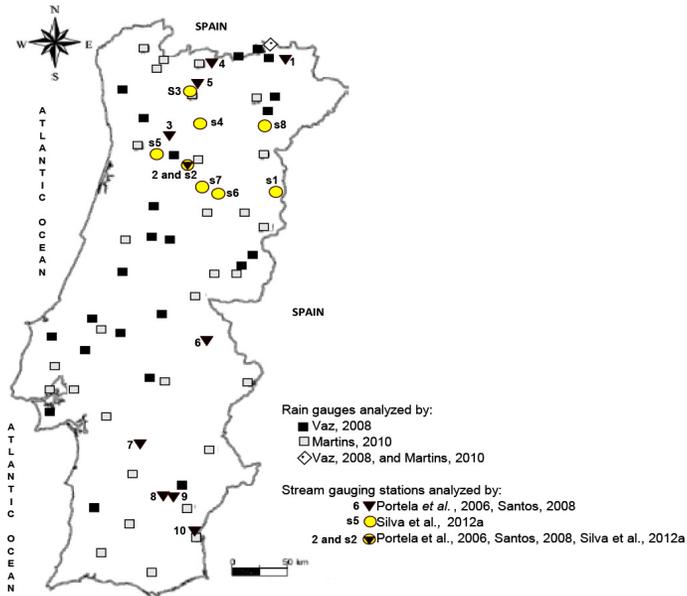
Figure 12: Location of the rain gauges analyzed by Vaz [23] and Martins [24] (23 and 31 rain gauges, respectively) and of the stream gauging stations analyzed by Portela *et al*. [21,22] and Silva *et al*. [25] (10 and 8 gauging stations, respectively).

identified by the rank of its initial year). The vertical axes were made dimensionless by dividing the estimates of the maximum annual daily rainfall by the average of the *Pamd* sample in the 70-year period and the horizontal axes represent non-exceedance probability, *F*. The estimates of *Pamd* for the non-exceedance probability of 0.99 (100-year return period) are highlighted.

Figure 13 shows that for Vinhais rain gauge (North of Portugal) the estimates based on the latest records are not as high as those supported by the oldest records. The opposite situation occurs in Serpa gauge (South of Portugal) while in Pernes (Center of Portugal) both estimates are very close. One of the conclusions that can be drawn out from the results exemplified in Fig. 13 is that different periods need to be analyzed in order to ensure safe/conservative design rainfalls. Another conclusion is that the behavior of the extreme rainfall time series may refuse (like in Vinhais or even in Pernes) or confirm (like in Serpa) the extreme rainfall upwards trend that, for Portugal, is generally pointed out as denoting the climate change effect.

Martins [24] also analyzed long rainfall series with the purpose of identifying changes in the intra-annual pattern instead of changes in the inter-annual pattern, as it was done in the studies previously mentioned. Based on the monthly rainfalls, from 1910/11 to 2003/04, in 31 rain gauges stations evenly distributed over mainland Portugal (Fig. 12), different procedures were applied, by means of moving average techniques complemented by the Student and the Mann–Whitney statistical tests aiming at identifying changes in:

- the contribution to the annual rainfall of the 3 months with highest rainfall;
- the most frequent period of the year of occurrence of the maximum monthly rainfall;
- the period of the year in which 20%, 40%, 60% and 80% of the annual rainfall is achieved;
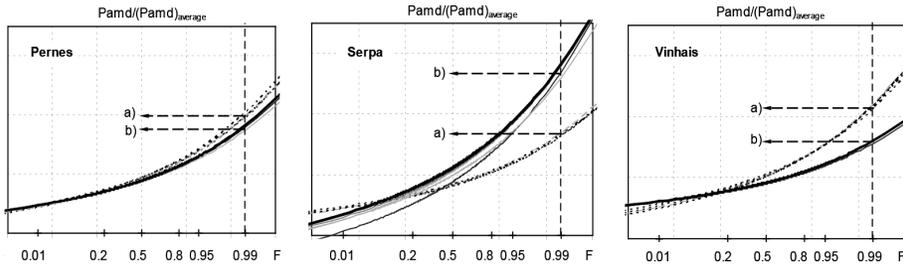
Figure 13: Gumbel law applied to different periods of 25 years of records. Rain gauges of Pernes, Serpa and Vinhais (numbers 3, 12 and 13 of Fig. 8, also included in Fig. 12). The grey-black dashed lines relate to the more recent five subsets of 25 years each and the grey-black continuous lines to the earliest five subsets of 25 years each. (a) and (b) are the mean values of the estimates of *Pamd* for the 100-year return period (non-exceedance probability of 99%) given by the previous subsets, respectively.

- the contribution to the annual rainfall of each one of the four trimesters of the year relatively to a 25-year average trimester.

The only hint of change in the intra-annual rainfall pattern with statistical significance that was detected among the majority of the 31 rain gauges analyzed by Martins [24] suggested a progressive and effective replacement of the second trimester of the hydrological year (from January to March) by the first trimester (from October to December), which became the most frequent period of occurrence of the maximum monthly rainfall, and the period with the highest contribution to the total annual rainfall. This shift, which is also due to the decrease in the rainfall in March, reflects a notorious change in the within-the-year temporal pattern of the rainfall in Portugal.

3.4 Performance of artificial reservoirs: simulation algorithms

Along with the analysis of long rainfall series, a study focused on trend detection in stream-flows series and on the behavior of artificial reservoirs was also carried out [21,14]. In fact, due to the temporal irregularity that characterizes the Portuguese hydrologic regime (in average, 80% of the surface water resources occurs in the wet semester, from October to March; in the driest regions of the country, the previous percentage can raise up to 95%), most of the water supplies are ensured by artificial reservoirs created by dams, a significant part of these infrastructures having been built in the early 1950s and 1960s. Therefore, a question arose: due to the expectable consequences of the climate change, are those reservoirs still able to ensure the amount of water adopted as design criteria with the reliability required by each type of water use? The issue is especially relevant in the case of irrigation reservoirs because both the crop water requirements and the water availability are influenced by the effects more often identified as resulting from the climate changes, namely, the decrease in the precipitation and the increase in the temperature.

To answer the previous question, the performance of 10 hypothetical irrigation reservoirs located in river sections coincident with stream gauging stations under natural or pristine conditions (Fig. 12) was analyzed by means of computational simulation techniques [14,21].

The gaps in the monthly flow samples, as well as the extension of those samples to the 94-year period (from October 1910 to September 2004) adopted in the study were computed based on water budget techniques applied to rainfall and evapotranspiration data. Those techniques were prior calibrated and validated based on the available streamflow records.

The changes along time in the performance of each reservoir were described in terms of the changes (increase or decrease) in the storage capacity required to satisfy a given water demand with a given reliability. For that purpose, the recording period was divided into 94 - 30 + 1 = 65 consecutive subsets of 30 years and the operation of the reservoir simulated in each one of those subsets. Different water demands and reliabilities were considered. The water demands were defined for the first year of the analyzed period (1910/1911) as percentage of the long-term mean annual flow volume and made vary along time exactly in the same ratio of the temporal variation of the crop evapotranspiration regarding its value also at the beginning of the analyzed period (1910/1911).

Some of the trends detected are represented in Fig. 14. In the figure, the black arrows denote worse constraints – decrease (-) in the inflows to the reservoir or need for higher (+) storage capacity to ensure the same water demand with the same reliability – and the light grey arrows better constraints – increase (+) in the inflows or need for smaller (-) storage capacity to ensure a given water demand with a given reliability. The water demands were expressed as percentage of the long-term mean annual inflows to the hypothetical reservoirs and reliabilities of 80% and 90% were considered. On a monthly basis, the reliability can be understood as the percentage of months with total fulfillment of the water requirements, as previously said. The reliability applied to irrigation supply is generally around 80%.

Figure 14 shows that most of the case studies – with special emphasis on those located in the Centre and in the South of Portugal – denotes loss of reliability as more storage capacity would presently be required to ensure the same water demand with a given guaranty. In some case studies, this even happens when increase in the water inflows occurred, meaning that such increase is not enough to compensate the increase in the crop water requirements eventually combined with an increase in the temporal irregularity of the flow regime. However, it should be pointed out that all the increases/decreases under consideration were very small and often almost negligible, as exemplified in Fig. 15 for the storage capacity, C, of the hypothetical reservoir located at Castro Daire case study (stream gauging station number 2 of Figs 12 and 14).

General location	Stream gauging station		River/main watershed	Watershed area (km²)	Trend in the annual inflows	Trend in the storage capacity as a function of the water demand and of the reliability of the water supply					
	Number	Name				Water demand (% of the long term mean annual inflow)					
						30	50	70	30	50	70
						Reliability of the water supply					
						80%			90%		
North of Portugal	1	Vinhais-Qta da Ranca	Tuela/Douro	455	+	-	-	-	+	-	-
	2	Castro Daire	Paiva/Douro	291	-	+	+	+	+	+	+
	3	Cabriz	Sampaio/Douro	17	-	-	-	-	+	-	-
	4	Vale Giestoso	Beça/Douro	77	+	-	-	-	-	-	-
	5	Cunhas	Beça/Douro	338	-	+	+	+	+	+	+
Center of Portugal	6	Couto de Andreiros	Seda/Tejo	244	-	+	+	+	+	+	+
South of Portugal	7	Torrão do Alentejo	Xarrama/Sado	465	-	+	+	+	+	+	+
	8	Albernoa	Terges/Guadiana	177	+	+	+	+	+	+	+
	9	Monte da Ponte	Terges/Guadiana	707	+	+	+	+	+	+	+
	10	Vascão	Vascão/Guadiana	428	+	-	-	+	-	-	+

Figure 14: Artificial reservoirs for irrigation purposes. Trends in the annual inflows and in the storage capacities (period from October 1900 to September 2004) (note: the green arrows denotes better constraints and the red ones worse constraints).

3.5 Non-stationarity in the occurrence rate of floods: the kernel occurrence rate estimation method applied to POT data

Figure 12 also has the general locations of the eight unregulated Portuguese catchments that were analyzed by Silva *et al.* [25] regarding the changes in the flood occurrence rates – Table 2.

With the application of a peak over threshold, POT, sampling technique to a time series, two types of data can be obtained: time data, that is, the instants of occurrence of extreme events, and peak value data, namely the magnitude of the extreme events themselves. When aiming at analyzing the non-stationarities in the occurrence rate of flood events, only the results from the time data are relevant. Accordingly, the kernel occurrence rate estimation method and the respective bootstrap simulations were applied to the POT time data sampled from the mean daily streamflow series, extended by the pseudodata outside the observation interval. To fix the bandwidth, h, of eqn. (20) the Silverman's rule of thumb was used [72, p. 48], which resulted in bandwidths from 1725 days (sample S4) to 2157 days (sample S7). Some of the results achieved are presented in Fig. 16.

Figure 16 shows that the occurrence rates of extreme events in time series of mean daily flow exhibit significant inter-annual variability. In fact, several samples denote a peak of $\widehat{\lambda}(t)$ in the 1960s such peak being significantly higher than the upper limit of the bootstrap confidence band at 1990. The increase that, according to the climate change, should occur in the extreme events towards the present is not visible in any of the stations with recent data. The figure also shows that the intensity of the inhomogeneous Poisson process in some of the mean daily streamflows samples exhibit common trends, such as: (a) a peak in $\widehat{\lambda}(t)$, indicating a higher frequency of extreme events, in the early 1960s in the graphs with available data in those years; (b) in graphs S6 and S7, a peak in the 1930s followed by a decrease in intensity until a minimum is reached in the late 1940s; (c) in the graphs with data until the late 1990s and 2000s, lower occurrence rates in the more recent years.

The fact that such trends are visible in mean daily flow series from unregulated rivers indicates that they are not due to possible anthropogenic influences. The $\widehat{\lambda}(t)$ estimates obtained for the rainfall data, though not presented, corroborate this hypothesis since, although the correspondence is not perfect, they exhibit some of the same trends that are visible in the flow data of the catchments under the influence of those particular rainfall gauging stations.
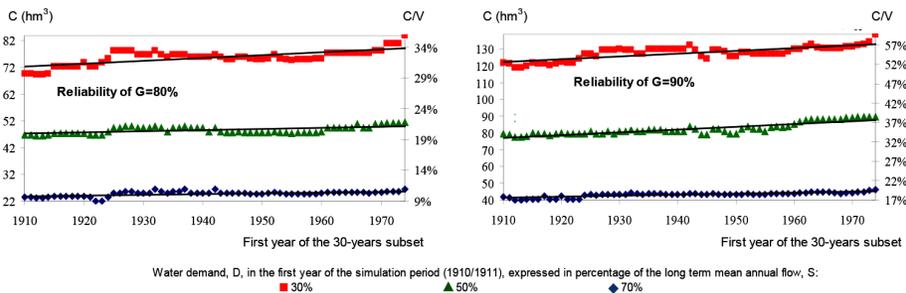

Figure 15: Castro Daire case study (stream gauging station number 2 of Figs 12 and 14). Reliabilities, *G,* of 80% and 90% and water demands in the first year (1910/1911) of 30%, 50% and 70% of the long-term mean annual inflow, *V,* to the hypothetical reservoir. Variation (in volume and dimensionless) of the storage capacity, *C,* along the 65 consecutive subsets of 30 years each.

Table 2: Characteristics of the mean daily streamflows analyzed by Silva *et al*. [25].

| Code	Name	Period of records (number of years)	Mean annual flow depth (mm)	Catchment area (km^2)	POT sampling threshold values, u (m^3 /s)
S1	CasteloBom	1957/58-2003/04(47)	348	897	69.1
S2	Castro Daire	1945/46-2003/04(59)	738	291	47.6
S3	Cunhas	1949/50-2005/06(57)	824	338	61.7
S4	ErmidaCorgo	1956/57-2005/06(50)	888	291	57.3
S5	Fragas da Torre	1946/47-2005/06(60)	992	660	145.3
S6	Ponte de Juncais	1918/19-1974/75(57)	492	604	65.9
S7	Ponte Sta. Clara-Dao	1921/22-1972/73(52)	455	177	17.8
S8	Quinta das Laranjeiras	1942/43-2005/06(64)	246	3464	188.8
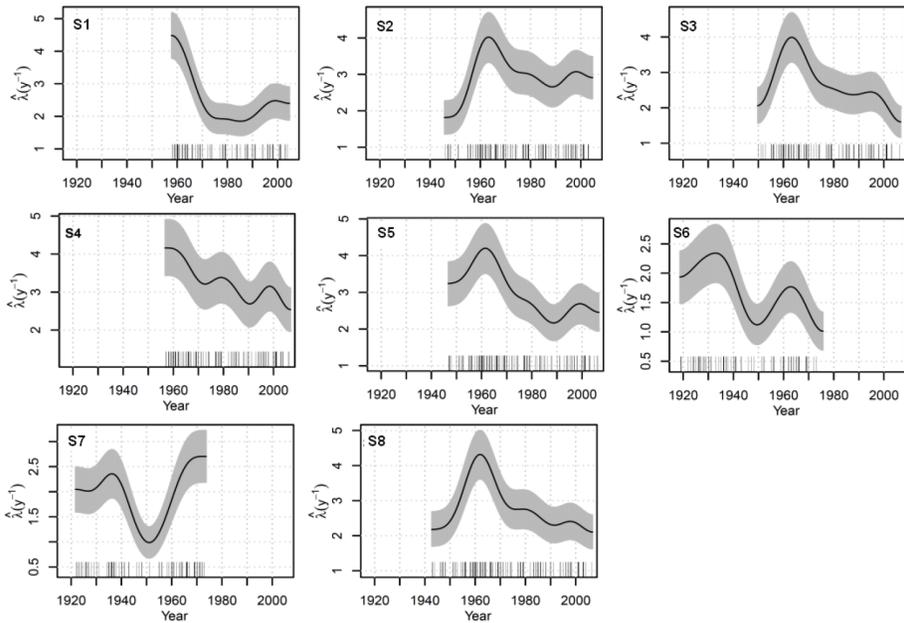
Figure 16: Estimated flood event occurrence rates (black lines) with 95% confidence intervals (grey area). The vertical ticks indicate the points in time when events occurred (POT time data). The code in the top left corner of each graph identifies the data series (Fig. 12 and Table 2) (adapted from [25]).

The results from the additional analysis aiming at ascertaining whether or not the phase of the of NAO has an influence on the occurrence rate of floods in the watersheds of Table 2 are presented in Fig. 17 that shows, for each streamflow sample, the number of floods per hydrological year, λ_k (discrete POT time data), plotted against the winter NAO indices of the corresponding years.
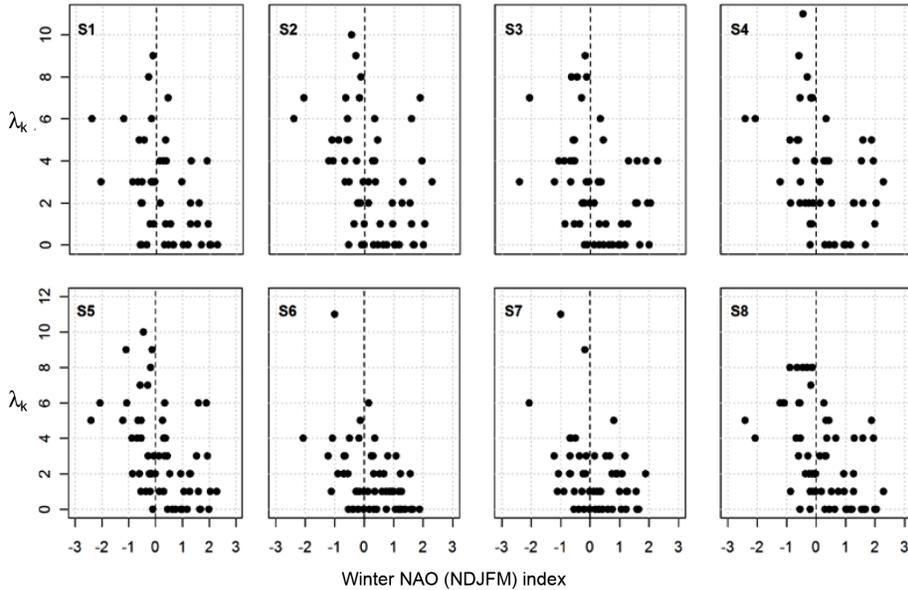
Figure 17: Number of floods in a hydrological year, *lk*, plotted against the winter NAO (NDJFM) index of the same year (adapted from [35]).

The results of Fig. 17 suggest that years with positive NAO indices have a lower number of floods than years with negative NAO indices. Even if that correlation does not seem to be particularly strong, the previous figure clearly shows that for every analyzed sample: (i) the majority of years without floods have positive NAO indices and (ii) the years with the highest floods do not occur in positive NAO phases. They also suggest that an increase in the rate of flood occurrence might be related to a decrease in NAO indices. These results are still being investigated aiming at establishing improved statistical flood models under the assumption of non-stationarity.

4 FINAL REMARKS

Although the results presented are supported by theoretically sound models based on extensive hydrological data, they are only the outcome from one of the possible global approaches aiming at understanding the trends in some of the hydrological time series and their relation with the expected signs of the climate change: they rely on the expectation that the past records can already provide information about those signs. That expectation can be arguable especially due to narrow time window of the available hydrological samples.

Somehow contradicting the skepticism that may entail an approach based on available records, it is more often mentioned that the Earth is already suffering the climate change effects: it is no longer a matter of future climate scenarios but instead of frequent abnormal climate occurrences. If changes are already happening, then they should be present in some of the hydrologic time series, with emphasis to those series more closely related to the weather, as the rainfall series.

And so, prior to any skepticism regarding trend analysis, in one hand, supported by hydrological records or, in other hand, provided by greenhouse gas emission scenarios, it is necessary

to decide whether or not the climate change is already taking place and producing consequences. The authors of the present chapter believe that some of the available records already mirror the effects of the climate changes, which makes the trend analysis based on those records worthwhile. Also, any improvement towards the capability of applying relatively simple models to 'extract' from the records signs of a changing climate can be very useful in terms of the establishment of criteria applicable to the design of some infrastructures.

Regarding the results achieved, though some anomalies were already detected – such as the reduction of the rainfall in March or the shift in the period of the year with more precipitation – in general terms, they showed that the hydrologic series can be much more resilient than the human perception and that it is difficult, for the time being, to clearly identify signs of the climate changes in such series. This circumstance suggests that further studies and scientific judgments are required because, somehow, there is a gap between what is already considered as resulting from the climate change and the effective behavior denoted by some of the hydrologic time series. To improve the knowledge about the climate, it is fundamental to pursuit with the continuous monitoring of the hydrological variables.

But does this mean that the stationarity assumption of most of the hydrologic models is no longer valid? Will the future be statistically different from the past and, if so, how can the hydrological models and the design criteria allow for this dissimilarity? Though for the time being this is still an unsolved question it undoubtedly points towards the need to account for hydrologic uncertainty, for instance, based on risk analysis tools. Also, the frequency models relying on stationarity should be revised in view of integrating possible non-stationarities, for example, by means of external variables, such as the NAO or sea surface temperature, SST [73].

A final comment regarding freshwater availability, in terms of social awareness, it is of crucial relevance separating between water shortness (both quantity and quality) due to the increase in the water usage by the modern society and due the climate change, which undoubtedly will aggravate dramatically the former shortness. Along with the first signs of the climate change, but also far beyond such signs, the quantity/quality of the fresh water had become progressively insufficient, which makes fundamental increasing the awareness about the unquestionable need for a more sustainable use of the water because its scarcity is already a fact *per se*.

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