Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2020.25856

194 (2020) 343–357
August

Climate changes impacts in the upper Paiva River: today and in the future

Vitor Sousa[a,*], Inês Meireles[b], Alexandre B. Gonçalves[a], Ana Paula Falcão[a]

[a]*CERIS, Department of Civil Engineering, Architecture and Georesources, Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001, Lisbon, Portugal, Tel. +351 218 418 381; emails: vitor.sousa@tecnico.ulisboa.pt (V. Sousa), alexandre.goncalves@tecnico.ulisboa.pt (A.B. Gonçalves), ana.p.falcao@tecnico.ulisboa.pt (A.P. Falcão)*
[b]*RISCO, Civil Engineering Department, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal, email: imeireles@ua.pt (I. Meireles)*

Received 8 October 2019; Accepted 17 March 2020

ABSTRACT

The Paiva River is a tributary of the Douro River in northern Portugal with a length of 110 km and a catchment area of 790 km^2. Nowadays, its upper section dries completely by the end of the dry season every year. The individuals living in communities along the river are consistent in identifying the beginning of this phenomenon by the end of the 1990 s or early 2000 s. In the present research, the potential causes for this are identified, evaluated, and discussed. The direct human consumption was possible to exclude due to the decrease of both population and water-intensive activities in the period of interest. Considering the information available, climate changes are identified as the main driver for the complete dry out of the upper section. Specifically, the differences in the precipitation distribution along the year were found to be statistically significant and the increase of the number of consecutive days without rain could be related to the depletion of the underground water. Considering rainfall pattern forecasts for 2050 based on various climate change scenarios and global circulation models, it is possible to conclude that the already poor environmental condition of the upper Paiva River section will degrade even further in the future.

Keywords: Climate change; Drying; Upper Paiva River; Rainfall; Runoff

---

1. Introduction

The majority of the macro-scale hydrological modeling studies accounting for climate change scenarios, both at continental [1,2] and global [3–7] scales, forecast variations on the hydrological regime of continental water bodies (rivers and lakes). Despite the variability between the various studies and the uncertainty associated with the models used [8], several of them are consistent in suggesting that global warming will intensify the hydrologic cycle. This implies an increase of the global mean precipitation as well as of the frequency and intensity of precipitation extremes [9–11].

However, these changes are expected to be heterogeneous throughout the globe. In fact, the regional climate models for Europe point toward an increase in both mean and extreme precipitation in the North [12–14], whereas in the South (Mediterranean region), it is forecasted a decrease in the mean precipitation and an increase in the extreme events [15,16]. For regions with a Mediterranean climate, De Girolamo et al. [17] present a very complete literature review of studies dealing with flow regime alteration and report results on an Italian river basin. The literature analyzed is consistent in estimating a reduction in the total flow, with some identifying the temporal shift in peak flows and the increase of the number of days without flow. Furthermore, regardless of the sometimes contradicting results when estimating rainfall patterns under climate change conditions at the more refined time and spatial

---

* Corresponding author.

Presented at the 7th International Conference on Sustainable Solid Waste Management, 26–29 June 2019, Heraklion, Crete Island, Greece

scales, several points of the globe are already experiencing the effects of climate changes in the natural habitats (e.g., Asia [18,19]; Africa [20–22]; Australia [23]; Europe [24,25]).

Specifically, for Portugal, there are fewer studies, but the global and the regional studies alike point to an alteration of the rainfall pattern, estimating an increase in the difference between wet and dry seasons [26–28]. In addition to the higher rainfall in the winter and lower rainfall in the summer, some studies also predict an overall reduction of the total annual rainfall [29,30]. The most recent studies [31,32] are more pessimistic in terms of total annual rainfall reduction, forecasting also a decrease of the number of the days with precipitation above 1 mm and an increase of the number of days with precipitation above 20 mm. The forecasted more intense weather events over Portugal mainland, namely shorter and more intense rainfall events and longer and more frequent droughts, along with the reduction in the total rainfall lead to estimates that point toward the reduction of the total flow, more severe floods, and droughts in some the major rivers [33].

Most of the related literature found focus either on forecasting future flow regime under climate change scenarios or reporting changes in flow regime patterns in large river basins. However, in such cases, the flow regime is governed by both the climate and human activities (e.g., dam building, land use, and water abstraction). In fact, the dynamics of the human activities within a river basin may have a substantial impact on the flow regime that is difficult to model in order to accurately quantify the climate change contribution. Major rivers not only have a natural higher water storage capacity (e.g., groundwater, ponds) but in many cases also artificial water storage capacity installed (e.g., dams). This enables the possibility of transferring more water from the wet season to the dry season, maintaining the ecologic flow to support the natural and human communities depending on the rivers. This dampening effect of climate change trends present in large rivers networks was demonstrated by Chezik et al. [34]. Naturally, doing so will put pressure on the water availability for human consumption and energy production, but that is a distinct challenge that will not be discussed herein.

Smaller watercourses, such as creeks, tributaries, and even the upstream sections of major rivers, tend to lack both the natural and the artificial storage capacity to cope with a change in the time pattern of the rainfall (no lakes, glaciers, or large snowcaps accumulating water). The flow in the rivers is exclusively driven by surface and subsurface runoffs. The subsurface runoff includes the subsurface stormflow flow and the baseflow. Since the surface runoff and stormflow flow respond rapidly to rainfall, modifications on the temporal distribution of the rainfall can only be absorbed by the groundwater storage capacity that controls the baseflow. Assuming that the pattern forecasts for Portugal mainland are correct, the increase in seasonality will impact most severely on the small watercourses, even more if a total annual flow reduction is also observed.

In addition to the uncertainty associated with forecasting climate changes, when exploring the influence on the hydrology of water bodies the magnitude of the uncertainty increase even further and a correct assessment is difficult [35–37]. Additionally, the hydrology of water bodies is not driven by climate alone, with the direct human actions over the river basin playing also a role and the combined effect is non-linear [38,39]. For Portugal mainland, and the Tagus River specifically, Hattermann et al. [40] compares the level of uncertainty from Global Circulation Models and Regional Circulation Model simulations and Vetter et al. [41] evaluates the sources of uncertainty. The studies confirm the strong decreasing trend the flow in the Tagus River, along with substantial differences depending on the model used for simulating climate change. The influence of the hydrologic model was found negligible and the representative concentration pathways was the most important source of uncertainty.

The present research explores the potential link between the drying of the upper Paiva River, reported by the riverine communities to have started around the turn of the XXI century, and climate changes. Climate changes, as well as the resulting consequences on the environment, are smooth processes that may take several years to become evident. However, if the climate changes may be smooth and with time, eventually, imperceptible to individuals that gradually get used with the new weather patterns, the impacts tend to be much more evident when there is a dramatic change in the ecosystem within a generation period. Individuals memories are more accurate to point out absolute changes (e.g., a river drying or not) than recalling subtle differences of naturally random phenomena (e.g., separating rainfall pattern changes from the natural variability between wet and dry years). The study presents some distinctive features from the mainstream research on this topic, namely: (i) it is based on an observed flow regime change, instead of forecasting scenarios; (ii) the direct human influence on the flow regime (land use, water abstraction) was evaluated and could be excluded as the main driver for the observed change; (iii) it does not resort to any hydrologic model to relate rainfall with runoff; (iv) statistically significant relation between the rainfall pattern change and flow range was found; and (v) the known hydraulic dynamics of the upper Paiva River are consistent in explaining the influence of the observed rainfall pattern change on the flow regime. After relating the observed hydrologic regime change in the upper Paiva River with the recorded precipitation pattern evolution over, we make some extrapolations considering future climate changes. The research aims at alerting for the relevance of climate changes on small water bodies, where the flow regime changes can be even more critical than on large water bodies. In the case study analyzed, the climate changes consequence was the shift from a perennial to a non-perennial river. The impact of such a transformation on the ecosystems is, in principle, more severe than a simple flow reduction. Furthermore, considering that small water bodies are less monitored, it is possible that numerous similar situations are being overlooked throughout the globe.

2. Case study

The Paiva River starts at Serra da Nave and flows to the Douro River. The river basin is close to the Atlantic Ocean, covering an area of 790 km^2 with an average altitude of 567 m, ranging from 49 m (at the confluence with the Douro

River) and 1,361 m (Serra de Montemuro). The Paiva River is regarded as one of the most beautiful rivers in Portugal and enjoys the reputation of being mostly in pristine condition. Based on the river classification system developed for the implementation of the EU Water Framework in Portugal [42], the few small northern mountain rivers (type *M*) and most of the small northern rivers (type *N*1; ≤100) of all Douro River basin are located in the Paiva River basin.

The Paiva River and its main tributaries are classified as good or higher quality water bodies in the Douro Hydrographic Region Management Plan [43]. Considering the Köppen–Geiger scale, the Paiva River water basin is classified as Csb, corresponding to a warm-summer Mediterranean climate with influence from the Atlantic Ocean. The monthly rainfall ranges from an average maximum of 831 mm in December to an average minimum of 0 mm in July, August, and September and the annual rainfall ranges between 878 and 3,005 mm, with an average of 1,616 mm. The monthly temperature ranges from an average maximum of 20.9°C in July to an average minimum of 3.6°C in January and the annual average temperature is of 10°C. The monthly relative humidity is always above 60% on average (from 58.3% in August to 90% in January) and the annual average is nearly 74%. December is the month with fewer sun hours, only 97 in terms of average minimum, and July, with an average maximum of 325 h, the month with most sun hours. In annual terms, there are between 2,335 and 2,400 h of sun. The annual Piche evaporation and potential evapotranspiration are, on average, 990 and 693 mm, respectively. The Piche evaporation ranges from over 170 mm in August, to 25 mm in January, and the evapotranspiration from 112 mm in July, to 12 mm in January.

The reach with roughly 20 km long between the headwaters (1,012 m) and Vila Nova de Paiva (743 m) defines the upper Paiva River. This division is not merely geographic, since the existence of a steep fall (from an altitude of 743–680 m along roughly 4 km downstream of Vila Nova de Paiva) and the increase in slope downstream Vila Nova de Paiva demarcate two morphologically distinct sections of the Paiva River. The upper Paiva River basin has nearly 100 km^2 (Fig. 1), extending over parts of the municipalities of Vila Nova de Paiva, Moimenta da Beira, Sernancelhe, and Sátão. Like the majority of the Paiva River, this reach is preserved in an almost natural state, with the exception of a few leisure areas and abandoned traditional weirs used in the past to divert water for irrigation and milling purposes. None of these human structures altered the river course or identity.

More than 50 individual interviews to long term residents in the communities along the upper Paiva River were carried out in the scope of an EGSP [44] study. The results confirm a consistent collective memory that the complete dry of the river by the end of the summer months (end of August and beginning of September) started roughly at the end of the 1990 s or early 2000 s. The interviewed referred that before there was always water flowing in the upper Paiva river and that by the mid-2000 s the drying became the regular pattern.

3. Data and methods

3.1. Socio-economic data

The Paiva River basin crosses over portions of 12 municipalities, making it hard to assess the exact population

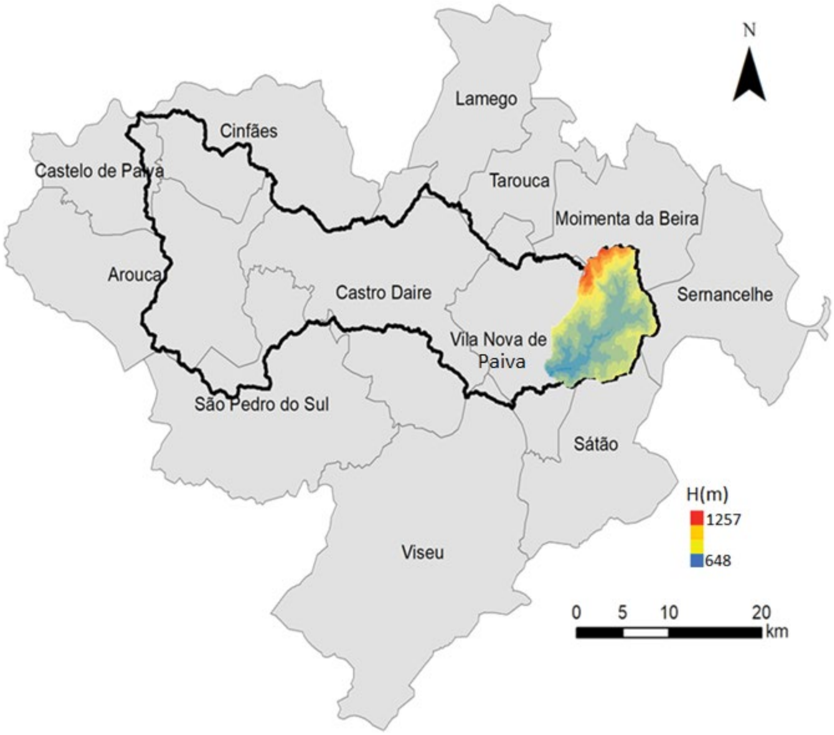

Fig. 1. Elevation map of the upper Paiva River basin.

within it. According to Sousa et al. [45], in 2008, there were 31,637 inhabitants in the Paiva River basin. However, the number of residents in inland regions of Portugal has been decreasing steadily over the last decades, particularly due to the migration to the main urban regions along the coast or even abroad. With the population decrease, the economic activity reduced, and changed from agriculture and livestock to some industry (limited) and, in the last decade or so, to tourism-related services (rural tourism accommodations). The weight of the primary economic sectors (agriculture and livestock) in the Paiva River basin is quite reduced nowadays.

According to the official census reports (https://censos.ine.pt/), the population within the upper Paiva River Basin decreased from around 5,400 residents in 1981, 5,100 in 1991, 4,600 in 2001 to only 4,000 in 2011. From all the parishes within the upper Paiva River Basin, only Vila Nova de Paiva recorded an increase in population from 1981 to 2001, followed by a decrease since. This is consistent with the general migration pattern in Portugal, characterized by people moving from rural areas to urban areas (Vila Nova de Paiva is the municipality headquarters) and to the coast in the search for better living conditions.

Detailed information about water abstraction from the upper Paiva River is not available, but most of the parishes are still supplied by local water sources (groundwater and water springs), that may or not be completely within the upper Paiva River basin, as they were in the past. There is only one parish (Caria), of the Municipality of Moimenta da Beira, which is presently supplied from Vilar dam reservoir. However, it is not expectable the water sources to have changed over time since the general policy in the Portuguese water sector has been to concentrate water sources to better control the water quality. In this regard, one of the major transformations in the water sector in Portugal was the split between bulk and retail water supply utilities. The former were responsible for the water abstraction and treatment, usually covering multiple municipalities, and the later distribute the water to the final users, mostly at a municipal level. Considering this evolution of the water sector and the inexistence of water transfer from the upper Paiva River to supply communities outside its basin, it is possible to conclude that the use of water resources is driven by the population within the basin and their activities.

The average per capita water consumption in Portugal between 1991 and 2009 was quite constant around 60 L/habitant/d, varying between 54.8 L (in 1995) and 66.8 L (in 2004). As such, there is no indication that water consumption in the upper Paiva River basin may have increased significantly over time. This hypothesis is strengthened also by the significant decline in agriculture, linked to the decrease of the population in the rural areas, and the absence of any new significant water-intensive human activity in the area. The only exception is an increase in tourism-related services following the exponential increase observed at a national level over the last 5 y. The number of night stays in Portugal increased only roughly 10 million between 1995 and 2010, from 35 to 45 million, but in 2018 it exceeded 70 million. This increase in tourists could sustain the possibility of an increase in water consumption, particularly during the dry season. However, it is worth noticing that before 2010–2012, tourists would almost exclusively visit the coastal regions of Portugal, in particular the south, and inland regions such as the upper Paiva River basin would almost only receive visits from family members of the residents in the area. Looking for places to stay (e.g., www.booking.com; www.airbnb.com; www.cm-paiva.pt) there are less than 20 offers within the upper Paiva River basin, with only one hotel (2006), one motel (N/A), and the majority being guesthouses and rural tourism accommodations (after 2012) that make use of houses that were no longer used after the population migrations. Furthermore, the tourism boom took place several years after the drying of the river was reported to have started, implying it may be an aggravating factor but not the origin.

Excluding the direct human action as an explanation for the complete dry of the upper Paiva River by the end of the summer, both through water consumption and land use, climate changes becomes a valid possibility to be the main driver.

3.2. Climate and hydrologic data

In Portugal, the data from the majority of the existing hydrometric and udometric stations are freely available through the National Water Resources Information System (Sistema Nacional de Informação de Recursos Hídricos – SNIRH), managed by the Portuguese Environment Agency (Agência Portuguesa do Ambiente – APA), and accessible at http://snirh.apambiente.pt/.

Within the Paiva river basin there are 10 hydrometric stations, 7 in the Paiva River, and 3 in tributaries, but none of them in the upper Paiva River. The station closest to the upper Paiva River basin is installed 24 km downstream from Vila Nova de Paiva, in Castro Daire, defining a basin with 288 km^2. The Castro Daire station is equipped with a limnigraph and there are records of water level and discharge between 01/10/1945 and 30/09/2011, with data missing from 01/10/2004 to 30/09/2006.

The network monitoring precipitation is considerably denser, but has suffered several adjustments over time. The various introduction and removal of udometric stations resulted in a series of records with variable lengths and periods. To characterize the upper Paiva River Basin and the basin defined by the location of the hydrometric station, 20 udometric stations were selected (Fig. 2). Table 1 identifies the udometric stations selected and presents some rainfall statistics along with the length of the record series since 1945/1946. Rainfall records before 1945/1946 were excluded since there is no data on runoff and the relation between both is unknown.

3.3. Statistical analysis

The statistical tests used to assess changes in the runoff and rainfall patterns were: (i) trends (Mann–Kendall, Spearman's *R*, Linear Regression); (ii) jump in mean (distribution free CUSUM, cumulative deviation, Worsley likelihood ratio); and (iii) difference in mean/median (Wilcoxon rank sum, Student *t*-test). The tests used are defined by the WMO [46] as official tools for analyzing hydrologic data. Several studies demonstrate their efficiency

Fig. 2. Location of udometric stations within or near the Paiva River basin.

Table 1
Udomedric station in the area of interest

Station	Annual rainfall (mm)				Number of years with records since 1945/1946
	Maximum	Minimum	Average	Standard deviation	
01 – *Ariz*	*2,418.60*	*761.00*	*1,352.81*	*425.36*	*40*
02 – Brufe (Barreiros)	1,501.70	607.00	1,072.51	249.95	17
03 – Calde	1,541.80	522.80	1,021.80	275.44	20
04 – *Carregal*	*1,759.50*	*135.00*	*873.36*	*386.97*	*38*
05 – Castro Daire	3,336.10	870.90	1,651.73	495.54	56
06 – Castro Daire (Lamelas)	1,292.90	1,213.80	1,263.60	43.35	3
07 – *Forninhos*	*1,472.10*	*445.50*	*870.88*	*252.04*	*21*
08 – *Lapa*	*1,906.80*	*491.20*	*1,115.69*	*345.80*	*19*
09 – *Leomil*	*2,049.90*	*525.90*	*1,044.09*	*358.60*	*54*
10 – Mezio (Paiva)	3,530.30	821.50	1,956.51	661.64	58
11 – *Paradinha*	*1,027.80*	*350.90*	*676.59*	*191.70*	*17*
12 – Pendilhe	3,968.30	881.40	1,822.11	674.08	53
13 – Pindelo dos Milagres	1,817.20	745.90	1,247.77	305.75	17
14 – Queiriga	**1,740.00**	**617.90**	**1,119.87**	**276.29**	**21**
15 – *Quinta da Fumadinha*	*1,490.00*	*693.10*	*983.75*	*221.10*	*21*
16 – *Sarzedo*	*1,150.80*	*624.30*	*884.42*	*180.37*	*13*
17 – Sátão	2,081.90	411.50	1,162.63	375.77	41
18 – Tarouca	**2,810.80**	**551.50**	**1,109.82**	**430.74**	**50**
19 – Touro	**2,763.50**	**270.50**	**1,448.35**	**563.83**	**57**
20 – Vila Nova de Paiva	**2,378.00**	**608.50**	**1,379.77**	**396.11**	**50**

Bold stations are located in the border between the basin of the upper Paiva River downstream section and the hydrometric station section.
Italic stations are located in the limit or within the upper Paiva River basin.
Remaining stations are located in the limit or within the basin between upper Paiva River downstream section and the hydrometric stations' section.

in analyzing hydrologic data series and other variables, including studies specifically in the context of climate changes [20,47–51].

The non-parametric Mann–Kendall evaluates the significance of a trend in a series, independently of whether its shape is linear or non-linear [52,53]. The Spearman's rho is a non-parametric rank-based test alternative to the Person test for evaluating the correlation between variables and can be used for detecting monotonic trends in time series [54]. Testing the significance of the linear regression coefficients, in particular the coefficient representing the slope is another option to evaluate trends, but implies the assumption that the error is normally distributed.

Both the tests for the difference in mean/median and the tests for the jump mean are classified by the WMO as tests for detecting steep changes on the series [46]. However, the former require prior knowledge of the change-point time. The non-parametric rank-based distribution-free CUSUM test evaluates the maximum cumulative sum of the signs of the difference from the median [55,56]. The cumulative deviation test [57] uses a rescaled cumulative sum of the deviations from the mean, instead of the sign of the deviation from the median used in the CUSUM. The version of the test assuming normality was used herein. Like the Student's *t*-test, the Worsley likelihood ratio test [58] also assumes normality, but is suitable for use when the change-point time is unknown. The Student's *t*-test is a standard parametric test for testing whether two samples have different means and the Wilcoxon rank sum (Wilcoxon–Mann–Whitney test/Mann–Whitney test/Mann test/Rank-sum test) is the equivalent non-parametric version, evaluating the differences in ranks between two independent sample groups [54,59,60].

Randomness was also tested using non-parametric tests [61], in particular the median crossing, turning points, and rank difference, as well as a parametric test, Autocorrelation, assuming normality [62].

3.4. Climate change modeling

Estimating the impact of climate changes in weather patterns at a local scale requires three major elements: (i) forecasting of the greenhouse gas concentration in the atmosphere; (ii) simulating the impact of the greenhouse gas concentration on the global circulation of the atmosphere, and (iii) downscaling the changes in the global circulation of the atmosphere to specific locations in the globe.

The most consensual greenhouse concentration scenarios are set by the IPCC – Intergovernmental Panel on Climate Change [63]. Four representative concentration pathways (RCP) for the greenhouse gas concentration trajectory are defined in the fifth assessment report (AR5), namely RCP2.6, RCP4.5, RCP6, and RCP8.5. These scenarios are labeled according to the radiative forcing estimated for the year 2100. The RCP8.5 estimates an exponential increase in C02-equivalent concentration. The RCP2.6 forecasts a slight increase in C02-equivalent concentration until 2030, followed by a stabilization and a gradual decrease from 2060 onwards. The remaining scenarios are intermediate situations.

The impact of greenhouse gas concentration on the circulation of the atmosphere is modeled using general circulation models (GCMs). GCMs employ mathematical models based on the Navier–Stokes equations to simulate the circulation of the atmosphere (or/and ocean). In order to enable the computations to be executed, it uses a grid with a resolution of 1°–5° in latitude and longitude. As such, the circulation is modeled using columns of atmosphere covering from 100 km to more than 500 km at ground level and represents average weather conditions at a macro scale.

The last element attempts to extrapolate the changes forecasted by the GCMs to a specific location, considering its particularities (e.g., topography). This is often done with statistical downscaling by establishing a statistical relationship between the GCMs simulations for past periods and existing meteorological data from ground stations. This statistical relationship is then used to extrapolate the weather conditions for the GCMs forecasts using the various RCP scenarios. The statistical downscaling includes also a spatial interpolation of the GCMs results.

In our research, the rainfall in the upper Paiva River basin in 2050 was estimated using a third-order Markov rainfall generator (MarkSim – http://gismap.ciat.cgiar.org/MarkSimGCM/docs/doc.html). The software was developed to be a generalized downscaling and data generation method. For that purpose, it works on the differences between the baseline and future prediction using a 5th order polynomial to estimate the time trend in each pixel from the GCM output and a cubic convolution to interpolate to a grid of 1 km. This provides the monthly average climate at each point. Then, a daily rainfall simulator generates precipitation series using a third-order Markov process. The transfer probabilities (probability of rain considering the previous 3 d), probability coefficients related to the effect of each of the 3 previous days and the correlation matrix of the baseline probabilities were estimated from historical rainfall data from over 10,000 stations around the globe with more than 10 y of records (most have more than 15–20 y and some even more than 100 y of records). This was intended to avoid the need for recalibration every time the model is used. In each simulation, the rainfall is randomly initialized and the precipitation series is generated preserving the overall pattern forecasted for that location and respecting the downscaling. Further information regarding the tool can be found in Jones and Thornton [64] and Wilby et al. [65]. An ensemble of 17 GCMs was used and only the two extreme RCP (RCP2.6 and RCP8.5) scenarios were considered. For each RCP scenario, 50 replications of the daily rainfall forecast were obtained.

4. Results and discussion

The first step was to assess changes in the annual runoff. Fig. 3 presents the annual and monthly runoff values recorded in the station at Castro Daire from 1945–1946 to 2003–2004. The annual runoff measured ranged from roughly 50 to over 570 million cubic meters, revealing the high inter-annual variability but no visible change in pattern. The regression of the runoff over time has a positive slope, but it is not statistically significant, as none of the statistical tests for trend, jump in mean, and difference in mean/median at a significance level of 5%. The monthly runoff depicts a pattern traditional for a region with clearly

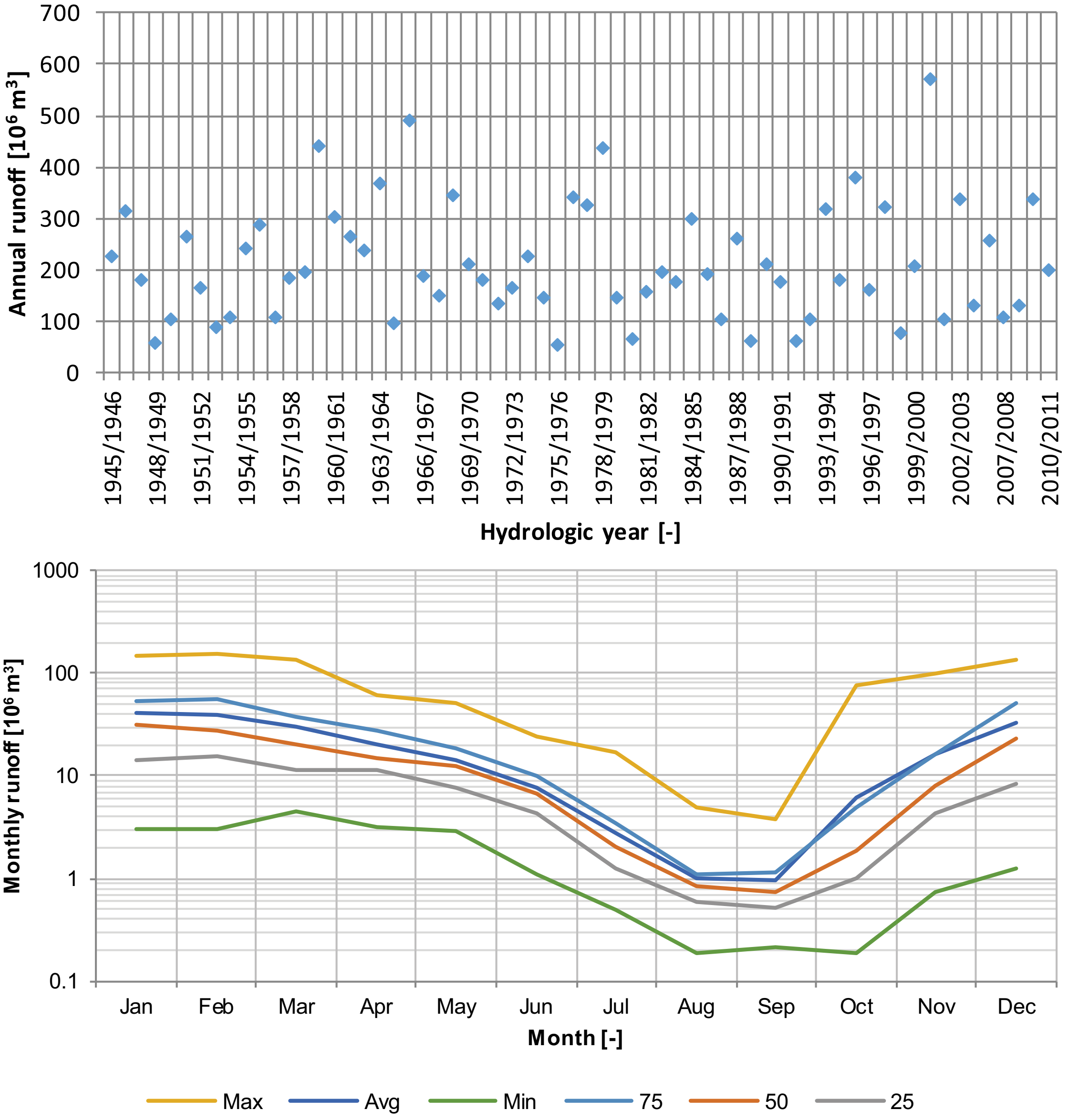

Fig. 3. Annual (top) and monthly (bottom) runoff patterns at Castro Daire hydrometric station.

demarked wet and dry seasons, typical of the Mediterranean climate. In average, the volume of water recorded in the wetter months (December and January) ranged between 30 and 40 million cubic meters, while in the dry months it was around 1 million cubic meters. Analyzing each month individually, January and March reveal the steepest increase and decrease trends, respectively. Still, neither the regression coefficient nor the results of statistical tests for trend, jump in mean, and difference in mean/median were statistically significant at a significance level of 5%.

The annual runoff does not indicate any change in the volume flowing in the river at Castro Daire, with the slight increase being consistent with the decrease in population and water-intensive activities identified. At a monthly scale, there are indications toward a change in the time distribution of the runoff. October, November, December, and January show positive trends, while February, March, April, and June have negative trends, but none of the results is statistically significant for the available dataset. The absence of data since 2011 may be relevant for the analysis, but the pattern of decreasing flow in the months preceding the summer is consistent with the drying observed by the end of the dry season.

The comparison of the average annual rainfall in more than 2,000 weather stations in Europe and North Africa [66] revealed that the variability is higher in the regions located around the latitude of 40°N. At this latitude, the average annual rainfall varies from less than 500 mm to over 3,000 mm. This variability is also observed in the upper Paiva River basin (Fig. 4). The annual and monthly rainfall correspond to the arithmetic average of the records available from the udometric stations listed in Table 1.

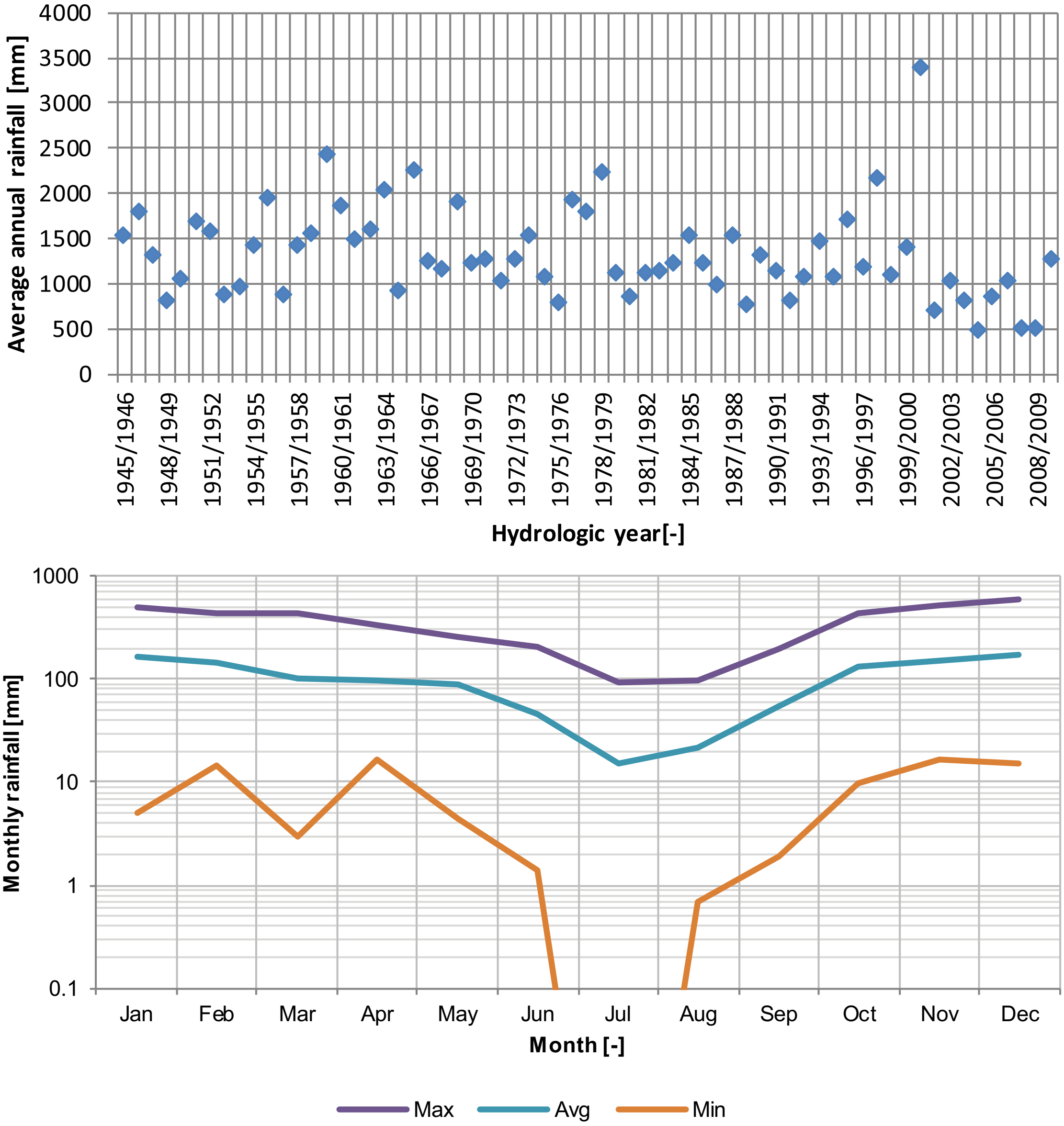

Fig. 4. Average annual (top) and monthly (bottom) rainfall patterns from the 20 udometric stations listed in Table 1.

The maximum and minimum monthly rainfall was estimated as the arithmetic average of the maximum and minimum values recorded in each station for each month. The average of the minimum in July is 0, which makes it impossible to represent on a logarithmic scale. Since the goal herein is not to model directly runoff from rainfall, but rather explore if there is a change in the rainfall pattern that could be an explanation for the drying phenomenon observed, the relative weight of each station for characterizing the rainfall in the upper Paiva River basin was not accounted for.

Comparing with the runoff results, the decreasing trend in rainfall amount is considerably more noticeable. With the exception of the hydrologic year 1999/2000, the average annual rainfall has been decreasing steadily from 1,500 to 1,000 mm and the regression coefficient of the slope is statistically significant for a significance level of 0.1. Table 2 resumes the results of all statistical tests used on the average annual rainfall data series, revealing statistically significant results in all categories but not for all tests. However, these results vary when applied to each udometric station depending on several factors, namely the length and the period covered by the data series. Furthermore, the reformulation of the monitoring network that took place during the early 2000s broke the continuity of the record series (only two stations have rainfall data for the hydrologic year of 2001/2002) and the number of stations recording after the reformulation reduced to roughly half (20–11).

To illustrate individual station results, we present exclusively the annual rainfall data from the stations with the longest record series since the hydrometric stations were installed (1945/1946). The four stations with the most

Table 2
Statistical test on the average annual rainfall of the 20 udometric stations listed in Table 1

Test	Statistics	Critical values (α)			Turning year
		0.01	0.05	0.10	
Trend					
Mann–Kendall	3.547	*2.576*	*1.960*	*1.645*	–
Spearman's *R*	2.730	*2.576*	*1.960*	*1.645*	–
Linear regression	1.989	2.690	2.010	*1.680*	–
Jump in mean					
Distribution free CUSUM	12.000	13.141	*10.965*	*9.836*	1978
Cumulative deviations	1.166	1.520	1.270	*1.140*	2000
Worsley likelihood ratio	3.658	3.790	*3.160*	*2.870*	2000
Difference in mean/median					
Wilcoxon rank sum	3.751	*2.576*	*1.960*	*1.645*	–
Student *t*-test	3.348	*2.690*	*2.010*	*1.680*	–
Randomness					
Median crossing	0.000	2.576	1.960	1.645	–
Turning points	3.879	*2.576*	*1.960*	*1.645*	–
Rank difference	1.175	2.576	1.960	1.645	–
Autocorrelation	0.556	2.576	1.960	1.645	–

Values in *italic* indicate statistically significant results

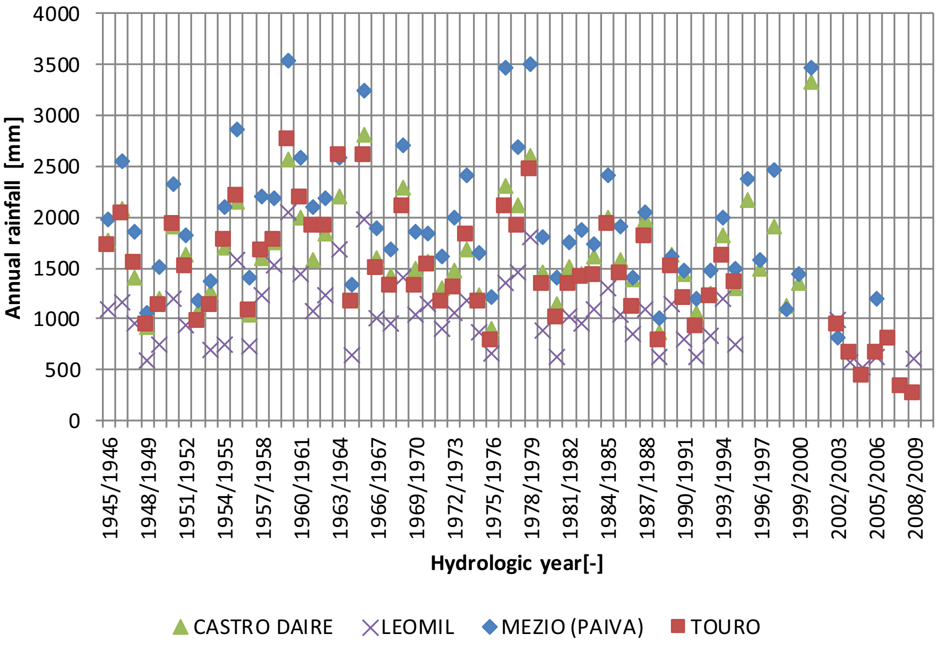

Fig. 5. Annual (top) and monthly (bottom) rainfall patterns at Castro Daire (station 5), Leomil (station 9), Mezio (station 10), and Touro (station 18) stations.

complete records are presented in Fig. 5. The stations have continuous records until the mid-1990s, when some stations were deactivated and others upgraded. From 1995/1996 until 2000/2001 only two stations have records and in 2001/2002 none of these four stations has records. Until 2008/2009, the availability of records became intermittent and then it ceased completely due to the lack of funds to maintain the stations. This was motivated by the worldwide economic crisis that was particularly harsh on Portugal and it is still to be solved. Presently, the rainfall data is only available from IPMA – Instituto Português do Mar e da Atmosfera (Portuguese Institute for Sea and Atmosphere), which is not freely accessible and has a much coarser network (no station in the upper Paiva River basin).

As for the annual rainfall, the data from Mezio, Touro, and Leomil stations present statistically significant decreasing trends, jump in mean, and difference in median/mean. Testing the data from Castro Daire station did not produce any statistically significant result. A possible explanation might be the location, since Castro Daire station is the most distant from the upper Paiva River basin from this group of 4. Still, it is more probable that the coincidence of an extremely wet year (2000/2001) with the end of the series somewhat masked any changing pattern that might exist in the series.

The statistical analysis of the monthly rainfall for individual stations was also carried out. Since the Castro Daire was the station amongst the four with the longest data series that did not present any statistically significant result in terms of the annual and monthly rainfall, it was considered the critical to detect monthly trends. Table 3 presents the results for the Spring months, revealing a statistically significant decreasing trend. Similar results were found for the remaining stations, consistent with statistically significant rainfall decline during spring also reported in previous studies [26,67–73]. This result is apparently contradictory with the results obtained for the runoff, however it may be explained by: (i) the difference in size of the river basin at Castro Daire hydrometric station and the upper Paiva River basin; and (ii) eventual measurement errors before and after the reformulation of the udometric stations network in 2000–2001.

However, the rainfall in the months of the dry season did not reveal any statistically significant result and the doubt whether the rainfall reduction in the months preceding the summer was the explanation for the observed drying persisted.

A decrease in the annual rainfall was found along with a decrease of the monthly rainfall in the spring months, particularly May, and an increase in December and January. The variations in annual and monthly rainfall alone do not allow to explain the drying of the upper Paiva River, but combined with the increase of the maximum number of consecutive days without rain it becomes consistent with the time to deplete the upper Paiva River groundwater supply. Daveau [74] studied the hydrogeology of the Paiva River basin in general and estimated that it is capable of retaining the groundwater for up to 2 months. Considering that this estimate is valid for the upper Paiva River basin, an additional analysis was carried out to verify if there was any change on the maximum number of consecutive days without rain.

The results of the tests done on the data from Castro Daire station are presented in Table 4, confirming the existence statistically significant trend, jump in mean, and difference in mean/median in the maximum number of consecutive days without rain. Similar results were found for the stations with records from the 1950s to the 1990s and for the series of the average maximum number of consecutive days without rain of all stations.

The number of consecutive days without rain increased from an average of 28, until 1975, to 41, until 2003 (Fig. 6). Considering that the maximum number of consecutive days

Table 3
Statistical test on the Spring month (March, April, and May) rainfall at Castro Daire station (station 5)

Test	Statistics	Critical values (α)			Turning year
		0.01	0.05	0.10	
		Trend			
Mann–Kendall	7.553	*2.576*	*1.960*	*1.645*	–
Spearman's *R*	2.428	2.576	*1.960*	*1.645*	–
Linear regression	2.047	2.690	*2.010*	*1.680*	–
		Jump in mean			
Distribution free CUSUM	12.000	*11.526*	*9.617*	*8.627*	1969
Cumulative deviations	2.227	1.520	*1.270*	*1.140*	2001
Worsley likelihood ratio	3.608	3.790	*3.160*	*2.870*	2000
		Difference in mean/median			
Wilcoxon rank sum	10.090	*2.576*	*1.960*	*1.645*	–
Student *t*-test	1.008	2.690	2.010	1.680	–
		Randomness			
Median crossing	1.000	2.576	1.960	1.645	–
Turning points	0.683	2.576	1.960	1.645	–
Rank difference	0.386	2.576	1.960	1.645	–
Autocorrelation	0.258	2.576	1.960	1.645	–

Values in *italic* indicate statistically significant results.

Table 4
Statistical test on the maximum number of consecutive days without rain at Castro Daire station (station 5)

Test	Statistics	Critical values (α)			Turning year
		0.01	0.05	0.10	
Trend					
Mann–Kendall	2.710	*2.576*	*1.960*	*1.645*	–
Spearman's *R*	2.708	*2.576*	*1.960*	*1.645*	–
Linear regression	2.809	*2.690*	*2.010*	*1.680*	–
Jump in mean					
Distribution free CUSUM	10.000	11.526	*9.617*	*8.627*	1975
Cumulative deviations	1.745	*1.520*	*1.270*	*1.140*	1975
Worsley likelihood ratio	3.969	*3.790*	*3.160*	*2.870*	1975
Difference in mean/median					
Wilcoxon rank sum	2.624	*2.576*	*1.960*	*1.645*	–
Student *t*-test	2.468	2.690	*2.010*	*1.680*	–
Randomness					
Median crossing	0.714	2.576	1.960	1.645	–
Turning points	1.025	2.576	1.960	1.645	–
Rank difference	1.077	2.576	1.960	1.645	–
Autocorrelation	1.707	2.576	1.960	*1.645*	–

Values in *italic* indicate statistically significant results.

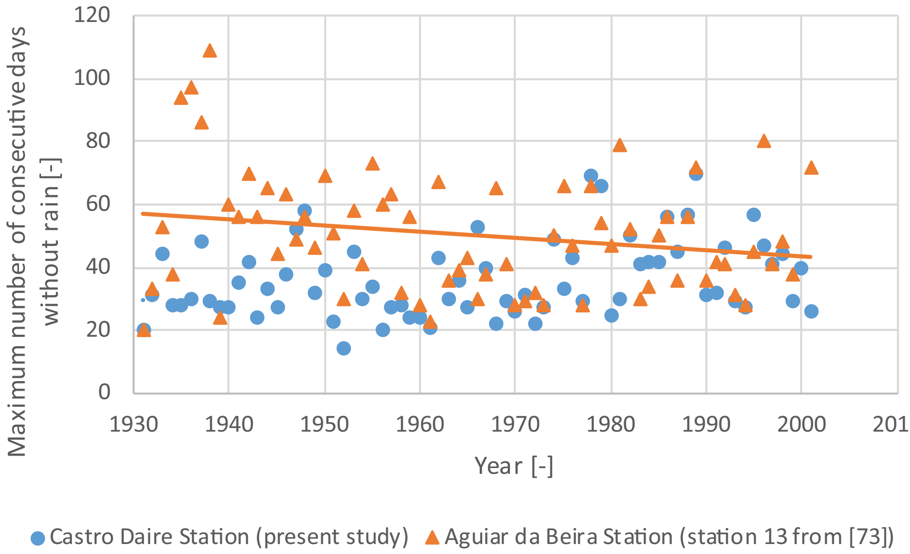

Fig. 6. Evolution of the maximum number of consecutive days without rain at Castro Daire (station 5) and Aguiar da Beira Station (station 13 from [73]).

without rain takes place during the dry season along with the rainfall reduction observed in May, the small amount of rainfall record in June, July, and August associated with the 2 months groundwater retention capability explain the drying of the river by the end of August until the first significant rain events in October.

The increase in the number of consecutive days without rain apparently contradicts the study of Santo et al. [72]. However, their study analyzed the number of consecutive days without rain by seasons and not for the full year. Considering the full year for the Aguiar da Beira station used by Trigo and DaCamara [73], which is the closest to the upper Paiva River basin, the difference in trends becomes visible.

Confirming the possibility of climate changes being the driver for the drying observed currently, estimating the future was done for the year 2050. Fig. 7 presents the average monthly rainfall recorded between 1945 and 2009 and the average monthly rainfall of 50 replications for the year 2050 for the two extreme emission scenarios (RCP8.5 and RCP2.6). The results point toward a further decrease in the amount of rainfall in March, June, and September, and a decrease in the remaining. This is consistent with generalized conclusions from climate changes studies that point for more extreme weather events in Portugal [32]. For rainfall, this represents a reduction in the total annual amount and a concentration of the bulk of the annual total in a shorter period of time since the total number of days with rain decreases.

Additionally, the average maximum number of consecutive days without rain in 2050 is estimated to be 52 and 53, for the RCP2.6 and RCP8.5 scenarios, respectively. For the 50 replications, the maximum number of consecutive days without rain varied from 25 to 87.

Despite all the uncertainty associated with climate change forecasts, even more in terms of rainfall at a monthly and daily time scales, there are little indications that the drying of the upper Paiva River will reduce in the future. In fact, the evolution of the temporal distribution of the rainfall forecasted will tend to increase the dry period of the upper Paiva River, aggravating the environmental impacts for the aquatic ecosystems that are already debilitated. The only exception may be the forecasted increase in June that could mitigate somewhat the drying phenomenon.

Analyzing the data at an annual scale using the *t*-test, it is possible to conclude that the total annual rainfall forecasted for 2050 considering the RCP2.6 and RCP8.5 scenarios are not statistically distinct for a *p*-value of 0.01. This indicates that, regardless of the emissions scenario considered, the annual rainfall forecasts are similar. Comparing the forecasted rainfall with the average annual rainfall series until 2009, the *t*-test results confirm statistically significant results. Fig. 8 illustrates how the spread and the average of the annual rainfall forecasted for 2050 (50 simulations) decrease when compared to the records between 1945 and 2009.

5. Conclusion

The consequences of climate changes on large watercourses tend to be more difficult to disclose because of the masking effect from direct human activities. Additionally, these large water bodies will require substantial hydrological alterations to clearly reveal the consequences. Small rivers, on the other hand, are in many cases in their natural condition and the impacts from small changes in the hydrology will immediately become visible. Furthermore, large water bodies are more resilient to climate changes than small rivers.

Exploring the potential causes for the drying of the upper Paiva River observed in the last two decades was explored, it was possible to exclude the direct human action as the main driver. This conclusion was based on the observed decrease in population, along with an accompanying and significant decay in commercial and industrial activity, implying a reduction in total direct water consumption. The analysis of the discharge records between 1945/1946 and 2010/2011 did not show any statistically significant relevant trend/change in the annual runoff, indicating that the total amount of water flowing at Castro Daire remained relatively stable. However, in terms of rainfall a statistically significant decreasing trend in the rainfall amount. In face of this apparently contradictory result and considering the time to exhaust the groundwater, the evolution of the number of consecutive days without rain was also evaluated.

Combining all the results obtained, it is possible to conclude that the changes in the rainfall pattern are the underlying cause for the upper Paiva River evolving from a perennial to a non-perennial river. Making some extrapolation, it is highly probable that the upper Paiva River is not

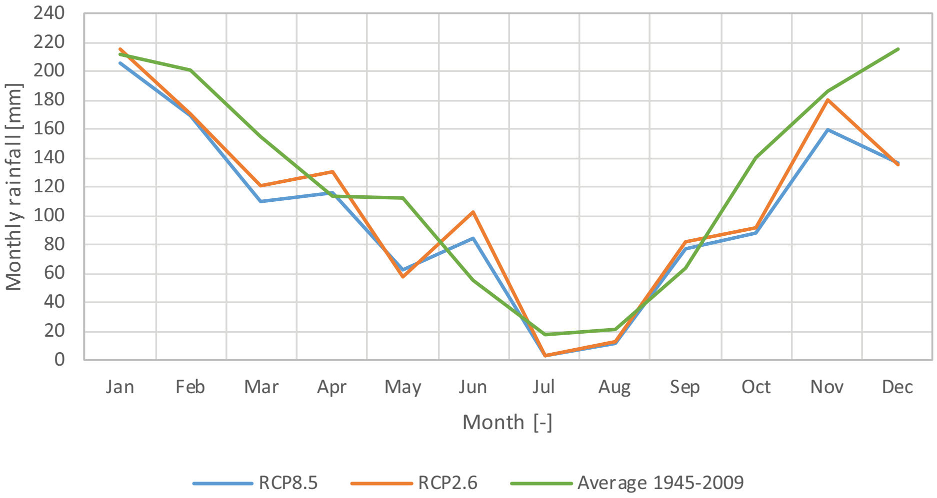

Fig. 7. Comparison of the monthly rainfall recorded between 1945 and 2009 and forecasted for 2050.

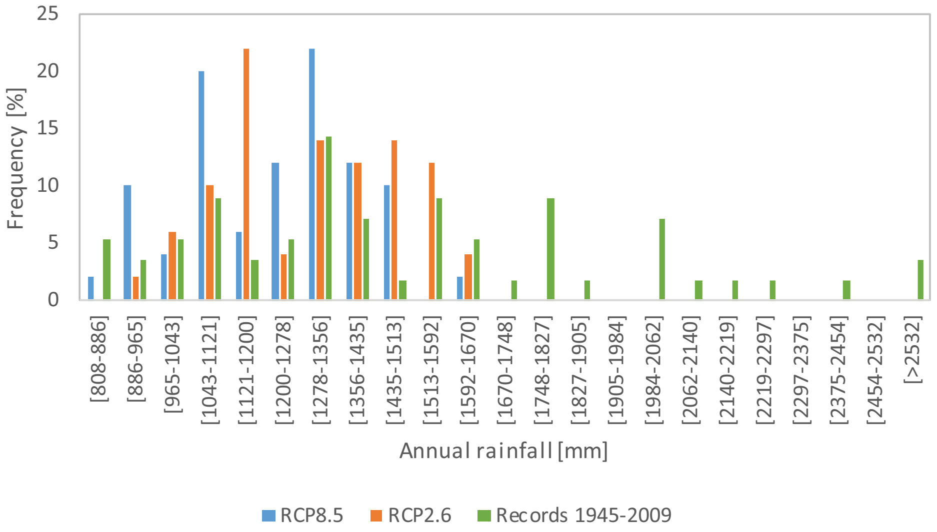

Fig. 8. Histogram of the annual rainfall recorded between 1945 and 2009 and forecasted for 2050.

a unique case, neither in Portugal, nor in other regions of the globe. The fact that smaller rivers and upstream sections of rivers are less monitored and located in regions sparsely habituated regions, may result in these situation being unnoticed. Nevertheless, the environmental impact, particularly in terms of the biodiversity in these ecosystems is significant.

The rainfall pattern in climate changes scenarios obtained using the MarkSim tool forecast a worsening of the drying of the upper Paiva River, since the rainfall is expected to decrease and the maximum number of consecutive days without rain to increase even further.

Expanding the findings of the present study to the vast number of small rivers or upstream sections of medium and major rivers existing in Portugal and other regions of the globe facing similar hydrological evolutions, the losses at all levels (environmental, social, and economic) are tremendous and there is little or nothing that can be done. In the case of the upper Paiva River, the already declining agriculture can no longer rely on the river to be revived and the investments made in tourism (e.g., the fluvial beach at Vila Nova de Paiva) are useless due to the lack of water when they were supposed to be used.

Acknowledgments

This study was possible with the financial support of EGSP – Sistemas de Energia e Potência and is part of a more extensive study on the upper Paiva River natural and human interaction.

The authors also would like to thank the anonymous reviewer for is very pertinent comments for streamlining the manuscript both in objectiveness of its scope and support of the methods and results.

References

[1] N.W. Arnell, The effect of climate change on hydrological regimes in Europe: a continental perspective, Global Environ. Change, 9 (1999) 5–23.

[2] B. Lehner, P. Döll, J. Alcamo, T. Henrichs, F. Kaspar, Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis, Clim. Change, 75 (2006) 273–299.

[3] N.W. Arnell, Climate change and global water resources, Global Environ. Change, 9 (1999) S31–S49.

[4] P. Döll, J. Zhang, Impact of climate change on freshwater ecosystems: a global-scale analysis of ecologically relevant river flow alterations, Hydrol. Earth Syst. Sci., 14 (2010) 783–799.

[5] F.C. Sperna Weiland, L.P.H. van Beek, J.C.J. Kwadijk, M.F.P. Bierkens, Global patterns of change in discharge regimes for 2100, Hydrol. Earth. Syst. Sci., 16 (2012) 1047–1062.

[6] M.T.H. van Vliet, W.H.P. Franssen, J.R. Yearsley, F. Ludwig, I. Haddeland, D.P. Lettenmaier, P. Kabat, Global river discharge and water temperature under climate change, Global Environ. Change, 23 (2013) 450–464.

[7] C.J. Vörösmarty, P. Green, J. Salisbury, R.B. Lammers, Global water resources: vulnerability from climate change acid population growth, Science, 289 (2000) 284–288.

[8] M. Shen, J. Chen, M. Zhuan, H. Chen, C.-Y. Xu, L. Xiong, Estimating uncertainty and its temporal variation related to global climate models in quantifying climate change impacts on hydrology, J. Hydrol., 556 (2018) 10–24.

[9] T.N. Palmer, J. Räisänen, Quantifying the risk of extreme seasonal precipitation in a changing climate, Nature, 415 (2002) 512–514.

[10] G.A. Meehl, T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver, Z.-C. Zhao, Global Climate Projections, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, H.L. Miller, Eds., Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom, New York, NY, USA, 2007.

[11] B. Kirtman, S.B. Power, J.A. Adedoyin, G.J. Boer, R. Bojariu, I. Camilloni, F.J. Doblas-Reyes, A.M. Fiore, M. Kimoto, G.A. Meehl, M. Prather, A. Sarr, C. Schär, R. Sutton, G.J. van Oldenborgh, G. Vecchi, H.J. Wang, Near-Term Climate Change: Projections and Predictability, T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley, Eds., Climate Change 2013: The Physical Science Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel

on Climate Change, Cambridge University Press, Cambridge, United Kingdom, New York, NY, USA, 2013.

[12] C. Frei, R. Scholl, S. Fukutome, J. Schmidli, P.L. Vidale, Future change of precipitation extremes in Europe: intercomparison of scenarios from regional climate models, J. Geophys. Res., 111 (2006) D06105, doi: 10.1029/2005JD005965.

[13] G. Nikulin, E. Kjellström, U. Hansson, G. Strandberg, A. Ullerstig, Evaluation and future projections of temperature, precipitation and wind extremes over Europe in an ensemble of regional climate simulations, Tellus Ser. A, 63 (2011) 41–55.

[14] J. Rajczak, P. Pall, C. Schär, Projections of extreme precipitation events in regional climate simulations for Europe and the Alpine Region, J. Geophys. Res. Atmos., 118 (2013) 3610–3626.

[15] X. Gao, J.S. Pal, F. Giorgi, Projected changes in mean and extreme precipitation over the Mediterranean region from a high resolution double nested RCM simulation, Geophys. Res. Lett., 33 (2006) L03706, doi: 10.1029/2005GL024954.

[16] F. Giorgi, P. Lionello, Climate change projections for the Mediterranean region, Global Planet. Change, 63 (2008) 90–104.

[17] A.M. De Girolamo, F. Bouraoui, A. Buffagni, G. Pappagallo, A. Lo Porto, Hydrology under climate change in a temporary river system: potential impact on water balance and flow regime, River Res. Appl., 33 (2017) 1219–1232.

[18] R.C. Bastakoti, J. Gupta, M.S. Babel, M.P. van Dijk, Climate risks and adaptation strategies in the lower Mekong River basin, Reg. Environ. Change, 14 (2014) 207–219.

[19] S. Xiao, X. Peng, Q. Tian, Climatic and human drivers of recent lake-level change in East Juyan Lake, China, Reg. Environ. Change, 16 (2016) 1063–1073.

[20] M.A. Degefu, W. Bewket, Variability and trends in rainfall amount and extreme event indices in the Omo-Ghibe River Basin, Ethiopia, Reg. Environ. Change, 14 (2014) 799–810.

[21] H. Hamandawana, R. Chanda, Environmental change in and around the Okavango Delta during the nineteenth and twentieth centuries, Reg. Environ. Change, 13 (2013) 681–694.

[22] M. Natkhin, O. Dietrich, M.P. Schäfer, G. Lischeid, The effects of climate and changing land use on the discharge regime of a small catchment in Tanzania, Reg. Environ. Change, 15 (2015) 1269–1280.

[23] J.S. Risbey, Dangerous climate change and water resources in Australia, Reg. Environ. Change, 11 (2011) 197–203.

[24] M. de Luis, K. Čufarm, M.A. Saz, L.A. Longares, A. Ceglar, L. Kajfež-Bogataj, Trends in seasonal precipitation and temperature in Slovenia during 1951–2007, Reg. Environ. Change, 14 (2014) 1801–1810.

[25] B. Ziv, H. Saaroni, R. Pargament, T. Harpaz, P. Alpert, Trends in rainfall regime over Israel, 1975–2010, and their relationship to large-scale variability, Reg. Environ. Change, 14 (2014) 1751–1764.

[26] J. Corte-Real, B. Qian, H. Xu, Regional climate change in Portugal: precipitation variability associated with large-scale atmospheric circulation, Int. J. Climatol., 18 (1998) 619–635.

[27] J. Corte-Real, B. Qian, H. Xu, Circulation patterns, daily precipitation in Portugal and implications for climate change simulated by the second Hadley Centre GCM, Clim. Dyn., 15 (1999) 921–935.

[28] R.M. Trigo, J.P. Palutikof, Precipitation scenarios over Iberia: a comparison between direct GCM output and different downscaling techniques, J. Clim., 14 (2001) 4422–4446.

[29] APA, Fifth National Communication to the UNFCCC on Climate Change, Agência Portuguesa do Ambiente (APA), Amadora, Portugal, 2010. Available at: http://unfccc.int/national_reports/annex_i_natcom/submitted_natcom/items/4903.php (accessed June 13, 2015).

[30] F.D. Santos, K. Korbes, R. Moita, Climate Change in Portugal: Scenarios, Impacts, and Adaptation Measures, SIAM Project, Gradiva, 2002. Available at: www.siam.fc.ul.pt/ (accessed June 20, 2015).

[31] P.M.M. Soares, R.M. Cardoso, D.C.A. Lima, P.M.A. Miranda, Climate change and the Portuguese precipitation: ENSEMBLES regional climate models results, Clim. Dyn., 45 (2015) 1771–1787.

[32] P.M.M. Soares, R.M. Cardoso, D.C.A. Lima, P.M.A. Miranda, Future precipitation in Portugal: high-resolution projections using WRF model and EURO-CORDEX multi-model ensembles, Clim. Dyn., 49 (2017) 2503–2530.

[33] C.G. Kilsby, S.S. Tellier, H.J. Fowler, T.R. Howels, Hydrological impacts of climate change on the Tejo and Guadiana Rivers, Hydrol. Earth Syst. Sci., 11 (2007) 1175–1189.

[34] K.A. Chezik, S.C. Anderson, J.W. Moore, River networks dampen long-term hydrological signals of climate change, Geophys. Res. Lett., 44 (2017) 7256–7264.

[35] M.P. Clark, R.L. Wilby, E.D. Gutmann, J.A. Vano, S. Gangopadhyay, A.W. Wood, H.J. Fowler, C. Prudhomme, J.R. Arnold, L.D. Brekke, Characterizing uncertainty of the hydrologic impacts of climate change, Curr. Clim. Change Rep., 2 (2016) 55–64.

[36] J. Joseph, S. Ghosh, A. Pathak, A.K. Sahai, Hydrologic impacts of climate change: comparisons between hydrological parameter uncertainty and climate model uncertainty, J. Hydrol., 566 (2018) 1–22.

[37] V. Krysanova, C. Donnelly, A. Gelfan, D. Gerten, B. Arheimer, F. Hattermann, Z.W. Kundzewicz, How the performance of hydrological models relates to credibility of projections under climate change, Hydrol. Sci. J., 63 (2018) 696–720.

[38] I.B. Karlsson, T.O. Sonnenborg, J.C. Refsgaard, D. Trolle, C.D. Børgesen, J.E. Olesen, E. Jeppesen, K.H. Jensen, Combined effects of climate models, hydrological model structures and land use scenarios on hydrological impacts of climate change, J. Hydrol., 535 (2016) 301–317.

[39] D. Pumo, E. Arnone, A. Francipane, D. Caracciolo, L.V. Noto, Potential implications of climate change and urbanization on watershed hydrology, J. Hydrol., 554 (2017) 80–99.

[40] F.F. Hattermann, V. Krysanova, S.N. Gosling, R. Dankers, P. Daggupati, C. Donnelly, M. Flörke, S. Huang, Y. Motovilov, S. Buda, T. Yang, C. Müller, G. Leng, Q. Tang, F.T. Portmann, S. Hagemann, D. Gerten, Y. Wada, Y. Masaki, T. Alemayehu, Y. Satoh, L. Samaniego, Cross-scale intercomparison of climate change impacts simulated by regional and global hydrological models in eleven large river basins, Clim. Change, 141 (2017) 561–576.

[41] T. Vetter, J. Reinhardt, M. Flörke, A. van Griensven, F. Hattermann, S. Huang, H. Koch, I.G. Pechlivanidis, S. Plötner, O. Seidou, B. Su, R.W. Vervoort, V. Krysanova, Evaluation of sources of uncertainty in projected hydrological changes under climate change in 12 large-scale river basins, Clim. Change, 141 (2017) 419–433.

[42] INAG, Tipologia de Rios em Portugal Continental no Âmbito da Implementação da Directiva Quadro da Água, I – Caracterização Abiótica, Ministério do Ambiente, do Ordenamento do Território e do Desenvolvimento Regional, Instituto da Água, Portugal, 2008. Available at: https://www.apambiente.pt/dqa/assets/tipologia-de-rios-em-portugal-continental.pdf ((in Portuguese).

[43] APA/ARH Norte, Plano de Gestão da Região Hidrográfica do Douro, Agência Portuguesa do Ambiente (APA), Administração da Região Hidrográfica do Douro (ARH Douro), Portugal, 2012. Available at: https://www.apambiente.pt/?ref=16&subref=7&sub2ref=9&sub3ref=834#pgbh-tabela (in Portuguese).

[44] EGSP, Caracterização das Comunidades Biológicas e Identificação de Fatores Limitantes no Troço Superior do Rio Paiva – Relatório Final, EGSP – Energia e Sistemas de Potência, Lisboa, Portugal, 2015 (in Portuguese).

[45] V. Sousa, I. Meireles, A. Gonçalves, A.P. Falcão, A D(r)ying River: The Upper Paiva, In: WatefCon 2018, 5–7 September, Aveiro, Portugal, 2018.

[46] WMO, Detecting Trend and Other Changes in Hydrological Data, WCDMP-45, WMO/TD 1013, World Meteorological Organisation, Geneva, 2000.

[47] H. Hisdal, K. Stahl, L.M. Tallaksen, S. Demuth, Have streamflow droughts in Europe become more severe or frequent?, Int. J. Climatol., 21 (2001) 317–333.

[48] F. Lespinas, W. Ludwig, S. Heussner, Impact of recent climate change on the hydrology of coastal Mediterranean rivers in Southern France, Clim. Change, 99 (2010) 425–456.

[49] T. Razavi, H. Switzman, A. Arain, P. Coulibaly, Regional climate change trends and uncertainty analysis using extreme indices: a

case study of Hamilton, Canada, Clim. Risk Manage., 13 (2016) 43–63.

[50] J.R. Westmacott, D.H. Burn, Climate change effects on the hydrologic regime within the Churchill-Nelson River Basin, J. Hydrol., 202 (1997) 263–279.

[51] S. Yue, P. Pilon, G. Cavadias, Power of the Man-Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series, J. Hydrol., 259 (2002) 254–271.

[52] M.G. Kendall (Ed.), Rank Correlation Measures, Charles Griffin, London, 1975.

[53] H.B. Mann, Nonparametric tests against trend, Econometrica, 13 (1945) 245–259.

[54] S. Siegel, N.J. Castellan, Nonparametric Statistics for the Behavioural Sciences, McGraw-Hill, New York, 1988, p. 399.

[55] F.H.S. Chiew, T.A. McMahon, Detection of trend or change in annual flow of Australian rivers, Int. J. Climatol., 13 (1993) 643–653.

[56] C.A. McGilchrist, K.D. Woodyer, Note on a distribution-free CUSUM technique, Technometrics, 17 (1975) 321–325.

[57] T.A. Buishand, Some methods for testing the homogeneity of rainfall records, J. Hydrol, 58 (1982) 11–27.

[58] K.J. Worsley, On the likelihood ratio test for a shift in location of normal populations, J. Am. Stat. Assoc., 74 (1979) 365–376.

[59] D.R. Helsel, R.M. Hirsch (Eds.), Statistical Methods in Water Resources, Vol. 49, In: Studies in Environmental Science, Elsevier, Amsterdam, 1992, pp. 1–522.

[60] WMO, Analysing Long Time Series of Hydrological Data with Respect to Climate Variability and Change, WCAP-3, WMO/TD-No 224, World Meteorological Organisation (WMO), Geneva, Switzerland, 1988.

[61] R.B. Grayson, R.M. Argent, R.J. Nathan, T.A. McMahon, R. Mein, Hydrological Recipes: Estimation Techniques in Australian Hydrology, Cooperative Research Centre for Catchment Hydrology, Australia, 1996.

[62] G.E.P. Box, G. Jenkins, Time Series Analysis: Forecasting and Control, Holden-Day, San Francisco, CA, 1976.

[63] IPCC, Climate Change 2014: Synthesis Report, Core Writing Team, R.K. Pachauri, L.A. Meyer, Eds., Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, IPCC, Geneva, Switzerland, 2014.

[64] P.G. Jones, P.K. Thornton, Generating downscaled weather data from a suite of climate models for agricultural modelling applications, Agric. Syst., 114 (2013) 1–5.

[65] R.L. Wilby, J. Troni, Y. Biot, L. Tedd, B.C. Hewitson, D.M. Smith, R.T. Sutton, A review of climate risk information for adaptation and development planning, Int. J. Climatol., 29 (2009) 1193–1215.

[66] F.C. Rego, M.S. Rocha, Climatic patterns in the Mediterranean region, Ecol. Mediterr., 40 (2014) 49–59.

[67] M.I.P. de Lima, S.C.P. Carvalho, J.L.M.P. de Lima, Investigating annual and monthly trends in precipitation structure: an overview across Portugal, Nat. Hazards Earth Syst. Sci., 10 (2010) 2429–2440.

[68] M.I.P. de Lima, A.C.P. Marques, J.L.M.P. de Lima, M.F.E.S. Coelho, Precipitation Trends in Mainland Portugal in the Period 1941–2000, Proceedings of the Fourth InterCeltic Colloquium on Hydrology and Management of Water Resources, Guimarães, Portugal, IAHS Publ., 310 (2007) 94–102.

[69] C.M. Mendes, M.F. Coelho, Variabilidade Climática em Portugal Continental—Quantidade de Precipitação; Índice Regional de Anomalia; Tendência; Variabilidade por Decénios e Triénios, Monografia No. 43, INMG, Lisbon, 1993 (in Portuguese).

[70] P.M.A. Miranda, M.A. Valente, A.R. Tomé, R. Trigo, M.F.E.S. Coelho, A. Aguiar, E.B. Azevedo, O Clima de Portugal nos Séculos XX e XXI, F.D. Santos, P. Miranda, Eds., Alterações Climáticas em Portugal, Cenários Impactos e Medidas de Adaptação, Projecto SIAM II, Gradiva, 2006, pp. 47–113.

[71] D. Paredes, R.M. Trigo, R. García-Herrera, I.F. Trigo, Understanding precipitation changes in Iberia in early spring: weather typing and storm-tracking approaches, J. Hydrometeorol., 7 (2006) 101–113.

[72] F.E. Santo, A.M. Ramos, M.I.P. de Lima, R.M. Trigo, Seasonal changes in daily precipitation extremes in mainland Portugal from 1941 to 2007, Reg. Environ. Change, 14 (2014) 1765–1788.

[73] R.M. Trigo, C.C. DaCamara, Circulation weather types and their influence on the precipitation regime in Portugal, Int. J. Climatol., 20 (2000) 1559–1581.

[74] S. Daveau, As Águas: Comentários e Actualização: A Vegetação: Comentários e Actualização, Vol. 2, O. Ribeiro, H. Lautensach, Geografia de Portugal, Comentários e Actualizações de Suzanne Daveau, João Sá da Costa, Lisboa, 1987–1991, pp. 487–535; 585–603 (in Portuguese).