Climatic Change (2010) 99:425–456
DOI 10.1007/s10584-009-9668-1

Impact of recent climate change on the hydrology of coastal Mediterranean rivers in Southern France

Franck Lespinas · Wolfgang Ludwig · Serge Heussner

Received: 11 June 2007 / Accepted: 6 July 2009 / Published online: 8 October 2009

Abstract The purpose of this paper is to analyse the regional impact of recent climate change on the water resources in southern France. We produced spatial reconstructions of the monthly evolutions of temperature, precipitation and water discharge in 15 watersheds of six coastal river basins and examined the major changes based on trend analysis for the last 40 years. In this part of the Mediterranean, the general warming trend was strongly enhanced by changes in the atmospheric circulation patterns, characterized by a northward extension of the subtropical high pressure domain during spring and summer. During these seasons, monthly warming rates could achieve almost twice the mean annual warming rates. Although annual precipitation did not follow clear trends, water discharge significantly decreased in one third of the watersheds and accounted for an estimated 20% reduction of the water resources in this region. This concerns both the highest and lowest watersheds. In the former, the reduction is likely the result of a temperature induced switch of snowfall to rainfall at high altitudes. In the latter, the reduction of discharge seems to come from lower groundwater levels, which may be related to the temperature increase too, but also have other origins. The recent climatic evolution is consistent with most modelling simulations for the future, indicating that the reduction of the water resources will hold on, probably still enhanced by decreases in precipitation.

F. Lespinas (✉) · W. Ludwig · S. Heussner
Cefrem—Centre de Formation et de Recherche sur l'Environnement Marin (UMR 5110-CNRS/Université de Perpignan), Université de Perpignan, 52, avenue Paul Alduy, 66860 Perpignan Cedex, France
e-mail: franck.lespinas@univ-perp.fr

W. Ludwig
e-mail: ludwig@univ-perp.fr

S. Heussner
e-mail: heussner@univ-perp.fr

1 Introduction

Understanding the impact of climate change on the water cycle on Earth is one of the major challenges in assessing socio-economic pressures in the near future. The Mediterranean region lies in transition between the arid climate of North Africa and the temperate and rainy climate of central Europe and is affected by interactions between mid-latitude and tropical processes. This area has shown large climate shifts in the past (Luterbacher et al. 2006) and was identified as one of the most prominent “Hot-Spots” in future climate change projections (Giorgi 2006). Both climate observation and modelling studies revealed a general trend toward drier and warmer conditions during the last and forthcoming decades (Gibelin and Déqué 2003; Norrant and Douguédroit 2005; Christensen et al. 2007; Giorgi and Lionello 2007). Shortening of the water resources, already endemic in many of the Mediterranean riparian countries, may severely increase in the future (Milly et al. 2005).

Despite the general importance of water resources for local economies, studies on the impact of climate change on the water cycle in the Mediterranean region and adjacent areas are relatively sparse and mainly focus on larger river basins (e.g. Etchevers et al. 2002; Caballero et al. 2007). One reason for this is that most impact studies rely on modelling with general circulation models (GCM), which are often too coarse in their spatial resolution to correctly reproduce the local climatic processes induced by the complex physiography of the Mediterranean drainage basin. However, neglecting small river basins in scientific evaluations may bias the resulting conclusions, as they are very abundant in this part of the world (Milliman 2001).

The recent temperature increase since the late 1970s is generally considered to be the first clear sign of a human induced climate change (Trenberth et al. 2007). Observation studies that focus on the hydroclimatic evolution of typical coastal river systems during this period can therefore help for a better understanding of the possible effects of climate change on water resources in the Mediterranean region. In this study, we examined the hydroclimatic functioning of six coastal river basins located in southern France for the period 1965–2004. These are the Tech, Tet, Agly, Aude, Orb and Herault rivers (Fig. 1), which are typical coastal rivers that can also be found in many other parts of the Mediterranean basin. Temperature increase during the 20th century in south-western France (0.110–0.130°C/decade for 1901–2000, Moisselin et al. 2002) was particularly important compared to the global average (0.084°C/ decade for 1901–2005, Brohan et al. 2006). This region could be thus highly appropriate to detect climate induced changes in the natural water cycle.

According to the locations of the major gauging stations, 15 watersheds could be distinguished in our study for which the monthly and annual water fluxes and temperature records exist (discharge) or could be reconstructed via a dense station network and spatial interpolation techniques (precipitation and temperature). These watersheds cover a large range of natural and anthropogenic characteristics, which is important when evaluating whether the observed changes may be induced by climate change or not. Our objectives were to detect recent trends in the climatic evolution in this region, to relate them to changes in atmospheric circulation, to quantify their impacts on the water resources in the investigated watersheds and to assess the vulnerability of these watersheds with respect to future climate trends.

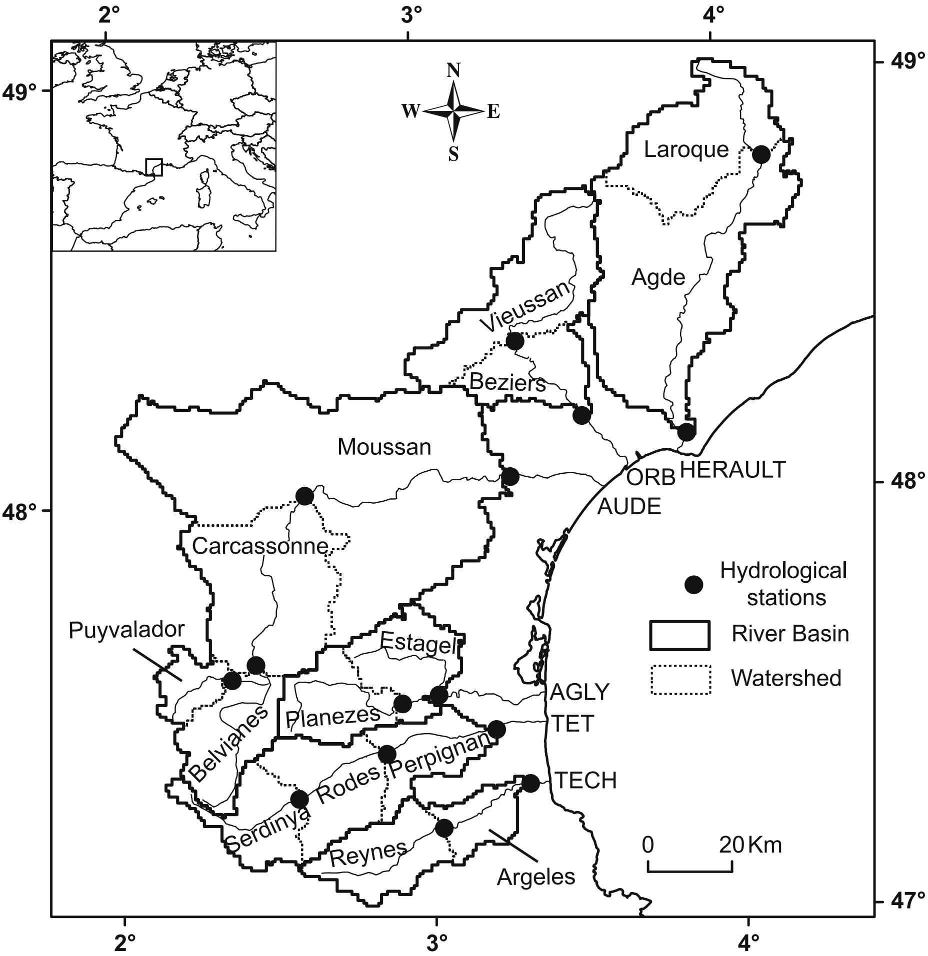

Fig. 1 Location of the studied rivers, hydrological stations and corresponding watersheds

2 Datasets and methods

2.1 Water discharge

Discharge (Q) data were obtained from the HYDRO data base hosted at the French Ministry of Environment, centralizing most of the hydrological records in France. They were recovered both in daily and in monthly time resolutions. We selected 15 discharge gauging stations with less than 15% missing values for the investigated period from 1965 to 2004 (Fig. 1). The 1965 starting year was chosen because data availability and station density were clearly insufficient before this date, both for gauging and climatic stations.

Most of the retained discharge records largely cover the 1965–2004 period (Fig. 2), although some start later, end earlier or display gaps in the middle of the records. Because of the replacement of older gauging stations by newer ones, four of the records have been completed by linear regressions with records from neighbouring stations that were only used to fill data gaps. All of these neighbouring stations are situated close to the main stations, without the confluence of additional tributaries in between (Figs. 1 and 2). Pearson's correlation coefficients between the overlapping discharge records were always very high (r^2 between 0.97 and 1.0) and differences in the average discharges were always lower than 15% (9%, 15%, 5% and 8% for Moussan, Rodes, Reynes and Argeles, respectively).

Discharge values in this study were used as specific net discharge values (Q-net). This means that for each station, we only considered the water discharge that was created in the corresponding watershed and consequently subtracted the measured water discharge by the water discharge at the closest upstream station (if any). The resulting discharge was then divided by the watershed area and the units changed from cubic meters per year (month, day) to millimeters per year (month, day).

2.2 Watershed delineation

Delineation of the watershed contours was performed on the basis of the relevant sections of the GTOPO30 global 30 arc sec Digital Elevation Model (DEM) of USGS (2000), after implementation into the ArcInfo GIS software and conversion of the geographical coordinates to the French national projection system Lambert Conformal Conic III. For correction purposes, the river drainage networks were digitized from maps and also implemented into the GIS in order to recondition the DEM (Hellweger 1997). Sinks of the DEM were automatically filled and a flow direction grid was generated by the GIS software. A comprehensive description of all the methods applied to the DEM can be found in Maidment and Djokic (2000). The automatically generated flow direction grid did not always overlap with the real drainage network and numerous manual corrections were necessary to improve the fit between both networks. Finally, the corrected flow direction grid allowed us to delineate the different watersheds according to the geographical position of the considered discharge gauging stations (Fig. 1). These contours were then used to

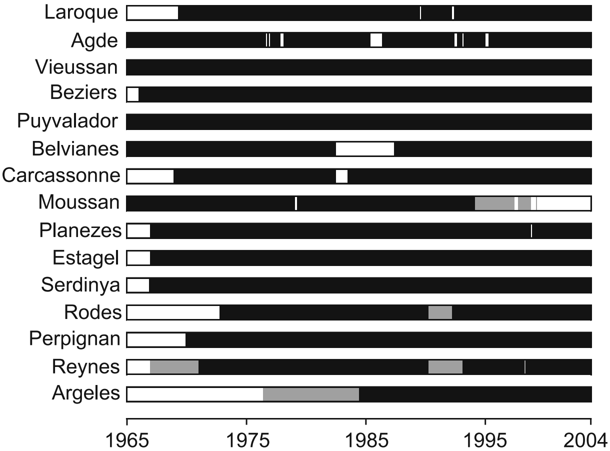

Fig. 2 Temporal coverage of the discharge records. *Black bars*: complete time series; *grey bars*: the gauging station was temporarily or definitively replaced by a neighbouring station and the time series were reconstructed by linear correlation between overlapping records of both stations (see text); *white bars*: data missing

extract the average watershed characteristics from the GIS climatologies we created (see below) and from other freely available GIS data bases.

2.3 Precipitation and temperature data

2.3.1 Homogenization of datasets

Precipitation (P) and temperature (T) data were provided by Meteo-France in monthly resolution via the Climatheque data base server. Temperatures were taken as the average of minimum and maximum temperatures, which is a common practice in meteorological studies (Moisselin et al. 2002). Only meteorological stations with less than 20% of missing values were retained, resulting in a total of 127 stations for precipitation and 49 for temperature. The total number of gaps in the time series represented about 2.2% for precipitation and 6.7% for temperature. As the existence of these gaps could bias the successive interpolations (Section 2.3.2), the climatic time series were homogenised before being used for interpolation. The too large number of stations excluded the possibility of filling the gaps one by one from classical regression techniques (i.e. by regression with well correlated series or one reference series). We therefore used the method proposed by Laborde (2000). For each station, each gap is filled by the mean value calculated over the whole observation period. Then, a Principal Component Analysis (PCA) is performed on the matrix of the so-filled data, resulting in principal component (PC) loadings and scores that are used to make new estimations of the missing data. A second PCA is then performed on the matrix of observations with newly estimated missing data, leading to new PC loadings and scores that are again used to fill the data gaps and so on. Estimation of the missing observations changes at each PCA iterative step made on the matrix of observations. Successively estimated missing values follow a decreasing exponential law and a stable value can be reached after six to seven PCA iterations (Laborde 2000). After having done several tests with our data, we always fixed the number of iterations to eight as this produced the most realistic predictions.

This method was originally developed to fill gaps in annual precipitation series. In our case, we divided our climatic dataset in 12 monthly subsets and treated each of them separately. When filling the gaps, the main difficulty was to select the number of PCs to be taken into account in the iterative process. Following the assumption that climatic data are always spatially structured, Laborde (2000) suggested to hold only PCs that display a spatial structure. Analyses of omnidirectional variograms of the first PC made on the matrix of observations have therefore been very useful in selecting the relevant number of the PCs. Figure 3 shows an example of the omnidirectional variograms of the five first PCs corresponding to the standardised precipitation data for January. In this case, only the four first PCs have been taken into account since variable projections on the fifth PC presented no clear spatial correlation. For the others months, the number of relevant PCs varied between three and six.

The above described method provides good results in particular for precipitation for which spatial structures are typical. For temperature, however, no clear spatial patterns could be detected in our data set, probably because of the strong connection with elevation, which can easily overwhelm any spatial pattern. Due to the lack of a clear selection criterion, we always retained the three first PCs for all of our monthly datasets.

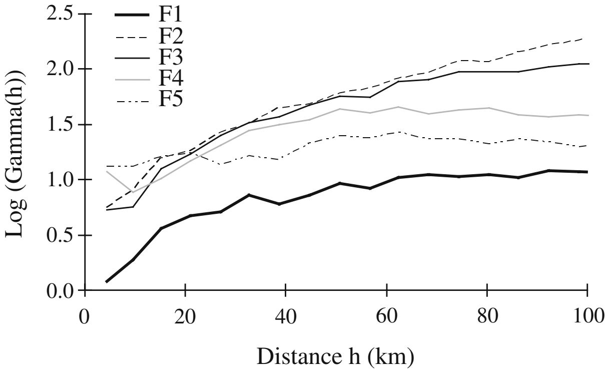

Fig. 3 Example of omnidirectional semivariograms of the variable projections for the first five principal components for precipitation in January

Climatic datasets can also be affected by the occurrence of artificial breaks in the time series (Heino 1997; Mestre 2000). These breaks are caused by modifications of instrumentation and/or the station location and orientation, as this is often the result of an evolution to the optimal measurement conditions defined by the World Meteorological Organisation (WMO). Location changes can, in particular, produce non-stationary time series that are not suitable for trend analysis (Mestre 2000). For this reason, we implemented several tests for the detection of breaks in our climatic time series after the gaps have been filled. These tests were the non-parametric Pettitt's test (Pettitt 1979), the parametric Buishand's test (Buishand 1984), the bayesian method of Lee and Heghinian (Lee and Heghinian 1977) and the Hubert's segmentation procedure (Hubert et al. 1989). A comprehensive description of these tests can be found in WMO (2000). If breaks could be detected with at least one of these tests, the respective dates were compared with the station metadata, listing all major changes that occurred during the data acquisition. Whenever we encountered a coincidence between location changes and detected break dates, we removed the stations from our dataset. The break tests allowed us to identify four doubtful stations for temperature and 10 for precipitation. The number of remaining stations for spatial interpolations was hence reduced to 45 for T and 117 for P (Fig. 4).

2.3.2 Spatial interpolation

For comparison with the discharge data, the climatic parameters had to be spatialised and averaged for the 15 watersheds delineated in Section 2.2. Based on a sampling of our data, performances of different interpolators were assessed and compared using cross-validation. In this procedure, each observation is temporarily removed from the dataset and estimated using the remaining data. The comparison between the different interpolators was based on the values of the classical Root Mean Square Error (RMSE) and the Mean Square Error (MSE) criterions (Goovaerts 2000). The RMSE is used as a measure of error magnitude while the MSE is used as a guide for bias in estimates.

For precipitation, the smallest errors were obtained for the Ordinary Kriging (OK) method while the largest errors were obtained for the deterministic methods (not shown). This is in agreement with most studies comparing interpolation techniques (a comprehensive description of them can be found in Goovaerts 1997) which concluded that for precipitation, geostatistical algorithms (kriging and its

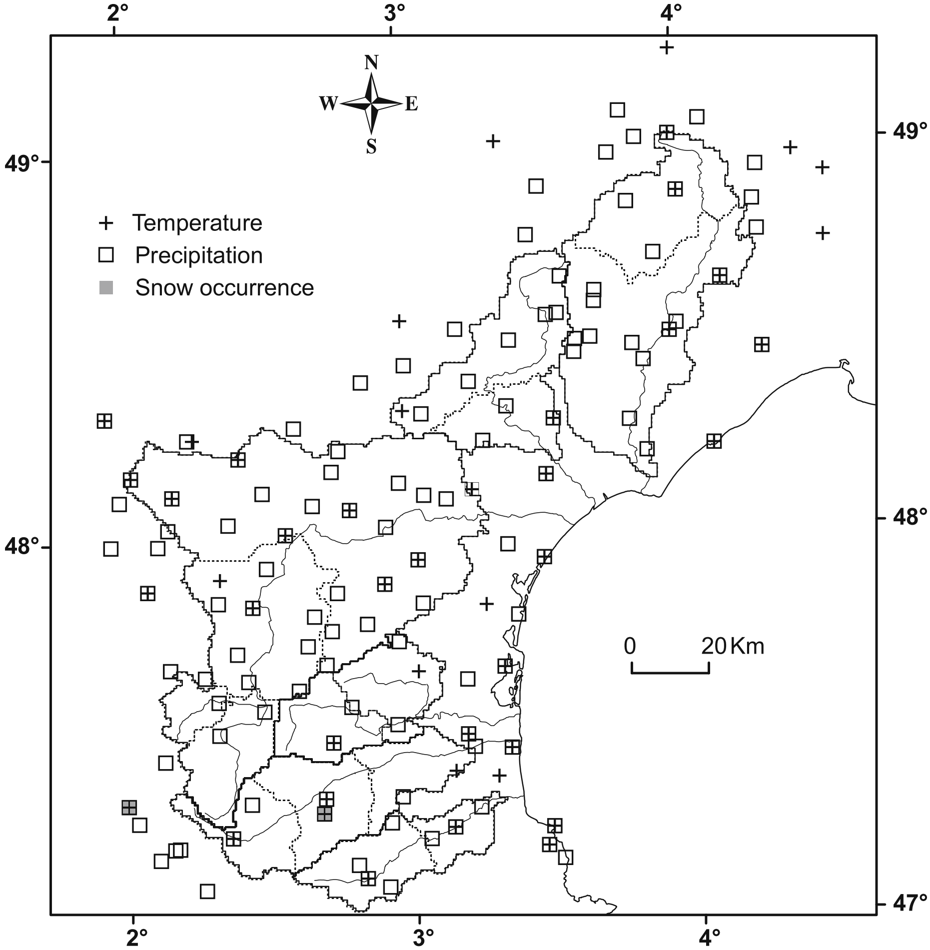

Fig. 4 Location of the meteorological stations retained for spatial interpolations

by-products) generally produce better results than classical deterministic methods (i.e. Inverse Distance Weighting, Thiessen polygon; Goovaerts 2000; Lloyd 2005). This is because the former techniques take into account the spatial structure of P data (Creutin and Obled 1982). OK was therefore retained to produce spatially gridded data layers of monthly precipitation. At final, considering for all the months of the period 1965–2004, RMSE ranged from 2 to 94 mm with a median of 21 mm while MSE ranged from -1.1 to 1.7 mm with a median close to 0 mm. These rather low values indicate that our precipitation grids were of good quality.

For temperature, our interpolation method was different, given the strong relationship between this climatic parameter and elevation. A first step consisted in predicting the monthly temperature values as a function of the collocated elevation through a simple linear model:

$$Temperature = a^* \ Elevation + b \tag{1}$$

Variance of temperature explained by the linear models ranged from 42% to 98% with a median of 84% ($n = 480$). These linear models allowed us to obtain monthly temperature grids from our DEM, which were averaged for each watershed. The next step was an interpolation of the residual values between the observed and modelled station temperatures. Clear spatial patterns between residuals were mostly lacking and different interpolation algorithms were tested through cross-validation for individual months. Comparison of the RMSE and MSE cross-validation parameters again gave advantage to the OK technique. We therefore interpolated the residual temperatures in the same way as we did for precipitation. Finally, they were averaged for each watershed and added to the theoretical watershed averages (see above) in order to obtain the final temperature values.

2.4 Statistical analyses

We used the non-parametric Mann–Kendall (MK) test to detect significant trends in the hydroclimatic time series for 1965–2004. This test is independent of whether its shape is linear or non-linear (Mann 1945; Kendall 1975). WMO (2000) defined it to be an official tool in detection of trends in hydrologic data and many studies showed this test to be efficient in identifying trends in hydrologic and other variables, especially in the context of the ongoing climate change (e.g., Westmacott and Burn 1997; Ab Razak and Christensen 2001; Hisdal et al. 2001; Yue et al. 2002). The Mann–Kendall test statistic is given by:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}\left(x_j - x_k\right) \tag{2}$$

where the x_j are the sequential data values, n is the length of the data set and $\operatorname{sgn}(x_j - x_k)$ is equal to 1, 0 or −1 if $x_j - x_k$ is greater than, equal to, or less than zero respectively. The null-hypothesis, H_o, is that the data are uniformly distributed random variables (i.e. no existing trend in the data set). A standard normal variable value Z is then determined and is related to a *p*-value for a specific trend. This *p*-value gives the probability of obtaining the observed value for the Mann–Kendall statistic when in fact no trend exists. We considered detected trends with a *p*-value lower than 0.1 as significant and determined the magnitude of the long-term change by a simple linear model fitted between the tested variable and time.

For correlation analyses between two independent parameter series, we used both the Pearson's and the Spearman's rho correlation tests. The former was selected when the parameters followed a normal distribution. Otherwise the latter test was used. The non-parametric Spearman's rho test is a rank correlation test that allows identifying relationships between the different parameters independently of the shape of the relationship. For both tests, only correlations with a *p*-value lower than 0.1 were considered as statistically significant. A more comprehensive description of these tests can be found in Helsel and Hirsch (1992).

To investigate the complex relationships existing between surface climatic parameters and atmospheric circulation, we applied canonical correlation analyses (CCA) between the time series of the watershed averaged climatic parameters and the gridded 500 hPa geopotential height fields. The latter were taken from the

NCEP/NCAR reanalysis datasets (Kalnay et al. 1996; Kistler et al. 2001) in a 2.5 × 2.5 grid point resolution in a large domain covering the European and Mediterranean areas. CCA is appropriate to search for linear relationship between two sets of space/time dependent variables, selecting pairs of spatial patterns of each variable set such that the time dependent pattern amplitudes are optimally correlated. For each selected pair, CCA creates two canonical roots that are constructed from weighted sums of the original data, one for each variable set. The time series of the canonical roots describe the strength and the sign of the corresponding pattern for each realization in time. Before performing the CCA, both variable sets were submitted to a PCA and projected onto their PCs. Only a limited number of the PCs were retained for subsequent CCA, avoiding noise and accounting for most of the total variance in the data sets. Previous studies demonstrated that CCA is a powerful tool for studying the variability of temperature (Xoplaki et al. 2003a, b) and precipitation (Xoplaki et al. 2004) in connection with the large scale atmospheric circulation in the Mediterranean region. For more details on the CCA method, we refer to these studies and the references cited therein.

3 Results

3.1 Physical characteristics of the watersheds

3.1.1 Natural and anthropogenic characteristics

The basin contours delineated in the Section 2.1 were used to determine the natural and anthropogenic characteristics of the watersheds from different datasets, giving an overview of their variability in the investigated region (Table 1). Area, mean elevation and mean slope values range respectively from 201 to >3,000 km^2, from 233 to >1,700 m and from 2.4° to 10.8°, highlighting the very different morphologic conditions of the studied watersheds. Those in high and steep regions (i.e. Laroque, Vieussan, Puyvalador, Belvianes, Serdinya, Rodes and Reynes) are only under weak anthropogenic influence, with natural vegetation representing more than 75% of the total area, mostly forest. This is also reflected by the low population density (6–28 inhabitants/km^2). In the watersheds further downstream, agricultural land use, often vineyards, is more abundant and covers between 33% and 58% of the total area. Population density is also more important with values ranging from 20 to 417 inhabitants/km^2.

Major reservoirs were built in six of the 15 watersheds (Tables 1 and 2) in order to provide water for irrigation, to produce hydropower and to protect the downstream plains from flash-floods, which can be particularly violent in this area. Most of the reservoirs were constructed before 1965. The regulated areas (in % of the total watershed areas) strongly vary from one watershed to another, ranging from 6% (Agde) to 100% (Puyvalador).

Water extraction for irrigation can have an important effect on the river discharges too (Table 3). The strongest impact concerns the Tet and Tech rivers, where intensive irrigation has a more than 1,000 years history (Ruf 2001) and the extracted amounts of water in the corresponding lowland watersheds surpass by far the amounts in the

Table 1 Average environmental characteristics of the studied watersheds

River	Watershed	Perimeter (km)	Area (km^2)	Elevation (m)	Slope (°)	% Natural vegetation	% Agriculture	% Urban	Population density (inhabitants/km^2)	% of regulated watershed area
Herault	Laroque	184	837	612	5.3	87.0 (44.0)	12.1	0.9	24	–
Herault	Agde	320	1740	238	2.8	53.8 (20.3)	42.5	3.3	58	6%
Orb	Vieussan	220	891	531	5.5	82.2 (65.8)	15.7	1.8	29	14%
Orb	Beziers	132	432	233	3.0	55.4 (37.4)	42.0	2.5	48	–
Aude	Puyvalador	96	201	1101	5.9	75.9 (59.6)	23.7	0.4	8	100%
Aude	Belvianes	138	533	1412	9.1	90.7 (61.8)	7.9	0.8	7	–
Aude	Carcassonne	191	1143	406	3.7	53.1 (40.6)	45.0	1.8	75	–
Aude	Moussan	405	3079	271	2.4	41.3 (26.4)	56.2	2.3	40	–
Agly	Planezes	115	433	657	6.4	78.8 (52.3)	19.7	1.0	7	94%
Agly	Estagel	142	472	346	4.9	69.6 (29.6)	29.3	1.1	20	–
Tet	Serdinya	148	418	1729	10.8	94.2 (47.3)	4.6	0.6	6	13%
Tet	Rodes	144	546	1070	10.0	87.8 (43.4)	10.8	1.1	31	96%
Tet	Perpignan	132	393	276	3.0	42.5 (18.9)	49.9	7.6	417	–
Tech	Reynes	130	480	1009	9.4	91.9 (65.6)	7.0	1.1	23	–
Tech	Argeles	103	250	265	4.3	49.7 (39.0)	43.6	6.8	108	–

Data sources: Columns 3–6: USGS (2000); Columns 7–9: IFEN (2007)—Reference period: 2000 (numbers in brackets in column 7 indicate % of forest cover); Column 10: INSEE (2005)—Reference period: 1999. Column 11: BRL (2007). Data were extracted with ArcInfo software tools

Table 2 Reservoir constructions in the studied watersheds

Watershed	Name	Setting date	Water storage capacity (in mm^3)
Agde	Salagou	1969	102
Agde	Olivettes	1989	44
Vieussan	Avene	1962	33
Puyvalador	Matemale	1959	0.56
Puyvalador	Puyvalador	1932	0.04
Planezes	Caramany	1994	27.5
Serdinya	Les Bouillouses	1910	0.05
Rodes	Vinca	1976	24.2

Data from BRL (2007)

other rivers further in the North. Water extraction is also notable in the Beziers watershed, where it is used to satisfy the drinking water demand of the population in the neighbouring cities (DIREN 2004).

3.1.2 Climatic conditions

The investigated watersheds cover a wide range of climatic characteristics (Table 3). The highest watershed, Serdinya (Table 1), lies in the Pyrenees in the SW part of the study area, where a permanent snow cover in winter is frequent. The lowest watershed corresponds to the downstream basin of the Orb River (Beziers) further to the N, where snowfall is rare. Mean annual temperature is highly linked to elevation ($r^2 = 0.98$, $n = 15$), with a vertical gradient of −0.54°C/100 m. Mean annual precipitation generally follows a decreasing gradient both from upstream to downstream and from North to South (Fig. 5). The wettest watersheds are thus in the hinterlands of the Herault and Orb rivers (i.e. Laroque and Vieussan), whereas the driest ones are in the coastal plains in the South (Perpignan, Argeles and Estagel).

The seasonal variability of precipitation, expressed by the ratio of monthly maximum to minimum precipitation, also follows a decreasing gradient from N to S, but increases downstream (Table 3). Ratios of > 4.5 are typical for the watersheds of the Herault and Orb rivers in the N, while ratios of <2 are found for the upstream watersheds of the Tech, Tet and Aude rivers in the SW. In the former, precipitation is more abundant in October, with a second maximum in December/January (Fig. 6). In the latter, spring precipitation (April/May) is particularly important, even exceeding sometimes winter precipitation. Furthermore, the October peak is absent there, in contrast to most other watersheds. According to the definition of the Mediterranean climate type of Köppen (in Trewartha 1943), for which the strong contrast between summer and winter precipitation is one of the dominant characteristics, only seven of the 15 watersheds fulfil the selection criterion of at least three times as much precipitation in the wettest winter month compared to the driest summer month. These are the watersheds of the Orb and Herault rivers and the lowest watersheds of the Agly, Tet and Tech rivers. Hence, the watersheds of the Aude River, which is the largest river in the study area, cannot be properly considered as being subjected to a Mediterranean climate type. They all show lower intra-annual precipitation variability.

Table 3 Average hydroclimatic characteristics of the studied watersheds

River	Watershed	Annual T (°C)	Tmax–Tmin (°C)	Annual P (mm)	Pmax / Pmin	Annual Q-net (mm)	Q-net /P	Qmax-Qmin (mm)	F-index (%)	M-index	Q extraction (mm)	% Karstic	EAWC (mm)
Herault	Laroque	10.9	15.9	1377	5.2	778	0.55	106	14.6	66	1	56	291
Herault	Agde	13.4	16.0	950	5.2	384	0.40	54	14.4	41	2	36	313
Orb	Vieussan	11.6	15.6	1121	4.7	809	0.71	92	13.8	52	1	16	302
Orb	Beziers	13.5	15.8	811	4.9	305	0.38	59	14.8	35	39	–	356
Aude	Puyvalador	8.7	14.5	1016	2.0	445	0.44	72	10.9	55	–	92	318
Aude	Belvianes	7.1	14.1	875	1.7	625	0.69	60	10.9	51	–	16	253
Aude	Carcassonne	12.4	15.4	877	2.5	223	0.24	35	11.5	39	5	3	319
Aude	Moussan	13.1	15.6	822	3.0	219	0.26	36	11.8	36	5	–	327
Agly	Planezes	11.5	14.9	864	2.8	340	0.38	45	12.7	40	–	51[a]	232
Agly	Estagel	13.3	15.2	788	3.8	121	0.13	30	14.6	34	6	45[a]	251
Tet	Serdinya	5.7	13.7	801	1.9	414	0.51	44	11.3	51	–	–	278
Tet	Rodes	9.3	14.2	801	1.8	353	0.44	47	13.0	42	82	–	275
Tet	Perpignan	13.9	15.0	727	3.2	−51	−0.13	47	15.7	30	221	–	271
Tech	Reynes	9.8	14.1	937	2.0	521	0.54	49	13.7	47	28	–	304
Tech	Argeles	14.1	14.8	765	3.5	274	0.31	62	15.9	32	70	–	265

Tmax–Tmin difference between the average temperatures of the warmest and coldest months; *Pmax/Pmin* ratio of the average precipitation in the wettest and in the driest months; *Q-net* difference between the discharge values at the basin outlet station and the upstream gauging station, divided by the watershed area; *Qmax–Qmin* difference between the average discharge in the wettest and in the driest months; *F-index* (%) Fournier index = sum of (monthly P^2/annual P), see Corine (1992); it is here expressed as percentage of the mean annual precipitation; *M-index* aridity index of Martonne; *Q extraction* anthropogenic extraction of surface waters in 2004 (source: Agence de l'Eau RMC 2006); % *Karstic* percentages of large individual karstic aquifer areas in the watersheds; *EAWC* easily available water capacity according to ECESBN (2004)

[a] Indicate that they are mixed with other sedimentary rocks (Agence de l'Eau RMC 2006)

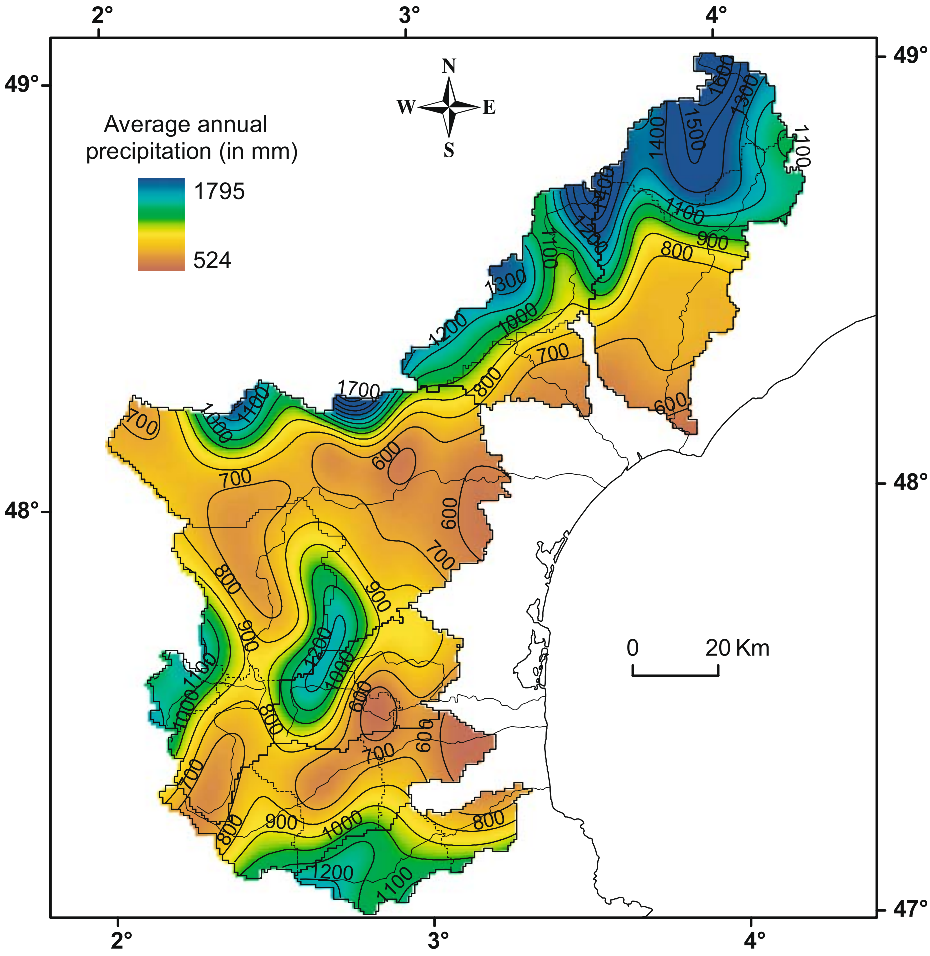

Fig. 5 Mean annual precipitation isohyets in the study region (average over the period 1965–2004)

3.1.3 Water discharge

The highest specific water discharge values (Table 3) are found in the upstream watersheds (e.g. Laroque, Vieussan and Belvianes) where precipitation is high and the anthropogenic influence is limited. However, the drainage intensity of 809 mm in the Vieussan watershed is particularly high when compared to the annual precipitation. Here, not all water is rain derived, since karstic sources and water deviation from the Vebre, a tributary of the Adour-Garonne River system in the west of our study area, contribute to additional water inputs from outside the drainage area (DIREN 2004). Inversely, the lowest discharge values are found in the downstream watersheds where precipitation is generally lower and surface water extraction more important. The lowest value of −51 mm corresponds to the Perpignan watershed, where anthropogenic water extraction exceeds the runoff generation within the watershed (Table 3).

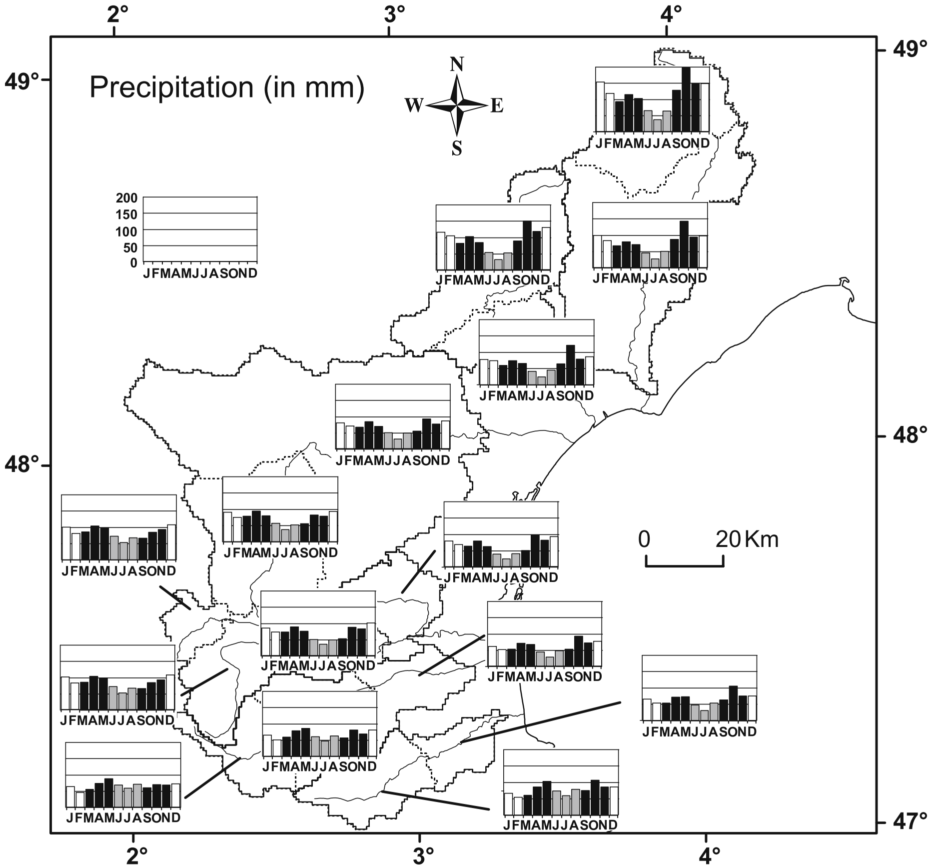

Fig. 6 Distribution of average monthly precipitation in the considered watersheds (average of 1965–2004). Horizontal graduations indicate the 50, 100, 150 and 200 mm values. *Bars* are shaded from *white to black colours* according to the different seasons

Average annual Runoff Ratios (RR = specific discharge/precipitation) and correlation analysis between the annual time series of discharge and precipitation give additional information on the hydrologic functioning of the studied watersheds. Both have been calculated on the basis of the hydrological year that extends from September to August in this area. Water levels in soil reservoirs are lowest in late summer, and differences of their water content from one year to another do not much influence the relationships between Q and P. RR is the greatest (>0.5) in the uppermost watersheds and decreases further downstream (Fig. 7a), due to stronger evaporative water loss at higher temperatures. Beside the outstanding value of the Vieussan watershed (see above), the greatest ratio is observed for the Belvianes watershed (RR = 0.69), which shows the second highest elevation of all watersheds. It is therefore surprising that in the Serdinya watershed, which is even higher, RR is only 0.51. This might be an artefact, since there is evidence that real discharge may be underestimated because of the presence of a major deviation for irrigation at this station (for a discussion, see Ludwig et al. 2004). Lowest runoff ratios values

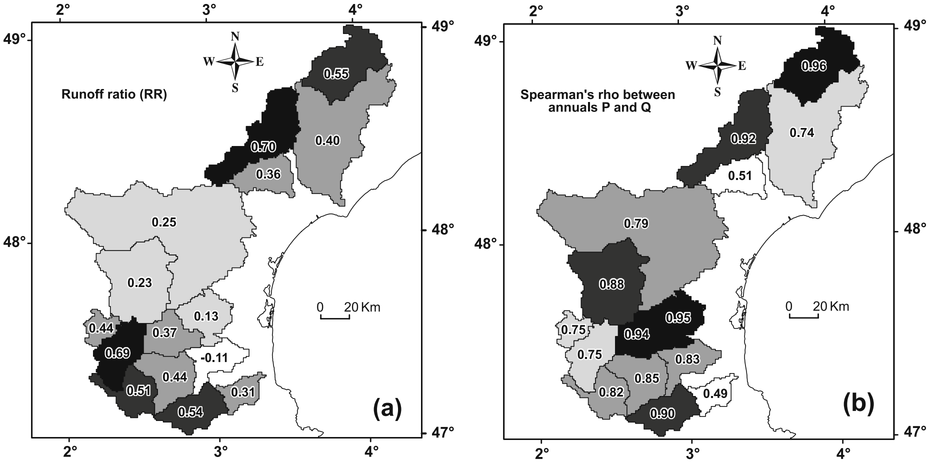

Fig. 7 **a** Mean annual Runoff Ratio (RR) for the period 1965–2004, calculated as Q-net over P in the considered watersheds (see text). **b** Spearman's rho correlation coefficients between Q-net and P for the same period. The reported values have been calculated on the basis of the hydrologic year that extends from September to August. Watershed *colours* from *black to white* reflect high to low values of RR (**a**) and rho (**b**)

are found for the Estagel watershed (RR = 0.13) and naturally also for Perpignan, where RR is negative (see above). The Agly River is the only of the six investigated rivers that is often completely dry during the warm season close to its mouth because of water losses to the karstic underground in the Estagel watershed (Salvaire and Teisseire-Dufour 2002).

Rho correlation coefficients between annual Q and P series show a spatial structure as well (Fig. 7b). They are greatest in the northern upstream watersheds (Laroque and Vieussan), where runoff is highly linked to precipitation. Further downstream, the coefficients generally tend to decrease in the entire study region, here probably related to anthropogenic influence and the interactions with the soil and groundwater reservoirs, which are more important in these watersheds (Table 3). Only in the downstream watersheds of the Tet and Agly rivers, Q and P are still highly correlated. From a hydrological viewpoint, these watersheds have the lowest soil water contents (see EAWC in Table 3). They are mainly active in years with heavy flash-floods, which may increase the correlation coefficients. Finally, it is also worth mentioning the rather low coefficients found in the Argeles and Beziers watersheds (rho = 0.49 and 0.51, respectively). In the former, our precipitation estimates might be less reliable because precipitation stations from Spain were missing in our dataset, which reduces the reliability of the spatial interpolations in this area. In the latter, the P–Q relationships are also strongly influenced by the decreasing discharge trend (see Section 3.2.3).

3.2 Trends

3.2.1 Temperature

Mean annual temperature strongly increased in the entire study area, in particular since the late 1970s (Fig. 8). Inter-annual variability of this parameter has increased

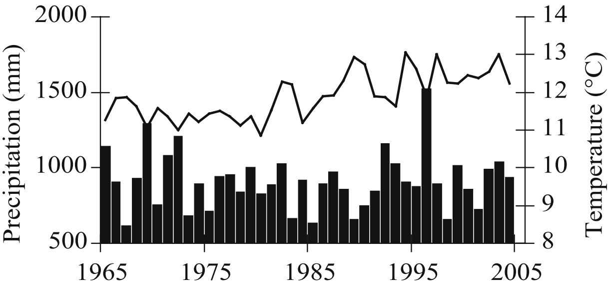

Fig. 8 Evolution of mean annual temperature (*solid line*) and mean annual precipitation (*black charts*) averaged over the entire study area

too. The magnitude of the mean annual temperature increase during this 40-year period is around 1.5°C for most watersheds (Table 4). All trends are highly significant (p-value < 0.01 for 14 watersheds). Warming was however less important in the vicinity of the Pyrenees in the south-west (Fig. 9a), with a minimum value in the Serdinya watershed. Here the mean annual temperature increased on average only by 0.8°C ($p < 0.05$).

Monthly evolutions of temperature show that the general warming was unevenly distributed over the different seasons (Table 4). Highest warming was recorded in spring and summer (March to August) in all watersheds. The 2 months with the strongest warming are March and August with an average temperature increase of about 2.8°C. Warming was important in June too (around 2.2°C on average). Temperature also increased in winter (December to February), but with a lower magnitude. Finally, no temperature increase was observed in autumn.

Table 4 Estimated significant temperature changes for 1965–2004 (in °C)

Watershed	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Laroque	0.9	–	**2.7**	1.0	2.2	**2.4**	**2.0**	**3.2**	–	–	–	1.4	**1.6**
Agde	1.1	–	**2.7**	1.0	**2.1**	**2.3**	**2.1**	**3.1**	–	–	–	1.5	**1.7**
Vieussan	–	–	**2.9**	–	2.1	**2.3**	1.8	**3.0**	–	–	–	1.5	**1.6**
Beziers	1.1	–	**2.9**	–	2.2	**2.2**	1.9	**3.0**	–	–	–	1.5	**1.6**
Puyvalador	–	–	**3.0**	–	1.8	2.1	–	**2.6**	–	–	–	–	**1.2**
Belvianes	–	–	2.8	–	–	2.0	–	**2.3**	–	–	–	–	**1.0**
Carcassonne	–	–	**2.8**	–	2.1	**2.1**	1.4	**3.0**	–	–	–	–	**1.4**
Moussan	–	–	**2.9**	0.9	2.2	**2.2**	1.6	**3.1**	–	–	–	–	**1.6**
Planezes	–	–	2.5	–	1.8	**2.1**	–	**2.8**	–	–	–	–	**1.2**
Estagel	–	–	**2.8**	1.0	2.1	**2.2**	1.4	**2.9**	–	–	–	1.2	**1.5**
Serdinya	–	–	2.7	–	–	1.9	–	2.0	–	–	–	–	0.8
Rodes	–	–	2.6	–	1.6	2.1	–	**2.5**	–	–	–	–	**1.1**
Perpignan	–	–	**2.8**	1.0	2.0	**2.3**	1.6	**3.0**	–	–	–	1.2	**1.6**
Reynes	–	–	**2.8**	–	1.6	2.2	–	**2.6**	–	–	–	–	**1.2**
Argeles	1.0	–	**2.9**	1.0	2.0	**2.3**	1.6	**3.0**	–	–	–	1.3	**1.6**

Trends are detected by the MK test for trends and estimated by linear regression over time whenever they were significant (normal format: $0.05 < p$-value < 0.1; underlined format: $0.01 < p$-value < 0.05; bold format: p-value < 0.01). No trends are indicated by "–"

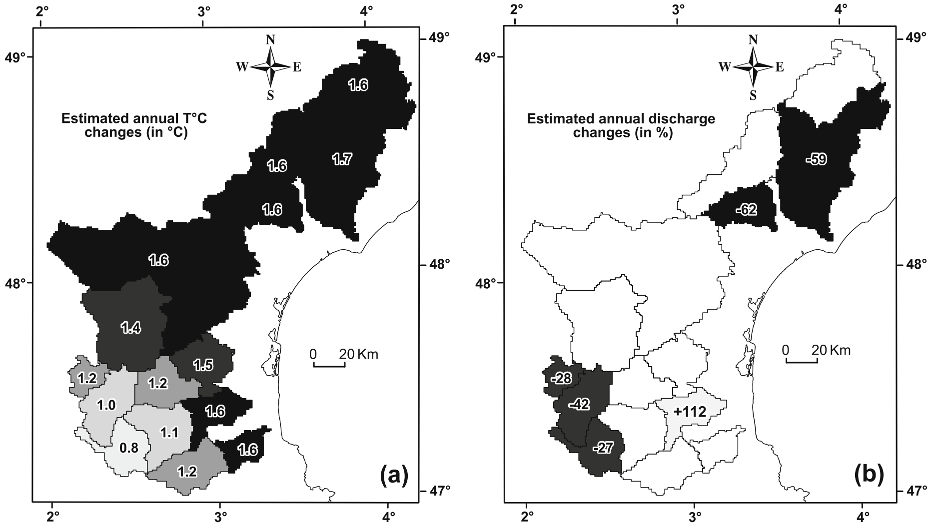

Fig. 9 Estimated trends for the period 1965–2004 of (**a**) mean annual temperature (in °C) and (**b**) mean annual discharge (in %). Only trends with *p*-values lower than 0.1 are shown. Watershed *colours* from *black to white* reflect high to low values in (**a**) and low to high values in (**b**)

3.2.2 Precipitation

Mean annual precipitation was highly variable during the study period but did not follow significant trends for any of the investigated watersheds (Fig. 8). Also for the monthly series, clear trends are missing (Table 5). Only in the northernmost watersheds (Laroque, Agde and Vieussan) precipitation significantly decreased in

Table 5 Estimated significant precipitation changes for 1965–2004 (in %)

Watershed	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Laroque	−51	−62	–	–	–	–	–	–	–	–	–	–	–
Agde	−45	–	–	–	–	–	–	–	–	–	–	–	–
Vieussan	−37	−29	–	–	–	–	–	–	–	–	–	–	–
Beziers	–	–	–	–	–	–	–	–	–	–	–	–	–
Puyvalador	–	–	–	–	–	–	–	–	–	–	–	–	–
Belvianes	–	–	–	–	–	–	–	–	–	–	–	–	–
Carcassonne	–	–	–	–	–	–	–	–	–	–	–	–	–
Moussan	–	–	–	–	–	–	–	–	–	–	79	–	–
Planezes	–	–	–	42	–	–	–	–	–	–	–	–	–
Estagel	–	–	–	–	–	–	–	–	–	–	–	–	–
Serdinya	–	–	–	–	–	–	–	–	–	–	–	–	–
Rodes	–	–	–	–	–	–	–	–	–	–	–	–	–
Perpignan	–	–	–	–	–	–	–	–	–	–	–	–	–
Reynes	–	–	–	–	–	–	−35	–	–	–	–	–	–
Argeles	–	–	–	–	–	–	–	–	–	–	–	–	–

For further explanations, see Table 4

January and February. For the other months, the few tendencies that appeared in our data were mostly positive but weakly significative. April is the only month during which precipitation tended to increase in almost all watersheds but not significantly (p-values from 0.09 to 0.44).

3.2.3 Water discharge

Mean annual discharge significantly decreased for Serdinya, Puyvalador, Belvianes, Beziers and Agde (Table 6 and Fig. 9b). The first three watersheds are located in the southwestern part of the study area, close to the Pyrenees, with high average elevations and mostly covered by natural vegetation (Table 1). The last two watersheds correspond to the downstream parts of the Herault and Orb rivers (Fig. 9b). Here, elevation is rather low and natural vegetation covers only slightly more than 50% of the area. For both groups, correlation between the annual P and Q series were generally lower than for the other watersheds (Fig. 7b), which can be related to the different trend evolutions of both parameters. Perpignan is the only watershed where the mean annual discharge followed a positive trend. When summing up the estimated changes for the six watersheds that exhibit significant trends, it can be estimated that the mean annual water discharge in the entire study region decreased by about 20% between 1965 and 2004.

3.2.4 Land use and anthropogenic water extraction

Land use and other anthropogenic factors could also have followed significant changes during our study period, with possible impacts on the water resources. In particular reforestation can have a negative feedback on river discharges via enhancement of evapotranspiration (Rambal 1987; Andréassian 2004). In southern France, as in many other regions of Europe, reforestation is a well known phenomenon which is directly linked to the abandonment of farmland during the second half of the last century. In order to quantify this trend in our study area, we digitized the

Table 6 Estimated significant changes of specific water discharge (Q-net) for 1965–2004 (in %)

Watershed	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Laroque	−65	**−82**	−55	–	–	**−63**	−43	−49	–	–	–	–	–
Agde	−93	**−97**	**−83**	−77	–	–	−64	−81	−66	–	–	–	−59
Vieussan	–	−29	–	–	–	–	–	–	–	–	–	–	–
Beziers	–	−62	–	–	–	−149	**−206**	**−156**	**−108**	–	–	–	−62
Puyvalador	–	–	–	−26	**−32**	**−47**	**−57**	**−46**	−43	–	–	–	−28
Belvianes	**−51**	–	−41	– **56**	−45	−44	**−39**	−12	–	–	−46	−45	**−42**
Carcassonne	–	–	−73	–	–	–	–	–	–	–	–	–	–
Moussan	–	−57	−81	–	–	–	–	365	–	–	640	–	–
Planezes	–	–	**−70**	–	–	–	69	**443**	104	–	−85	–	–
Estagel	–	–	–	–	–	–	–	−58	−390	−126	–	–	–
Serdinya	–	–	–	–	–	−44	**−45**	−25	−67	–	–	–	−27
Rodes	−41	−69	−78	–	–	–	–	–	–	–	–	–	–
Perpignan	–	–	–	–	–	–	–	–	**58**	–	223	254	112
Reynes	–	–	−49	–	–	–	−52	–	–	–	–	–	–
Argeles	–	–	–	–	–	–	–	–	–	–	–	–	–

For further explanations, see Table 4

forest inventory maps that were established by the National Forest Inventory agency (IFN 2007). These inventories exist for the years 1970, 1974, 1980, 1983, 1991 and 1996 although they do not always cover the same areas. They were used to estimate relative surface of forest cover in all watersheds for the corresponding years. Increase of forest cover was found to be highly linear, which led us to calculate an average growth rate for the period 1970–2000 (Fig. 10). Our results confirm that increase of forest cover occurred everywhere during this 30-year period, ranging from 13% (Moussan) to 25% (Rodes) of the total watershed areas.

For a quantitative reconstruction of the water extractions for irrigation, the available data only allowed to go back to the late 1980s (Table 7). These data indicate that water extractions remained more or less constant during the 1990s before they slightly increased until 2004.

4 Discussion

4.1 Climate variability and large-scale atmospheric circulation

4.1.1 Temperature

The strong temperature increase in the investigated watersheds is remarkable compared to the global warming. Brohan et al. (2006) reported a warming trend of 0.33°C/decade for the period 1979–2005 on land in the Northern Hemisphere and of 0.27°C/decade in both hemispheres. This is largely lower than warming we recorded in our study area, which is about 0.49°C/decade for the period 1979–2004. Such a

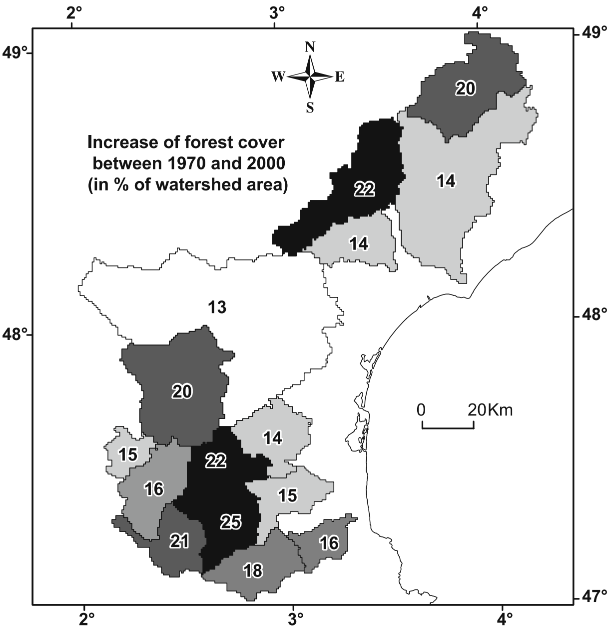

Fig. 10 Evolution of forest cover from 1970 to 2000 (in % of the watershed area). Watershed *colours* from *black to white* reflect low to high values of % forest cover increase. Data from IFN (2007)

Table 7 Evolution of surface water extraction for irrigation

Watershed	Extractions (mm/year)		
	1987–1992	1993–1998	1999–2004
Laroque	2	2	2
Agde	6	14	18
Vieussan	2	1	1
Beziers	30	32	39
Puyvalador	0	0	0
Belvianes	1	1	0
Carcassonne	8	7	6
Moussan	5	4	8
Planezes	10	6	1
Estagel	2	2	5
Serdinya	1	0	1
Rodes	57	59	113
Perpignan	226	167	195
Reynes	17	20	26
Argeles	59	42	69

Data from Agence de l'Eau RMC (2006)

strong warming suggests that local changes in the atmospheric circulation pattern may have enhanced the general warming.

By far most of the temperature increase occurred during spring and summer, when the monthly warming rates achieve almost twice the annual rates (see above). During these seasons, the study region is under the influence of the relative stable subtropical high pressure conditions, reaching their maximum in summer. Xoplaki et al. (2003a) studied the variability of summer (June to September) air temperatures over the entire Mediterranean area in connection to the large scale atmospheric pressure conditions and thermic predictors (thickness patterns and Mediterranean SST) during the second half of the last century. Based on canonical correlation analyses (see Section 2.4), they demonstrated that the average warming of about 0.08°C/decade can be related to a canonical mode which, in its positive phase, represents warm summers, blocking conditions (deviation of westerly winds towards northern Europe), subsidence and atmospheric stability over the Mediterranean. They suggested this mode to control the long-term changes in the Mediterranean summer temperature, allowing for a surplus of solar radiation reaching the surface when high pressure systems are persistent. This is in good agreement with Casty et al. (2007) who detected an increased influence of the Azores High in summer towards central Europe and the Mediterranean during the last 40 years. Also the work of Chen et al. (2002), based on satellite measurements of radiative energy fluxes since 1985, supports the hypothesis of a northward extension of the subtropical high pressure domain.

Focussing more specifically on our study region and using the same statistical tool as Xoplaki et al. (2003a) confirms that the temperature evolution from March to August is highly connected to the mid-altitude regional pressure conditions. In particular the gridded 500 hPa geopotential height fields (Z500), also frequently used in other studies to investigate the atmospheric circulation patterns in the Mediterranean region (e.g. Giorgi et al. 2004a, b; Casty et al. 2005; Giorgi and Lionello 2007), are powerful predictors for the temperature evolution. CCA made on the time series of the first PC of March to August averaged Z500 and surface air temperature series resulted in a unique canonical root for temperature (CR-T) that is highly correlated with temperature series in all investigated watersheds (*r* between 0.92 and 0.99, see Fig. 11a). Correlation between the corresponding Z500 canonical root (CR-Z500) and the 500 hPa geopotential heights is more variable at larger regional scales, but also shows very high correlation coefficients (>0.9) over the study region (Fig. 11b). Since the temperature evolution in the studied watersheds was uniform, no additional canonical modes were produced in our analysis.

The temporal evolutions of both CCA modes (Fig. 11c) are also highly correlated ($r = 0.95$) and follow a significant positive trend towards higher temperatures and pressure conditions. This is clear evidence that the extension of the subtropical high pressure domain is mainly responsible for the strong temperature increase in our watersheds. In this context, one can also notice that the two months with the strongest warming are March and August (Table 4), which approximately mark the beginning and the end of the spring and summer seasons. It is therefore indicated that the extension of the subtropical high pressure domain is not only a spatial but also a temporal phenomenon. Similar canonical modes are found when CCA are performed for individual months from March to August. Each month is characterized by a positive pressure field anomaly over our study area and CR-Z500 follow

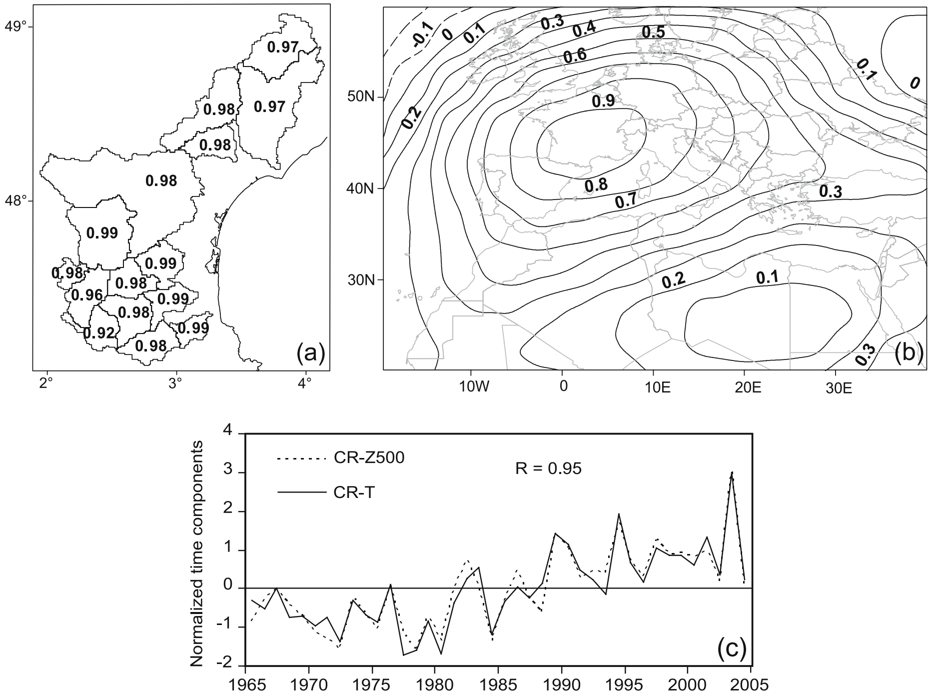

Fig. 11 **a** Spatial correlation (*r* values) between the March to August watershed temperature and the canonical root of this parameter (CCA-T) over the study region; **b** spatial correlation (contour map of r) between the March to August 500 hPa geopotential heights and the canonical root of this parameter (CR-Z500) in the Mediterranean region; **c** normalized time series of both CR-500 (*dashed lines*) and CR-T (*solid line*) during the study period

significant positive trends in March, May, June and August (not shown). These are also the months for which temperature increase was greatest.

4.1.2 Precipitation

One may be surprised that precipitation did not follow clear trends in the studied watersheds, although changes in the atmospheric circulation occurred. Precipitation is known to be more independent from large-scale climate states than temperature, especially in summer when precipitation events are mainly controlled by local-scale convective processes and other factors such as soil humidity. Furthermore, the circulation changes described above mainly concern the spring and summer periods, whereas most precipitation falls from October to March (Fig. 6). Xoplaki et al. (2004) considered these months as the wet season in the entire Mediterranean region and showed that corresponding precipitation generally shows less spatial averaged predictability compared to summer temperature. They could nevertheless demonstrate that variations of the NAO index are mainly responsible for interdecadal changes of the Mediterranean precipitation throughout the twentieth century.

The NAO index is associated with changes to westerlies over the North Atlantic and Europe (Hurrell 1995; Wanner et al. 2001). High positive indices of NAO are generally associated with a lower occurrence of depressions in southern Europe and hence lower probabilities of precipitation occurrence in this area, since the Atlantic air masses are deviated further to the North. Inversely, negative indices indicate that these air masses can reach the Mediterranean region and increase precipitation there. Negative correlation between precipitation and NAO is therefore a widespread feature in the Mediterranean drainage basin in winter, when most of precipitation occurs (Mariotti and Struglia 2002). Spearman's rho correlation coefficients between precipitation in the studied watersheds and the NAO index confirm this. All are negative but significant for most watersheds only in winter (Fig. 12). This is not the case during the warm season (late spring and summer), when this region is dominated by the subtropical high pressure regime (Bolle 2003).

It is now largely documented that the NAO index followed a significant increasing trend in winter and early spring since 1965, leading to a general precipitation decrease in Mediterranean (e.g. Hurrell 1995; Wanner et al. 2001; Xoplaki et al. 2004). This precipitation decrease was however not recorded in our study region. But it is interesting to note that the few watersheds that recorded a significant precipitation decrease during January and February (Laroque, Agde, Vieussan; see Table 5) are those for which correlations between P and NAO index are the strongest (Fig. 12). The general NAO influence in our study region is therefore confirmed but it is obviously not strong enough to provoke long-term trends for annual precipitation. This result is in agreement with Vicente-Serrano and Lòpez-Moreno (2006) who studied the influence of the NAO index on precipitation variability in the Northeast of Iberian Peninsula, close to the southern limit of our study area. Here precipitation variability seems to respond better to atmospheric variability at more detailed (synoptic) spatial scales than NAO variability. This can explain the stationary behaviour (and even the slight upward trends) of annual precipitation they found along the Mediterranean coast during the last decade.

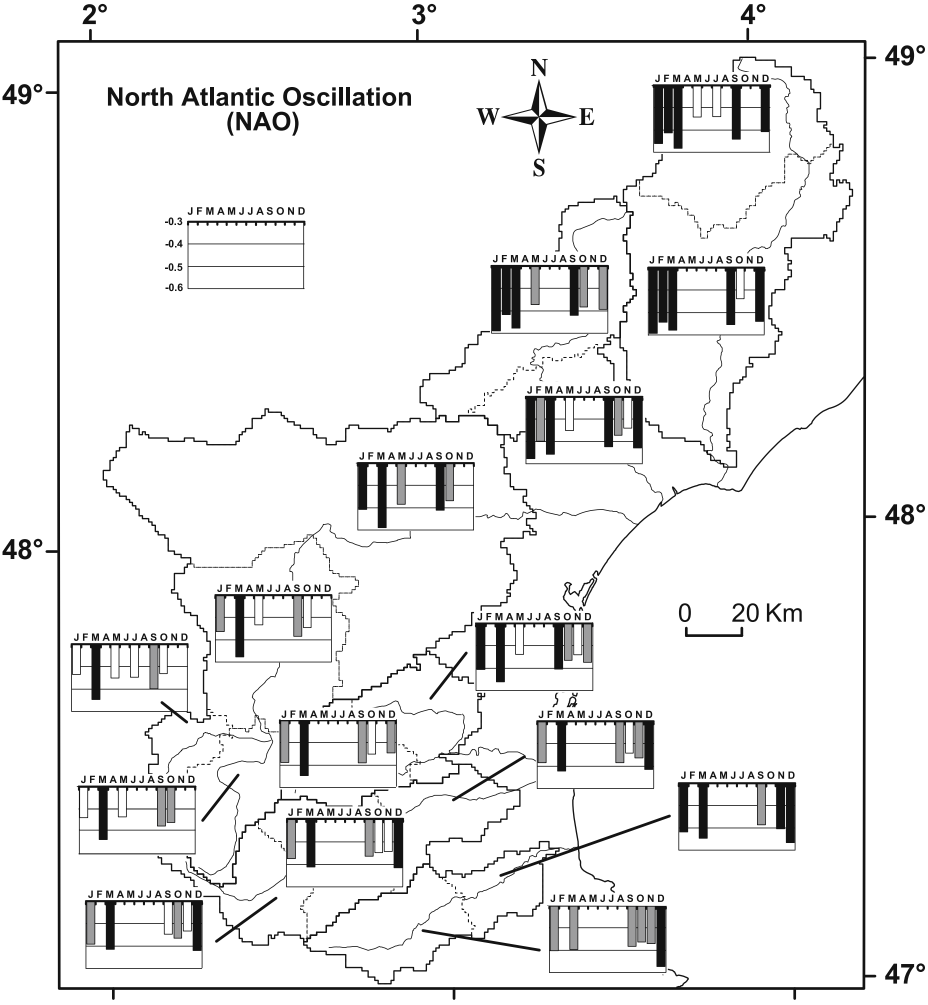

Fig. 12 Significant Spearman's rho correlation coefficients between average monthly precipitation and NAO index in the considered watersheds. NAO index was downloaded from http://www.cru.uea.ac.uk/cru/data/nao.htm. *Bars are coloured in white* for $0.05 < p$-value < 0.1, in *grey* for $0.01 < p$-value < 0.05 and in black for p-value < 0.01

4.2 Climatic controls on water resources

4.2.1 Mountainous watersheds

A major finding of our work is the reduction of the water resources in the study region: one third of the watersheds recorded a significant decrease of the mean annual discharge from 1965 to 2004. As precipitation did not change, it is likely that this decrease is mainly related to the temperature increase. It is therefore interesting to consider also the evolution of the runoff deficit (E = precipitation minus discharge) and of the runoff ratio in the watersheds (Table 8). As expected, runoff deficit significantly increased in most cases, by more than 95% in the Agde, Beziers and Belvianes watersheds. Runoff ratio, on the other hand, mostly decreased. RR is generally negatively correlated with temperature and positively correlated with precipitation. For Puyvalador, Belvianes and Serdinya, the three mountainous watersheds with a significant decrease of the mean annual water discharge, temperature explains a greater variability of the observed RR changes than precipitation. This suggests that the decreasing capacity of these watersheds to produce runoff was rather related to enhanced evapotranspiration via increasing temperature than to the variability of precipitation.

An influence of temperature on discharge is also indicated by the trend analysis of the monthly discharge series (Table 6). Among the 180 individual series of all watersheds, 51 significant trends have been detected as negative and eight as positive. Most decreasing trends occurred in spring and summer. March, July and August have the greatest number of significant decreasing trends (eight, seven, and seven, respectively). These months were also characterised by the highest temperature increase (Table 4), without change in precipitation (Table 5). In winter and autumn, decreasing discharge trends are less abundant. Only for Laroque and Agde, high negative trends from January to March exist, but here also precipitation decreased during these months, which might be imprinted in the discharge records.

Our finding of decreasing discharge trends in the mountainous watersheds of the French Pyrenees are in good agreement with the results of López-Moreno et al. (2008), who studied the hydroclimatic evolution of Mediterranean watersheds on the Spanish side of the Pyrenees. This study also reports a significant discharge reduction in many watersheds during 1955–1995, which was attributed to an increase in potential evapotranspiration (derived from temperature and radiation data), a decrease in

Table 8 MK trend analyses and Spearman's rho correlation statistics for water balance (E = Precipitation − Discharge), runoff ratio (RR) and annual T and P

Watershed	E trend (%)	rho (E–T)	rho (E–P)	RR trend (%)	rho (RR–T)	rho (RR–P)
Laroque	**45**	0.39	**0.59**	−24	−0.43	**0.71**
Agde	98	–	–	**−53**	–	0.43
Vieussan	68	–	–	−18	–	**0.44**
Beziers	**160**	**0.44**	0.37	−73	−0.37	0.40
Puyvalador	21	–	**0.52**	**−25**	**−0.43**	–
Belvianes	**212**	**0.53**	–	**−39**	**−0.64**	0.39
Carcassonne	–	–	–	–	–	**0.75**
Moussan	24	–	**0.55**	–	–	**0.59**
Planezes	–	–	–	–	–	**0.77**
Estagel	–	–	**0.68**	–	–	**0.87**
Serdinya	–	–	0.33	−19	**−0.44**	0.32
Rodes	**75**	–	**0.52**	−42	**−0.54**	**0.63**
Perpignan	–	–	**0.48**	–	–	**0.80**
Reynes	**48**	0.23	–	−25	−0.29	**0.58**
Argeles	36	0.40	–	–	−0.42	0.43

All parameters have been calculated on the basis of the hydrological years (September to August). For further explanations and significance levels, see Table 4 precipitation during certain periods of the year (while annual precipitation remained unchanged), a negative trend in snow accumulation at high altitudes as well as to a re-growth of natural vegetation following the abandonment of farmland.

Puyvalador, Belvianes and Serdinya have average elevations above 1,000 m and are mostly covered by natural vegetation. They have an important snow cover during the cold season and it is likely that the hydrological trends relate to changes in snow accumulation. Lòpez-Moreno and Garcìa-Ruiz (2004) studied role of snow on discharge regime in Central Spanish Pyrenees. They found a significant negative trend in snow accumulation during winter for the second half of the twentieth century, with immediate consequences on discharge regimes. Both the annual average discharge and the relative importance of springtime high flows decreased. The few snow records we could find in the south-western part of our study region confirm that snowfall strongly decreased in the elevated regions of the Pyrenees, probably more than at lower altitudes (Fig. 13). Such a large decrease of snow cover could easily explain the abundant discharge decreasing trends for Puyvalador, Belvianes and Serdinya during the snowmelt period, which stretches from April to August in our study area (Table 6).

It is also remarkable that the general warming was clearly lower in the mountainous watersheds in the southwestern part of our study region than in the other watersheds (Section 3.2.1). In a study based on a greater station density in the Tet basin, Ludwig et al. (2004) also reported a much lower temperature increase in the upstream part of the Tet compared to the downstream part. They attributed this to the possibility of artefacts in the temperature records or to the existence of local microclimates. But the spatially consistent trend of a lower temperature increase revealed in our study is an argument against this and identifies the warming anom-

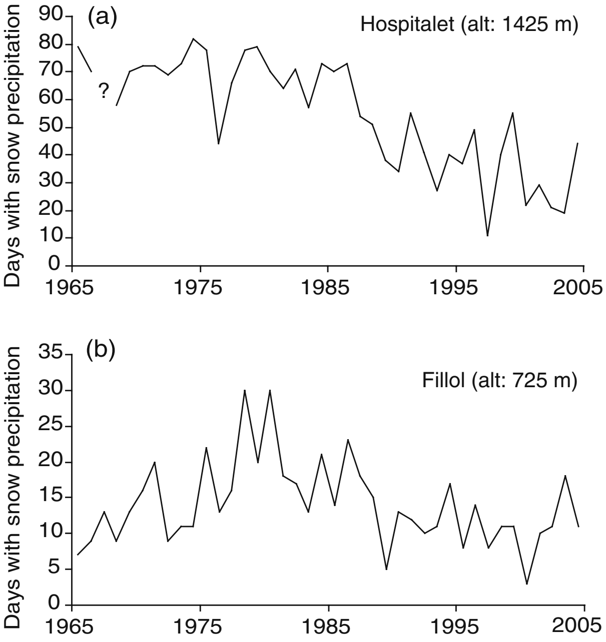

Fig. 13 Evolution of the number of days with snowfall at two meteorological stations in the Pyrenees: **a** Hospitalet at 1,425 m (W of the Serdinya watershed); **b** Fillol at 725 m (in the Rodes watershed). See Fig. 4 for precise location of both stations

alies as a regional pattern. Snowfall and permanent snow cover inhibit evaporation, but when temperature increase and snow turns to rain, water can infiltrate the soil and becomes available for subsequent evapotranspiration. The latter may strongly increase and the additional latent heat flux may even partly counterbalance the general warming through reduction of the sensible heat flux between the surface and atmosphere. Modelling and observation studies on the effect of irrigation on dry soils in California demonstrated that increasing soil humidity can have a strong negative feedback on surface air temperatures at larger spatial scales (e.g. Bonfils and Lobell 2007; Kueppers et al. 2008). Our data do not allow a general distinction between the evolutions of solid and liquid precipitation in all watersheds and further research is needed to follow the question whether the warming anomalies may relate to enhanced evapotranspiration. But it is worthy to note that the differences in the warming trends are mainly recorded during the cold season, when snowfall is frequent. During spring and summer, the anomalies are much less important and the warming occurred almost uniformly in the entire study region (not shown).

4.2.2 Lowland watersheds

The two lowland watersheds that recorded a significant decrease of the mean annual discharge are Beziers and Agde. Here, identification of the possible climatic controls on this decrease is less evident. In the former watershed, correlation coefficients in Table 6 show that T and P explain about the same RR variability and that E is significantly correlated with T. In the latter watershed, however, a clear influence of T on RR cannot be evidenced. Beziers and Agde have the lowest elevations and can be widely connected with the uppermost groundwater reservoirs (BRGM 2002; Petelet-Giraud and Negrel 2007). A full understanding of the detected discharge trends therefore also requires considering the evolution of minimum discharges. The latter were defined in our study as the lowest discharge values from the daily discharge series for each month or each year. MK tests show that significant decreasing trends for the monthly minimum discharges are abundant in many watersheds, with a clustering in spring and summer (Table 9). This is in agreement with the strong warming during these seasons and June, July and September show consequently the greatest number of negative trends (nine, eight and eight respectively). But on an annual scale, decreases of minimum discharge were clearly the most important in the Beziers and Adge watersheds, underlining their outstanding positions.

In rivers connected to groundwaters, a long term decrease of minimum discharge may reflect a general lowering of the groundwater levels. In the case of Beziers and Adge, such a lowering of groundwaters could directly result from the temperature increase. Indeed, strong warming during spring and summer leads more frequently to base flow conditions, a situation that can lead to depletion of the groundwater reservoirs. On the long term, groundwaters contribute less to the total river discharge and the average discharge decreases too. However, in the cases of the Beziers and Agde watersheds it not excluded that the mean annual discharge trends are the combined effect of precipitation and temperature. Negative precipitation trends were recorded in the upstream parts of the Orb and Herault rivers in January and February (Table 5). Winter precipitation can be particularly important for recharging groundwaters and their decrease may also have contributed to lower groundwater levels further downstream.

Table 9 Estimated significant changes of minimal daily discharge for 1965–2004 (in %)

Watershed	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Laroque	–	**−69**	**−56**	**−49**	–	**−53**	−38	−33	−44	–	–	–	–
Agde	–	**−71**	−70	**−50**	–	−58	**−64**	**−55**	**−64**	−59	–	–	**−77**
Vieussan	–	–	−30	–	–	–	–	−25	−44	−40	–	–	−30
Beziers	–	−45	−49	−46	−50	**−75**	**−86**	**−79**	**−87**	**−61**	−46	–	**−92**
Puyvalador	–	**85**	**65**	–	–	**−57**	**−63**	−37	–	–	–	–	105
Belvianes	**−56**	−39	−32	**−53**	−41	**−64**	**−40**	−19	−28	−28	**−50**	−45	−28
Carcassonne	–	–	–	**−58**	−46	**−58**	−47	–	**−58**	**−48**	**−52**	–	−48
Moussan	–	–	−39	–	–	−65	−46	–	–	–	–	–	–
Planezes	–	–	−54	−60	–	–	**214**	**1722**	187	–	–	−40	–
Estagel	–	–	–	−61	–	–	–	–	–	–	–	–	–
Serdinya	–	–	–	–	–	**−55**	−47	**−49**	**−76**	−27	–	–	**−42**
Rodes	–	–	–	–	–	−54	–	–	–	–	–	–	−34
Perpignan	–	–	–	–	–	–	–	–	–	–	–	–	–
Reynes	–	–	–	–	–	–	–	–	−34	–	–	–	–
Argeles	–	−37	–	–	–	–	–	–	–	–	–	–	–

For further explanations, see Table 4.

4.3 Anthropogenic controls on water resources

4.3.1 Land use changes

In their study on the mountainous watersheds on the Spanish side of the Pyrenees, López-Moreno et al. (2008) suggested that the reforestation is one of the major drivers leading to the general discharge decrease. Our data confirm that reforestation was a widespread phenomenon in our study area during the second half of the last century (see Section 3.2.4). But we found also the lowest reforestation rates in the high mountainous watersheds and in Beziers and Adge compared to the other watersheds (Fig. 10). This does not point to forest growth as being the major driver for the decline in the water resources in our study area, although it may have contributed to increasing evapotranspiration and/or to lowering of the groundwater levels in the downstream watersheds.

4.3.2 Damming

Among the reservoirs that can have a major impact on discharge regimes, only the Vinca and Caramany dams were constructed during the study period in the Rodes and Planezes watersheds, respectively (Tables 1 and 2). Both watersheds were not characterized by significant changes of their water resources. The former reservoir is generally filled in spring and summer and emptied in autumn, which can explain the positive discharge trend in September in the Perpignan watershed (Table 6). The Caramany dam, in the other hand, mainly supports discharge during summer. It is therefore not surprising that discharge significantly increased for the July to September months in the Planezes watershed. As dams generally contribute to better control water resource in both watersheds, they are also likely responsible for the lack of significant trends in their minimal discharges series too (Table 9).

4.3.3 Water extraction

Water extraction for irrigation remained more or less constant since the 1980s, except during the most recent years that depict an increase (Table 7). By far the greatest water extractions exist in the middle and lower watersheds in the Tet and Tech rivers where no significant changes in water resources was recorded. On the contrary, Perpignan is the only watershed where the mean annual discharge followed a significant positive trend, even if this may be considered with some caution as the specific discharge is negative (Table 3). This positive trend probably reflects a more efficient control of water use for irrigation after the Vinca dam construction in 1976, situated at the entrance of this watershed.

Of course, it has also to be mentioned that irrigation is not the only form of anthropogenic water consumption in our study region. A major unknown is the water consumption via uncontrolled pumping of groundwater for irrigation and other purposes, for which no data are available. This could have contributed to the lowering of the upper groundwater levels too, especially in the Agde and Beziers watersheds where the demographic pressures on the water resources increased (Montginoul et al. 2005). It is therefore not excluded that anthropogenic activities contributed at least partly to the observed decreases of water discharge in these watersheds.

5 Conclusions

The data collected and processed in our work allowed a detailed reconstruction of the hydroclimatic evolution in southern France during the last 40 years. As in many other parts of the world, temperature strongly increased since the late 1970s, likely one of the first clear sign of a human induced climate change (Trenberth et al. 2007). In this part of the Mediterranean drainage basin, the general warming trend was also strongly enhanced by changes in the atmospheric circulation patterns, characterized by a northward extension of the subtropical high pressure domain in spring and summer. During these seasons, monthly warming rates could achieve almost twice the mean annual warming rates. Annual precipitation, on the other hand, did not follow clear trends. Only in the northernmost watersheds winter precipitation significantly decreased, most likely as the result of a northward displacement of the westerly winds reflected by the positive trend of the North Atlantic Oscillation.

Our data reveal a strong climatic pressure on the water resources. About one third of the investigated watersheds recorded significant decreases in their mean annual water discharge. This concerns both the highest and lowest watersheds in the study region. In the former, the reduction of the water resources is likely to be related to a temperature induced switch of snowfall to rainfall at high altitudes, which can enhance water losses through evapotranspiration. Our results therefore confirm the findings of previous studies which demonstrated that river basins with important snow cover are particularly vulnerable to the risk of decreasing water resources (e.g. Etchevers et al. 2002; Caballero et al. 2007). The reduction of discharge in the lowland watersheds seems to be related to lower groundwater levels, which could have decreased their contribution to the surface flow. This may directly relate to the temperature increase, but decreases of winter precipitation in the upstream watersheds, anthropogenic water use and land use changes can be superimposed too. Although our study area is not very large in size (about 12,000 km^2), detection and understanding of the observed changes was only possible after decomposition of the six studied rivers into 15 watersheds. This has to be considered as an important result too, as it underlines the complex functioning and small scale differences that often characterizes the coastal river basins in Mediterranean context.

The observed hydroclimatic trends refer to the recent past and do not allow speculation about possible evolutions in the future. But most GCM climate simulations agree that the observed trends towards warmer temperatures in the northern Mediterranean will hold on during the forthcoming decades (Christensen et al. 2007), with the strongest warming rates during summer. This is different in northern Europe, where warming should mainly occur in winter. Many of the GCM models also predict a general precipitation decrease, which would have much more drastic consequences on the water resources than those already observed in this study. Reliable evaluation of this requires the availability of robust hydrological modelling tools, which have not only to be validated for steady state conditions, but which also need to demonstrate their abilities to reproduce the hydrological responses under changing climatic conditions in the past. Data sets as ours might be particularly suitable for the development and validation of such modelling tools.

Acknowledgements This study was undertaken as part of the long-term environmental observation program ORME (Observatoire Régional Méditerranéen de l'Environnement) and has been financially supported by the CNRS-EDD in the framework of the French Zone-Atelier network. We are especially grateful to Meteo-France for supply of the temperature and precipitation records in the framework of the Climatheque agreement between MF and UPVD. The two anonymous reviewers are acknowledged for their valuable comments on the previous versions of the manuscript.

References

Ab Razak IA, Christensen ER (2001) Water quality before and after deep tunnel operation in Milwaukee, Wisconsin. Wat Res Res 35:2683–2692

Agence de l'Eau RMC (2006) Bibliothèque de téléchargement de données sur l'eau du bassin Rhône-Méditerrannée. Available via DIALOG. http://sierm.eaurmc.fr/telechargement/index.php. Accessed 23 Jun 2006

Andréassian V (2004) Waters and forests: from historical controversy to scientific debate. J Hydrology 291:1–27

Bolle HJ (2003) Climate, climate variability and impacts in the Mediterranean area: an overview. In: Bolle HJ (ed) Mediterranean climate: variability and trends. Springer, Heidelberg

Bonfils C, Lobell D (2007) Empirical evidence for a recent slowdown in irrigation-induced cooling. Proc Nat Acad Sci 104(34):13582–13587. doi:10.173/pnas.0700144104

BRGM (2002) Projet Pactes—Module: contribution des eaux souterraines aux crues et inondations; site de l'Hérault. BRGM/RP-51718-FR

BRL (2007) Carte des ouvrages gérés par BRL et des territoires ou périmètres irrigués desservis. Available via DIALOG. http://www.brl.fr/References/LanguedocRoussillon.htm. Accessed 15 Nov 2007

Brohan P, Kennedy J, Harris I, Tett SFB, Jones PD (2006) Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. J Geophys Res 111:D12106. doi:10.1029/2005JD006548

Buishand TA (1984) Tests for detecting a shift in the mean of hydrological time series. J Hydrol 73:51–69

Caballero Y, Voirin-Morel S, Habets F, Noilhan J, LeMoigne P, Lehenaff A, Boone A (2007) Hydrological sensitivity of the Adour-Garonne river basin to climate change. Water Res Res 43:W07448. doi:10.1029/2005WR004192

Casty C, Handorf D, Raible CC, Gonzalez-Rouco JF, Weisheimer A, Xoplaki E, Luterbacher J, Dethloff K, Wanner H (2005) Recurrent climate winter regimes in reconstructed and modelled 500 hPa geopotential height fields over the North Atlantic/European sector 1659–1990. Clim Dyn 24:809–822

Casty C, Raible CC, Stocker TF, Wanner H, Luterbacher J (2007) A European pattern climatology 1766–2000. Clim Dyn 29:791–805

Chen J, Carlson BE, Del Genio AD (2002) Evidence for strenghtening of the tropical general circulation in the 1900's. Science 295:838–841

Christensen JH, Hewitson B, Busuioc A, Chen A, Gao X, Held I, Jones R, Kolli RK, Kwon WT, Laprise R, Magaña Rueda V, Mearns L, Menéndez CG, Räisänen J, Rinke A, Sarr A, Whetton P (2007) Regional climate projections. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (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

CORINE (1992) Soil erosion risk and important land resources in the southern regions of the European Community, Report EUR 13233. Office for Official Publications of the European Communities, Brussels

Creutin JD, Obled C (1982) Objective analysis and mapping techniques for rainfall fields: an objective comparison. Water Res Res 18:413–431

DIREN - Direction Régionale de l'Environnement (2004) Atlas des zones inondables du bassin versant de l'Orb: Méthode hydrogéomorphologique. Available via DIALOG. http://www.languedoc-roussillon.ecologie.gouv.fr/zi/hydrogeomorphologie/orb/rapport/caracteristiques_orb.pdf. Accessed 12 Dec 2005

Etchevers P, Golaz C, Habets F, Noilhan J (2002) Impact of a climate change on the Rhone River catchment hydrology. J Geophys Res 107(D16):4293. doi:10.1029/2001JD000490

European Commission and the European Soil Bureau Network (ECESBN) (2004) ESDB v2.0: the European soil database distribution version 2.0, CD-ROM, EUR 19945 EN. Available via DIALOG. http://eusoils.jrc.it/ESDB_Archive/ESDB_Data_Distribution/ESDB_data.html. Accessed 27 Dec 2006

Gibelin AL, Déqué M (2003) Anthropogenic climate change over the Mediterranean region simulated by a global variable resolution model. Clim Dyn 20:327–339

Giorgi F (2006) Climate change hot-spots. Geophys Res Lett 33:L08707. doi:10.1029/2006GL025734

Giorgi F, Lionello P (2007) Climate change projections for the Mediterranean region. Glob Planet Change 63:90–104. doi:10.1016/j.gloplacha.2007.09.005

Giorgi F, Bi X, Pal JS (2004a) Mean, interannual variability and trends in a regional climate change experiment over Europe. I. Present-day climate (1961–1990). Clim Dyn 22:733–756

Giorgi F, Bi X, Pal JS (2004b) Mean, interannual variability and trends in a regional climate change experiment over Europe. II: climate change scenarios (2071–2100). Clim Dyn 23:839–858

Goovaerts P (ed) (1997) Geostatistics for natural ressources evaluation. Oxford University Press, New York

Goovaerts P (2000) Geostatistical approachs for incorporating elevation into the spatial interpolation of rainfall. J Hydrol 228:113–129

Heino R (1997) Metadata and their role in homogenization. In: First seminar for homogenization of surface climatological data, Budapest, Hungary, Hungarian Meteorological Service, 5–8

Hellweger F (1997) AGREE-DEM Surface Reconditioning System. Available via DIALOG. http://www.ce.utexas.edu/prof/maidment/GISHYDRO/ferdi/research/agree/agree.html. Accessed 3 June 2004

Helsel DR, Hirsch RM (eds) (1992) Statistical methods in water resources, studies in environmental science 49. Elsevier, Amsterdam

Hisdal H, Stahl K, Tallaksen LM, Demuth S (2001) Have streamflow droughts in Europe become more severe or frequent? Int J Climat 21:317–333

Hubert P, Carbonnel JP, Chaouche A (1989) Segmentation des séries hydrométéorologiques. Application à des séries de précipitations et de débits de l'Afrique de l'Ouest. J Hydrol 110:349–367

Hurrell JW (1995) Decadal trends in the North Atlantic oscillation: regional temperatures and precipitation. Science 269:676–679

INSEE (2005) Recensement de la population 1999. Available via DIALOG. http://www.insee.fr/fr/insee_regions/languedoc/home/home_page.asp. Accessed 12 Dec 2005

Institut Français de l'Environnement (IFEN) (2007) Couverture d'occupation des sols Corine Land Cover. Available via DIALOG. http://www.ifen.fr/. Accessed 16 Jul 2007

Inventaire Forestier National (IFN) (2007) Résultats des inventaires départementaux (1998–2004). Available via DIALOG. http://www.ifn.fr/spip/. Accessed 2 May 2007

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo KC, Ropelewski C, Wang J, Leetmaa A, Reynolds R, Jenne R, Joseph D (1996) The NCEP/NCAR 40 year reanalysis project. Bull Am Meteorol Soc 77(3):437–472

Kendall MG (ed) (1975) Rank correlation measures. Charles Griffin, London

Kistler R, Kalnay E, Droegemeier (2001) The NCEP-NCAR 50-year Reanalysis: monthly means CD-ROM and documentation. Bull Am Meteorol Soc 82:247–267

Kueppers LM, Snyder MA, Sloan LC, Cayan D, Jin J, Kanamaru H, Kanamitsu M, Miller NL, Tyree M, Du H, Weare B (2008) Seasonal temperature responses to land-use change in the western United States. Glob Planet Change 60:250–264

Laborde JP (2000) Eléments d'hydrologie de surface. Avaialable via DIALOG. http://www.cig.ensmp.fr/~hydro/BIB/man.htm. Accessed 15 Mar 2006

Lee AFS, Heghinian SM (1977) A shift of the mean level in a sequence of independent normal random variables—a Bayesian approach. Technometrics 19(4):503–506

Lloyd CD (2005) Assessing the effect of integrating elevation data into the estimation of monthly precipitation in Great Britain. J Hydrol 308:128–150

Lòpez-Moreno JI, Garcìa-Ruiz JM (2004) Influence of snow accumulation and snowmelt on streamflow in the Central Spanish Pyrenees. Hydrol Sci J 49(5):787–802

López-Moreno JI, Beniston M, García-Ruiz JM (2008) Environmental change and water management in the Pyrenees: facts and future perspectives for Mediterranean mountains. Glob Planet Change 61:300–312

Ludwig W, Serrat P, Cesmat L, Garcia-Esteves J (2004) Evaluating the impact of the recent temperature increase on the hydrology of the Têt River (Southern France). J Hydrol 289:204–221

Luterbacher J, Xoplaki E, Casty C, Wanner H, Pauling A, Küttel M, Rutishauser T, Brönnimann S, Fischer E, Fleitman D, Gonzàles-Rouco FJ, Garcìa-Herrera R, Barriendos M, Rodrigo F, Gonzales-Hidalgo JC, Saz MA, Gimeno L, Ribera P, Brunet M, Paeth H, Rimbu N, Felis T, Jacobeit J, Dünkeloh A, Zorita E, Guiot J, Türkes M, Alcoforado MJ, Trigo R, Wheeler D, Tett S, Mann ME, Touchan R, Shindell DT, Silenzi S, Montagna P, Camuffo D, Mariotti A, Nanni T, Brunetti M, Maugeri M, Zerefos C, De Zolt S, Lionello P, Nunes MF, Rath V, Beltrami H, Garnier E, Le Roy Ladurie E (2006) Mediterranean climate variability over the last centuries. A review. In: Lionello P, Malanotte-Rizzoli P, Boscolo R (eds) Mediterranean climate variability. Elsevier, Amsterdam, pp 27–148

Maidment D, Djokic D (eds) (2000) Hydrologic and hydraulic modelling support with geographic information systems. ESRI, Redlands

Mann HB (1945) Non-parametric tests against trend. Econometrica 13:245–259

Mariotti A, Struglia MV (2002) The hydrological cycle in the Mediterranean region and implications for the water budget of the Mediterranean Sea. J Climate 15:1674–1690

Mestre O (eds) (2000) Méthodes statistiques pour l'homogénéisation de longues séries climatiques. Thesis, University of Paul-Sabatier, Toulouse

Milliman JD (2001) Delivery and fate of fluvial water and sediment to the sea: a marine geologist's view of European rivers. Sci Mar 65(2):121–132

Milly PCD, Dunne KA, Vecchia AV (2005) Global Pattern of trends in streamflow water availability in a changing climate. Nature 438:347–350

Moisselin JM, Schneider M, Canellas C, Mestre O (2002) Les changements climatiques en France au XX^{e} siècle. La Météorologie 38:45–56

Montginoul M, Rinaudo JD, Lunet de Lajonquiere Y, Garin P, Marchal JP (2005) Simulating the impact of water pricing on households behaviour: the temptation of using untreated water. Water Policy 7:523–541

Norrant C, Douguédroit A (2005) Monthly and daily precipitation trends in the Mediterranean (1950–2000). Theor Apll Clim 83(1–4):89–106. doi:10.1007/s00704-005-0163-y

Petelet-Giraud E, Negrel P (2007) Geochemical flood deconvolution in a Mediterranean catchment (Hérault, France) by Sr isotopes, major and trace elements. J Hydrology 337:224–241, doi:10.1016/j.jhydrol.2007.01.037

Pettitt AN (1979) A non-parametric approach to the change-point problem. Appl Stat 28(2):126–135

Rambal S (1987) Evolution de l'occupation des terres et ressources en eau en régions méditerranéennes karstiques. J Hydrology 93:339–357

Ruf T (2001) Droits d'eau et institutions dans les Pyrénées-Orientales. Histoire et Sociétés Rurales 16:11–44

Salvaire H, Teisseire-Dufour P (eds) (2002) La spéléologie catalane dans un siècle de spéléologie pyrénéenne. Trabucaire

Trenberth KE, Jones PD, Ambenje P, Bojariu R, Easterling D, Klein Tank A, Parker D, Rahimzadeh F, Renwick JA, Rusticucci M, Soden B, Zhai P (2007) Observations: surface and atmospheric climate change. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (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

Trewartha GT (1943) Köppen's classification of climates. In: McGraw M (ed) An introduction to weather and climate. Pearson, New York

USGS (2000) GTOPO30: A global 30 arc-second elevation data set. Developed at the US Geological Survey EROS Data Centre. Available via DIALOG. http://edcdaac.usgs.gov/gtopo30/gtopo30.html. Accessed 17 June 2004

Vicente-Serrano S, Lòpez-Moreno JI (2006) Influence of atmospheric circulation at different spatial scales on winter drought variability through a semiarid climatic gradient in Northeast Spain. Int J Clim 26(11):1427–1453

Wanner H, Brönnimann S, Casty C, Gyalistras D, Luterbacher J, Schmutz C, Stephenson DB, Xoplaki E (2001) North-Atlantic oscillation—concepts and studies. Survey in Geophys 22: 321–381

Westmacott JR, Burn DH (1997) Climate change effects on the hydrologic regime within the Churchill-Nelson River Basin. J Hydrol 225:67–91

World Meteorological Organisation (WMO) (2000) Detecting trend and other changes in hydrological data, WCDMP-45, WMO /TD 1013

Xoplaki E, Gonzalez-Rouco JF, Gyalistras D, Luterbacher J, Rickli R, Wanner H (2003a) Interannual summer air temperature variability over Greece and its connection to the large-scale atmospheric circulation and Mediterranean SSTs 1950–1999. Clim Dyn 20:523–536. doi:10.1007/s00382-002-0291-3

Xoplaki E, Gonzalez-Rouco JF, Luterbacher J, Wanner H (2003b) Mediterranean summer air temperature variability and its connection to the large-scale atmospheric circulation and SSTs. Clim Dyn 20:723–739. doi:10.1007/s00382-003-0304-x

Xoplaki E, Gonzalez-Rouco JF, Luterbacher J, Wanner H (2004) Wet season Mediterranean precipitation variability: influence of large-scale dynamics and trends. Clim Dyn 23:63–78

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