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IMPACTS OF CLIMATE AND LAND USE CHANGE ON HISTORICAL STREAMFLOW IN THREE HEADWATERS IN CATALONIA (NE SPAIN)

Eduard Pla[*], Gabriel Borràs[**], Diana Pascual[*], Robert Savé[***], Sergio Vicente-Serrano[****], Javier Zabalza[****]

[*]*CREAF* eduard.pla@uab.cat, d.pascual@creaf.uab.cat
[**]*OCCC Oficina Catalana del Canvi Climàtic* gborras@gencat.cat
[***]*IRTA Institut de Recerca i Tecnologia Agroalimentàries* robert.save@irta.cat
[****]*IPE-CSIC Instituto Pirenaico de Ecología* svicen@ipe.csic.es, jzabalza@ipe.csic.es

Water resources vulnerability under changing environment at a regional scale has been a relevant topic in the Mediterranean region in recent years, due to the high sensitivity of water to climate conditions and land use transformation. This is especially critical in areas with high water demands as a consequence of the increase of irrigated lands and urban consumptions, as is the case of the Iberian Peninsula. In this work, the headwaters of three river basins in Catalonia (Segre, Ter and Muga) were selected as case studies. These headwaters are located in the Eastern part of the Pyrenees with a progressive gradient of Mediterranean conditions among them. Streamflow and climate trends of the three headwaters were gathered for the period 1950-2013 to identify impacts of the climatic changes on the hydrological trends. In parallel, land use changes were assessed comparing land use and land cover maps between 1970 and 2005. A general growth of natural vegetation, as a consequence of crops and pastures abandonment has been reported. The observed decrease of precipitation and mainly the increase of the atmospheric water demand has affected streamflow evolution in the three basins. The streamflow records in the last five decades show a clear negative trend in the three analysed headwaters. Nevertheless, there are noticeable spatial differences that may be related to other subjacent changes. In Segre headwaters streamflow reduction is mostly explained by climate change. This pattern partially appears in Ter headwaters. However, in Muga headwaters, the decrease in water resources has been more important than that expected by the observed climate evolution. This work explores the causes of these spatial differences and relates them to the different historical land use and land use changes and to the Mediterranean conditions influence. The understanding of these subjacent processes are crucial to face global change impacts in the Mediterranean region, especially when negative evolution of water resources is expected to be accentuated in the future as a consequence of climate change projections.

Key words: streamflow, climate change, land use change, forest, Mediterranean

1. Introduction

Climate processes have a direct influence on the availability of water resources. Current climate change is affecting water resources availability in the Mediterranean basin (García-Ruiz et al. 2011, Vicente-Serrrano et al. 2014). In addition, these processes converge with current land cover changes and human water management, which may accentuate the decrease in river flows, groundwater and reservoir storages (Bates et al. 2008, Mariotti et al. 2008, Vicente-Serrano et al. 2016). Future climate and land cover scenarios for the Iberian Peninsula suggest higher water stress as a consequence of precipitation decrease and increased atmospheric water demand driven by temperature (Pascual et al. 2015).

In parallel, the role of Mediterranean mountain areas in water resource availability is highly relevant. The whole Mediterranean basin is mainly dependent on runoff from mountain areas which, in this context, can represent 50–90% of the total supply (García-Ruiz et al. 2011). In Iberian mountains like the Pyrenees, a general abandonment of agriculture, together with a reduced human pressure on forest and pastures, has favoured the expansion of the forested area (Grove and Rackham, 2001, Hill et al. 2008). In fact, the effects of forest expansion is suggested as one of the main factors driving the reduction in runoff in headwaters of the Iberian Peninsula (Begueria et al. 2006, Gallart and Llorens 2004, Morán-Tejeda et al. 2010).

Understanding the role of land use and land use changes on the hydrological response of river basins and their runoff trends has been of major interest during the last decades in eco-hydrology (Jiang et al. 2015). In this work we have studied the recent evolution of climate and streamflows in the past five decades in the headwaters of three river basins in Catalonia (Segre, Ter and Muga). These headwaters are located in the Eastern part of the Pyrenees with a progressive gradient of Mediterranean conditions among them, different land use arrangements and a different intensity of historical land cover changes. We first use trend analysis to identify changes in climate variables and surface runoff. The divergence between observed and expected streamflow considering climate conditions were attributed to land cover changes. Using different hydrological indicators, land use change trends and the Budyko curve (Budyko 1974), we have explored the causes of the spatial differences among the headwaters and we have related them to the land use, the land use change and the influence of the different Mediterranean conditions. The understanding of these subjacent processes is crucial to face global change impacts in the Mediterranean region, especially when negative evolution of water resources is expected to be accentuated in the future (Pascual et al. 2015). Challenges will be faced in maintaining the quantity and quality of mountain runoff, through preservation of mountain environments, while ensuring sustainable use of the available water resources (Messerli et al. 2004)

2. Study area

The three study headwaters in Segre, Ter and Muga river basins (Catalonia, north-eastern Spain, figure 1) are located in the Eastern Pyrenees. These three river basin headwaters represent a climatic gradient from most high-altitude Pyrenean conditions of Segre catchment and Ter, to the most coastal conditions of the Muga headwaters. The headwaters delimitation in each river basin correspond to the upstream part of the river basin, previous to the large dams built in the middle reaches. In this work, we selected the sub basins which drain to the following gauging stations (fig. 1): la Seu d'Urgell and Organyà (Segre), Roda de Ter (Ter) and Boadella (Muga). They represent respectively a 28%, 70% and 25% of the whole river basin surfaces. Segre and, to a greater extent Ter headwaters, have small reservoirs for hydropower uses. The headwaters of these river basins have distinct surface area (3724 km^2 for Segre, 2105 km^2 for Ter and 184 km^2 for Muga). Altitudes rise from 500 to 2900 m.a.s.l. in Segre and Ter headwaters. In contrast, Muga elevation ranges from 100 to 1500 m.a.s.l. The precipitation ranges from 700 to 1200 in Segre and Ter headwaters. The amount of snow precipitation in winter season is especially relevant in Segre headwaters, followed by Ter. Muga headwaters represents the most coastal environmental conditions, with a precipitation range from 700 to 1000 mm, with little importance of snow precipitation.

According to the Land Cover Map of Catalonia (LCMC 2005) Segre headwaters is dominated by forests (60%), with a substantial surface area also devoted to pastures (16%), shrublands (12%) and crops (7%). Ter headwaters is also dominated by forests (60%), with a 20% of pastures, 10% of crops and 8% of shrublands. Finally, Muga is the most highly forested headwaters (92% of forests), with other marginal land uses (3% of shrublands and 2% of crops).

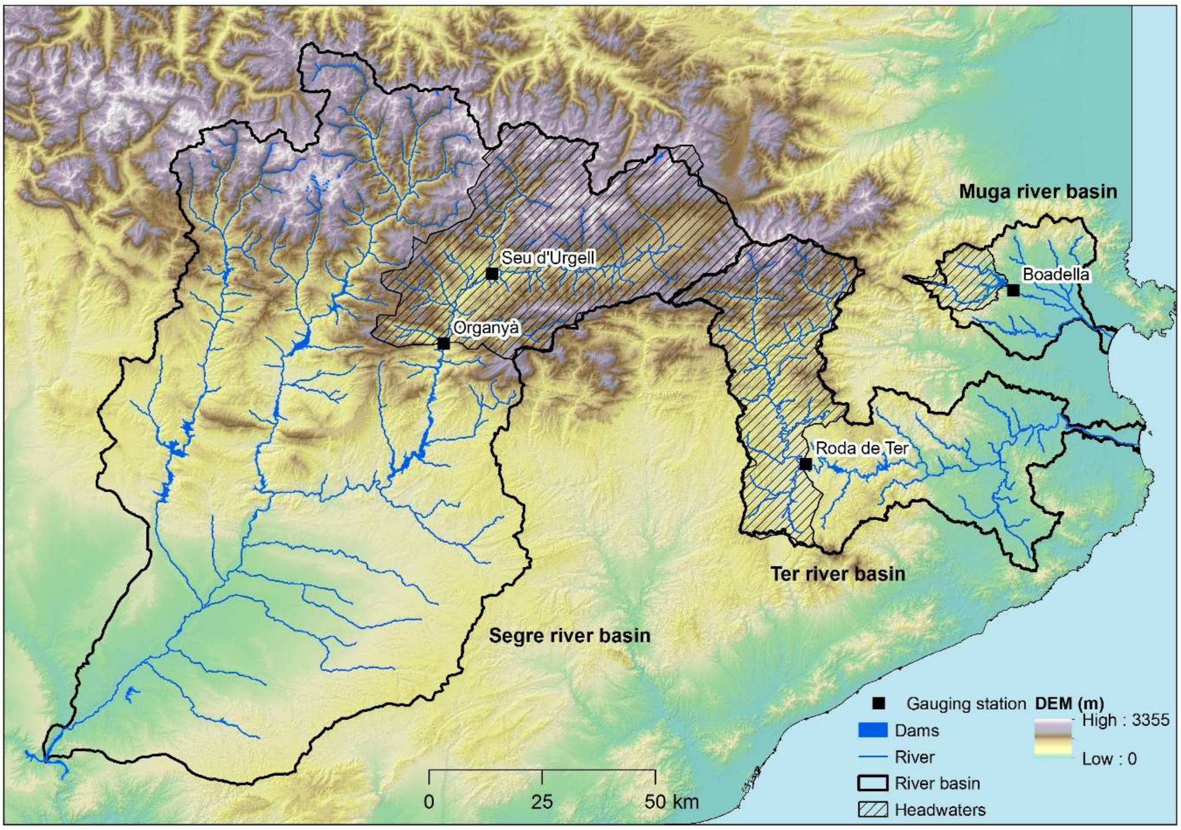

Figure 1. Map of the selected river basins in this work. The selected headwaters correspond to the striped area upstream of the gauging stations shown.

3. Materials and methods

We have used precipitation and temperature data series from the complete historical meteorological network maintained by the Spanish and Catalan meteorological agencies. We have focused on the period 1960-2013. Daily meteorological records were carefully reconstructed, quality controlled and homogenised.

Using Tmax- and Tmin-gridded layers, we calculated the Potential Evapotranspiration (ETo) and the evaporative demand (AED) using the equation of Hargreaves and Samani (1985), which only requires information on temperature and extra-terrestrial solar radiation.

In the three river basins, daily streamflow records from gauging stations were also available and provided by the Catalan Water Agency (ACA) and the Ebro River Basin Management Authority (CHE). We analysed trends in climate and hydrological series and the connection of these trends with land cover changes using different statistical techniques. To determine changes in the dependence of streamflow on climate variability, we calculated the annual runoff coefficients (ratio between streamflow and precipitation, using hydrological years, from October to September). This allows the determination of possible changes in the relationship between precipitation and streamflow during the studied period. Through this analysis, Actual Evapotranspiration (ETa) can be estimated at river basin scale.

Next, we created monthly statistical linear models between regional climatic variables and streamflow based on a regression analysis. The use of linear relationships offered a very simple framework with the possibility of interpreting the residuals of the model as the unknown element in the water balance approach and the possibility of studying the changing relationship between the variables through time. We performed a stepwise multiple linear regression model between the climatic (precipitation and ETo) (independent variables) and streamflow (dependent variable) in each sub basin. The models provided streamflow predictions only based on the observed evolution of the climate variables used. The percentage of change in predicted streamflow, based on climate changes between 1951 and 2013, was compared with observed streamflow change.

We also applied the Budyko approach (Budyko 1974) in order to assess what are the main factors that control water balance in the headwaters. This holistic approach assumes that the equilibrium water balance is controlled by water availability and atmospheric demand. The water availability can be estimated by precipitation, the atmospheric demand represents the maximum possible evapotranspiration and is often associated with potential evapotranspiration. According to Budyko framework, the ratio of potential evaporation to precipitation ETo/P (also called climatic dryness index) identifies the main factor controlling river basin evaporation, where if ETo/P < 1 the evaporation is limited by energy supply, and if ETo/P > 1 the evaporation is limited by water supply.

Finally, in order to assess the main land use changes in these headwaters, we compared through GIS techniques the first available land cover map in the region representative of land conditions in the decade of 1970 (using the Crop and Land Use Map of Spain MCA 1970) with the official 2005 land cover map (LCMC 2005).

4. Results and discussion

The streamflow records in the last five decades show a general clear negative trend in the three analysed headwaters, which range in average from -25% to -50%, being the Muga headwaters the most affected by this decrease (figure 2). The observed changes in climate, in particular the decrease of precipitation and mainly the increase of the atmospheric water demand, has affected streamflow evolution in the three basins.

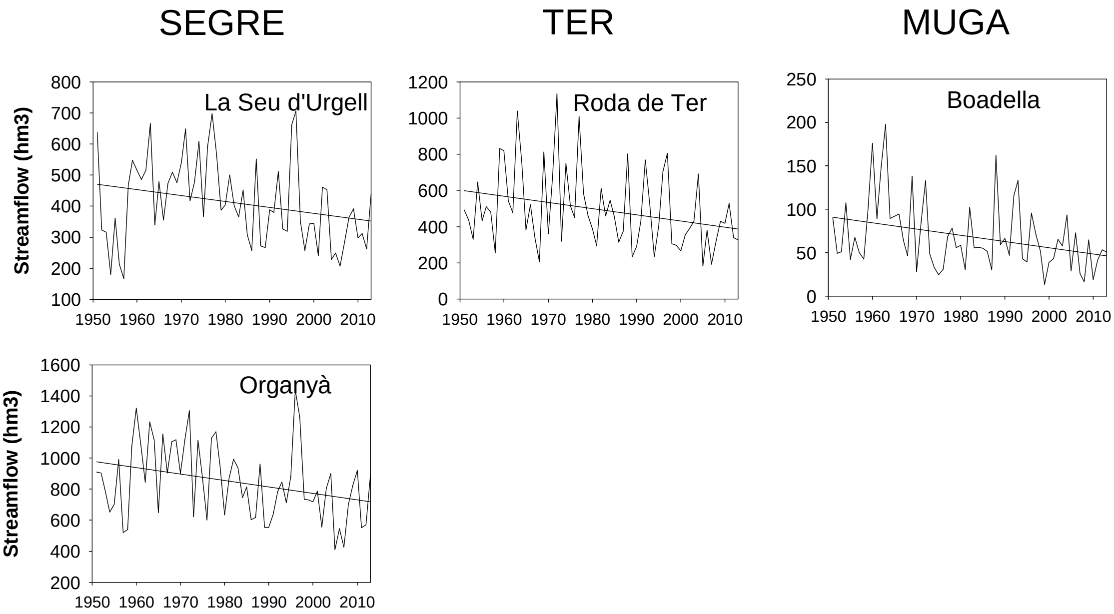

Figure 2. Streamflow (hm^3) trends observed in the gauging stations of the selected headwaters

The decrease in water streamflow can be almost totally explained by climate evolution in Segre headwaters. In Ter headwaters, using Roda de Ter gauging station, the same trend could be confirmed. On the contrary, in Muga headwaters, the observed streamflow decrease is clearly more important than could be expected by the observed climate evolution. The change in the runoff coefficient confirms these first trends, showing a significant decrease of this indicator in Muga and, to a lesser extent, in Roda de Ter gauging station (table 1).

Table 1. Changes in observed streamflows, expected streamflows according to climate evolution and runoff coefficient of the analysed hydro-climatic series.

	% change in observed streamflow	% change in streamflow expected by climate evolution	% change in runoff coefficient (Q/P)
Segre headwaters			
Organyà	-26.4	-28.0	-3.9
La Seu d'Urgell	-25.1	-28.1	-2.7
Ter headwaters			
Roda de Ter	-35.3	-38.8	-17.2
Muga headwaters			
Boadella	-49.0	-30.7	-41.3

The representation of these gauging stations using the Budyko framework (figure 3) displays the main differences in the drivers controlling the water balance in each headwater.

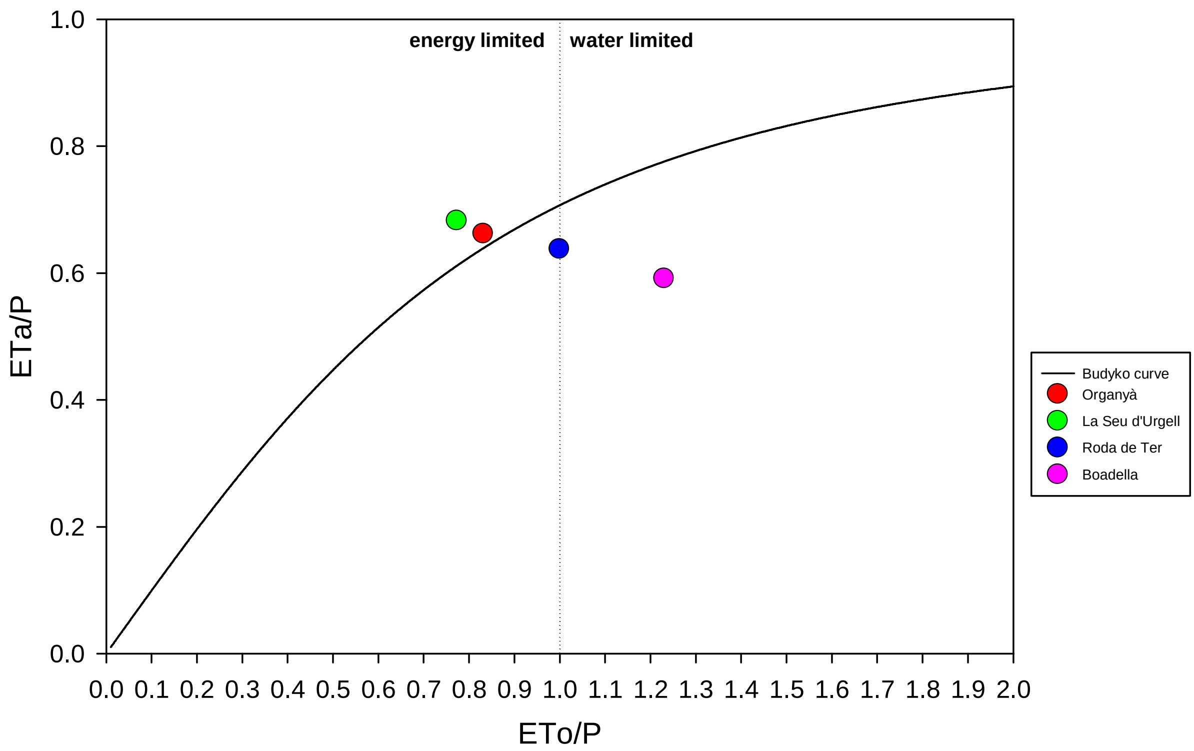

Figure 3. Budyko curve and position of each selected gauging stations for the whole period analysed.

There is a group of sub basins mainly energy-limited (la Seu d'Urgell and Organyà) which are the stations with less influence of the Mediterranean conditions but with a clear influence of Pyrenean high-altitudinal conditions. On the other hand, Boadella, which is the most coastal gauging station, is a clearly water limited sub basin. Roda de Ter shows an intermediate position also related with its geographical and altitudinal position. The changes in y-axis, related to the ratio Eta and P, can be explained by other headwaters processes like land use structure and land use changes during the analysed period.

When we analyze the single temporal evolution in the Budyko curve of the Boadella gauging station (figure 4), we confirm a progressive amplification of the water-limitation of this headwaters in recent periods, with more aridity and water stress.

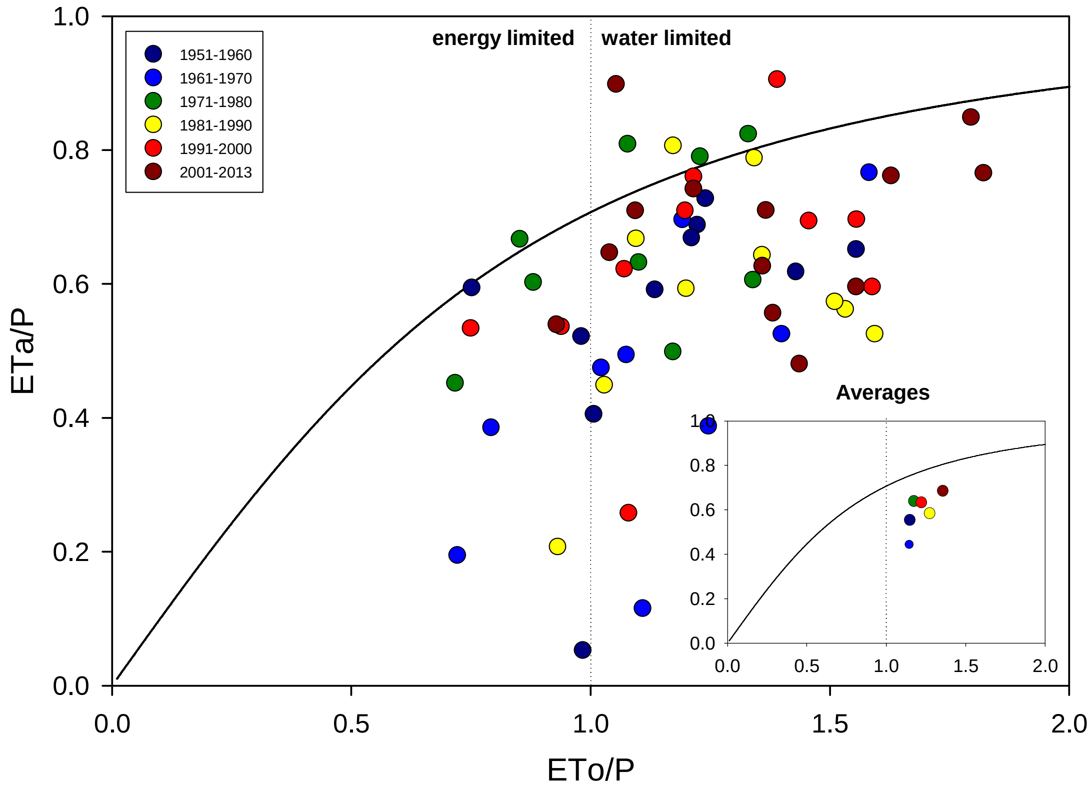

Figure 4. Budyko curve and temporal position for Boadella gauging station, annually and for time-slice.

Related to land use changes (figure 5), we have observed an increase of natural vegetation surface growth, as a consequence of rural land abandonment, in the headwaters of the three basins in the period 1970-2005. This trend is clearly remarkable in the Muga headwater (with a 20% of forest increment in what already was a forested headwaters in 1970, at the expense of shrubland area loss). Segre and Ter headwaters show a similar trend: the forest increment is over 10-12% with an important loss of pastures (-10 to -15%). The initial land use structure of the selected headwaters linked to the intensity of land use changes (especially afforestation) is one of the subjacent processes which explains the spatial differences among headwaters streamflow decrease. This process can be synergically amplified when the headwaters water balance is water-limited according to Budyko framework.

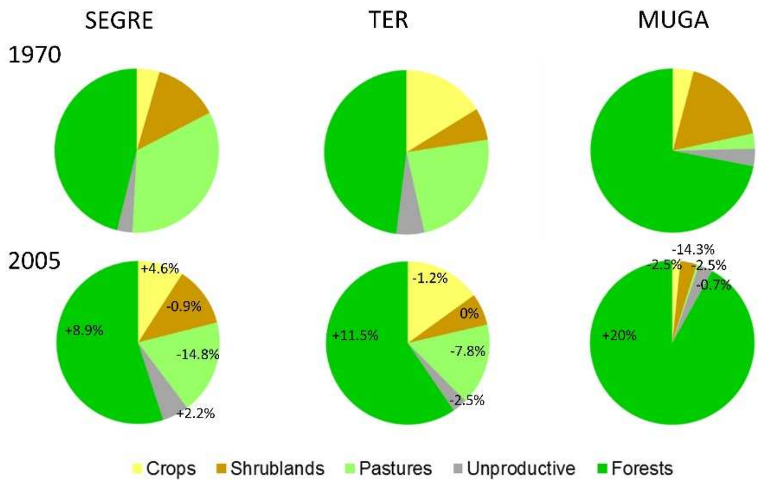

Figure 5. Land use and land use changes in the selected headwaters according to the comparison between the Crop and Land Use Map of Spain (MCA 1970) and the Land Cover Map of Catalonia (LCMC 2005)

5. Conclusion

We have shown that the evolution of water resources in three river headwaters located in the Catalan Pyrenees (NE Spain) have clearly decreased in the last five decades as a consequence of the combined influence of climate evolution and land cover changes. The three headwaters describe a gradient of Mediterranean influence: Segre and Ter show a greater Pyrenean high-altitudinal conditions influence than Muga, which is the most coastal headwater.

The most Mediterranean headwaters (Muga) has suffered the most relevant streamflow decrease (-48.96%), -30.65% explained by climate evolution and -18.31% explained by other subjacent factors. In addition, a decrease in the runoff coefficient (-41.25%) has been reported for the same period.

In 1970’s decade, the Segre and Ter headwaters had similar land use structure (50% of forest) and similar expansion of forest land (10-12%) together with a remarkable reduction of pastures (-15%) have been reported during the last four decades. Muga headwaters had 70% of forest area at the end of the 60’s and an increment of 20% of forests has been reported for the same four-decade period. These differences in forest area and forest area increase in the last decades could explain why the observed reductions in streamflow in Muga headwater are not only related to the climate evolution but also to the land use structure and land use changes.

We conclude that the Muga is the most clearly water-limited headwaters of the ones analysed, showing a consistent Mediterranean gradient (distance to sea). These environmental constraints amplifies the effect of land use structure and land use changes on streamflow evolution.

The understanding of these subjacent processes are crucial to face global change impacts in the Mediterranean region, especially when negative evolution of water resources is expected to be accentuated in the future as a consequence of the climate change projections.

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