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Reference


DOI : 10.1016/j.gloplacha.2007.10.004

Available at:
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Environmental change and water management in the Pyrenees: Facts and future perspectives for Mediterranean mountains

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Received 21 May 2007; accepted 16 October 2007
Available online 1 November 2007

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This paper analyses the effect of environmental changes observed in the 20th century on hydrology and water management in the southern Pyrenees, in terms of land use and climate. Moreover, a projected water-resource scenario for the 21st century is presented and discussed. Our results demonstrate that changes in precipitation, temperature, and snow accumulation, together with an increase in vegetation density in headwater regions, have led to a marked reduction in water availability in the region. Water resource managers have introduced major changes to dam operations to meet increasing water demand for irrigation purposes in lowland areas. Climatic and land-cover scenarios for the next century indicate that the sustainability of the equilibrium between available resources and water demand will be seriously threatened. These changes predicted for the Pyrenees may be representative of the changes that will occur within many other Mediterranean mountain sectors with similar climatic and socio-economic conditions.

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Keywords: climate change; land-use change; water resources; Mediterranean mountains; Pyrenees

1. Introduction

Mountains are the main source of water for many of the world’s rivers (Viviroli et al., 2003), particularly in Mediterranean and semi-arid environments where mountains behave as “islands” of humidity and rivers in lowland areas represent “oases” that contrast sharply with deforested and intensively eroded hillslopes. It is important to note that in the northern sector of the Mediterranean region there is a strong contrast between the location of humid areas (in the mountains) and sectors of human activity such as irrigated agriculture, industry, tourism, and population centres (in lowland and coastal areas). This means that extensive efforts are required to ensure a supply of water to irrigated areas and urban settlements via reservoirs and a complex network of canals. In addition, the Mediterranean climate is extremely irregular, with long, intense dry periods (Vicente-Serrano, 2006) and catastrophic floods (White et al., 1997; Beguería and Vicente-Serrano, 2006) that occur in such a manner that water is relatively scarce throughout much of the year, yet high flows threaten lives and property for a small number of days per year or even days per decade when flooding occurs. These problems mean that water-resource management is a key issue for land management in the Mediterranean region (López-Moreno et al., 2004).

The strong dependence of mountain water resources on climate fluctuations and land-cover characteristics means that environmental change directly affects the total amount and temporal distribution of stream flow, and hence has major implications for water management. It is well known that Mediterranean mountains have been strongly affected by environmental change and shifts in land-cover patterns. Since the beginning of the 20th century, and particularly since the 1960s, most of the cultivated areas in the Pyrenees have been abandoned, becoming replaced by dense shrubs and young forests (Vicente-Serrano et al., 2004) that have led to an increase in evapotranspiration. This process is considered to explain the continuous decrease in stream flow recorded within Pyrenean rivers since the middle of the last century (Beguería et al., 2006) and the associated impacts on water availability (Beniston et al., 1998) and hydromorphological conditions (Benito et al., 2005; Marzol et al., 2006).
Climate change has also been detected in the Pyrenees, particularly in terms of snowfall and snow accumulation (López-Moreno, 2005); this has had immediate consequences for springtime high flows (López-Moreno and García-Ruiz, 2004). These changes in snow accumulation and snowmelt affect patterns of reservoir management (López-Moreno et al., 2004) and most likely the quantity of water available in summer. If temperature in the future increases by between 2 and 4 °C, as projected by several climate-change models, we are likely to see a decrease in discharge of between 4 and 21% (Frederick, 1997) and declining mean annual water storage and power production. The main problem, among others, is that water planning and management in the past was based upon the assumption that future trends in climate, land cover, and water resources would be similar to those of the past. Another important problem is that the most strategic Pyrenean reservoirs are affected by siltation processes that progressively reduce their storage capacity.

Given the above, the current situation is characterised by (i) increasing water demand for agricultural and urban purposes, coinciding with (ii) changes in fluvial regimes, particularly in the annual average discharge and declining importance of springtime high flows; (iii) a dependence on large reservoirs that are becoming increasingly unsustainable due to siltation processes; and (iv) the impossibility of enlarging the actual storage capacity due to problems in finding new sites in which to site reservoirs and the existence of social and political barriers to the conventional policy of linking water management with the construction of reservoirs.

The main objective of this paper is to study the consequences of environmental changes for the availability of water and to ultimately relate these changes to recent changes in patterns of water-resource management. To achieve these goals, we study the temporal evolution of stream flow and the effects of these trends on water-management practices. Finally, a projected water-resource scenario is developed for upcoming decades, taking into account climate-change models and predicted changes in land cover.

2. The study area: physical characteristics and importance for water-resources management

The study area includes the southern slopes of the Pyrenees (Spanish side), and is bounded by the Atlantic Ocean to the west and the Mediterranean Sea to the east (Fig. 1). Altitude within the area ranges from 300 m to more than 3000 m above sea level (a.s.l.), with a highly contrasting relief. The climate in this region is subject to Atlantic and Mediterranean influences and the effect of macrorelief on precipitation and temperature. In the Central Ebro Depression, the average annual precipitation is approximately 300 mm and the average annual temperature ranges from 13 to 15 °C. In the mountains, annual precipitation exceeds 600 mm and sometimes reaches 2000 mm at the highest divides. The Foehn effect is frequently observed in the area, acting to enhance the difference in precipitation between the northern and southern slopes, as well as leading to higher temperatures upon southern slopes. Most of the annual precipitation falls during the cold season in the Atlantic areas and during spring and autumn in the Mediterranean regions. Summers are generally relatively dry in the Pyrenees, especially so in the Ebro Depression. The annual 0 °C isotherm is located at 2726 m a.s.l. (Del Barrio et al., 1990), and above 1600 m a.s.l. most of the precipitation falls as snow during the cold season (November–May).

The humid conditions of the Pyrenees is in stark contrast to the dry characteristics of large areas of the Ebro River Valley, emphasizing the importance of hydrology and water resources throughout the study region. For example, Pyrenean headwaters occupy 12% of the surface of the Ebro Valley, but generate 46.2% of the total runoff (López-Moreno, 2006). The relative abundance of water in the area led to the construction of numerous dams to...
regulate the main rivers. Most of the dams were built between the 1950s and the 1980s, leading to an increase in storage capacity from 50,000,000 to 300,000,000 m$^3$; this represents approximately one half of the mean annual runoff of Pyrenean rivers. This capacity enables the diversion of 1947 hm$^3$ yr$^{-1}$ to irrigate 295,748 ha of land (77% of the irrigated area of the Ebro Basin) and the generation of 62% of the hydropower produced in the region (López-Moreno, 2006).

Until the middle of the 20th century, most of the south-facing slopes below 1600 m a.s.l. were cultivated. The main hydrological and geomorphological consequences of this cultivation were an intensification of soil erosion processes and an increase in the torrential nature of fluvial channels (García Ruiz and Velro Garces, 1998). For this reason, most of the rivers are braided, with unstable channels. Since this time, the abandonment of farmland related to depopulation has been the most important feature of the Spanish Pyrenees. By 1970, all of the fields upon hillslopes had been abandoned. These areas were then recolonized by shrubs, and induced reforestation took hold in many areas that were previously cultivated and grazed. In summary, 22% of the total area of the Central Spanish Pyrenees consists of abandoned fields. At present, this area is occupied by forests (65%), shrubs (28%), and grazing meadows (7%).

3. Data and methods

3.1. Hydrological and climatic information

Daily precipitation and discharge data were obtained from 18 weather and 18 gauging stations along unregulated river sectors. Both variables show a reasonable spatial coverage of the study area (Fig. 1). For analysed reservoirs, information on water outflow (discharge downstream of the dam and water released to irrigation canals) and water stored in the reservoirs was provided by the Ebro River Hydrographic Administration. Where direct measurements of inflow were unavailable, they were estimated from the difference between outflow and the daily variation in stored water volume.

Snow depth at the end of April is obtained every year from 106 snow poles placed in the area in 1985 as part of the ERHIN program (Estimation of Winter Hydrological Water Resources program). The snow-depth time series showed a strong correlation with precipitation recorded between January and April and with April temperature.

These strong correlations enabled the reconstruction of a time series for spring snowpack between 1950 and 1999 (López-Moreno, 2005).

Gaps in the precipitation time series (less than 20% of the full record) were filled by means of linear regression with neighbouring stations. Gaps in the discharge time series were filled using the SACRAMENTO model from the Ebro River Hydrographic Administration (www.chebro.es), which shows good agreement with observed data (López-Moreno, 2006).

The quality and homogeneity of the time series were checked: anomalous records were identified and removed using a quartile-based range statistic (González-Rouco et al., 2001). Inhomogeneities in the time series were detected and subsequently removed according to the Standard Normal Homogeneity Test against an independent reference series (Alexandersson, 1986; Peterson et al., 1998).

Precipitation, evapotranspiration (see Section 3.2 below), and discharge time series were transformed into three-yearly regional indices. The regional index was defined as the normalized average of the normalized variables, and was developed in three steps: 1) normalization of the original annual time series by subtracting the mean and dividing by the standard deviation of the entire period (1950–1999); 2) calculation of the annual average for each variable; and 3) normalization of the averaged time series. The result is a synthetic index expressed in z-scores that summarize regional anomalies above or below the average (Borra daile, 2003), thereby enabling comparison of the three climatic and hydrologic variables.

3.2. Calculation of potential evapotranspiration

Climatic water balances for the region were obtained by subtracting potential evapotranspiration (PET) from precipitation. A number of different methods can be used to calculate PET (Allen et al., 1998). In recent decades, the International Commission for Irrigation (ICID), the Food and Agriculture Organization of the United Nations (FAO), and the American Society of Civil Engineers (ASCE) have adopted the physically based Penman–Monteith (PM) method (Allen et al., 1998) as the standard method to compute PET from climate data. The main drawback of this method is that PM demands a relatively large number of climatic parameters. In the Pyrenees, long-term records of relative humidity, wind speed, and solar radiation are almost non-existent, meaning that the use of the PM method as a regional approach is not feasible.

Several authors consider the empirical Hargreaves (HG) equation (Hargreaves and Samani, 1985) to be the best alternative under conditions of data scarcity (Xu and Singh, 2001; Droogers and Allen, 2002). This method only requires information on maximum and minimum temperature and extraterrestrial radiation (Droogers and Allen, 2002). On a monthly and annual basis, PET estimates obtained using HG and PM are very similar, differing by less than +/-2 mm day$^{-1}$ at a global scale (Droogers and Allen, 2002). In fact, across all of Eurasia the difference in the annual averages of PET daily estimates obtained using HG and PM are very similar, differing by less than +/-2 mm day$^{-1}$ at a global scale (Droogers and Allen, 2002).

The HG equation is an empirical one, it has provided good accuracy under contrasting climatic conditions in terms of temperature and precipitation (Hargreaves and Allen, 2003). This track record indicates that this is a reasonable approach for estimation of PET under a future greenhouse climate. The HG method is based on the following equation (Hargreaves, 1985):

$$ET_o = 0.0023 \cdot R_a \cdot TD^{0.5} \cdot (Tm + 17.8)$$

where PET is the daily reference evapotranspiration (monthly average; to obtain the monthly total, the result must be multiplied by the number of days in the month), $TD$ is the difference between the maximum and minimum temperatures in
°C (monthly averages), \( T_m \) is the average monthly temperature, and \( R_o \) is the extraterrestrial radiation in mm day\(^{-1}\), obtained by multiplying the \( R_o \) units in MJ m\(^{-2}\) day\(^{-1}\) by 0.408.

A climatic water balance (CWB) was obtained by the subtraction of potential evapotranspiration (PET) to precipitation (P). At an annual basis, it can be assumed that differences in the snowpack and the soil and subsoil storages are negligible, so the CWB can be considered as an approximation to the water available to be converted into runoff. An implicit assumption of the CWB is that the annual amount of water consumed by the plant cover and human activities remains constant (Beguería et al., 2003).

### 3.3. Creation of regional series and data analysis

Precipitation, evapotranspiration and discharge time series were transformed into three-yearly regional indices. The regional index was defined as the normalized average of the normalized variables, and was developed in three steps: 1) normalization of the original annual time series by subtracting the mean and dividing by the standard deviation of the entire period (1950–1999); 2) calculation of the annual average for each variable; and 3) normalization of the averaged time series. The result is a synthetic index expressed in z-scores that summarize regional anomalies above or below the average (Borradaile, 2003), thereby enabling comparison of the three climatic and hydrologic variables.

A predicted series for regional anomalies of annual discharge was obtained by applying a linear regression technique using the annual CWB as an independent variable. Thus, changes in the role of plant cover or human water uptake on river discharges could be inferred from the trends exhibited by the residuals (i.e., the difference between predicted and observed discharge anomalies), as they imply an alteration in the relationship between climate and runoff throughout the study area.

Temporal evolution in the different variables was tested against linear trends from 1950 to 1999 using the Spearman’s rank correlation statistical test. This particular statistical approach was chosen amongst other options to find significant trends in the series, because it is less affected by the presence of outliers and the fact that a series may not necessarily be normally distributed (Lanzante, 1996). The comparison between monthly trends in series of climate variables and runoff also helped to explain the impact of non climatic factors, such as the re-colonization of land by vegetation. In other cases, averages values of two consecutive periods (1950–1974 and 1975–1999) were compared to illustrate changes in hydrology and those related to dam operations in the last decades. Similarly, the average of reservoir inflows, outflows and water storage were computed for periods of low, medium and high snow accumulation. This procedure enabled to assess the effect of the interannual variability of snow accumulation in headwaters on reservoir management strategies.

### 3.4. Estimates of climate change for the Pyrenees

Information on predicted climate change was obtained from the outputs of precipitation and temperature from several Regional Climate Models (RCMs) developed by institutions collaborating in the PRUDENCE project (http://prudence.dmi.dk). The present study used data from the following models: HIRHAM: Danish Meteorological Institute (DMI); HIRHAM: Norwegian Meteorological Institute (METNO); HADCM3: Hadley Center (HC); RCAO: Swedish Meteorological and Hydrological Institute (SMHI); REGCM: International Center for Theoretical Physics (ICTP); and PROMES: Complutense University of Madrid (UCM), all of which were driven by the GCM HadAM3H for the European continent. Expected climatic change is provided for two contrasting greenhouse-gas-emission scenarios based on different hypotheses of economy and population trends into the future. A2 is characterised by much higher emissions of greenhouse gases than B2 (IPCC, 2001). In most cases, information provided in this work is referred to the A2 scenario. The resolution of these RCMs was close to 50 km (grid spacing of 0.44–0.5°).

Estimates of climate change were obtained by subtracting the layers of the control runs (1961–1990) from the predicted future climate (2070–2100). Results shown here correspond to an ensemble of the six employed RCMs. Validation of data provided by RCM outputs using observed temperature and precipitation for the control period in Pyrenees revealed the existence of biases below 1°C for temperature and 20% for precipitation (López-Moreno et al., in press). These accuracy levels are in line with those of other studies carried out for the European continent (Giorgi et al., 2004; Dequé et al., 2005).

### 4. Results

#### 4.1. Observed changes in Pyrenean discharge: trends in relation to climatic evolution

Fig. 2 shows the interannual evolution of river discharge observed at 16 Pyrenean gauging stations between 1950 and 2000. A similar pattern is observed for the overall records: cyclic behaviour at scales of 15–20 years, but with a statistically significant negative long-term trend.

The regional time series for climatic variables for the 1955–1995 period depicts a tendency for the Pyrenean climate toward a lower capacity of runoff generation. Table 1 shows that precipitation (P) has a negative and statistically significant trend (\( \alpha<0.05 \)) in February, March, and June, remaining near stationary for the rest of the year. Annual precipitation exhibits a statistically insignificant negative trend. Potential evapotranspiration (PET) shows significant increases in February, March, and June, July, and August, as well as for mean annual values. The combination of P and PET reveals a statistically significant (\( \alpha<0.05 \)) negative trend for the climatic water balance (CWB) for February and March, and insignificant negative coefficients from June to September. A significant (\( \alpha<0.05 \)) negative trend is found for annual data, suggesting a reduction in runoff generation capacity in the Pyrenees due to climatic causes.

Fig. 3 shows changes in the hydrological response of Pyrenean headwaters to climate over recent decades. This figure shows the predicted annual variability of the regional time series of discharge obtained from linear regression using the annual CWB as an independent variable. Predicted and observed time series show a
high agreement ($r^2 = 0.7$), but the predictions are generally underestimates during the first few decades and overestimates in more recent years. Thus, the residuals of the model exhibit a marked negative trend, revealing a tendency toward progressively reduced runoff generation under given climatic conditions. The growth of vegetation following the abandonment of farmland in the study area is the only factor capable of explaining the detected change in the hydrological response of the Pyrenees.

A comparison of the monthly trends of regional discharge and CWB reveals noticeable differences in the magnitude of change in each variable (Fig. 4). Thus, discharge exhibits negative coefficients for every month except December, with statistically significant values obtained for winter, spring, and summer; however, CWB is only significant, with lower coefficients than discharge, during fewer months of winter and summer. For some months, CWB remains stationary or even exhibits non-significant positive coefficients. The effect of the expansion of plant cover on runoff generation and changes in snow accumulation might potentially explain the discrepancy in the observed monthly trends of climate and discharge.

Fig. 5 shows the synthetic time series of snow accumulation in April from 1950 to 1999 (López-Moreno, 2005). The evolution of the time series suggests the following: i) marked

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Trends (Spearman’s rho) of regional series of climatic variables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P$</td>
</tr>
<tr>
<td>January</td>
<td>$-0.03$</td>
</tr>
<tr>
<td>February</td>
<td>$-0.36$</td>
</tr>
<tr>
<td>March</td>
<td>$-0.39$</td>
</tr>
<tr>
<td>April</td>
<td>0.13</td>
</tr>
<tr>
<td>May</td>
<td>0.08</td>
</tr>
<tr>
<td>June</td>
<td>$-0.34$</td>
</tr>
<tr>
<td>July</td>
<td>$-0.05$</td>
</tr>
<tr>
<td>August</td>
<td>$-0.11$</td>
</tr>
<tr>
<td>September</td>
<td>$-0.02$</td>
</tr>
<tr>
<td>October</td>
<td>0.08</td>
</tr>
<tr>
<td>November</td>
<td>0.03</td>
</tr>
<tr>
<td>December</td>
<td>$-0.1$</td>
</tr>
<tr>
<td>Annual</td>
<td>$-0.18$</td>
</tr>
</tbody>
</table>

* Trends are statistically significant ($\alpha < 0.05$).
interannual variability; and ii) the existence of a significant negative trend, with the maximum concentration of years above the 75th centile at the beginning of the time series and a concentration of years below the 25th centile in recent decades.

4.2. Impacts of hydrological changes on water-resources management

Fig. 6 shows monthly average inflows into different Pyrenean reservoirs for the periods 1959–1979 and 1980–1999. Given the results presented in Section 4.1, a reduction in the amount of water flowing into reservoirs is not surprising. The reduced inflow is recorded in most months of the year, but is specially marked in spring. Moreover, for the four analysed cases the timing of maximum inflow has shifted from June to May.

Table 2 lists temporal trends of the amount of water diverted to irrigation canals and outflow released downstream the dams of the three main reservoirs that supply water for agriculture. The results provide a good example of how water demand is increasing in the region, showing positive and significant coefficients for water diverted to canals despite the observed progressive reduction in water availability. Downstream of the dams, the negative trends in the discharge of the Aragón, Ésera and Cinca rivers are more marked than those recorded under unregulated conditions (upstream sectors). On an annual basis, Fig. 7 depicts how reservoir management leads to dramatically declining river flows in comparison with the evolution of the unregulated discharges shown in Fig. 2. Thus, the need to meet greater demand under a more restrictive water-availability framework is achieved strongly reducing discharge in the downstream river.

The important role of snow accumulation in terms of water management strategies is apparent from Fig. 8, which shows the inflows, stored water, and water released downstream from the Yesa and Barazona dams in winter and spring. The figure also
shows the amount of water diverted to the respective irrigation canals in spring and summer. Average monthly values of snow accumulation were calculated for years of high, medium, and low snow accumulation in April. The different levels of snow accumulation were classified according to the centile-based classification scheme shown in Fig. 5. Inflows for years assigned to Group 1 (>75th centile) are clearly higher than those for years assigned to Groups 2 and 3. The differences between Group 2 (between the 25th and 75th centiles) and Group 3 (<25th centile) are moderate during spring and winter; however, stored water reaches similar levels for the three groups of years, enabling the diversion of similar volumes of water for irrigation purposes regardless of the amount of accumulated snow. The maintenance of the same water supply under different snow-
accretion conditions is achieved by strong control of the amount of outflow released to the Aragón and Ésera rivers, with outflow reduced when accumulated snow has been low.

4.3. Predicted scenarios in the Pyrenees for relevant hydrological variables

RCMs provide valuable information for predicting the conditions of the key variables related to the availability of water resources in the 21st century. Fig. 9 shows the mean expected change (average of six RCMs) in annual CWB under the A2 scenario. According to the RCMs, CWB will decline across the entire study area. The magnitude of the decrease will range from 100 to 400 mm, with the effect being strongest in the highest sectors of the Central Pyrenees. Fig. 9 also shows the area where CWB was positive (precipitation exceeds potential evapotranspiration) during the control period (1960–1990) and in the future scenario (2070–2100). Positive CWB sectors can be considered as the most favourable areas for runoff generation. A strong correlation is observed between positive areas during the control period and those sectors with the most generation. A strong correlation is observed between positive areas during the control period and those sectors with the most generation. A strong correlation is observed between positive areas during the control period and those sectors with the most generation.

5. Discussion and conclusions

The Pyrenees, as most Mediterranean mountains, has been subjected to pronounced environmental change that can be summarized as follows.

i) Farmland has been abandoned as a consequence of migration to urban settlements in lowland areas, resulting in a reduction in the area under cultivation in the Pyrenees from 30 to 2% of the total area (Molinillo et al., 1997; Vicente-Serrano et al., 2004; Lasanta et al., 2005). This process of abandonment led to an increase in plant-cover density, commonly accelerated by reforestation activities carried out to mitigate the effects of torrential floods within rivers and ravines and to reduce the siltation of reservoirs within the valley bottoms (Ortígosa et al., 1990).

ii) Changes are recorded in climatic variables related to runoff generation, such as precipitation (P), potential evaporation (PET), climatic water balance (CWB), and snow accumulation.

The sum of the changes in climate and land use have led to a reduction in river discharge, forcing water managers to adjust operation schemes for reservoirs. This paper details the magnitude of the effects of environmental change that occurred in the second half of the 20th century in terms of water availability and water management. The results highlight the risk of a likely amplification of past trends when forced by a greenhouse climate.

The obtained results reveal that climate trends are leading to more restrictive conditions for runoff generation due to an increase in PET and a decrease in P during certain periods of the year, as well as a negative trend in snow accumulation at high altitudes; however, the trend in discharge shows a steeper gradient than that for CWB, suggesting the key role of plant regeneration in abandoned agricultural areas.

The increasing importance of interception and transpiration has been described in previous studies. Beguería et al. (2003 and 2006) reported decreasing stream flow in the Central Spanish Pyrenees, regardless of climatic oscillations, between 1945 and 1995. Similarly, a reduction in sedimentation rates has been observed within large reservoirs in recent decades. A clear reduction in sediment sources has also been detected, as well as the partial stabilization of fluvial channels and alluvial fans (Beguería et al., 2006). Furthermore, although rainfall amount did not change over the last 50 years at the level of the 90th percentile, in the case of floods a clear and statistically significant
Fig. 7. Annual outflow released downstream of the Yesa (A), Barasona (B), and El Grado (C) reservoirs.
negative trend was observed (López-Moreno et al., 2006). This result indicates that although the effect of vegetation cover on very intense rainfall events appears to be limited (Niehoff et al., 2002; De Roo et al., 2003), vegetation cover may noticeably reduce the frequency and intensity of floods during moderate events, corresponding to those events with a return period of about 1 year. Similar conclusions were reported by Gallart and Llorens (2003) in a study of the entire Ebro Basin, northeastern
Spain. Many other studies have obtained similar results for other parts of the world (e.g., Andréassian, 2004).

This study also revealed that the hydrological changes are already noticeably affecting inflows into the Pyrenean reservoirs in two ways: i) a reduction in the annual incoming water volume; and ii) changes in the seasonal distribution of inflow, with a reduction in spring discharge and the earlier occurrence of the annual maximum monthly flow. The latter changes are closely related to the negative trend of snow accumulation in the Pyrenees associated with recent shifts in atmospheric circulation over the Iberian Peninsula (López-Moreno, 2005; López-Moreno and Serrano-Vicente, 2006). This is very important because snowmelt is the main source of spring runoff, and it determines the main characteristics of the Pyrenean river regimens (López-Moreno and García-Ruiz, 2004).

At the same time, water demand in the region is increasing, especially that for agricultural purposes in the lowlands. Several irrigation areas have been enlarged, and crops with high water requirements have been introduced to meet consumer demand and to combat saline soil (Causapé et al., 2004).

Water managers have adapted dam operations to satisfy the increasing water requirements. Using the Yesa reservoir as a case study, López-Moreno et al. (2004) showed how the target of Mediterranean reservoirs is to reach maximum storage volume at the end of spring, when the main irrigation period begins, so that irrigation can continue until the end of summer. To achieve this objective regardless of annual water availability, the patterns of downstream release are modified. Thus, in years with scarce water, the managers of the Yesa reservoir: i) drastically reduce outflow to the rivers in order to increase storage levels; and ii) end the irrigation season with a storage level lower than the long-term average, making it more difficult to fill the reservoir in the following year.

This paper reveals that a similar strategy, based on a dramatic reduction in the amount of water released downstream the dams, is adopted in other reservoirs of the Central Pyrenees to address the problem of the progressive reduction of Pyrenean discharge. During the driest years, outflows are extremely low in the channels downstream of reservoirs, corresponding to the release of the minimum ecological flow for most of the year. This confirms the fact that maintaining a water supply adequate to meet current demand would be seriously jeopardized if current trends of climate, plant cover, and discharge continue into the future.

RCMs for the 21st century predict adverse conditions for runoff generation. An ensemble of RCMs for the Pyrenees predicts mean increases in annual temperature of 2.8 °C and 4 °C for the B2 and A2 scenarios, respectively, which greatly exceeds the 0.9 °C increase observed in the Pyrenees during the 20th century (Bucher and Dessens, 1991). Precipitation is predicted to decrease by an average of 10% and 15% in the B2...
and A2 scenarios, respectively, although the uncertainties involved in predictions of precipitation mean that these estimates must be considered with caution.

According to the predicted changes described in this work, the tendency of the climatic water balance will be clearly negative. The most favourable sectors for runoff generation are expected to be those most strongly affected by climate change. CWB can only be considered as an approach to runoff generation, as the increase in evapotranspiration is offset by the availability of water from vegetation (actual evapotranspiration).

In any case, the results shown here point toward a continuation or even an acceleration of the current decrease in Pyrenean discharge as a consequence of climate change.

The RCMs also predict a reduction in the hydrological significance of snow in the study region during the 21st century. Predicted wintertime warming exceeds 2.5 °C in the highest sectors under the A2 scenario, meaning that the 0 °C isotherm will rise by more than 400 m, assuming a lapse rate of 0.6 °C/100 m. This will result in a sharp reduction in the area of snow accumulation during winter, a likely amplification of the observed tendency toward less water during spring, and a shift toward earlier maximum flows.

The results presented in this paper indicate future problems in maintaining current water supply to lowland areas around the Pyrenees. In fact, the adjustments already introduced into reservoir management strategies are approaching unsustainable levels and are clearly inadequate in terms of possible future trends of water availability and demand.

The capacity of mankind to reverse climate change at short- to medium-term timescales has yet to be demonstrated; however, an appropriate understanding of the importance of land management for water-resource availability could optimize the availability of water resources. This is an important matter because the process of revegetation of abandoned farmland and overgrazed areas is far from complete. Moreover, forests are able to spread as a consequence of the abandonment of subalpine summer pastures, and a warming climate will lead to an upward shift in the upper limit of forests (Essery, 1998; Beniston, 2003).

The management of land cover with the aim of improving the availability of water resources is a complex task, as the goal is to obtain higher runoff coefficients while maintaining slope stability, ensuring low erosion rates, reducing reservoir siltation, and mitigating the risks associated with flood events (López-Moreno et al., 2006; López-Moreno, 2006; Beguería et al., 2006). In addition, any adaptation to the predicted trends in water resources will need to consider certain factors that currently receive little attention, including the generalized implementation of water-saving practices and technologies, appropriate water pricing for different uses, and the careful selection of economic activities for the future, based on those less dependent on an abundant supply of water.

Acknowledgments

This study was supported by the projects PROBASE: CGL2006-11619 and CANOA: CGL 2004-04919-c02-01, both financed by the Spanish Commission of Science and Technology (Ministry of Education and Science) and FEDER. Research undertaken by the first author was supported by a postdoctoral fellowship from the Spanish Ministry of Education and Science.

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