Impact of climate and land use change on water availability and reservoir management: Scenarios in the Upper Aragón River, Spanish Pyrenees

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HIGHLIGHTS
• First simulation of combined land cover and climate change in the hydrology of the Pyrenees
• First simulation of management of a Pyrenean reservoir under for future scenarios
• Deep hydrological changes are projected for the next future in the Pyrenees.
• Expected difficulties to supply water demand under obtained projections

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ABSTRACT
Streamflows in a Mediterranean mountain basin in the central Spanish Pyrenees were projected under various climate and land use change scenarios. Streamflow series projected for 2021–2050 were used to simulate the management of the Yesa reservoir, which is critical to the downstream supply of irrigation and domestic water. Streamflows were simulated using the Regional Hydro-Ecologic Simulation System (RHESSys). The results show that increased forest cover in the basin could decrease annual streamflow by 16%, mainly in early spring, summer and autumn. Regional climate models (RCMs) project a trend of warming and drying in the basin for the period 2021–2050, which will cause a 13.8% decrease in annual streamflow, mainly in late spring and summer. The combined effects of forest regeneration and climate change are expected to reduce annual streamflows by 29.6%, with marked decreases affecting all months with the exception of January and February, when the decline will be moderate. Under these streamflow reduction scenarios it is expected that it will be difficult for the Yesa reservoir to meet the current water demand, based on its current storage capacity (476 hm3). If the current project to enlarge the reservoir to a capacity of 1059 hm3 is completed, the potential to apply multi-annual streamflow management, which will increase the feasibility of maintaining the current water supply. However, under future climate and land cover scenarios, reservoir storage will rarely exceed half of the expected capacity, and the river flows downstream of the reservoir is projected to be dramatically reduced.

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1. Introduction

Mediterranean mountains yield a large proportion of runoff at the basin scale, and are key to ensuring water supply to downstream lowland areas (Viviroli et al., 2007; García-Ruiz et al., 2011). The need to optimize the management of water generated in headwaters has led to the construction of numerous dams to enable synchronization of the timing of runoff production and water demand. The Spanish Pyrenees is a good example of this process, as the headwaters involved produce most of the surface water resources in the Ebro basin (Batalla et al., 2004; López and Justribo, 2010; López-Moreno et al., 2011), and they are regulated by many medium and large reservoirs to ensure the water supply for agriculture, hydropower production, industry, tourism and domestic uses in the semiarid lowlands of the basin (García-Vera, 2013). In this area the reservoirs generally store water from autumn to mid spring, and release water to downstream areas and irrigation channels in late spring and summer, when water demand is higher (López-Moreno et al., 2004, 2008). Exceptions to this management regime are those dams that are also devoted to hydropower production, as these exhibit a double period of water release in winter and summer, coinciding with peaks of energy demand (López-Moreno and García-Ruiz, 2004).
Scientists and water managers have observed with concern an almost generalized decline in the runoff and water yield from Mediterranean rivers in recent decades (García-Ruiz et al., 2011, and references therein). Two explanations proposed for this trend are a shift in climatic conditions and changes in land cover because of land use changes. An increase in temperature, generally between 1 and 2 °C, has been observed in the region since the beginning of the 20th century (Brunetti et al., 2004; Alpert et al., 2008), and in association with an increase in the evaporative demand by the atmosphere, may have caused a decrease in runoff (Lespinas et al., 2010; Liuzzo et al., 2010). A decrease in precipitation has also been identified as a cause of reduced runoff in many Mediterranean basins (García-Ruiz et al., 2011). Thus, the magnitude of the decrease in precipitation is amplified in the magnitude of decrease in runoff (Ashoffeh et al., 2013). For example, Zhang et al. (2009) quantified a 15–25% decrease in runoff of the Yellow River as a consequence of a 10% decrease in precipitation. Voudris et al. (2012) estimated that a decrease of <20% in precipitation in Crete would lead to a 29–32% reduction in runoff. In mountainous areas the increased temperature has also caused a decrease in snow accumulation in mid and high altitude sites, which has often been amplified by negative trends in winter precipitation. The result is an earlier onset of snowmelt and a decrease in the spring peak flows, with a consequent earlier start to the water deficit period (López-Moreno and García-Ruiz, 2004; Senatore et al., 2010). Land use change has also been identified as one of the major environmental impacts in the Mediterranean headwaters in recent decades. In the European Mediterranean mountains the most characteristic change has been a dramatic increase in the area covered by shrubs and forest, which has occurred as a consequence of land abandonment (García-Ruiz and Lana-Renault, 2011).

The Pyrenees is an outstanding example of the environmental changes noted above (López-Moreno et al., 2008). In the last five decades, temperature has increased between 1 and 2 °C (El Kenawy et al., 2012) and winter precipitation has decreased around 10% (López-Moreno et al., 2011), leading to a decrease in snow accumulation in winter and spring (López-Moreno, 2005). In addition, almost 90% of the agricultural land in the mountains was abandoned in recent decades, and natural revegetation has been accelerated by systematic afforestation works aimed at preventing erosion in highly degraded headwaters (Lasanta, 1988; López-Moreno et al., 2008). The result has been a significant decrease in river discharges (Beguería et al., 2003; Gallart and Llorens, 2003; López-Moreno et al., 2008) and runoff coefficients (Lasanta et al., 2000; García-Ruiz et al., 2008; López-Moreno et al., 2011), which have forced reservoir managers to reduce outflows downstream of dams throughout most of the year. This has enabled the maintenance of (or in some cases an increase in) the amount of water diverted to irrigation channels and hydropower production (López-Moreno et al., 2004).

The future sustainability of water demand in the region is uncertain, as the Mediterranean area has been identified as one of the areas worldwide most affected by climate change (Giorgi, 2006; Nogués-Bravo et al., 2008), and where runoff is expected to undergo a sharper decline (Milly et al., 2005; Nohara et al., 2006). Climate change is expected to have substantial effects on the hydrological cycle in the Pyrenees (Majone et al., 2012; García-Vera, 2013). The observed revegetation process is far from complete, as many abandoned fields have not yet been colonized by forests, and an increase in temperature together with a decrease in livestock pressure may lead to an increase in the forest cover in the subalpine belt.

Although it is well known that climate and land use change interact in the evolution of runoff generation, both factors are generally studied separately (Tong et al., 2012). Thus, there are no reported studies that have considered future water availability in the Pyrenees under a combination of projected trends in land cover and climatic conditions.

In this study, streamflows in the Upper Aragón River basin were simulated using the Regional Hydro-Ecologic Simulation System (RHESSys) under the climatic and land cover conditions recorded in recent decades, and using a set of climatic and land cover scenarios predicted for the future. The selected case study is of particular interest as the basin drains to the Yesa reservoir, which is one of the most important in the Pyrenees because it supplies water for irrigation to the second largest irrigated area in the Ebro basin, and more recently for domestic use in Zaragoza, which is the largest city of the Ebro basin (700,000 inhabitants). López-Moreno et al. (2004) showed that the decrease in runoff that has occurred in the upper Aragón basin since 1960 has led to a dramatic reduction in outflows downstream of the Yesa reservoir, affecting its capacity to satisfy the demand for irrigation water. It has also been shown that if similar trends continue it may not be possible to satisfy the current levels of water demand. For this reason the Ebro River Administration Authority (Confederación Hidrográfica del Ebro – CHE) has commenced work to enlarge the Yesa dam, with the aim of more than doubling the current storage capacity of the reservoir. Thus, the second objective of this study was to simulate the management of the Yesa reservoir based on its current capacity (479 hm³) and its projected capacity (1079 hm³) under various climate and land cover change scenarios. This will aid assessment of whether future water demand in the region can be met under changing environmental conditions.

2. Study area

The Upper Aragón River basin has an area of 2181 km² (Fig. 1). The highest altitudes occur in the north of the basin (Collarada Peak, 2886 m). The Aragón River flows north–south across the Paleozoic area (limestone, shale and clay), the Inner Sierras (limestone and sandstone) and the flysch sector, then enters the Inner Depression (marls) and flows westward.

The average annual precipitation exceeds 1500 mm in the northernmost sector of the basin, and is approximately 800 mm in the Inner Depression. The rainiest seasons are spring and autumn, although precipitation in winter is also substantial. Summer is generally dry, with isolated rainstorm events caused by convective processes. The mean annual temperature of the basin is 10 °C, and it increases from north to south as a consequence of the decrease in altitude to the south. At altitudes exceeding 1500 m a.s.l. snow cover is generally continuous from December to April, and lasts longer in the higher altitude areas of the basin (López-Moreno and García-Ruiz, 2004). River regimes reflect the distribution of the climatic characteristics, and the accumulation and melting of the snowpack. Long-term annual mean runoff is 915 hm³. Winter flow is low as a consequence of the retention of precipitation as snow and ice, while the annual peak flow occurs in spring, coinciding with the annual peak rainfall and melting of the snowpack. The minimum river flows occur in summer, but increase with the onset of autumn precipitation. The differences between winter low flows and spring peak flows tend to diminish as the river reached the lower lying areas of the basin, and hence snow covers a smaller percentage of the drained area (López-Moreno and García-Ruiz, 2004).

Vegetation cover has been strongly impacted by human activities. Historically, cultivated areas have been located below 1600 m a.s.l., in the valley bottoms, perched flats and steep, south-facing hillslopes, which were managed even under shifting agriculture systems (Lasanta, 1988). Forests (Pinus sylvestris, Pinus uncinata, Fagus sylvatica, etc.) remain relatively well preserved on the northfacing slopes and everywhere between 1600 and 1800 m. Below this elevation is also possible to find remaining natural forests of Quercus pyrenaica. The sub-alpine belt (up to 2200 m) was extensively burnt during the Middle Ages to increase the pasture areas. During the 20th century, most cultivated fields were abandoned, except in the valley bottoms. Abandoned fields, which represent about 25% of the total area, have been affected by a natural process of plant recolonization, particularly with Buxus sempervirens, Genista scorpius, Rosa gr. Canina, Juniperus communis and Echinopsart horridum
or have been reforested with Pinus laricio and Pinus sylvestris.

3. Data and methods

3.1. Climatic and hydrological data

Daily precipitation and temperature data were recorded at 14 stations located in the Ebro basin or adjacent areas (Fig. 1) between 1975 and 2006. The data, collected and managed by the Spanish Meteorological Agency (AEMet), were subject to checking a multistep approach of quality control, reconstruction and homogenization (Vicente-Serrano et al., 2010; El Kenawy et al., 2012).

Information on reservoir storage fluctuations, inflows and outflows were provided by the Ebro Basin Administration Authority (CHE). The outflow downstream of the reservoir was calculated by adding the outflow from the Aragón River recorded immediately downstream of the dam to the volume of water diverted through the Bardenas canal, which irrigates large areas in the lowlands of the Aragón River basin.

Information on vegetation land cover for the years 1986, 1997 and 2007 was obtained from the National Forest Inventory (1:50000). The vegetation classes in the inventory were reclassified into 8 categories: grassland (13.9% of the basin); deciduous broad forest (mainly Fagus sylvatica, 3.8%); evergreen needle forest (35.5%); Quercus forest (10.3%); shrub (12.4%); bare soil (13.5%); agricultural (6%); urban (<1%); and water (<1%).

Soil types were derived from the European Soil Database (Joint Research Centre, http://eusoils.jrc.ec.europa.eu/) at a spatial scale of 1 km²; the data includes information on soil types and many of the soil parameters required by RHESSys (texture, bulk density and organic content). Other required parameters for the soils (texture, bulk density, field capacity, content in organic matter, etc.) and vegetation (leaf area index, stomatal conductance and interception) were obtained from the available literature (Stanhill, 1970; Wösten et al., 1999; Jones et al., 2004, 2005; Cho et al., 2012).

3.2. Climate change and land cover scenarios

Temperature and precipitation simulated by regional climate models (RCMs) for a control period (1970–2000) and a future time slice (2021–2050) were obtained from the ENSEMBLES project database (http://www.ensembles-eu.org/; Hewitt and Griggs, 2004). This comprises a number of transient simulations of climate from 1950 to 2100 at high spatial resolution (25 km² grid size; approximately 0.2°) for the A1B scenario of moderate greenhouse gas emissions (Nakićenovic et al., 1998). The RCMs and their driving global circulation models (GCMs) were: C4I (HadCM3Q16); CNRM (ARPEGE); DMI (ECHAM5-r3); ETHZ (HadCM3Q0); GISS (IPSL); HC (HadCM3Q0); ICTP (ECHAM5-r3); KNMI (ECHAM5-r3); METNO (HadCM3Q20); MPI (ECHAM5-r3); SMHI (HadCM3Q3); and VMGO (HadCM3Q0).

The RCMs have been shown to reasonably reproduce observed precipitation and temperature for the control period in the Pyrenees. In general, expected errors in temperature span 1–1.5 °C, and expected errors in precipitation oscillate between 10 and 25% (López-Moreno et al., 2008, 2011). No other models have been shown to better reproduce the climate in the Pyrenees, as their skill scores are highly variable for temperature and precipitation, and also with respect to season. For this reason we used the average change projected by the various RCMs, and used the 25th and 75th percentiles in the magnitude of change in precipitation and temperature to represent the inter-model variability.

Two land cover scenarios were used (Fig. 2 and Table 1). In the first scenario land cover remained unchanged for the coming decades. The second scenario was based on the expected evolution of land cover, assuming that the remaining shrub areas will evolve into evergreen needle forests, as has generally been observed for the agricultural fields abandoned several decades ago (Lasanta et al., 2005). This scenario also assumed an upward shift of the tree line (to 2000 m a.s.l.) as a consequence of the decrease in livestock pressure (O’Flanagan et al., 2011), and is facilitated by warmer climate conditions. We did not consider changes in forest type associated with the replacement of coniferous
forests by more mature forest types (broadleaf forests), as this process is slow and very spatially complex, unlike the rapid colonization of abandoned fields by coniferous forests (Vicente-Serrano et al., 2006).

3.3. The RHESSys model

The RHESSys is a hydro-ecological model designed to simulate integrated water, carbon and nutrient cycling and transport over complex terrain at small to medium scales (Tague and Band, 2004). Simulated processes include vertical fluxes of humidity (interception, transpiration, evapotranspiration and groundwater recharge), and lateral fluxes between spatial units (Band et al., 2000). From the digital elevation model of the study area at a resolution of 100 m of cell size, the basin is subdivided in a hierarchical organization of landscape units, which enables different processes to be modeled at various scales, and enables the basic modeling units to be of arbitrary shape rather than strictly grid based (Tague and Band, 2004). The spatial levels define a hierarchy comprising progressively finer units. Each spatial level is associated with different processes modeled by the RHESSys and at a particular scale. At the finest scale patches are typically defined by areas in the order of m², while basins (km²) define the largest scale. The modeling units are defined by the user prior to running the model, with partitioning tailored to take advantage of the patterns of variability within the landscape. This procedure permits efficient parameterization and reduces the error associated with landscape partitioning. Band et al. (1991), Lammers et al. (1997) and Tague et al. (2000) provide further justification and discussion of partitioning strategies.

A Monte-Carlo simulation by running the model iteratively using different values of each parameter to be calibrated was used to find optimum sets of the following four parameters: i) depletion of hydraulic conductivity with depth (m); ii) hydraulic conductivity in saturated soils (K); iii) infiltration through macropores (gw1); and iv) lateral water fluxes from hillslopes to the main channel (gw2). The period 1996–2006 was used to calibrate the model, whereas the period 1975–1995 was used for validation. The Nash-Sutcliffe Efficiency (NS), the percentage of bias (PBIAS) and the ratio between the mean squared error and the standard deviation (RSR index) were used to quantify the capacity of the model to adequately reproduce the observed monthly streamflows. The mathematical formulation of the three indices, as well as the scale of goodness according to their scores, is described by Moriasi et al. (2007). Following the completion of quality assurance for the hydrological simulations for the observed period, new simulations were performed according to the climate and land cover projections noted in Section 3.2. Using the so-called “delta approach”, the observed series of temperature and precipitation were modified using monthly data values obtained from the comparison of the simulated climatic data for the future time slice (2020–2050) and the control period (1970–2000). Thus, new model runs used calibrations obtained from 1996 to 2006, but was run with the modified climate series for each RCM in combination with the two land cover scenarios considered: unaltered conditions from the control period (1); and afforestation (2).

3.4. Simulation of management of the Yesa reservoir

To assess how streamflow changes may affect the management of the Yesa reservoir, the storage capacity and the outflows downstream of the dam were simulated using as inputs the monthly inflows to the reservoir and the storage level in the previous month. The management of the reservoir follows a simple formula based on progressive filling of the reservoir from October to May, and the maintenance of a variable portion of the storage capacity free to allow for snowmelt and the possibility of floods. The maximum level of storage increases progressively from 80% in October to 95% in May. Such values have been determined from historical series, as several years have systematically shown a maximum storage very similar to these selected thresholds. Water diversion to the Bardenas canal varies seasonally, increasing from winter to summer, but is kept constant between years. As the main purpose of the reservoir is to provide water for irrigation, interannual variation in water release to the canal is generally low, and for the purposes of this study was considered to be constant. The release of water to the Aragón River, downstream of the dam, was calculated taking into account: i) the minimum environmental flow applied to the Yesa reservoir (based on the minimum flows observed in the long-term series, which have oscillated between 20 and 50 hm² month⁻¹; and ii) the maximum storage capacity threshold for each month. For periods of water scarcity a minimum storage of 50 hm² was used, because the location of the spillways

Table 1

<table>
<thead>
<tr>
<th>Surface area and percentage of each land cover type in the basin under the two scenarios shown in Fig. 2.</th>
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<tbody>
<tr>
<td>Observed conditions (km²)</td>
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<tr>
<td>--------------------------</td>
</tr>
<tr>
<td>Deciduous broad forest</td>
</tr>
<tr>
<td>Evergreen needle forest</td>
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<tr>
<td>Quercus forest</td>
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<tr>
<td>Pastures</td>
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<td>Shrub</td>
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<td>Agricultural use</td>
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<tr>
<td>Urban use</td>
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<tr>
<td>Water</td>
</tr>
</tbody>
</table>

Fig. 2. The land cover scenarios considered in the study. A: current land cover; B: plausible revegetation scenario.
does not allow release of water below this level. In such situations, four options of progressively increasing impact were considered to avoid this critical level being reached: i) water release to the Bardenas canal for irrigation reduced by 50%; ii) the ecological discharge set at 20 hm³ for each month of the year; iii) no water release to the Bardenas canal for irrigation, and an ecological discharge maintained at 20 hm³; and iv) all inflow to the reservoir released downstream of the dam.

Fig. 3 shows the observed long-term (1969–2009) average monthly regimes for inflow, outflow and reservoir storage, and the simulated values of these three parameters using the model based on the management assumptions are described above. In general, the model accurately simulated the management operation of the reservoir and the seasonality of the three hydrological parameters, although it slightly overestimated the storage levels by September and October. Thus, the model correctly simulated the maximum water storage recorded in spring, the total outflow released to the river and the Bardenas canal (key factors in ensuring water supply during the irrigation season), and outflows to the river downstream of the reservoir.

4. Results

4.1. Climate change projections for the Upper Aragón River basin

Fig. 4 shows the projected change in annual and seasonal precipitation and temperature in the Upper Aragón River basin. The inter-model average indicates a generalized increase in temperature for the period 2021–2050 relative to the control period (1970–2000). Warming is expected to oscillate between 1.5 °C in spring and 2.4 °C in summer, with an average annual warming of 1.8 °C. There was marked variability in the magnitude of the temperature change evident among the various RCMs. However, they all projected a trend of warming of approximately 1 °C for the A1B scenarios, but some of the models indicated an annual warming of slightly < 3 °C. The RCMs also indicated an average decrease of 10% in annual precipitation relative to the control period, with the greatest decrease expected to occur in summer (−18%) and the smallest in winter (−4%). For precipitation there was also marked variability among the models, which was particularly evident for summer, and some models suggested no changes in precipitation, or slight increases during autumn, winter and spring.

4.2. RHESSys simulation of observed streamflows in the Upper Aragón River basin

Fig. 5A shows the monthly observed and simulated runoff in the Yesa basin for the validation period. Fig. 5B shows boxplots of the distribution of observed and simulated seasonal and annual runoff, and the corresponding error estimators (NS, PBIAS and RSR). Despite some discrepancies between observed and simulated values, the RHESSys adequately reproduced the most characteristic seasonal cycles and the interannual streamflow variability recorded in the Upper Aragón River basin. Error estimates indicated that the simulations were ‘good’ or ‘very good’ for the four seasons, based on the goodness scale of Moriasi et al. (2007). Thus, NSE values were generally > 0.6, PBIAS did not exceed 15%, and RSR was < 0.5. The lowest level of accuracy occurred for spring, when NSE values were < 0.6. The interannual average spring flow was reproduced well, but peak flows during the wettest years were sometimes not adequately modeled.

4.3. Streamflow changes under land cover and climate change scenarios

Fig. 6 shows the average monthly streamflow regime simulated by the RHESSys under the two land cover scenarios and the climate conditions corresponding to the 1986–2006 period. In general, the river regimes under both land cover scenarios were similar, although the monthly magnitudes exhibited remarkable differences. Thus, under the afforestation scenario described in Section 3.2, annual runoff is expected
to decrease by 16% (from 869.7 to 728.3 hm$^3$). The largest differences between scenarios 1 and 2 occurred in March (−18.9%), and from September to November, when the difference was approximately (or exceeded) 30%. The differences were less during the annual peak flow (May, −4.6%; June, −6.5%), and in winter (January, −12%; February, −9%).

Fig. 5. A: Observed and simulated monthly runoff in the Upper Aragón River basin for the validation period (1987–1997). B: boxplots showing the interannual variability of observed and simulated seasonal and annual runoff. The error/accuracy statistics are shown by numbers.

Fig. 6. Monthly river regimes simulated by the RHESSys under the observed land cover and revegetation scenarios.

Fig. 7 shows the simulated streamflow in the basin as a consequence of projected climate change under: A) the current land cover conditions scenario; and B) the general revegetation scenario. For the current land cover scenario the inter-model average indicated a decrease in annual runoff of 13.8% for the period 2021–2050, relative to the control period. The 25th and 75th percentiles for the streamflow, obtained using the various RCM outputs in the RHESSys simulations, corresponded to reductions of −10.1% and −19.7%, respectively. This shows marked variability among the RCMs in the simulation of future streamflows in the basin. Based on the inter-model average, spring and summer is projected to undergo the major decrease in runoff, particularly in May, when a decrease of 29.9% in streamflow was simulated. The streamflow from November to February was the least affected in the RCM projections, showing a streamflow decrease of <10%. The 25th and 75th percentiles for annual runoff showed substantial variability in the streamflow projections among the various RCMs. Some models indicated that there could be a slight increase in runoff in winter, and decreases in runoff in any month during the remainder of the year will not exceed 20%. In contrast, simulations by other models indicated a marked streamflow decrease throughout the year, and perhaps exceeding 40% in May.

The inter-model average for the climate change projections under the revegetation scenario indicated a fall of 29.6% in annual runoff. The combination climate and land cover change suggest a sustained decline in runoff from March to December, and particularly intense declines in summer and autumn, when streamflow is expected to be reduced by more than 40%. Only for January and February a moderate
is reached in spring the water level does not generally fall below 200 hm³ by the end of summer, which is advantageous in terms of filling the reservoir the following year. There were only two long periods, at the beginning and the end of the period when the reservoir was well below capacity, and in these cases the storage level was <100 hm³ at the end of summer.

Table 2 shows the number of months during the 20 years simulated in the study when some of the water restrictions described in Section 3.4 would be applied to avoid critically low storage levels (<50 hm³).

### 5. Discussion and conclusions

This study indicates that environmental (including climate and land cover) changes will seriously affect the hydrology of a representative Mediterranean headwater located in the central Spanish Pyrenees. In this case study the climate models predicted a marked increase in temperature (1–2 °C), even for a close time horizon (2021–2050) and the four RHESSys streamflow scenarios. Under the observed climate and land cover scenarios simulated by the RHESSys were included in the reservoir management model, the water stored in the reservoir decreased markedly, in some cases to levels approaching 100 hm³. However, the number of years exceeding the threshold of 400 hm³ was much higher than with the current capacity of the reservoir. It explains why the number of months when water restrictions would need to be applied reduced markedly compared with the situation under the current storage capacity. When both the CC and LCC scenarios were combined the reservoir storage only exceeded 600 hm³ once, and water restrictions would need to have been applied in 54 months, which is much less than the 92 months indicated under the current storage capacity. Simulated outflows from the enlarged reservoir reduced dramatically, especially if an environmental change (climatic or land cover, or both) was imposed, which would force releasing only the current environmental flow in most months of the analyzed period.

Large differences were found when the reservoir management was modeled in relation to the expected capacity following reservoir enlargement (1059 hm³) and the four RHESSys streamflow scenarios. Under the observed climate and land cover scenarios the water storage never dropped below 400 hm³. Nevertheless, when the climate and land cover scenarios simulated by the RHESSys were included in the reservoir management model, the water stored in the reservoir decreased markedly, in some cases to levels approaching 100 hm³. However, the number of years exceeding the threshold of 400 hm³ was much higher than with the current capacity of the reservoir. It explains why the number of months when water restrictions would need to be applied reduced markedly compared with the situation under the current storage capacity. When both the CC and LCC scenarios were combined the reservoir storage only exceeded 600 hm³ once, and water restrictions would need to have been applied in 54 months, which is much less than the 92 months indicated under the current storage capacity. Simulated outflows from the enlarged reservoir reduced dramatically, especially if an environmental change (climatic or land cover, or both) was imposed, which would force releasing only the current environmental flow in most months of the analyzed period.

5. Discussion and conclusions

This study indicates that environmental (including climate and land cover) changes will seriously affect the hydrology of a representative Mediterranean headwater located in the central Spanish Pyrenees. In this case study the climate models predicted a marked increase in temperature (1–2 °C), even for a close time horizon (2021–2050) and under a moderate greenhouse gas emission scenario (A1B). The evolution of precipitation is subject to much uncertainty and variability, but all models for the region project a decrease in annual precipitation. Summer is expected to be subject to the most extreme trends in warming and drying, whereas winter temperatures and precipitation are simulated to be least affected. Projections for this area are consistent with most of the climate change studies concerning the mountains of the western Mediterranean basin (Nogués-Bravo et al., 2008; García-Ruiz et al., 2011; López-Moreno et al., 2011). For the Upper Aragón River basin the climatic models predict a decline of 13.8% in annual runoff, which is consistent with the 19% decline indicated by García-Vera (2013) for the time slice 2040–2070, based on the A1B scenario.
The increase in vegetation in headwaters in the Mediterranean mountains is far from complete (García-Ruiz et al., 2011). It is clear that the expansion of forest and shrub cover reduces catchment yields and increases storage capacity (Weatherheada and Howden, 2009; Warburton et al., 2012), especially when this occurs in headwater areas (Zégre et al., 2010). However, the magnitude of the impact of land cover change on the hydrological response is dependent on the basin characteristics, vegetation type and age of the forests, intensity of precipitation events and spatial scale effects (Bunte and MacDonald, 1995; Andréassian, 2004; Calder, 2007). In this study the hydrological simulations were also conducted using the assumption that shrub areas may evolve to forest, and that shrub is very likely to colonize subalpine meadows (García-Ruiz et al., 2011). Although most of the basin area has already been affected by revegetation processes (Vicente-Serrano et al., 2006), revegetation may still occur in areas that are currently covered by shrubs and pastures. The reduction in

![Fig. 8. Monthly series of water storage levels and outflows downstream of the Yesa reservoir simulated for the actual storage capacity of the reservoir (8A and 8B) and for the expected future capacity following reservoir enlargement (8C and 8D).](image)

Table 2

<table>
<thead>
<tr>
<th>Restriction level</th>
<th>Current storage capacity (476 hm²)</th>
<th>Enlarged storage capacity (1057 hm²)</th>
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<td>OBS LCC CC LCC and CC</td>
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</tr>
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1: Water released to Bardenas canal for irrigation reduced by 50%.
2: As for 1, and the ecological discharge set at 20 hm³ for all months of the year.
3: All available water released to Bardenas canal for irrigation, and the ecological discharge maintained at 20 hm³.
4: All inflow released downstream of the reservoir.

The increase in vegetation in headwaters in the Mediterranean mountains is far from complete (García-Ruiz et al., 2011). It is clear that the expansion of forest and shrub cover reduces catchment yields and increases storage capacity (Weatherheada and Howden, 2009; Warburton et al., 2012), especially when this occurs in headwater areas (Zégre et al., 2010). However, the magnitude of the impact of land cover change on the hydrological response is dependent on the basin characteristics, vegetation type and age of the forests, intensity of precipitation events and spatial scale effects (Bunte and MacDonald, 1995; Andréassian, 2004; Calder, 2007). In this study the hydrological simulations were also conducted using the assumption that shrub areas may evolve to forest, and that shrub is very likely to colonize subalpine meadows (García-Ruiz et al., 2011). Although most of the basin area has already been affected by revegetation processes (Vicente-Serrano et al., 2006), revegetation may still occur in areas that are currently covered by shrubs and pastures. The reduction in
annual runoff associated with this hypothetical evolution of land cover (average, 16%) exceeds the reduction simulated under climate change projections. This confirms the need to study the combined effects of climate and land cover change to develop reliable scenarios of the future availability of water resources (Parajuli, 2010; Tong et al., 2012). In the Upper Aragon River basin the combined effect of climate and land use change is predicted to lead to a 29.8% decline in annual runoff. Moreover, land cover change mostly affects runoff in late winter, early spring (mainly March) and autumn. In spring, the amount of water consumed by vegetation is high, but represents a lower percentage of the annual peak of runoff. In winter, the effect of revegetation is less because the amount of water consumed is low because this is a period of vegetation dormancy. In summer, the reduction in water consumption through revegetation processes is moderate because of the low level of soil water availability, which explains the physiological, anatomical and functional strategies developed by the vegetation to respond to water stress (Chaves et al., 2003). Climate change is causing a reduction in peak flows during the spring thaw, which is occurring earlier in the season (López-Moreno and García-Ruiz, 2004; Christensen and Lettenmaier, 2007; Barnett et al., 2008; Dawadi and Ahmad, 2012), and is responsible for water shortages during summer. The simulations of climate and land cover change combined indicate a sustained decrease in runoff from late winter to the end of autumn, with reductions in river flows exceeding 30–40% relative to current levels. Little changes have been projected for winter, with some simulations indicating a slight increase in river flows, mostly related to an increase of snowmelt and a decrease of snow accumulating during the cold season.

A simplified water management scheme based on historical dam operations was used to model the fluctuations in water storage and outflows downstream of the reservoir. When the water storage fell below a critical threshold (50 hm$^3$), four water use restrictions of increasing severity were assumed for water released for irrigation purposes and the maintenance of environmental flows. Based on the current storage capacity of the dam (476 hm$^3$), the projected climate and land cover changes will severely affect the ability to supply the current water demand. The results suggest that the combined effects of climate and land cover change would lead to the need for restrictions on irrigation supply or environmental flows in 92 months (38.3%) in the 20 years of the simulation. Previous research based on historical observations indicates that the reductions in outflows downstream of the Yesa reservoir over recent decades are approaching critical levels (López-Moreno et al., 2008), which is consistent with the studies of other Mediterranean river basins. For example, based only on climate projections, Alcamo et al. (2007) simulated a decrease of 20–50% in hydropower production in the southern Mediterranean region by 2070. Similarly, Majone et al. (2012) projected an increase in the number of dry years and reduced availability of water for hydropower and irrigation in relation to another highly regulated Pyrenean river (the Gallego River), based on climate change simulated for the 2070–2100 period.

Enlargement of the Yesa reservoir to 1059 hm$^3$ will enable the application of multi-annual management strategies. Thus, water stored in wet years will be available for use in subsequent dry years. This may substantially reduce the number of months in which restrictions on dam outflows need to be applied. However, the projected climate and land cover changes could seriously affect the regime of the Aragon River downstream of the dam, which is modulated only by environmental flows, and restrictions may still be necessary in a substantial number of months (22.5%). Moreover, the reservoir would result clearly oversized, with almost any month with a storage exceeding 600 hm$^3$. Presented scenarios of runoff decline could be exacerbated if precipitation, that is subjected to an uncertainty close to 25% (López-Moreno et al., 2008), is reduced in a more intense way than indicated by the multi-model average. Oppositely, the pressure on water resources could be partially alleviated in case that precipitation will show an increase in the region, or revegetation scenario is altered by human management or the hypothetical occurrence of forest fires that frequently affect the Mediterranean areas. However, results of this study clearly point out to a marked increase in the probability of occurrence of water restrictions, particularly in a very likely context of increasing water demand from (i) the city of Zaragoza, where population is showing a steady increase in the last decades, which pretend to consume water from the Aragón River, substituting the actual supply from the Ebro river, (ii) the irrigated area in the lower course of the Aragón River, where the irrigated land is enlarging and the current irrigation modernization leads to an increase in water demand due to the expansion of highly water consuming crops (vegetables, alfalfa and corn, Playán And Mateos, 2006; Lecina et al., 2010); and the possibility to transfer river flows from the Ebro river to other areas of Spain for supplying water for tourism and agriculture (Ibáñez and Prat, 2003).

The results of this study highlight the need to develop flexible strategies for water management at the local scale (in terms of dam operations), but also at the basin scale. This will enable optimization of the use of available water in the Ebro basin, which is highly variable in time and space (García-Vera, 2013). The results also emphasize the need for more research and the implementation of water saving technologies, practices and a legal framework to ensure the supply and quality of water resources. In this context the integration of science and policy is a priority in addressing the challenges of water-related impacts under conditions of ongoing environmental change (Quevauviller, 2011).

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