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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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 hm^3). If the current project to enlarge the reservoir to a capacity of 1059 hm^3 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 may be dramatically reduced.

Key words: streamflow, climate change, land cover change, water resources, water management, Mediterranean mountains

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., 2008; 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, in press). 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., 2006).

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 (Ashofteh 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. Voudoris 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; Senator 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 ºC (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 reservoirs managers to reduce outflows downstream of dams throughout most of the year. This has enabled 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 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, in press). 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 know 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 hm^3) and its projected capacity (1079 hm^3) 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 km^2 (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 10ºC, 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 hm^3. 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 (*Pynus sylvestris, Fagus sylvatica*, etc) remain relatively well preserved on the northfacing slopes and everywhere between 1600 and 1800 m. 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 Echinospartum horridum* (Vicente-Serrano et al., 2006), 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 where 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 checkinga 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 km^2; 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 available literature (Stanhill, 1970; Cary and Hayden, 1973; Wösten et al., 1999, Jones et al., 2004, 2005; Cho et al., 2012).

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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

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at high spatial resolution (25 km^2 grid size; approximately 0.2°) for the A1B scenario of moderate greenhouse gas emissions (Nakicénovic et al., 1998). The RCMs and their driving global circulation models (GCMs) were: C4I (HadCM3Q16); CNRM (ARPEGE); DMI (ECHAM5-r3); ETHZ (HadCM3Q0); GKSS (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 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 facilitated by warmer climate conditions. We did not consider changes in forest type associated with 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 m^2, while basins (km^2) 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.

Calibration of the following four parameters was done using a Monte-Carlo simulation: 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 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. The observed series of temperature and precipitation were modified using monthly data values obtained from 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 1996–2006, 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 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 hm^3 $month^{-1}$; and ii) the maximum storage capacity threshold for each month. For periods of water scarcity a minimum storage of 50 hm^3 was used, because the location of the spillways 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 hm^3 for each month of the year; iii) no water release to the Bardenas canal for irrigation, and an ecological discharge maintained at 20 hm^3; and iv) all inflow to the reservoir released downstream of the dam.

Figure 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 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

Figure 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

Figure 5A shows the monthly observed and simulated runoff in the Yesa basin for the validation period. Figure 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

Figure 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%).

Figure 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 RCMs projections, showing a streamflow decrease < 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 suggests 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 reduction in runoff was indicated (–10.5% and –11.4%, respectively). The 25th and 75th RCM percentiles indicated substantial variability in the projected streamflow decreases under the various RCM projections.

4.3 Possible impact of the projected streamflow scenarios on the management of the Yesa reservoir

Figure 8 shows the monthly series of water storage levels and outflows (including river flows and water releases to the Bardenas canal) downstream of the Yesa reservoir, simulated for the actual storage capacity of the reservoir (Fig. 8A and 8B) and for the expected future capacity after the enlargement of the reservoir (Fig. 8C and 8D). We performed the RHESSys simulations under four different scenarios: (i) the observed climatic and current land cover conditions; (ii) the observed climatic conditions and the revegetation scenario; (iii) the climate change scenario (average of the RCM outputs) and the current land cover; and (iv) the climate change scenario (average of the RCM outputs) and the revegetation scenario.

If water stored in the reservoir was modeled using the RHESSys streamflow simulation under the observed land cover and climate conditions, the reservoir almost reached maximum storage capacity in early spring for most of the years. The stored amount would generally satisfy the water demands for irrigation and domestic uses during the peak period of demand in late spring and summer. When this amount of storage is reached in spring the water level does not generally fall below 200 hm^3 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 hm^3 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 hm^3). Based on these criteria it would not be necessary to apply water restriction during the simulation period under observed climate and land cover conditions. When the Yesa reservoir storage and outflows were modeled using streamflow simulations under climate (CC; inter-model average) or land cover change (LCC) scenarios separately, the number of years when the maximum storage capacity was not reached increased markedly. Consequently, the number of years when the minimum storage was < 100 hm^3 also increased markedly, resulting in longer periods of water scarcity. Modeling of the reservoir management showed that the outflows downstream of the dam were reduced, with long periods limited to environmental flows (Fig. 8B), and Table 2 shows that there were several periods when restrictions would need to be applied to the supply to the irrigation canal, and also to the release of environmental flows. Logically, the combination of land use and climate change will aggravate the situation, producing major decreases in the water stored in the reservoir, and a marked increase in the number of months in which restrictions on outflows will have to be applied.

Large differences were found when the reservoir management was modeled in relation to the expected capacity following reservoir enlargement (1059 hm^3) and the four RHESSys streamflow scenarios. Under the observed climate and land cover scenarios the water storage never dropped below 400 hm^3. 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 hm^3. However, the number of years exceeding the threshold of 400 hm^3 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 hm^3 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 analysed 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 emissions 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., 2012). 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 (in press) 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 and Lana-Renault, 2012). It is clear that the expansion of forest and shrub cover reduces catchment yields and increases storage capacity (Weatherhead and Howden, 2009; Warburton et al., 2012), especially when this occurs in headwater areas (Zegre 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, intensity of precipitation events and spatial scale effects (Bunte and MacDonald, 1995; Andreassian, 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 are 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 (Chávez et al., 1998). 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, 2008; Dawadi and Sajjad 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 has 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 studies of other Mediterranean river basins. 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 600hm^3. Restrictions will occur 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, Playón 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, in press). 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, 2010).

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REFERENCES

Alcamo J, Flörke M, Marker M. Future long-term changes in global water resources driven by socio-economic and climatic changes. Hydrological Sciences Journal 2007; 52 (2): 247–275.

Alpert P, Krichak SO, Shafir H, Haim D, Osetinsky I. Climatic trends to extremes employing regional modeling and statistical interpretation over the E. Mediterranean. Global and Planetary Change 2008; 63: 163-170.

Andréassian V. Waters and forests: from historical controversy to scientific debate. Journal of Hydrology 2004; 29(1): 1-27.

Ashofteh PS, Bozorg O, Mariño MA. Scenario Assessment of Streamflow Simulation and its Transition Probability in Future Periods Under Climate Change. Water resources Management 2013; 27: 255-274.

Band LE, Patterson P, Nemani R, Running SW. Forest ecosystem processes at the watershed scale: incorporating hillslope hydrology. Agricultural and Forest Meteorology 1993; 63: 93-126,

Band LE, Tague C, Brun S, Tenenbaum D, Fernandes R. Modelling watersheds as spatial object hierarchies: structure and dynamics. Transactions in GIS 2000; 4(3): 181-196.

Barnett TP, Pierce DW, Hidalgo HG, Bonfils C, Santer BD, Das T, Bala G, Wood AW, Nozawa T, Mirin AA, Cayan DR, Dettinger MD. Human-induced changes in the hydrology of the Western United States. Science 2008;319: 1080-1083.

Batalla RJ, Gómez CM, Kondolf M. Reservoir-induced hydrological changes in the Ebro River basin (NE Spain). Journal of Hydrology 2004; 290: 117-136**.**

Beguería, S., López-Moreno, J.I., Seeger, M. and García-Ruiz. Assesing the effects of climate oscillations and land-use changes on streamflow in the Central Spanish Pyrenees. Ambio 2003, 32 (4): 283-286.

Bunte K, MacDonald L H. Detecting changes in sediment loads: where and how is it possible. In W. Osterkamp (Ed.), Effects of scale on interpretation and management of sediment and water quality, International Association of Hydrologic Sciences Publication 1995; 226.

Brunetti M, Buffoni L, Mangianti F, Maugeri M, Nanni T. Temperature, precipitation and extreme events during the last century in Italy. Global and Planetary Change 2004; 40, 141-149.

Calder IR. Forests and water—ensuring forest benefits outweigh water costs. Forest Ecology and Management 2007; 251: 110–120.

Chaves MM, Maroco JP, Pereira JS. Understanding plant responses to drought—From genes to the whole plant. Funct Plant Biol 2003; 30(3):239–264.

Cho J, Myazaki S, Yeh P, Kim W, Kanae S, Oki T. Testing the hypothesis on the relationship between aerodynamic roughness length and albedo using vegetation structure parameters. International Journal of Biometeorology 2012; 56:411-418.

Christensen NS, Lettenmaier DP. A multimodel ensemble approach to assessment of climate change impacts on the hydrology and water resources of the Colorado River Basin, Hydrol. Earth Sys. Sci. 2007; 11(4): 1417-1434.

Dawadi S, Ahmad S. Changing Climatic Conditions in the Colorado River Basin: Implications for Water Resources Management. Journal of Hydrology 2012; 430–431: 127–141

El Kenawy A, López-Moreno JI, Vicente-Serrano SM. Trend and variability of temperature in northeastern Spain (1920-2006): linkage to atmospheric circulation. Atmospheric Research. Atmospheric Research 2012; 106: 159–180

Gallart F, Llorens P.. Observations on land cover changes and water resources in the headwaters of the Ebro catchment, Iberian Peninsula. Phys Chem Earth 2003; 29, 769-773.

García-Ruiz JM, Lana-Renault N. Hydrological and erosive consequences of farmland abandonment in Europe, with special reference to the Mediterranean region – A review. Agriculture, Ecosystems and Environment 2011; 140 (3-4): 317-338.

García-Ruiz JM, López-Moreno JI, Serrano-Vicente SM, Beguería S, Lasanta T, Mediterranean water resources in a global change scenario. Earth Science Reviews 2011; 105 (3-4): 121-139.

García-Vera MA. The application of hydrological planning as a climate change adaptation tool in the Ebro basin. Water Resources Development. In press, DOI:10.1080/07900627.2012.747128

Código de campo cambiado

Giorgi F. Climate change hot-spots. Geophysical Research Letters 2006; 33, L08707, doi:10.1029/2006GL025734.

Giorgi F, Lionello P. Climate change projections for the Mediterranean region. Global and Planetary Change 2008; 63, 90-104.

Hewitt CD, Griggs DJ. Ensemble-based predictions of climate changes and their impacts, EOS, Transactions AGU 2004; 85.

Ibáñez C, Prat N. The environmental impact of the Spanish national hydrological plan on the lower Ebro river and delta. Wat. Resour. Develop. 2003; 19(3): 485-500.

Jones RJA, Hiederer R, Rusco E, Loveland PJ, Montanarella L. The map of organic in top soils in Europe. Special Publication Ispra 2004; 72 (S.P.I.04.72). European Soil Bureau Research Report No. 17, EUR 21209 EN, 26pp. and 1 map in ISO B1 format. Office for Official Publications of the European Communities. Luxembourg.

Jones RJA, Hiederer R, Rusco E, Loveland PJ, Montanarella L. Estimating organic carbon in the soils of Europe for policy support. European Journal of Soil Science 2005; 56(5):655 – 671.

Lammers R, Band L, Tague C. Scaling behaviour in watershed processes. In: Scaling – up, P. Vangardingen, G. Foodyand p. Curran (Editors). Cambridge University Press 1997; 295-318.

Lasanta T. The process of desertion of cultivated areas in the Central Spanish Pyrenees. Pirineos 1988; 132, 15-36.

Lasanta T, Vicente Serrano SM, Cuadrat JM. Spatial-temporal variability of the plant landscape in the mediterranean highlands due to the abandonment of traditional land uses: a study of the Spanish Central Pyrenees. Applied Geography 2005; 25: 47-65.

Lasanta T, García-Ruiz JM, Pérez-Rontomé C, Sancho-Marcén C. Runoff and sediment yield in a semi-arid environment: the effect of land management after farmland abandonment. Catena 2000; 38, 265-278.

Lecina S, Isidoro D, Playón E, Aragüés R., Irrigation modernization and wáter conservation in Spain: the case of Riegos del Alto Aragón. Agricultural Water Management 2010; 97, 1663-1675.

Lespinas F, Ludwig W, Heussner S. Impact of recent climate change on the hydrology of coastal mediterranean rivers in Southern France. Climatic Change 2010; 99, 425-456.

Liuzzo L, Noto L, Vivoni E, La Loggia G. ”Basin-Scale Water Resources Assessment in Oklahoma under Synthetic Climate Change Scenarios Using a Fully Distributed Hydrologic Model.” J. Hydrol. Eng. 2010; 15(2), 107–122.

Lopez R, Justribo C. The hydrological significance of mountains: a regional case study, the Ebro River basin, northeast Iberian Peninsula. Hydrological Sciences Journal 2010; 55:2, 223-23.

López-Moreno JI, Beguería S, García-Ruiz JM. The management of a large mediterranean reservoir: storage regimes of the Yesa reservoir, Upper Aragón River basin, Central Spanish Pyrenees. Environmental Management 2004; 34 (4): 508-515.

López-Moreno JI García-Ruiz JM. Influence of snow accumulation and snowmelt on streamflow in the Central Spanish Pyrenees. International Journal of Hydrological Sciences 2004; 49 (5): 787-802.

López-Moreno JI. Recent variations of snowpack depth in the Central Spanish Pyrenees. Artic, Antartic, and Alpine Research 2005; 37 (2): 253-260.

López-Moreno JI, García-Ruiz JM, Beniston M. Environmental Change and water management in the Pyrenees. Facts and future perspectives for Mediterranean mountains. Global and Planetary Change 2008; 66 (3-4): 300-312.

López-Moreno JI, Vicente-Serrano SM, Moran-Tejeda E, Zabalza J, Lorenzo-Lacruz J, García-Ruiz JM. Impact of climate evolution and land use changes on water yield in the Ebro basin. Hydrology and Earth System Science 2011; 15: 311-322.

Majone B, Bovolo CI, Bellin A, Blenkinsop S, Fowler HJ. Modeling the impacts of future climate change on water resources for the Gallego river basin (Spain). in Water Resources Research 2012; 48: W01512.

Moriasi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. American Society of Agricultural and Biological Engineers 2007; 50(3): 885-900.

Nakicenovic N, Grübler A, McDonalds A. Global Energy Perspectives. Cambridge University Press 1998; Cambridge 299pp.

Nogués-Bravo D, Lasanta T, López-Moreno JI, Araújo MB. Climate warming in Mediterranean mountains during the XXIst century. Ambio 2008; 37 (4), 280-285.

Milly PCD, Dunne KA, Vecchia AV. Global pattern of trends in streamflow and water availability in a changing climate. Nature 2005; 437: 347-350.

Nohara D, Kitoh A, Hosaka M, Oki T. Impact of climate change on river discharge projected by multimodel ensemble. Journal of Hydrometeorology 2006; 7, 1076-1089.

O'Flanagan, P, Lasanta T, Errea-Abad MP. Restoration of sheep transhumance in the Ebro Valley, Aragon, Spain Geographical Review 2011; 101 (4): 556-575.

Parajuli PB. Assessing sensitivity of hydrologic responses to climate change from forested watershed in Mississippi. Hydrol. Process. 2010; 24 (26): 3785–3797.

Playón E, Mateos L. Modernization and optimization of irrigation systems to increase water productivity. Agricultural Water Management 2006; 80: 100-116.

Quevauviller P. Adapting to climate change: reducing water-related risks in Europe – EU policy and research considerations. Environmental Science and Policy 2011; 14: 722-729.

Senatore A, Mendicino G, Smiatek G, Kunstmann H. Regional climate change projections and hydrological impact analysis for a Mediterranean basin in Southern Italy. Journal of Hydrology 2010; 399: 70-92.

Stanhill G. Some results of helicopter measurements of the albedo of different land surfaces. Solar Energy 1970; 13: 59-66.

Tague C, Band L. RHESSys: Regional Hydro-Ecologic Simulation System: An object-oriented approach to spatially distributed modeling of carbon, water and nutrient cycling. Earth Interactions 2004; 8, 1:42.

Tague C, McMichael C, Hope A, Choate J, Clark R. Application of the RHRESSys model to a California semiarid shrubland watershed. Journal of the American Water Resources Association 2004; 02137, 575:589.

Tong STY, Sun Y, Ranatunga T, He J, Yang YJ. Predicting plausible impacts of sets of climate and land use change scenarios on water resources. Applied Geography 2012; 32: 477-489.

Vicente-Serrano SM, Beguería S, Lasanta T. Diversidad espacial de la actividad vegetal en el pirineo central español: análisis de los procesos de sucesión mediante imágenes Landsat (1984-2001). Pirineos 2006; 161: 59-84.

Vicente-Serrano S, Beguería S, López-Moreno JI, García-Vera MA, Stepanek P. A complete daily precipitation database for North-East Spain: reconstruction, quality control and homogeneity. International Journal of Climatology 2010; 30 (8): 1146-1163.

Viviroli D, Dürr HH, Messerli B, Meybeck M, Weingartner R. Mountains of the world – water towers for humanity: typology, mapping and global significance. Wat. Resour. Res. 2007; 43(7), W07447.

Voudoris K, Mavromatis T, Krinis P. Assessing runoff in future climate conditions in Messara valley in Crete with a rainfall-runoff model. Meteorological Applications 2012; 19 (4): 473-483.

Warburton ML, Schulze RE, Jewitt GPW. Hydrological impacts of land use change in three diverse South African catchments. Journal of Hydrology 2012; 414-415: 118-135.

Weatherheada EK, Howden NJK. The relationship between land use and surface water resources in the UK. Land Use Policy 2009; 265:243-250.

Wösten JHM, Lilly A, Nemes A, Le Bas C.. Development and use of a database of hydraulic properties of European soils. Geoderma 1999; 90: 169-185.

Zégre N, Skaugset A E, Som N A, McDonnell J J, Ganio LM. In lieu of the paired catchment approach: hydrologic model change detection at the catchment scale. Water Resources Research 2010; 46(11), W11544.

Zhang JY, Wang GQ, He RM, Liu CS Variation trends of runoffs in the Middle Yellow River basin and its response to climate change. Adv Water Sci 2009; 20(2):153–158

FIGURE CAPTIONS

Figure 1. Location and topography of the Upper Aragón River basin, including the distribution of the main streams in the basin.

Figure 2. The land cover scenarios considered in the study. A: current land cover; B: plausible revegetation scenario.

Figure 3. Observed and simulated long-term average monthly regime of inflow, outflow and water storage in the Yesa reservoir.

Figure 4. Projected change in seasonal and annual temperature and precipitation in the upper Aragon basin for the period 2021–2050 relative to the control period (1970–2000). The dots represent the inter-model average, and the upper (lower) and right (left) bars indicate the 75th and 25th percentiles, respectively.

Figure 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.

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

Figure 7. RHESSys streamflow simulations for A) current and B) revegetation land cover scenarios. For both land cover scenarios the simulations shown are under current (1975–2006) and future (A1B scenario) climate conditions, using the outputs of the various RCMs. The numbers indicate the average streamflow decrease among the various RCMs (in bold), and the values corresponding to the 75th (upper) and 25th (lower) percentiles.

Figure 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).

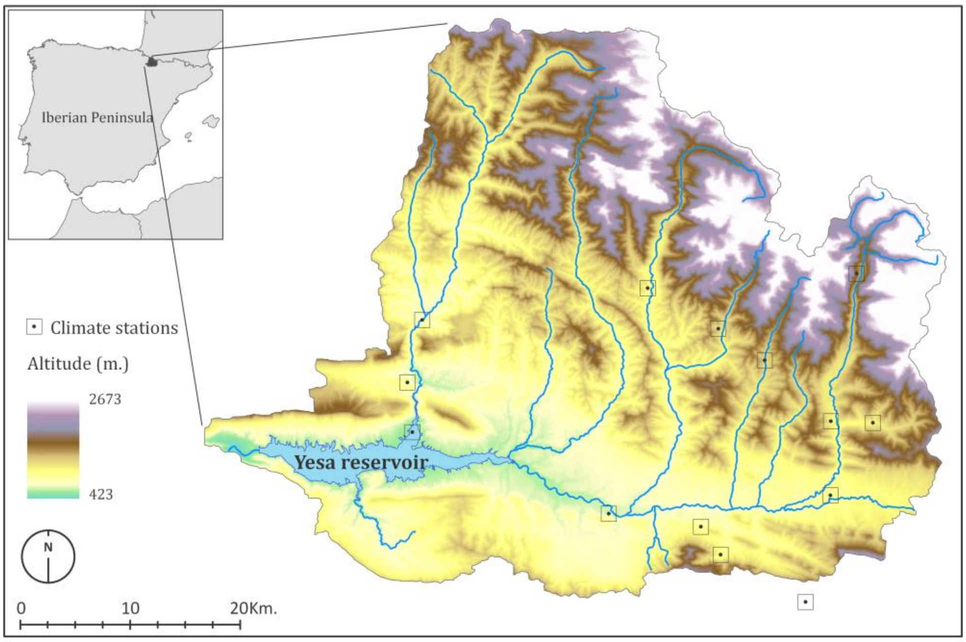

Iberian Peninsula
Climate stations
Altitude (m.)
2673
423
Yesa reservoir
N
0
10
20Km.

Figure 1

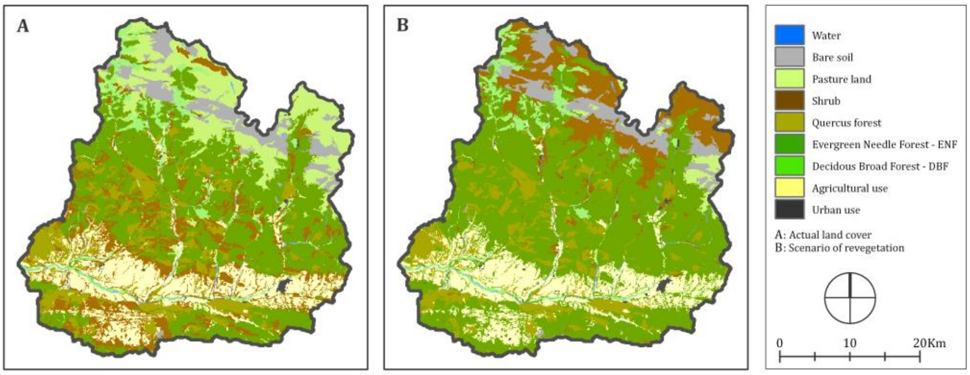

A
B
Water
Bare soil
Pasture land
Shrub
Quercus forest
Evergreen Needle Forest - ENF
Decidous Broad Forest - DBF
Agricultural use
Urban use
A: Actual land cover
B: Scenario of revegetation
0
10
20Km

Figure 2

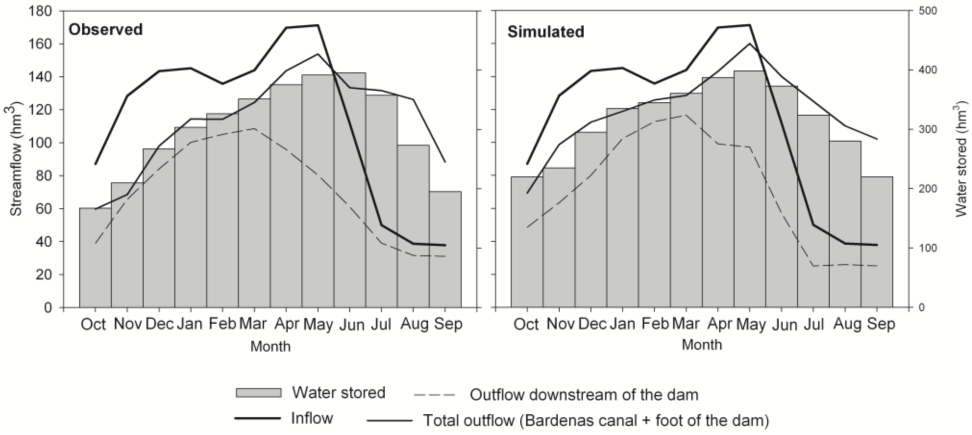

Observed
Simulated
Streamflow (hm^3)
Water stored (hm^3)
180
160
140
120
100
80
60
40
20
0
500
400
300
200
100
0
Oct Nov Dec Jan Feb Mar Apr May Jun Jul Aug Sep
Month
Water stored
Outflow downstream of the dam
Inflow
Total outflow (Bardenas canal + foot of the dam)

Figure 3

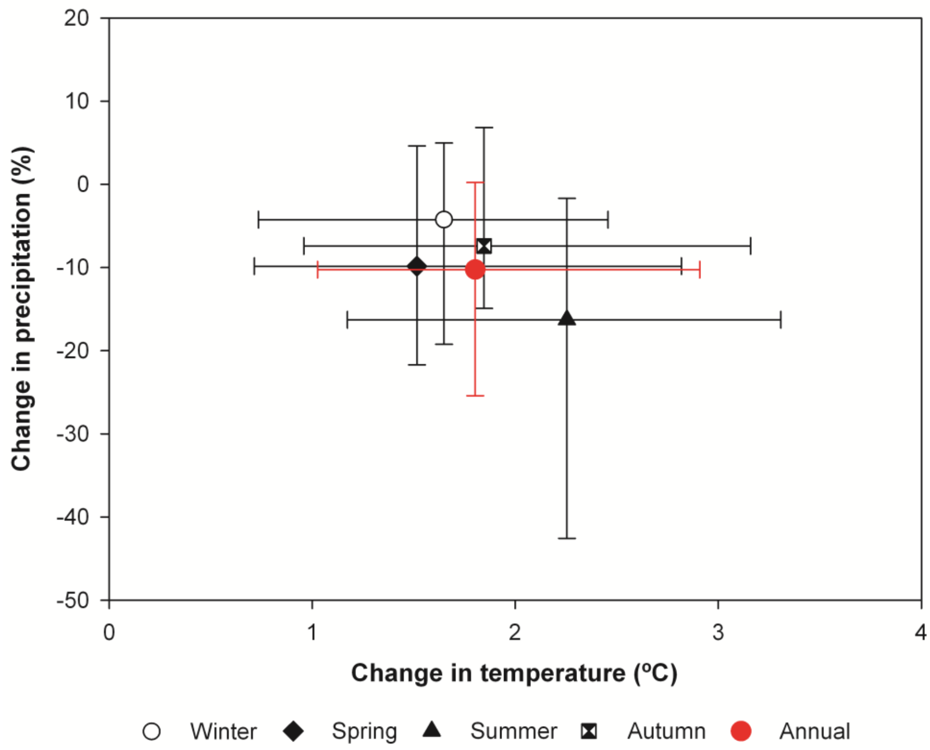
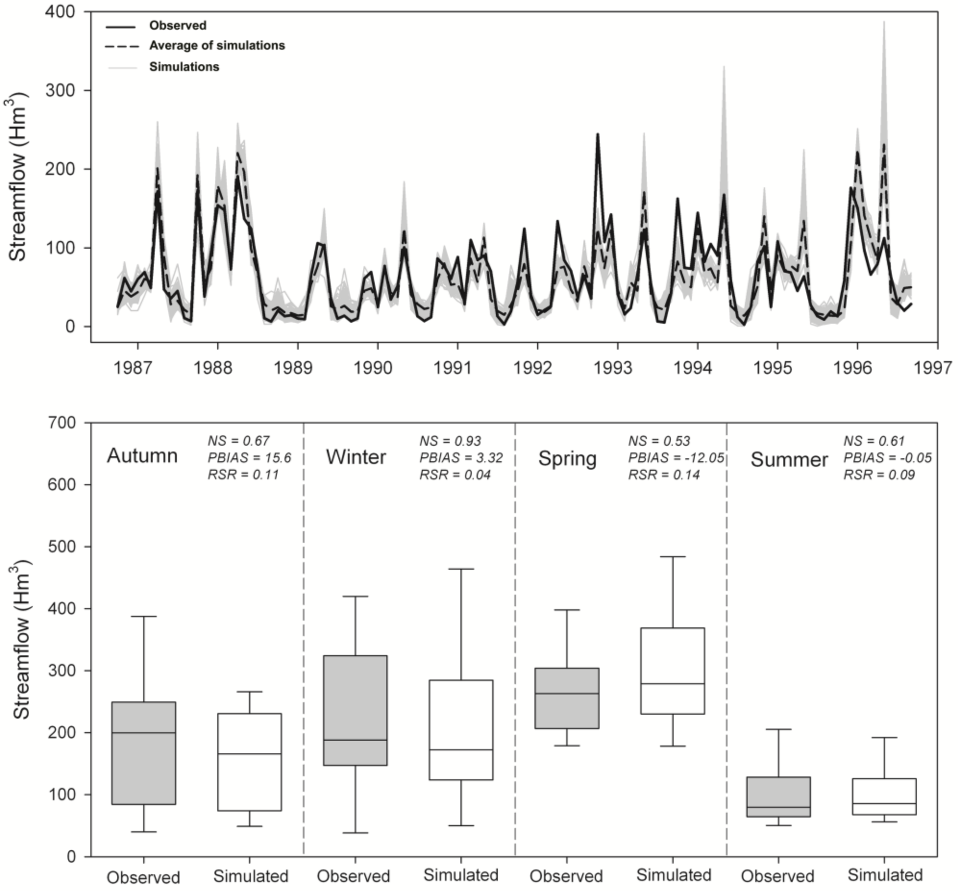
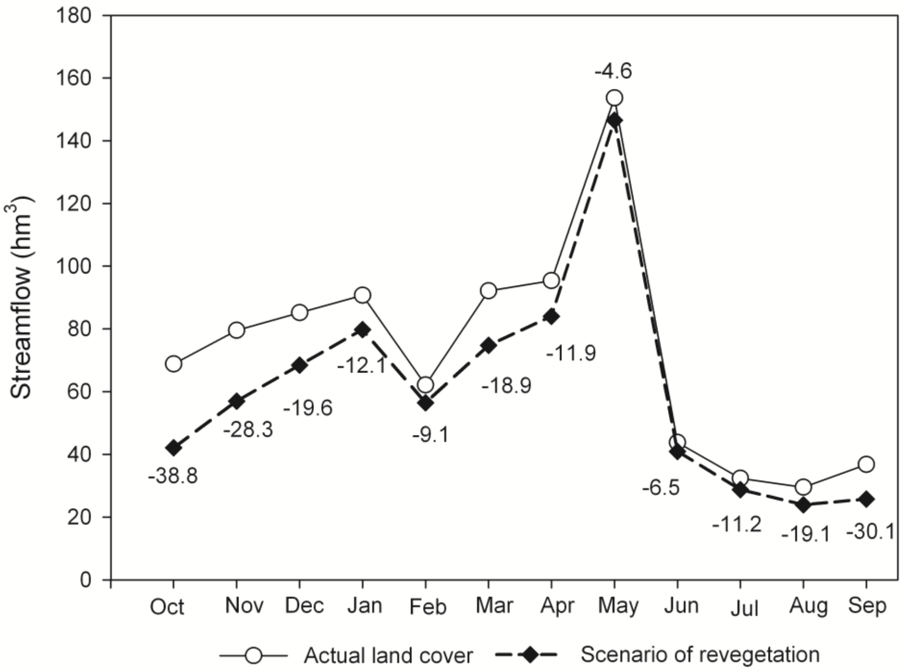

20
10
0
-10
-20
-30
-40
-50
Change in precipitation (%)
0
1
2
3
4
Change in temperature (ºC)
○ Winter
◆ Spring
▲ Summer
☒ Autumn
● Annual

Figure 4



Observed
Average of simulations
Simulations
Streamflow (Hm^3)
400
300
200
100
0
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
700
600
500
400
300
200
100
0
Autumn
NS = 0.67
PBIAS = 15.6
RSR = 0.11
Winter
NS = 0.93
PBIAS = 3.32
RSR = 0.04
Spring
NS = 0.53
PBIAS = -12.05
RSR = 0.14
Summer
NS = 0.61
PBIAS = -0.05
RSR = 0.09
Observed
Simulated
Observed
Simulated
Observed
Simulated
Observed
Simulated

Figure 5



Streamflow (hm³)
0
20
40
60
80
100
120
140
160
180
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
-38.8
-28.3
-19.6
-12.1
-9.1
-18.9
-11.9
-4.6
-6.5
-11.2
-19.1
-30.1
Actual land cover
Scenario of revegetation

Figure 6

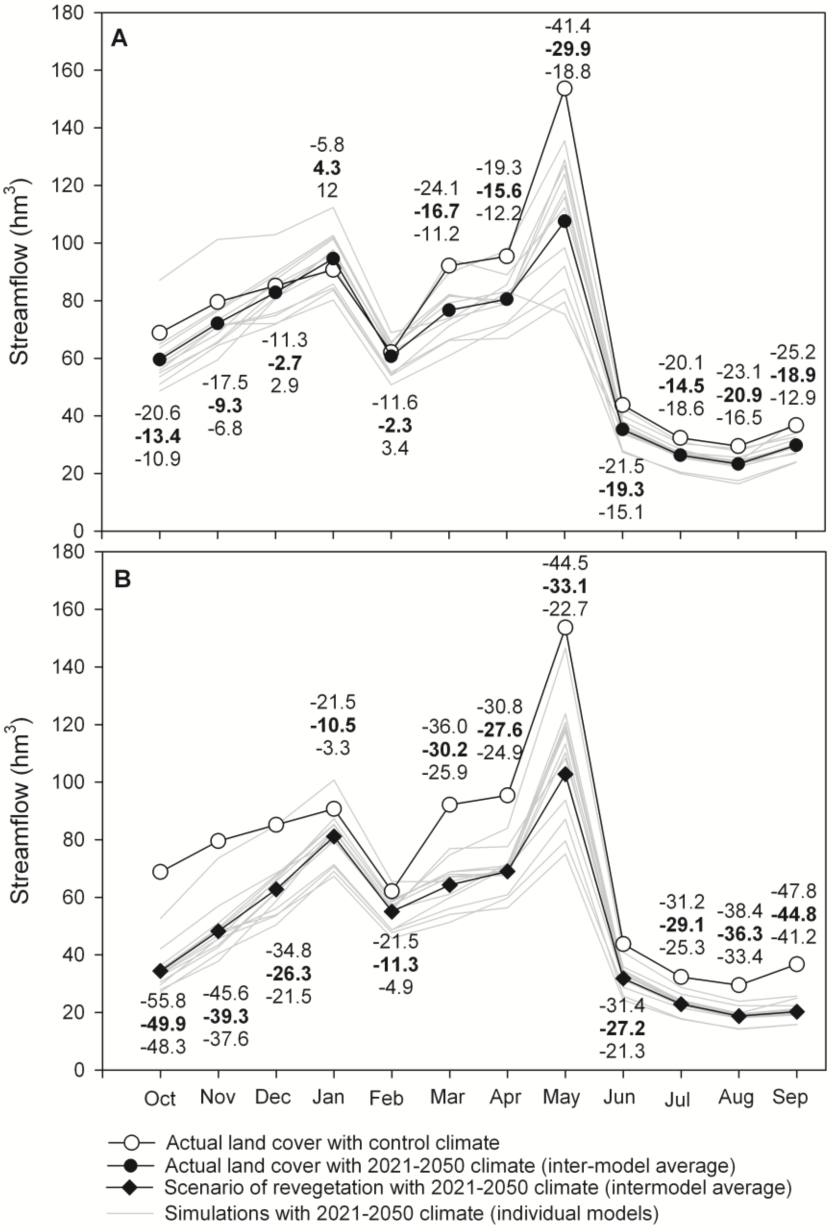

A
B
Streamflow (hm^3)
0
20
40
60
80
100
120
140
160
180
Oct
Nov
Dec
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
-20.6 **-13.4** -10.9
-17.5 **-9.3** -6.8
-11.3 **-2.7** 2.9
-5.8 **4.3** 12
-11.6 **-2.3** 3.4
-24.1 **-16.7** -11.2
-19.3 **-15.6** -12.2
-41.4 **-29.9** -18.8
-21.5 **-19.3** -15.1
-20.1 **-14.5** -18.6
-23.1 **-20.9** -16.5
-25.2 **-18.9** -12.9
-55.8 **-49.9** -48.3
-45.6 **-39.3** -37.6
-34.8 **-26.3** -21.5
-21.5 **-10.5** -3.3
-21.5 **-11.3** -4.9
-36.0 **-30.2** -25.9
-30.8 **-27.6** -24.9
-44.5 **-33.1** -22.7
-31.4 **-27.2** -21.3
-31.2 **-29.1** -25.3
-38.4 **-36.3** -33.4
-47.8 **-44.8** -41.2
Actual land cover with control climate
Actual land cover with 2021-2050 climate (inter-model average)
Scenario of revegetation with 2021-2050 climate (intermodel average)
Simulations with 2021-2050 climate (individual models)

Figure 7

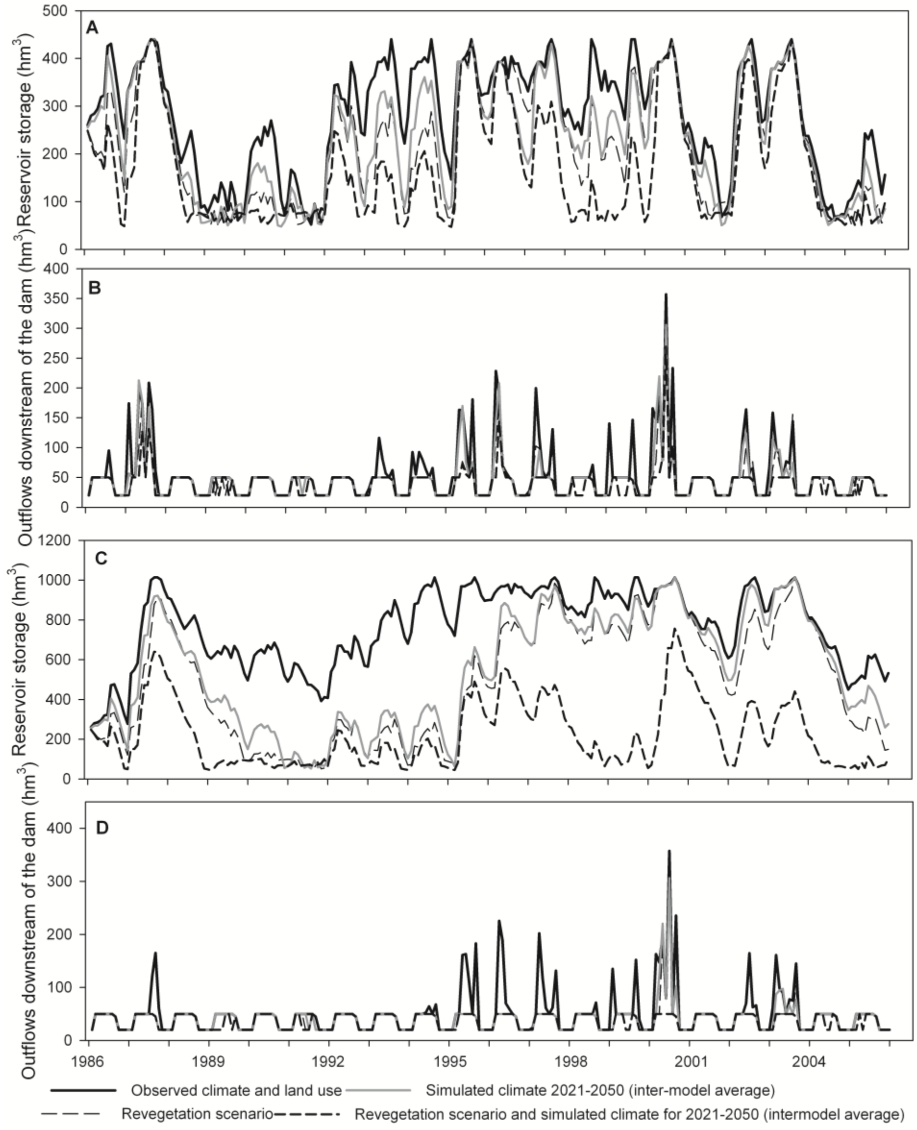

A
B
C
D
Reservoir storage (hm^3)
Outflows downstream of the dam (hm^3)
Reservoir storage (hm^3)
Outflows downstream of the dam (hm^3)
0
100
200
300
400
500
50
150
250
350
600
800
1000
1200
1986
1989
1992
1995
1998
2001
2004
Observed climate and land use
Simulated climate 2021-2050 (inter-model average)
Revegetation scenario
Revegetation scenario and simulated climate for 2021-2050 (intermodel average)

Figure 8

Table 1. Surface area and percentage of each land cover type in the basin under the two scenarios shown in Figure 2.

	Observed Conditions (km^2)	**Scenario of revegetation (km^2)**	**Change in the basin (%)**
Deciduous Broad Forest	56.7 (3.8 %)	56.7 (3.8 %)	0.0
Evergreen Needle Forest	523.5 (35.5 %)	750.9 (51 %)	+15.4%
Quercus Forest	151.6 (10.3 %)	151.6 (10.3 %)	0.0
Pastures	204.5 (13.9 %)	27.18 (1.8 %)	-12.0%
Shrub	182.6 (12.4 %)	232.6 (15.8 %)	+3.4%
Bare Rock	88.8 (6 %)	88.8 (6 %)	0.0
Agricola use	199 (13.5 %)	199 (13.5 %)	0.0
Urban use	6.3 (0.4 %)	6.3 (0.4 %)	0.0
Water	10.1 (0.7 %)	10.1 (0.7 %)	0.0

Table 2. Number of months during the simulation period (20 years) when water restrictions of various levels would be required under observed (OBS), land cover change (LCC), climate change (CC), and combined land cover and climate change (LCC and CC) conditions.

	Current storage capacity (476 hm^3)				Enlarged storage Capacity (1057 hm^3)			
Restriction level	OBS	LCC	CC	LCC and CC	OBS	LCC	CC	LCC and CC
1	0	2	5	6	0	1	2	5
2	0	11	13	23	0	2	2	14
3	0	8	16	56	0	2	8	32
4	0	0	1	7	0	0	0	3
Total	0	21	35	92	0	5	12	54

1: Water released to Bardenas canal for irrigation reduced by 50%.
2: As for 1, and the ecological discharge set at 20 hm^3 for all months of the year.
3: All available water released to Bardenas canal for irrigation, and the ecological discharge maintained at 20 hm^3.
4: All inflow released downstream of the reservoir.