Impacts of climate change on water resources in the Mediterranean Basin: A case study in Catalonia, Spain

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I started this work on May 2013, when I decided to enrol in the Master Programme. I have used as reference the databases and models that I developed during ACCUA project (https://www.creaf.uab.es/accua), in which I was involved for one year and a half. **My contribution to this work** has been: 1) definition of the hypothesis, objectives and methodology; 2) preparation of databases and maps to feed the hydrological model (except the soil map); 3) calibration and validation of the hydrological model based on gauging stations data; 4) adaptation of the climatic scenarios to the local conditions of the study area; 5) hydrological simulations under climate scenarios; 6) generation and interpretation of results; and 7) writing of the document and incorporation of contributors' proposals.

There have been **further valuable contributions** to the preparation of this work that I would like to highlight. Javier Retana, my supervisor, has provided me with scientific support and advice, has developed the statistical analysis and has reviewed several times the manuscript. Eduard Pla (CREAF) has supported me in developing the methodology, preparing the database and the hydrological modelling, and has reviewed the manuscript. Joan Albert Lopez-Bustins (Climatology Group, Barcelona University) has supported me with the climate data and the future climate scenarios and has reviewed the manuscript. Jaume Terradas and Anna Avila (CREAF) have also reviewed the manuscript. The soil maps were provided by the European Topic Centre for Spatial information and Analysis (ETC-SIA) and the climate projections by the Meteorological Service of Catalonia (SMC).

This work meets the format and instructions for the authors provided by the **Hydrological Sciences Journal** (Taylor&Francis publication with an impact factor of 1.114 in 2012). I selected this journal because my work was under the thematic scope of the journal and had an area of application and work scale similar to articles previously published in the journal.

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Most climate change projections show important decreases in water availability in the Mediterranean region by the end of this century. We assess those main climate change impacts on water resources in three medium-sized catchments with varying climatic conditions in north-eastern Spain. A combination of hydrological modelling and climate projections with B1 and A2 IPCC emission scenarios is performed to infer future stream flows. The largest reduction (22-48% for 2076-2100) of stream flows is expected in the headwaters of the two wettest catchments, while lower decreases (22-32% for 2076-2100) are expected in the drier one. In all three catchments, autumn and summer are the seasons with the most notable projected decreases in stream flow, 50% and 34%, respectively (2076-2100). Thus, ecological flows might be noticeably impacted by climate change in the catchments, especially in the headwaters of those wet catchments.

Keywords: climate change; water resources; stream flow; evapotranspiration; SWAT; Mediterranean Basin.

1. Introduction

It is well known that global climate change is the most important environmental threat that mankind currently faces (IPCC 2007a). Climate change will directly affect precipitation and temperature trends. These trends will have substantial effects on local water availability and stream flows (Arnell *et al.* 2011). In parallel, water demands are expected to increase because of population growth and land use changes (Garrido and Iglesias 2007). The Mediterranean area is recognized as one of the regions in the world most affected by climate change (IPCC 2007b). Most climatic models and scenarios predict less precipitation in the Mediterranean area, above all during the warmest six months of the year, and higher mean and maximal temperatures (IPCC 2007b).

Observational studies have already revealed a global trend in the Mediterranean Basin toward warmer conditions during recent decades and changes in seasonal rainfall patterns (IPCC 2007a, Bates *et al.* 2008, Ludwig *et al.* 2011), showing a warming rate higher than the global rate of almost 1ºC for the last century (Martin-Vide *et al.* 2011). Moreover, recent climatic models predict that the climate of the region will become warmer and drier at the end of the 21st century, with changes also in the seasonal distribution of precipitation (IPCC 2007b, EEA 2012). The combination of decreasing precipitation and increasing temperature, and thus increasing potential evapotranspiration (PET), may have a relevant impact on regional hydrological regimes (e.g. Wang *et al.* 2012) and water resources (Ludwig *et al.* 2011). At the same time, land cover changes in the region are increasing the pressure on water resources, mainly because of the increase in vegetation (forests and shrublands), irrigated surfaces and human water demands (Iglesias *et al.* 2007). As a consequence, water availability is expected to decrease noticeably in the region in the coming decades (Bates *et al.* 2008). The recurrence and increasing frequency of drought episodes in the Mediterranean further add to the complexity of water scarcity management, with negative implications for its current and future sustainability (Iglesias *et al.* 2007). Observational series have shown a significant increase in drought frequency in the Mediterranean since 1970 (Hoerling *et al.* 2012), causing high economic damage over the last two decades (CRED 2010).

Several studies have assessed the impacts of climate change on local water resources using a variety of projections and methodologies (e.g. Avila *et al.* 1996, Senatore *et al.* 2011, Hartmann *et al.* 2012, Bangash *et al.* 2013, Koutroulis *et al.* 2013). These studies have applied different downscaling procedures to improve the spatial resolution of the General Circulation Models (GCMs), adapting them to regional and local hydrological conditions. However, research efforts have not been able to lessen the uncertainties about the internal variability of climate, the future projections, the downscaling methods and the use of different hydrological models (Senatore *et al.* 2011, Koutroulis *et al.* 2013). Different hydrological models are currently used to assess climate change impacts on water resources. One of the most widely used models for this purpose is the Soil and Water Assessment Tool (SWAT) hydrological model (e.g. Lu *et al.* 2010, Wang *et al.* 2012, Faramarzi *et al.* 2013, Xu *et al.* 2013). However, this model has rarely been used in studies focused on Mediterranean catchments (Nunes *et al.* 2008).

Catalonia (in the northeast of Spain) provides an interesting case study for evaluating those trends predicted for the Mediterranean Basin, since it covers a high range of climate conditions in a small territory (annual precipitation ranges from 900-1,200 mm in the humid high altitudes to 500-700 mm in the dry coastal areas). Regional studies based on historical meteorological data have already confirmed an upward trend in mean temperature in Catalonia during recent decades (1950-2008) of 0.18-0.23ºC per decade (Llebot 2010). These studies have also revealed a statistically non-significant variation in annual precipitation in the region, and a statistically significant decrease in spring. All these processes, together with the increase in vegetation cover, irrigated surface and urban and tourist-related demands in Catalonia, have driven a general decrease in stream flows and a higher frequency of hydrological droughts (ACA 2009). The current hydrological changes in Catalonia already have several economic and environmental consequences, which may worsen under future climate conditions. Climate change projections for Catalonia developed by the Meteorological Service of Catalonia (SMC) estimate a statistically significant increase in mean annual temperature up to 4.0ºC by the end of the present century, especially in summer months (Barrera-

Escoda and Cunillera 2011). Projections also show a 17% decrease in precipitation and an increase of the frequency of extreme events.

In this article we assess the effects of projected climate changes on the water resources of three medium-sized catchments located in Catalonia. Climate change projections were provided by the SMC for A2 (medium-high) and B1 (medium-low) IPCC scenarios. Then, climate change projections were introduced into the calibrated and validated SWAT hydrological model. The study has three main objectives, focused on its geographic area: (1) to develop a methodology for evaluating climate change effects on modelled water resources at catchment level; (2) to evaluate how climate projections will affect stream flow and evapotranspiration (ET); and (3) to analyse whether the expected reduction of stream flow will compromise the maintenance of ecological stream flows. Ecological stream flow is the reference flow needed to guarantee the quality of freshwater and riparian ecosystems and the compatibility of human water uses in a catchment (ACA 2005).

The results of this study provide important information for water and land managers to understand, locate and quantify the impacts of climate change on water resources. These results may guide managers in implementing the sustainable management objectives of the European Commission's 2000 Water Framework Directive, and in designing and implementing adaptation measures in the study area.

2. Study area

The three study catchments, Fluvià, Tordera and Siurana (Catalonia, north-eastern Spain, Fig. 1) are representative of the Mediterranean's coastal heterogeneity. These three catchments represent a climatic gradient across the Catalan coast, from the humid conditions of Fluvià and Tordera to the semiarid climate of the southern catchment, Siurana. The three catchments internally contain a wide range of altitudes, land uses, pressures and environmental conditions. All three are non-regulated catchments, except for three small reservoirs in the Siurana stream, and they are similar in surface area (i.e., Fluvià: 973 km^2; Tordera: 865 km^2; Siurana: 615 km^2). The Fluvià catchment is highly forested (77% of the surface occupied by forestland) with a substantial surface area also devoted to agriculture (19%) and intensive tourist-related activity near the coast (LCMC 2005). This catchment is characterized by high internal climate variability and land use diversity, from the humid headwaters with annual mean precipitation above 1,000 mm to drier conditions (600-700 mm) at the coastal alluvial flat area (Fig. 1). The Tordera catchment, closer to the Barcelona Metropolitan Area, has a substantial urban and industrial development (9% of the total area). However, this last catchment also displays high forest coverage (81%), with agricultural lands (10%) concentrated in the mid-lands of the watercourse and in the river mouth. Annual mean precipitation (700-800 mm) in the Tordera catchment is lower than in the Fluvià catchment, but it is still representative of humid conditions (annual precipitation higher than 700 mm is considered humid in Catalonia (Llebot 2010)). Finally, the Siurana catchment represents the environmental conditions of southern, semi-arid Catalonia, with a mean precipitation around 500-600 mm. This catchment has a high proportion of croplands (22%) and is also highly forested (76%). The Siurana stream is a tributary of the Ebro River. The population in the Siurana catchment is small and has undergone an intense and continued rural exodus in recent decades, whereas the Fluvià and Tordera catchments have shown noteworthy population increases (Idescat 2012).

3. Material and methods

We evaluate the future impacts of climate change on water resources by simulating the hydrological cycle in the three catchments under different climate change scenarios. The process includes three main steps: 1) setting-up the hydrological model for the historical period (1984-2008) with observed stream flow and climate data; 2) generating climate projections based on the dynamic downscaling performed by the SMC for two IPCC scenarios; and 3) incorporating climate scenarios into the hydrological model to evaluate stream flow and evapotranspiration changes in the short term (2006-2030) and long term (2076-2100).

3.1. Hydrological model

The Soil and Water Assessment Tool (SWAT) (Arnold *et al.*1998) has been used to simulate the hydrological response to climate change. SWAT is a physically based, semi-distributed and continuous hydrological model that estimates surface and subsurface flow, erosion, sediment deposition and nutrient movement within the catchment, at a daily time step (Gassman *et al.* 2007). SWAT is based on the water balance equation in the soil, including processes such as interception, infiltration, surface runoff, evapotranspiration, percolation, lateral flow and groundwater recharge. For a full description of SWAT and its methods, see Neitsch *et al*. (2005). For this study, the surface runoff volume was estimated using a modification of the curve number (CN) method used by the Soil Conservation Service (SCS). PET was calculated using the Penman-Monteith method, whereas lateral flow was predicted through a kinematic storage model and channel flood routing was estimated using the Variable Storage method.

Model outputs used in this study included evapotranspiration (actual evapotranspiration (AET) and PET) and stream flow. Evapotranspiration was selected because of its important role in the hydrological regime in Mediterranean catchments.

For example, in the Catalan forests, evapotranspiration losses account for 70-90% of annual rainfall (Rodà *et al.* 1999). Mean annual and seasonal changes in stream flow were selected to show the effect of climate change on the water resources of the catchments. A specific analysis of the evolution of low stream flows was also carried out to determine the number of days per year with daily stream flow lower than the ecological stream flow. In this study, the ecological stream flow is defined as the amount of water needed to conserve the morphological and hydraulic characteristics of the river, together with the habitability for biological communities and their development. It may also guarantee the compatibility between the human water uses and the water needs for fluvial and environmental quality conservation. For this study, we use the reference ecological stream flow values fixed by the Catalan Water Agency (ACA 2005), which assigns to each river stretch and each month of the year the minimum ecological stream flow required. The ACA has defined the ecological stream flows for 10 locations in the Fluvià catchment, 17 in Tordera and 1 in Siurana. The Siurana catchment, as a tributary of the Ebro River, is managed by the Ebro Hydrographical Confederation, which does not have detailed analysis of ecological stream flows. The ACA has a unique reference value for the Siurana stream, only at its confluence with the Ebro.

3.2. Datasets

SWAT was loaded with climate, topography, land use and soil type data as inputs for the assessment of water resources. The model was then calibrated and verified at a daily time step with historical stream flow and reservoir management data (Siurana catchment) in a 3-year time span within the historical period 1984-2008.

3.2.1. Climate data

Modelling water resources requires long climate series with continuous and reliable precipitation and temperature data. We used a 25-year period (1984-2008) of climate data, the longest time span of reliable data for almost all stations. Daily meteorological data were obtained from stations managed by the Spanish State Meteorological Agency (AEMET) and by the SMC (Fig. 2). Some of the weather stations also provided data on radiation, relative humidity and wind speed, which were included in the model to estimate PET using the Penman-Monteith equation. The stations were chosen according to their locations within or close to the catchments, considering climatic heterogeneity and continuity in data series. We used 9, 8 and 7 weather stations, respectively, for the Fluvià, Tordera and Siurana catchments. As the hydrological model requires continuous daily data, climate series gaps were filled with the weather generator model included in SWAT (Sharpley and Williams 1990). Each catchment was then divided in sub-basins with quite homogeneous topographic characteristics and similar area. We identified 16 sub-basins in the Fluvià catchment, 17 in the Tordera and 15 in the Siurana (Fig. 2). SWAT uses the climate data from the station nearest the centroid of each sub-basin. Most weather stations were located at low altitude, so data underestimate precipitation in mountainous areas. For this reason, climate series were corrected for the effects of topography using GIS techniques. The relationship between climate and topography was derived from the digital elevation model (DEM, 30 m spatial resolution) of Catalonia (Catalan Cartographic Institute, ICC, 2012) and the Digital Climatic Atlas of Catalonia (Ninyerola *et al.* 2000). After gap filling and topography correction, we obtained continuous daily climate series, distributed through the territory per sub-basins, for the 1984-2008 period.

3.2.2. Land use and land cover data

Land use and land cover data were obtained from the Land Cover Map of Catalonia (LCMC 2000, 2 m spatial resolution) developed by CREAF. Land use attributes were taken from the crop and urban database of the SWAT model and adapted to local conditions.

3.2.3. Soil data

Soil data were specifically created for our purposes, using the Catalan Soil Map (1:25.000) (IGC 2012), the Catalan Geological Map (1:25.000) (IGC 2012), the Soil Atlas of Europe (1:1.000.000) (European Soil Bureau Network 2005), local data surveys from the European Soil Database (Joint Research Centre) and private agricultural surveys. The geological and European maps were used to estimate soil parameters where no local soil maps were available. In these cases, geological maps were crossed with the European Soil Atlas, creating different soil classes and adjusting the soil parameters with profile data and regressions. Soils were grouped through cluster analysis to reduce the number of soil classes.

3.2.4. Daily stream flows

Daily stream flows (in m^3s^{-1}) from gauging stations of the ACA were used to calibrate the hydrological model. Data availability depended on the catchments: 4 gauging stations in Fluvià, 6 in Tordera and 2 in Siurana (Fig. 2). Stream flow series were incomplete and of poor quality in some periods, so the hydrological model was calibrated and validated in 3-year periods. In the Siurana catchment, simulations included three small reservoirs. Two of them had daily outflow data from 1984 to 2008. Another one was managed for agricultural purposes and no data were available. This last reservoir was simulated as an uncontrolled one.

3.3. Climate modelling and downscaling

Climate projections were used to analyse the impacts of anthropogenic emissions at a regional or local level. Here, we used two possible emission scenarios defined by the IPCC (2007a): the A2 scenario, which assumes high anthropogenic emissions in a context of greater economic and regional development, and the B1 scenario, which assumes lower emissions in a context of greater environmental and global development. We used the results of the dynamic downscaling performed by the SMC for Catalonia (Barrera-Escoda and Cunillera 2010, 2011). The downscaling was based on the outputs of the atmosphere-ocean coupled model ECHAM5/MPI-OM (Marsland *et al.* 2003, Roeckner *et al.* 2003), developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) and the Max-Planck Institut für Meteorologie in Hamburg.

The dynamical technique of climate downscaling developed by the SMC consisted in the use of the MM5 mesoscale model (Grell *et al.* 1994, Dudhia *et al.* 2005). For evaluating the current climate (1971-2000 period), the MM5 model was fitted with ERA-40 reanalysis data (Kållberg *et al.* 2004) and nested simulations were obtained up to a resolution of 15 km. For projections into the 21st century, MM5 was adjusted to boundary conditions from ECHAM5/MPI-OM (Kållberg *et al.* 2004). Further details in the downscaling procedure can be found in Barrera-Escoda and Cunillera (2011).

The simulated series used for this study provided high temporal (6h) and spatial resolution (15 km) for the reference (1971-2000) and the projected (2001-2100) periods. The simulated hourly data provided by the SMC were transformed into daily data. A direct scale factor at daily resolution was applied to these simulated series in order to correct the divergence between real and simulated data (Lenderink *et al.* 2007). The values of the direct scale factor were obtained from the 1984-2000 common period of instrumental series of the weather stations in Figure 2 and simulated series for the reference period. We then introduced these scaled series into the SWAT program to obtain daily continuous series for each sub-basin for the study baseline period and the future period (1984-2100).

3.4. SWAT calibration, validation and simulations with climate projections

Model calibration was carried out at a daily time step with three main objectives: (1) to compare simulated curves generated with SWAT with those measured in the gauging stations, (2) to compare mean flow values and total contributions between simulated and measured data, and (3) to check the quality of data with the Nash-Sutcliffe efficiency (NSE) coefficient and the RMSE-observations standard deviation ratio (RSR), following Moriasi *et al.* (2007). The NSE coefficient and the RSR ratio equations and the statistics performance ratios are shown in Table 1.

Sensitivity analysis and preliminary model trials were developed using the Sensitivity Analysis Tool provided by SWAT (Van Griensven 2005) to identify the most influential parameters, which were adjusted during the calibration. These were parameters related to base flow generation, surface runoff and catchment response.

Calibration was performed both manually and through the SWAT Calibration and Uncertainty Program (SWAT-CUP, Abbaspour 2013) in 3-year periods. In a first stage, the SWAT Manual Calibration Helper was used to adjust the most sensitive parameters to a range of values. In a second stage, parameters were adjusted using SWAT-CUP and the range of values previously defined, estimating the best fit possible. A final manual calibration with the SWAT Manual Calibration Helper was needed to adjust by trial and error some parameters. For this calibration, water extractions for urban, industrial and agricultural uses were considered as consumptive water and removed from the catchment. In the Fluvià catchment, consideration was also given to the subterranean water transfer from the high watercourse to different points of the medium watercourse and to outside transfer beyond the southern limits of the catchment equivalent to 12 hm^3 per year (EPTISA 1988).

Figure 3a shows calibration outputs for daily stream flow (m^3s^{-1}) for one gauging station per catchment, usually the closest to the river mouth (Garrigàs in Fluvià, Can Simó in Tordera, and Cornudella de Montsant in Siurana, Fig. 2). The graphical comparison between simulated and measured data showed a good fit, although in all three catchments simulations underestimated high flood peaks and slightly overestimated base flows. One explanation could be the high spatial variability of the precipitation in the area, where the complex mountainous landscape causes orographic precipitation or convective phenomena that affect the climate (Barrera-Escoda and Cunillera 2011). This means that the precipitation measured in the weather station may be different than the total registered in the upstream area of the gauging station. Another reason can be the low capacity of the SWAT model structure to adequately account for hydrological extreme events (Ndomba *et al.* 2008). Table 2 compares simulated and measured stream flow data per catchment and per calibration period. In Fluvià and Tordera, simulations overestimated mean daily stream flow values (by 27 and 23%, respectively). The NSE and RSR statistics show a satisfactory fit, but the calibration was performed at a daily, instead of monthly, time-step; daily calibration leads to worse statistics due to the large increase in the size of samples for daily data (Moriasi *et al.* 2007).

The validation measures the model prediction capacity through the comparison between simulated results and measured data in a time period different from the calibration. Figure 3b and Table 2 show validation results per catchment and period at a daily time-step. As in the case of the calibration, simulations overestimated mean stream flow values, although in a lower percentage (20% in Fluvià and 8% in Tordera). Statistics showed a satisfactory fit, except in the Tordera catchment, where NSE was lower than 0.5 (Table 2).

Table 3 shows validation results at a monthly time-step for the whole period (1986-2008). Monthly stream flow data were estimated as mean value of daily stream flow per month, whenever daily data for the whole month were available. In the stations under study, monthly data for the whole period (1984-2008) were only available for Garrigàs (276 months in total), while the Can Simó station (Tordera catchment) had data for 125 months (45.3% out of the total) and the Cornudella station (Siurana catchment) for 129 months (46.7%). Both NSE and RSR statistics showed very good performance ratio for the Tordera catchment and good performance for both Fluvià and Siurana.

Simulations with climate projections considered land-use covers as constant throughout the 21st century. Due to the lack of water demand estimations for the 21st century, water extraction was not considered in the simulations of future conditions. Reservoirs were simulated as uncontrolled and mean daily outflow was fixed to a reference value, the ecological outflow, due to a lack of information about future reservoir regulations. ANOVA test was carried out for the comparisons between the values obtained in the short (2006-2030) and long term (2076-2100) periods of the two climate change scenarios (B1 and A2) with those of the baseline period (1984-2008).

4. Results

4.1. Climate change projections for the study areas

Projected average values of precipitation and temperature per each period (short term, 2006-2030, and long term, 2076-2100) and the projected variations with respect to the baseline period (1984-2008) are given in Table 4 for each catchment and scenario.

According to the projections, similar patterns are observed among the three catchments, with a general reduction in precipitation and a general increase in temperature, which are more accentuated in the less favourable scenario (A2) than in the lower emissions one (B1). Expected precipitation decreases in B1 oscillate between 4.7-6.0% in 2006-2030 and 15.0-17.4% at the end of the 21st century. Higher reductions are expected for A2: 5.9-6.9% for the period 2006-2030 and 22.0-26.2% for the period 2076-2100. A slight temperature increase by a similar amount (0.3-0.7ºC) is projected for the three catchments and the two scenarios (B1, A2) in the short term. At the end of the century, the temperature is expected to increase between 2.3-2.4ºC for B1 and 3.4-3.6ºC for A2.

4.2. Impacts of climate change on the hydrological regime

Hydrological simulations with climate projections showed a strong alteration in water dynamics in the three catchments during the 21st century. A generalized decrease in AET and stream flow, together with an increase of PET, is expected.

Table 5 shows the expected changes in AET and PET in the short term (2006-2030) and long term (2076-2100), compared with the baseline period (1984-2008). The expected temperature increase will contribute a 1.3-3.7%-increase in PET in the short term and a 12.7-23.8%-increase in the long term for both scenarios. The highest PET increases are expected in the wettest catchment, Fluvià, in the long term and for the A2 scenario, where a higher reduction of relative humidity is projected. Although PET will increase with the raise of temperature, AET will be reduced along the 21st century because of the expected precipitation decrease. Estimated AET-reductions are 1.8-7.0% in the short term and 12.8-20.5% in the long term, considering both scenarios. The highest AET reductions are projected in the drier catchment, Siurana, under the A2 scenario.

Table 6 shows the percentage of stream flow change per climate scenario at a headwaters sub-basin and at the river mouth of each catchment. Model simulations predict a significant decrease in stream flow over the course of the 21st century. Along a latitudinal gradient, the most drastic reductions are seen in the headwaters of the northern catchments (Fluvià and Tordera), while reductions are less severe in the southern catchment (Siurana). Under the B1 scenario, annual stream flow is projected to decline at the Fluvià and Tordera river mouths by 9% and 22-25% for the short and long terms, respectively. In the Siurana catchment, the scenario B1 predicts a slight stream flow increment in the short term at the headwaters and river mouth (4-5%) due to an expected precipitation increase between 2025 and 2050. Under the A2 scenario, more pronounced reductions are expected at the three river mouths, around 14-17% in the short term and 33-39% in the long term. The highest climate change effect is observed in the Fluvià headwaters, with a 48%-reduction in stream flow at the end of the century for the A2 scenario. ANOVA test indicated a significant decreasing trend for the long term period and both scenarios (p-value<0.05), except for the Siurana catchment under the B1 scenario. At the short term, expected changes are not statistically significant although they follow the same decreasing trend. This fact can be explained by the own climatic projections, where the majority of models foresees the most substantial changes by the end of the present century.

Figure 4 shows the distribution of stream flow reduction among seasons in the short and the long terms. In the short term, the simulations show a different trend for Tordera and Fluvià when compared with Siurana. For the wet catchments, Fluvià and Tordera, the largest reductions of stream flow are expected in spring (March, April and May) and summer (June, July and August) in scenario B1; whereas in A2 winter (December, January and February), spring and summer will undergo about 21% reduction in stream flow, 19% and 12%, respectively. Slight increases are expected in the Tordera catchment in winter and autumn (September, October and November) in the B1 scenario. Siurana shows a different trend in the short term, with increases in winter and autumn under B1, and larger decreases in the same seasons in A2. In the long term, autumn, summer and spring will show the stronger stream flow reduction in the B1 scenario for the three catchments. Slight increases are expected in winter in the Fluvià and Siurana catchments in the B1 scenario. Under the A2 scenario, general reductions are expected in all seasons.

Figure 5 shows the changes in the mean number of days per year and per period in which the circulating flow in the main courses is lower than the ecological stream flow. According to the baseline period, a significant number of river stretches of the three catchments, mainly in the headwaters, do not guarantee the minimum stream flow necessary to preserve the quality of the fluvial ecosystems. The B1 and A2 climate scenarios during the 21st century will affect the number of days per year when the stream flow will be lower than the ecological stream flow. In the short term, no significant changes are expected compared to the baseline period in both scenarios. The main courses of Fluvià and Tordera do not vary with respect to the baseline period, whereas the headwaters of both catchments and the Siurana catchment show a maximum increase of 30 days over the baseline period in both scenarios. In the long term, however, significant increases in the number of days are expected, especially in the headwaters of the wet catchments: models project more than 60 and 90 days in the Tordera and Fluvià catchments, respectively, in the A2 scenario. In the Siurana catchment, an increase of more than 60 days is expected for the end of the century in the same scenario. The B1 scenario shows a more moderate increase in the number of days than the A2 scenario.

5. Discussion

Our results suggest that water resources in Mediterranean catchments will be markedly modified by the predicted changes in climate at the end of the present century. Rise in temperature has a direct influence on PET, increasing vegetation water demands under drier conditions and, thus, reducing vegetation growth. AET will be reduced and, in consequence, soil water will not be sufficient to cover vegetation needs, thus limiting plant growth and development. In our assessment, the highest PET increase is expected in the wettest catchment, Fluvià, caused by a large decrease in relative humidity. The highest AET reduction is projected in the driest catchment, Siurana. PET increase and AET decrease are mainly determined by the expected rise in temperature and decrease in precipitation. These changes will affect the availability of water for the vegetation, not only by limiting vegetation growth and development (Vicente-Serrano *et al.* 2013), but also by affecting vegetation distribution and phenology, and by advancing or retarding the processes of the vegetation annual cycle such as flowering, pollination or fructification (Giannakopoulos *et al.* 2009).

In addition to changes in evapotranspiration, daily stream flow will decrease for the three catchments throughout the 21st century. A different trend was observed when comparing wet (Fluvià and Tordera) and dry (Siurana) catchments, with less severe reductions in the dry areas compared to wet ones. Similar stream flow reductions have been predicted for the end of the 21st century in other Mediterranean catchments. Thus, Senatore *et al.* (2011) inferred an overall reduction in the average yearly runoff from -25.4±6% to -41.2±5% (depending on the GCM used) for the Crati catchment in southern Italy. On the Island of Crete (Greece), a 33-48% decrease in the average water availability was estimated (scenario A2) by Koutroulis *et al.* (2013). In Catalonia, north-eastern Spain, a reduction between16% and 28% of the mean annual stream flows of the Catalan catchments is expected (ACA, 2009). Early studies in the Tordera headwaters projected a 30% stream flow decrease and a 13% PET increase for the end of the present century (Avila *et al.* 1996).

Our model also shows relevant seasonal changes in stream flow. Changes in seasonal stream flow may have important consequences in water supply for the environment and for agricultural and urban uses (Schröter *et al.* 2005), especially during dry seasons. Large reductions are expected in summer, the dry season within the Mediterranean climate domain, when water demands for irrigation (Rosenzwieg and Tubiello 1997) and tourism (Rico-Amorós *et al.* 2009) are heightened. Major reductions are also predicted in spring and autumn, which may have important consequences for natural and agricultural ecosystem functions (Miranda *et al.* 2011).

Climate change will also affect the minimum stream flow running in the main courses. In an ecological sense, expected stream flow reduction would imply longer periods in which stream flow would be lower than the ecological flow, affecting stream environment quality (Bates *et al.* 2008). Changes in ecological stream flow may affect species composition, biodiversity, productivity and life cycle of many aquatic species (Poff *et al.* 2002). The observed stream flow reduction in the Tordera River during the 20th century caused by water abstraction has led to a reported reduction in fish population densities, the number of benthic species and the occurrence and abundance of intolerant species (Benejam *et al.* 2010). Our results showed a strong increase by the end of the present century in the number of days per year with stream flow below the ecological flow. This trend was more evident in the headwaters of the Fluvià and Tordera catchments and in the whole Siurana catchment.

These climate change impacts will have a corresponding effect on water resources, ecosystems and sectors that need to be assessed in depth. Thus, a significant stream flow decrease will affect the recharge of the aquifer and the stream-aquifer relationship (Garrido and Iglesias 2007). The increase of environmental aridity, together with the expected changes in seasonal climatic variability, would affect woodland development and climatic suitability of some forest species (Serra-Diaz *et al.* 2012). These future impacts of climatic change would affect plants with growth and reproduction triggered by environmental conditions such as temperature or water availability. It would also disturb forest and other ecosystems functions, with a likely loss in biodiversity and increase in forest decline (Sarris *et al.* 2007) and forest fire risks (Moriondo *et al.* 2006). Phenological changes, together with lower water availability, may lead to changes in crop species and varieties, agronomic techniques and calendar (Giannakopoulos *et al.* 2009).

This type of assessment has to deal with a cascade of uncertainties associated with the different steps of the methodology: the uncertainty of climate projections, the uncertainty of the climatic downscaling procedures, and the uncertainty of the hydrological model, its ability to reproduce the reality and the quality of the input data for calibration and validation. Moreover, this assessment considers hydrological parameters and land cover as constant throughout the 21st century. To counteract this, our climate projections included two contrasted emissions scenarios, B1 and A2, in order to consider a range of future storylines that reduces the associated uncertainty. The downscaling procedure used by the SMC follows a standard process widely extended in similar studies. The SWAT hydrological model has been broadly applied, obtaining similar model fittings and statistics for North-American, African and Asian case studies (Lu *et al.* 2010, Wang *et al.* 2012, Faramarzi *et al.* 2013, Xu *et al.* 2013), enhancing SWAT as a useful tool to analyse the expected impacts of climate change on water resources. Future improvement of this assessment is needed to reduce uncertainties, including a larger spectrum of climate projections, the consideration of land use and water use scenarios and the effects of increased atmospheric CO_2 concentration on stream flow.

6. Conclusions

The consequences of climate change on water resources in three medium-sized Mediterranean catchments in Catalonia (north-eastern Spain) include a strong alteration in water dynamics over the course of the 21st century. Results highlight a future general reduction in stream flow during the present century, more accentuated in the headwaters of the wet catchments (Fluvià and Tordera) and in autumn and summer seasons. The expected reduction in evapotranspiration during the current century will affect vegetation growth, development and distribution. Moreover, the quality of the riparian ecosystems will be deteriorated by the increasing frequency of stream flows below ecological stream flows.

Our analysis reveals a greater vulnerability of wet catchments in northern Catalonia, which might be deeply affected by climate change despite their apparently good hydrological status. The ecosystems in these wet catchments appear to be more sensitive to changes in environmental conditions than the dry ones, which are likely to be better adapted to dry conditions.

The results of this study provide detailed and local information for water managers to identify major impacts of climate change on water resources at regional and local scale. This impact identification and quantification is the key to designing adaptation measures to face climate change threats. This study reflects the importance of incorporating these analyses into adaptive management in the Mediterranean region.

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Tables

Table 1 Equations for the statistics Nash-Sutcliffe efficiency (NSE) coefficient and RMSE-observations standard deviation ratio (RSR) and general performance ratings for the statistics for a monthly time step. Y_i^{obs} is the ith observation values sample for the constituent being evaluated, Y_i^{sim} is the ith simulated sample for the constituent being evaluated, Y^{mean} is the mean of observed data for the constituent being evaluated, and n is the total number of observations.

Performance rating	$RSR = \left[\frac{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}}{\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2}} \right]$	$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y^{mean}\right)^2} \right]$
Very good	0.00 ≤ RSR ≤ 0.50	1.00 ≤ NSE < 0.75
Good	0.50 < RSR ≤ 0.60	0.75 ≤ NSE < 0.65
Satisfactory	0.60 < RSR ≤ 0.70	0.65 ≤ NSE < 0.5
Unsatisfactory	RSR > 0.70	NSE ≤ 0.5

Table 2 Calibration and validation results at a daily time step: mean daily stream flow values (Qd) from both simulated and measured data and statistics in each catchment and period.

	Calibration					Validation				
	Period	Simulated Qd (m^3s^{-1})	Observed Qd (m^3s^{-1})	Statistics NSE	Statistics RSR	Period	Simulated Qd (m^3s^{-1})	Observed Qd (m^3s^{-1})	Statistics NSE	Statistics RSR
Fluvià, Garrigàs	1987-1989	9.1	7.1	0.5	0.7	1985-1987	8.5	7.1	0.5	0.7
Tordera, Can Simó	1996-1998	5.0	4.1	0.5	0.7	2002-2004	5.1	4.8	0.4	0.7
Siurana, Cornudella	1991-1993	0.2	0.2	0.6	0.7	1994-1996	0.4	0.3	0.7	0.6

Table 3 Validation results at a monthly time step: monthly mean of daily stream flow values (Qm) from both simulated and measured data and statistics in each catchment.

	Period	Simulated Qm (m^3s^{-1})	Observed Qm (m^3s^{-1})	Statistics NSE	Statistics RSR
Fluvià, Garrigàs	1986-2008	8.5	7.3	0.7	0.5
Tordera, Can Simó	1986-2008	3.9	3.5	0.8	0.4
Siurana, Cornudella	1986-2008	0.3	0.2	0.7	0.6

Table 4 Mean precipitation and temperature values per time span and per scenario. Precipitation and temperature changes are also shown.

		Mean annual precipitation			Mean annual temperature		
Catchment	Scenario	Reference period (1984-2008)	Short term (2006-2030)	Long term (2076-2100)	Reference period (1984-2008)	Short term (2006-2030)	Long term (2076-2100)
Fluvià	B1	1044.8	983.1 (-6.0%)	863.0 (-17.4%)	13.0	13.7 (+0.7ºC)	15.3 (+2.4ºC)
	A2		972.8 (-6.9%)	771.3 (-26.2%)		13.4 (+0.5ºC)	16.5 (+3.6ºC)
Tordera	B1	803.1	759.7 (-5.4%)	683.0 (-15.0%)	14.0	14.7 (+0.6ºC)	16.4 (+2.3ºC)
	A2		750.9 (-6.5%)	626.4 (-22.0%)		14.3 (+0.3ºC)	17.5 (+3.4ºC)
Siurana	B1	543.2	517.9 (-4.7%)	451.2 (-16.9%)	14.7	15.4 (+0.7ºC)	17.0 (+2.4ºC)
	A2		511.2 (-5.9%)	420.7 (-22.6%)		15.1 (+0.4ºC)	18.2 (+3.6ºC)

Table 5 Expected potential and actual evapotranspiration (PET and AET) change (%) per climate scenario, period and catchment compared to the baseline period (1984-2008)

		PET		AET	
Catchment	Scenario	Short term (2006-2030)	Long term (2076-2100)	Short term (2006-2030)	Long term (2076-2100)
Fluvià	B1	+3.4%	+13.2%	-1.8%	-12.8%
	A2	+1.9%	+23.8%	-3.1%	-13.8%
Tordera	B1	+3.4%	+12.7%	-4.2%	-12.9%
	A2	+1.3%	+18.0%	-4.6%	-19.0%
Siurana	B1	+3.7%	+13.3%	-7.0%	-15.1%
	A2	+2.5%	+20.3%	-4.8%	-20.5%

Table 6 Expected stream flow change (%) per climate scenario, period and headwaters/river mouth compared to the baseline period (1984-2008). Statistically significant changes using the ANOVA test are indicated in brackets: * p-value<0.05, ** p-value <0.01 and *** p-value < 0.001.

Catchment	Scenario	Short term (2006-2030)		Long term (2076-2100)	
		Headwaters	River mouth	Headwaters	River mouth
Fluvià	B1	-14%	-9%	-31% (**)	-22% (*)
	A2	-20%	-14%	-48% (***)	-39% (***)
Tordera	B1	-9%	-9%	-22% (*)	-25% (*)
	A2	-13%	-17%	-33% (**)	-37% (**)
Siurana	B1	+4%	+5%	-22%	-22%
	A2	-16%	-16%	-32% (*)	-33% (*)

Figures

Fig. 1 Location and mean annual precipitation (in mm) of the three catchments selected in Catalonia (north-eastern Spain) for the 1951-2000 period.

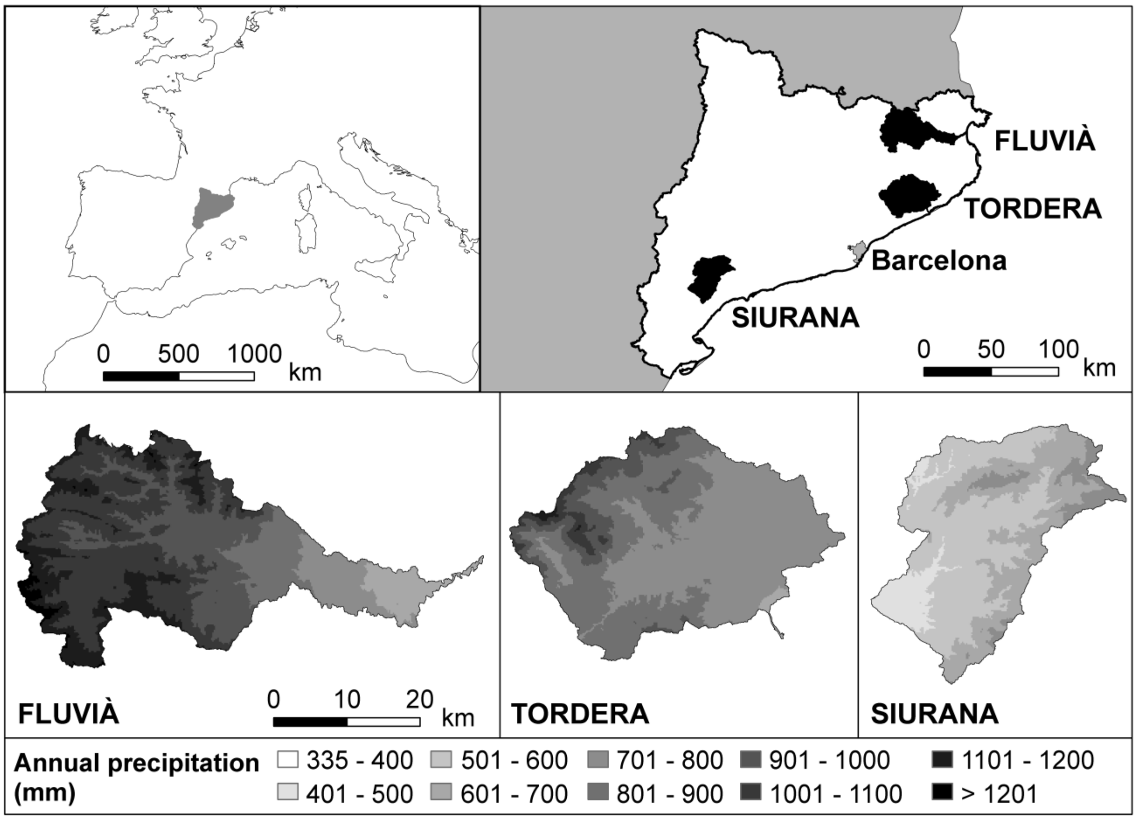

Fig. 2 Weather stations selected for historical data of precipitation and temperature, gauging stations selected to calibrate and validate the hydrological model, and the sub-basins identified from SWAT in the three catchments. The marked gauging stations (Garrigàs, Can Simó and Cornudella de Montsant) are considered in the results for SWAT calibration and validation.

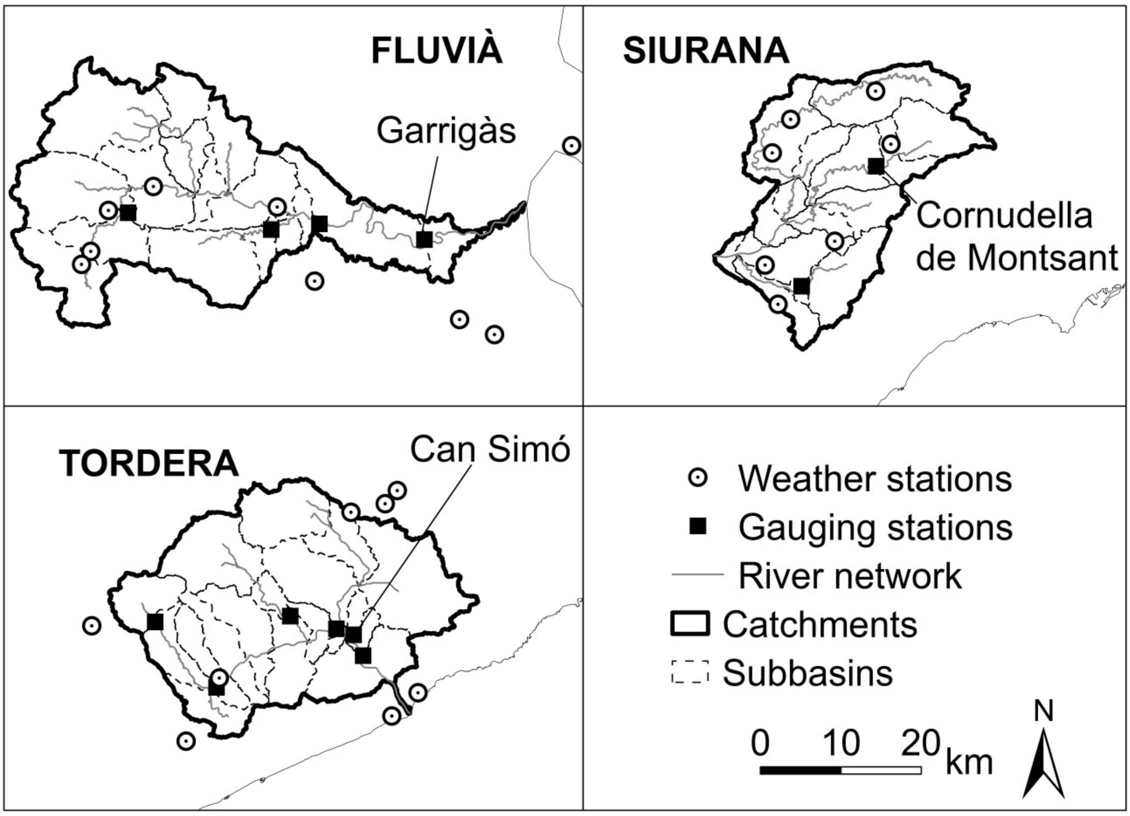

Fig. 3 3a (left): Calibration results at a daily time-step: measured (grey line) and simulated (black dashed line) daily stream flow (Qd) at three points, one per catchment: Garrigàs at Fluvià (1987-1989), Can Simó at Tordera (1996-1998) and Cornudella de Montsant at Siurana (1991-1993). 3b (right): Validation results at a daily time-step: measured (grey line) and simulated (black dashed line) daily stream flow (Qd) at three points, one per catchment: Garrigàs at Fluvià (1985-1987), Can Simó at Tordera (2002-2004) and Cornudella de Montsant at Siurana (1994-1996).

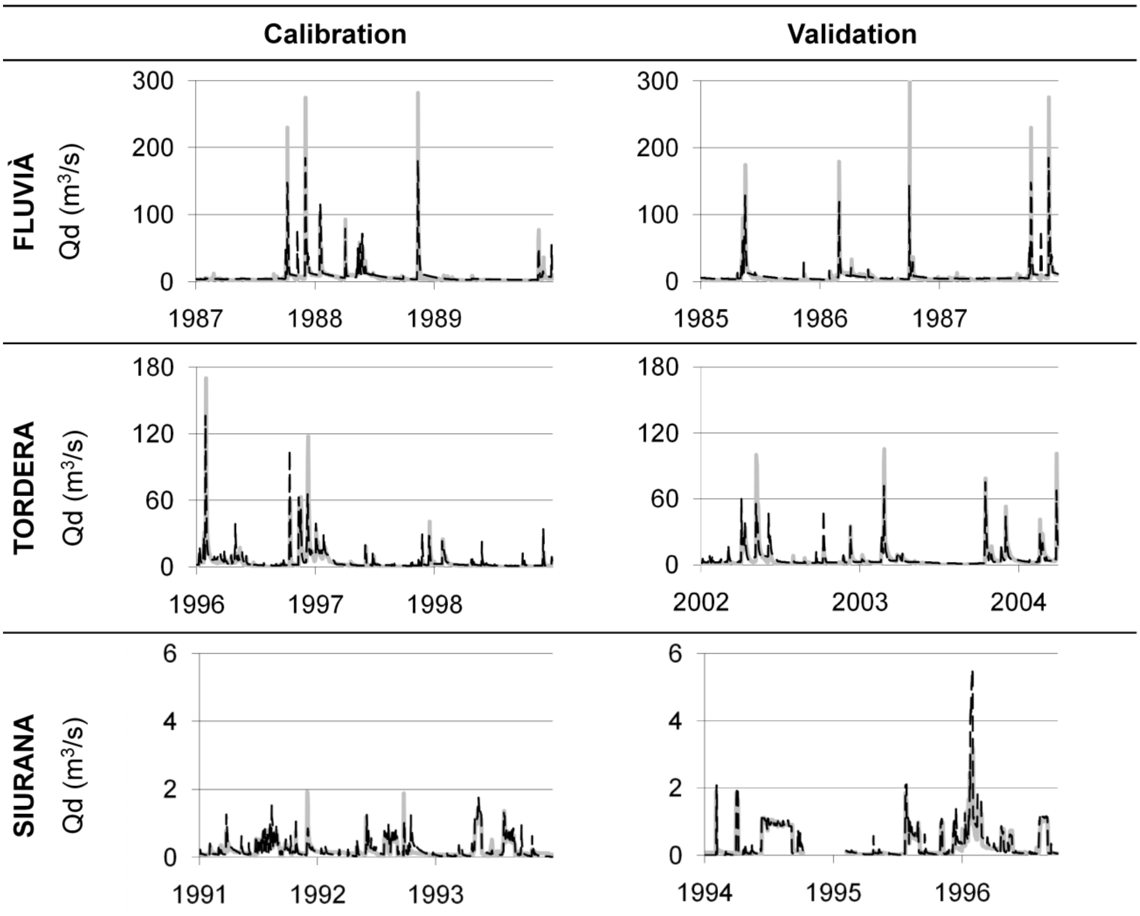

Fig. 4 Expected daily stream flow (Qd) change (%) for B1 (grey columns) and A2 (black column) scenarios, period and catchment per season (Win: winter, Spr: spring, Sum: summer, Aut: autumn) compared to the baseline period (1984-2008).

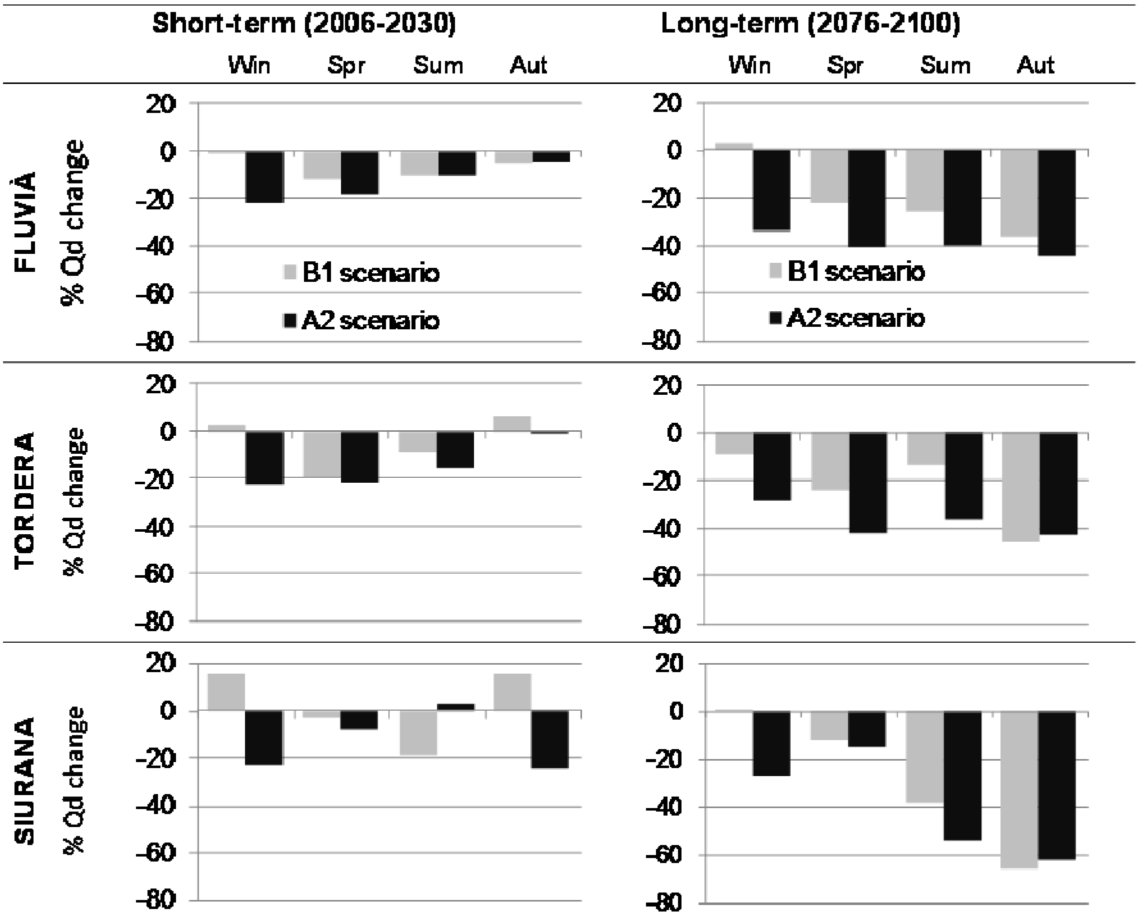

Fig. 5 Changes in the ecological stream flow in the three catchments: Number of days per year with a stream flow lower than the ecological flow for the baseline period (1984-2008), short term (2006-2030) and long term (2076-2100) for the B1 (5a, up) and A2 (5b, down) scenarios.