MEDACC

Demonstration and validation of innovative methodology for regional climate change adaptation in the Mediterranean area

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Impacts of climate and global change on the environmental, hydrological and agriculture systems in the LIFE MEDACC case study basins

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Executive summary

This deliverable contains the results and conclusions of the assessment of climate and global change impacts on the environmental, hydrological and agriculture systems in the LIFE MEDACC case study basins: Muga, Ter and Segre. This deliverable only displays the results of the assessment, whereas the methodology followed and the input data used can be consulted at the *Deliverable 13 Methodology to assess climate change impacts in the LIFE MEDACC case study basins: Generation of scenarios, vulnerability maps and quantification of impacts (Pascual et al. 2016).*

The first section makes a general introduction to the deliverable objectives. The second section delves into how the climate would be under the RCP4.5 scenario in the three case-study basins. The third section draws future socioeconomic scenarios for the basins. We have developed three land cover scenarios for the headwaters (afforestation, fire and forest management scenarios) and two water use scenarios for the medium and low basin courses (rational use of water resources and increased demand scenarios). The fourth section evaluates the future effects of the combined scenarios in the water cycle and dynamics of the three basins. To do so, we have introduced the climate and socioeconomic scenarios into the calibrated and validated hydrological models (RheSSys and SWAT). The fifth section foresees future changes in agriculture suitability, crop production and growing cycle using net irrigation needs (NIR) of major crops and a set of agroclimatic parameters. Finally, the sixth section evaluates the effects of climate change on forests by inducing climate change into the GOTILWA+ model and estimating future daily DC values for the climate scenario.

Contents

1. Introduction

One of the objectives of LIFE MEDACC project is the assessment of the impacts of climate and global change in the three case-study basins: Muga, Ter and Segre. This deliverable contains the results and conclusions of the assessment of climate and global change impacts on the environmental, hydrological and agriculture systems in the three basins.

The consequences of global warming impacts on agriculture, water resources management and ecosystems pose particular concern in the Mediterranean climates in the transition zone between the arid climate of North Africa and the temperate climate of central Europe. The Mediterranean region, characterized by a double stress (long and hot summers and cold or very cold wet winters; Terradas and Savé, 1992), is potentially highly vulnerable to existing adverse trends of warming and rainfall reduction and will likely be the region within Europe to firstly experience severe economical and sociological consequences from climate change. Observational studies have already revealed a global trend toward warmer conditions during the last decades and changes in rainfall seasonal patterns in the region (IPCC 2007, Bates et al. 2008, Ludwig et al. 2011). At the same time, land cover change processes are showing a general increase of the forests and the irrigated lands, which have increased the water demand, given the increased evapotranspiration rates of these land cover types (Iglesias et al. 2007). All these processes are driving a decrease of the water availability in large regions of the Mediterranean, which is expected to be more severe in the coming decades (Bates et al. 2008, Mariotti et al. 2008) and the management of water resources affects the vulnerability of natural ecosystems, socio-economic activities and human health.

The significant vulnerability of water resources, agriculture and forestry to climate variability makes these sectors highly susceptible to climate and global change projections for Catalonia. For this reason, an accurate quantification of the impacts of climate and global change scenarios on these sectors, using a **multidisciplinary approach is essential to identify vulnerabilities and design adaptation measures**, ensuring a successful impact of the project results.

For our multidisciplinary approach, we have developed the following steps:

- Regional downscaling at basin scale of the IPCC RCP4.5 scenario.
- Design of ad hoc of socioeconomic scenarios: three land cover scenarios for the headwaters (afforestation, fire and forest management scenarios) and two water use scenarios for the medium and low basin courses (rational use of water resources and increased demand scenarios).
- Calibration and validation of two hydrological models (RHESSys and SWAT), one agriculture model, one forest model (GOTILWA+) and one index of forest fire risk (Drought Code).
- Incorporation of climate and socioeconomic scenarios into the models to evaluate future impacts of climate and global.

This deliverable delves into the results and conclusions of the assessment of climate and global change impacts on the environmental, hydrological and agriculture systems in the LIFE MEDACC case study basins: Muga, Ter and Segre. The methodologies followed by the project and the input data used in the modelling can be consulted at *Deliverable 13 Methodology to assess climate change impacts in the LIFE MEDACC case study basins: Generation of scenarios, vulnerability maps and quantification of impacts (Pascual et al. 2016).*

2. How would be the climate?

2.1. Introduction

All the reports about climate noted that the temperatures have increased during the last decades, and 2001 to 2010 was the warmest period ever recorded and most climate models forecast an increase in temperature and a decrease in precipitation at the end of the 21st century. But the changes in precipitation are subject to greater uncertainty. It is expected, as the greenhouse gas emissions continue as now, that this trend will be the same (even worse) for the next years. This warming is spread around the world and the Mediterranean area is one of the most vulnerable regions in the world to the impacts of global warming. There are too many implications about the global warming as human health or ecosystems and also for many socioeconomical sectors as agriculture, tourism or energy production.

The increase of temperatures affects directly to mountains, which are considered the great reservoirs of fresh water for the lowlands (Viviroli, 2007), bringing forward the date of snow melt and its direct consequence on river regime. In the study area of MEDACC-Life Project the water is a key aspect, either for the water scarcity expected is a direct consequence of global change and the southern Europe is one of the areas with a high risk to droughts, which is a direct impact to citizens. As is explained in García-Ruiz et al (2011), the future scenarios for water resources in Mediterranean region suggest:

- *a progressive decline in the average streamflow (already observed in many rivers since the 1980s), including a decline in the frequency and magnitude of the most frequent floods due to the expansion of forests;*
- *changes in important river regime characteristics, including an earlier decline in high flows from snowmelt in spring, an intensification of low flows in summer, and more irregular discharges in winter;*
- *changes in reservoir inputs and management, including lower available discharges from dams to meet the water demand from irrigated and urban areas;*
- *hydrological and population changes in coastal areas, particularly in the delta zones, affected by water depletion, groundwater reduction and saline water intrusion. These scenarios enhance the necessity of improving water management, water prizing and water recycling policies, in order to ensure water supply and to reduce tensions among regions and countries.*

In this report the precipitation and temperature are analyzed for the period 2012-2050. As is explained in Deliverable 13, the changes applied to the series are based on The Third Report on Climate Change in Catalonia (TICCC) for feed the SWAT and RHESsys models. The Results show a clear trend to the increase of the temperatures and decrease of precipitation that are commented below. Is well known that climate and its interactions with other variables as soils and vegetation is basics to understand the changes in ecosystems and responses to any change. So, the development and analysis of climate series is very important to understand the evolution of streamflow, forest and agricultural systems of the studied basins in MEDACC-Life (Muga, Ter and Segre). All the analysis of the climate series compare the calibration period (2002-2011) with the periods 2021-2030 and 2031-2050.

2.2. Results

2.2.1. Changes in precipitation

For the studied period (2012-2050), average annual precipitation over Catalonia is expected to decrease by roughly 9% (Pyrenees: -9.9%, Inland: -7.7%, Coast: -8.9%). This decrease reflects, in part, that droughts periods are expected and considering the expected increase of the temperatures (as explained below), the scenario is not very positive. On Figure 1 is showed regional averages (each for the climatic areas) of total annual precipitation.

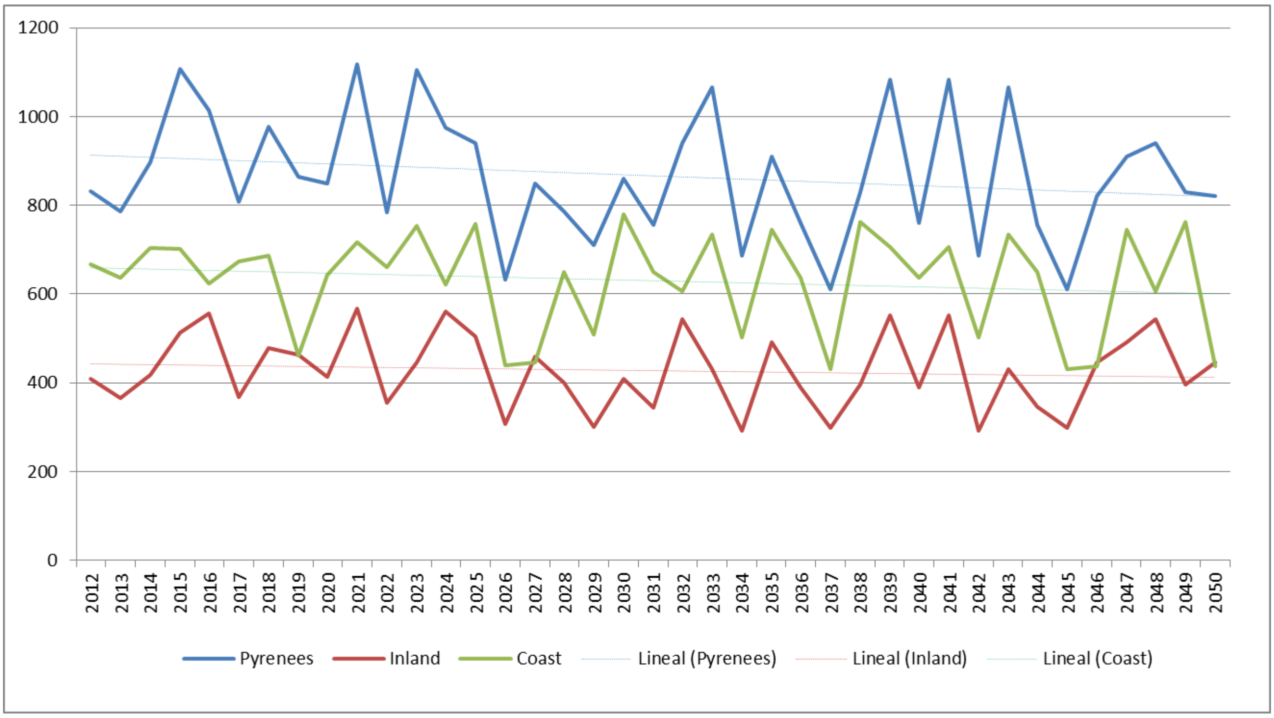


Figure 1. Total annual precipitation (2012-2050) in Catalonia climatic areas.

On Figure 2 is showed seasonal precipitation for 2012-2050 (compared to 2002-2012) as projected by the TICC. As expected, a negative trend is showed excepting the winter precipitation of Inland (+5.3%). The decrease of precipitation along first decades of XXI century is spread over the studied area being the Pyrenees the area where this trend is more marked. In addition, in autumn is where the most pronounced declines are registered as is also explained in Table 1 (-15.1% Pyrenees, -14% Inland, -11.6%). In short, high decrease in the mountains and in autumn, do not bode well about water resources, soil water content, forest development and agricultural systems.

	Pyrenees	Inland	Coast
Annual	**-9.9**	**-7.7**	**-8.9**
Winter	-8.6	5.3	-9.4
Spring	-11.1	-2.2	-6.7
Summer	-5.8	-9.2	-3.3
Autumn	-15.1	-14.3	-11.6

Table 1. Seasonal precipitation changes.

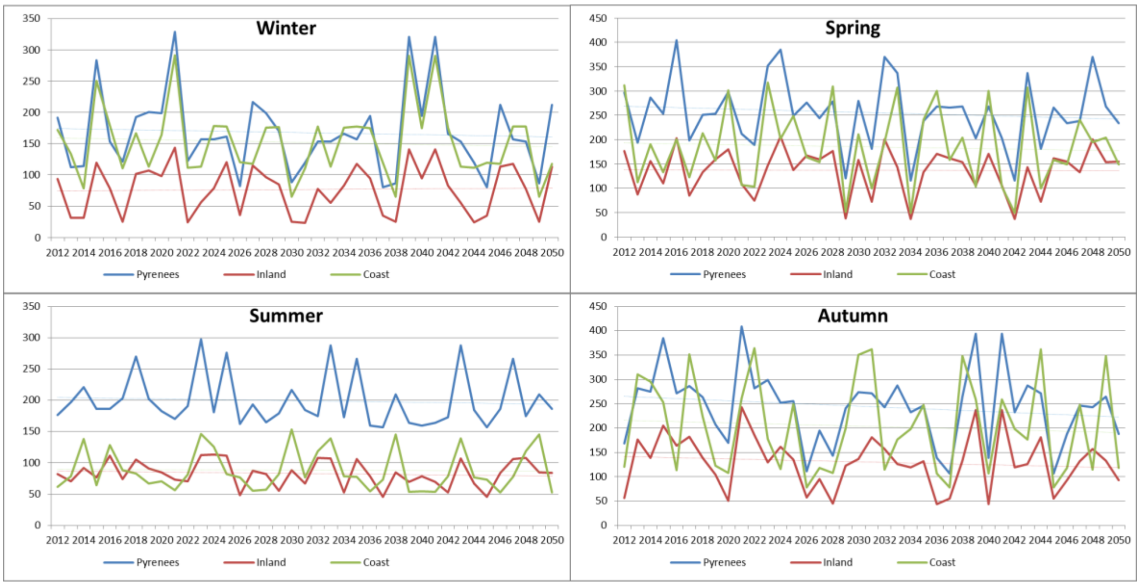


Figure 2. Seasonal precipitation (2012-2050).

2.2.2. Changes in temperature

The change in temperature established in TICC is +0.8 and + 1.4 ºC for 2012-2020 and 2031-2050 periods, respectively, being 1971-2000 the control period. Maximum and minimum temperatures show a clear positive trend being higher for the Pyrenean and Inland area (~+0.72 in 2021-2030 and +1.12 ºC in 2031-2050), while for the Coast is +0.6 and +0.94 for both periods, may be caused for the smaller range of temperature. In Figure 3 is showed the mean annual maximum and minimum temperatures for the three climatic areas. The temperature increase is quite similar in the three areas, being +0.37 ºC per decade for Pyrenees and Inland and +0.39 ºC for Coast.

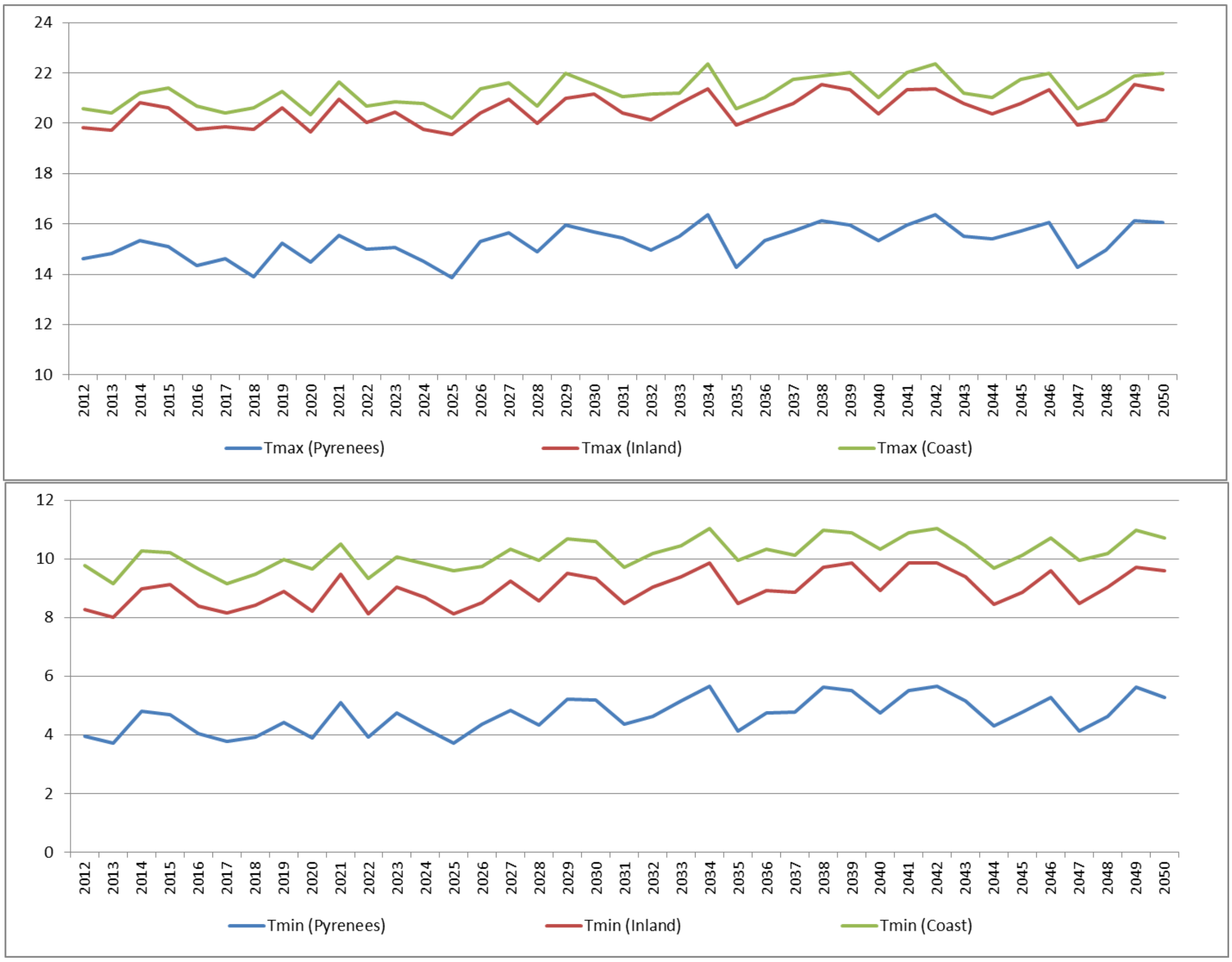


Figure 3. Maximum (up) and Minimum (down) Mean annual temperature in the three areas: Pyrenees in blue, Inland in red and Coast in green.

Figure 4 shows the changes of seasonal temperature in the different climatic areas. Autumn and winter show a slightly upward trend in comparison with spring and summer. The mean trend for the three areas analysed show increase per decade of: +0.3 in winter, +0.21 in spring, +0.25 in summer and +0.37 in winter.

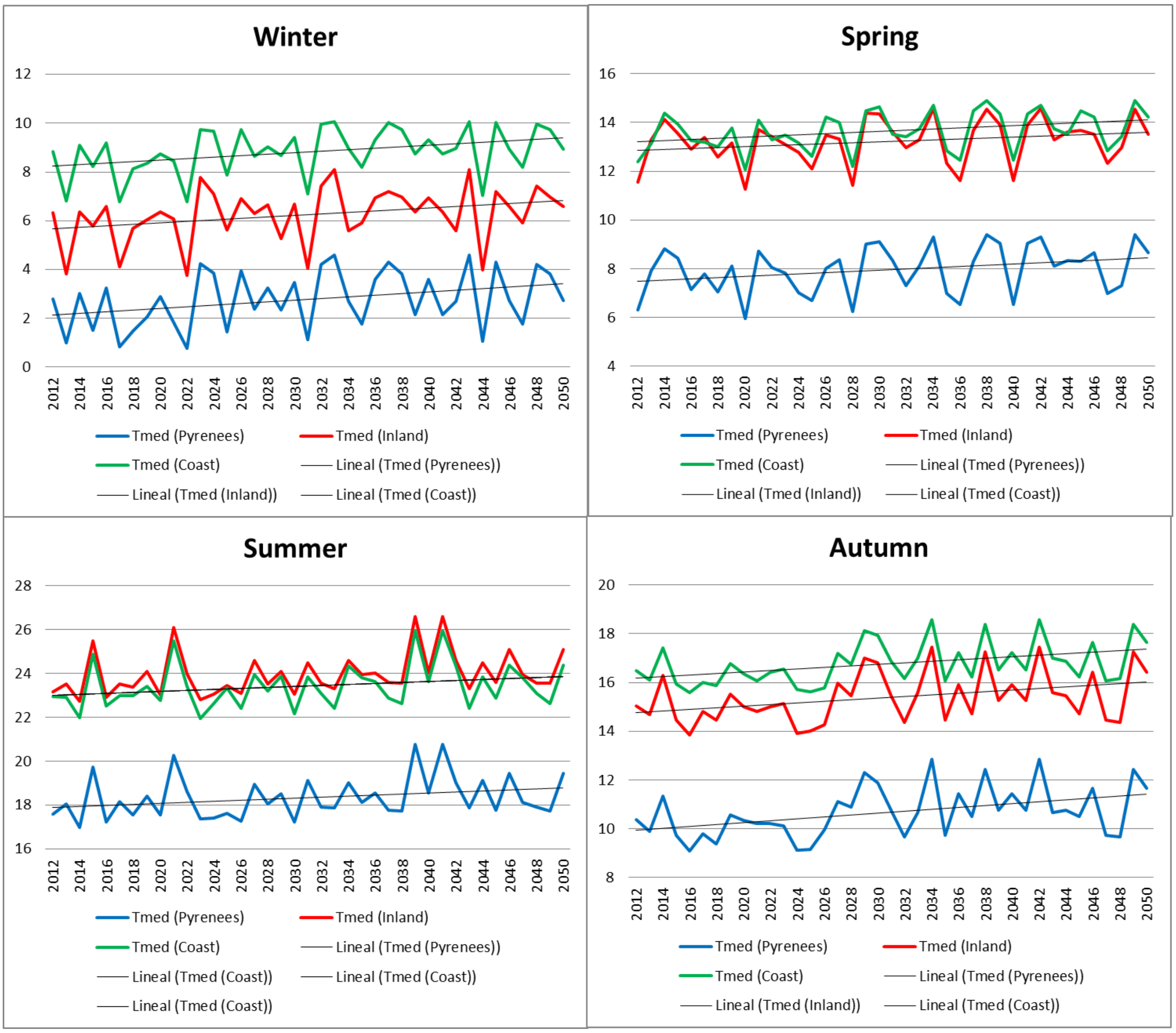


Figure 4. Seasonal temperature in the three climatic areas.

2.2.3. SPEI evolution

Standardized Precipitation Evapotranspiration Index (SPEI) has been calculated under indications in Vicente-Serrano, et al, 2010, for three meteorological stations from the three climatic areas: Pyrenees, Inland and Coast. The result (Figure 5) shows how the drought episodes will be more frequent and severe. The three stations show a similar pattern, dry/wet alternation until 2020 with a clear trend to drought conditions and a significant trend to drought episodes longer and stronger for the next period 2021-2050.

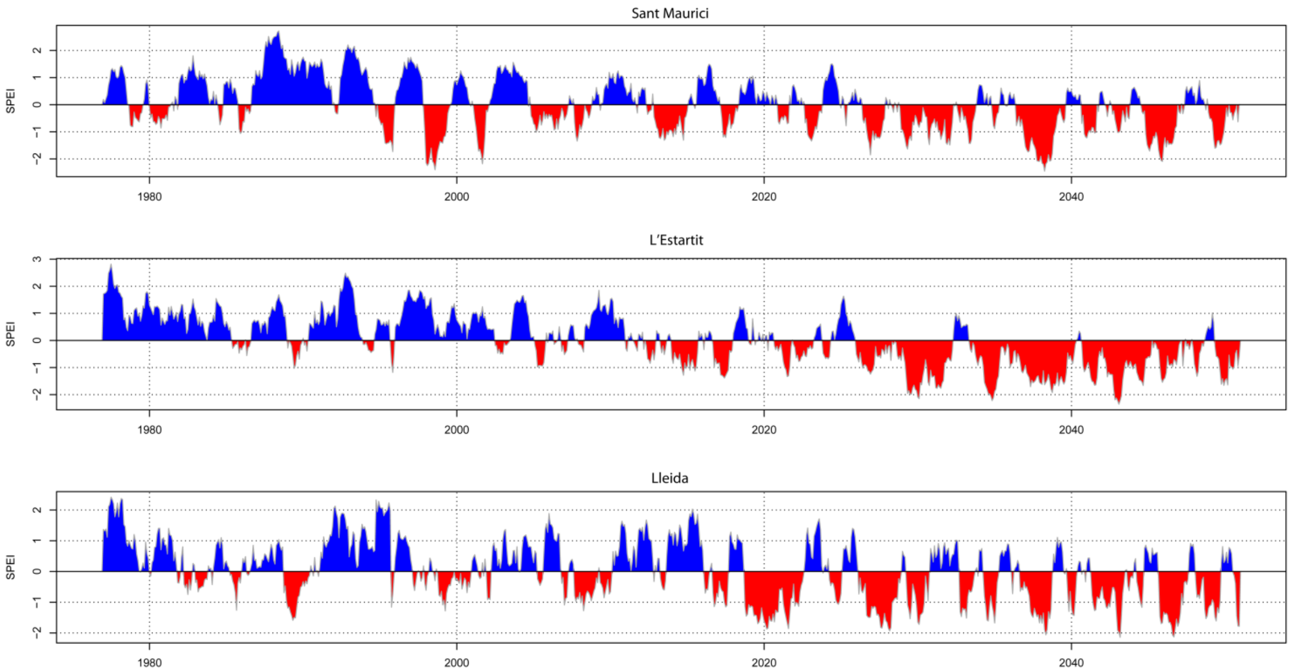


Figure 5. SPEI evolution (2012-2050) at 12-months temporal scale in Sant Maurici (Pyrenees), Lleida (Inland) and L'Estartit (Coast).

2.3. Conclusions

Taking into account the changes provided in TICCC the plausible scenario for the study area of MEDACC Life project (Basins of Muga, Ter and Segre rivers) is a general warming in all the climatic areas (Pyrenees, Inland and Coast) and in all the temporal horizons. Talking about precipitation, it seemed to be a decrease but this is less certain. Noteworthy is the great decrease in autumn and in spring, when the largest amount of precipitation is expected. In summary and analysing also the SPEI, the climate in Catalonia appears to lead towards drought episodes with water scarcity and a generalized warming.

3. How would be the territory?

3.1. Introduction

Global change refers not only to the changes in climate (climatic scenarios) but also to socioeconomic changes that include land use and land cover changes, demographic changes or changes in resources (water, energy, food) uses, among others. Global change scenarios draw alternative plausible options for different future socioeconomic developments (narrative storylines). These scenarios provide different views on the future of a certain study area by exploring what might happen given certain assumptions about the development of society and about environmental changes. Many international organizations and projects make use of scenarios that help them to plan an uncertain future (e.g. IPCC, UNEP ...)

For Life MEDACC project purposes, we considered key to include not only climate change scenarios but also global change scenarios. Initially, we planned to use land use change projections (2030) and demography and water demands projections (2030) based on scenarios developed in other European, national or local projects. Nevertheless, we did not find any existent scenario that taken into account the characteristics and dynamics of the case-study basins or that had enough spatial resolution to be appropriate for the project objectives. Therefore, we decided to develop socioeconomic scenarios designed ad hoc for the project.

The socioeconomic scenarios were developed based on experts' knowledge on main socio-economic sectors. A specific meeting was hold to discuss and agree different plausible futures of the three basins with experts covered the following areas: water management, forest sector, agriculture, demography and adaptation policies and strategies (partners from the OCCC). During this meeting, we set the time frame (2050) and the spatial frame (headwaters where changes in land cover occur and medium and low basins courses where changes in water demands occur, due to changes in water consumption in the agricultural, industrial and touristic sectors).

The following socioeconomic scenarios were drawn:

- <u>Land cover scenarios applicable to the headwaters:</u>
  - *Afforestation scenario (**AFOR**)*
  - *Fire scenario (**FIREFOR**)*
  - *Forest management scenario (**MANAGEFOR**)*
- <u>Water use scenarios applicable to the medium and low basin courses:</u>
  - *Rational use of water resources scenario (**RATUS**)*
  - *Increased demand scenario (**DEMINC**)*

3.2. Land cover scenarios

3.2.1. Afforestation scenario (AFOR)

This scenario foresees an increase in the forest area of the headwaters by 2057. The initial hypothesis of this scenario was that forests, mainly conifers, will colonize grass and shrub areas at high altitudes and shrub areas on slopes. The scenario was generated using a random forest algorithm specifically created for the project (the methodology can be consulted at Pascual et al. 2016).

The RF model provided a 200m-raster of the 2057 land cover for the whole Catalonia, based on past land cover changes (from 1993 to 2009) and some drivers that can explain the land cover changes (topography, climate, distance to urban areas or roads …). The RP model predicted an afforestation of 2,074 km^2 (a 6.5% more than in 2009) in Catalonia. This afforestation occurs on current shrubland (5.4%), grassland (1.0%) and agriculture (1.2%) areas (see more details at Pascual et al. 2016).

Hereinafter, we used the 200m-raster of the 2057 RF model output for drawing the AFOR scenario. For this purpose, we had to adapt the RF model output with the socioeconomic scenarios defined in the LIFE MEDACC project. Thus, the RF model output raster was used in the headwaters of the case-study basins, meanwhile the LCM 2005 was used in the medium and low courses. We used LCM 2005 for the medium and low courses because it is the cover map that we utilized for calibrating the hydrological models. After mosaicking both layers, the raster was resampled to 500 m for the Ter and Segre basins and to 100 m for Muga. Figure 6 shows the final AFOR scenario (2057) for the three basins. The changes with respect to the reference LCM 2005 are more evident in Ter basin (8.3% forest increase) than in Muga (4.2% increase) and Segre (5.5% increase) (Table 2). Forests expand mainly at the expense of shrublands (2.4-3.1% reduction) and grasslands (0.4-4.5% reduction).

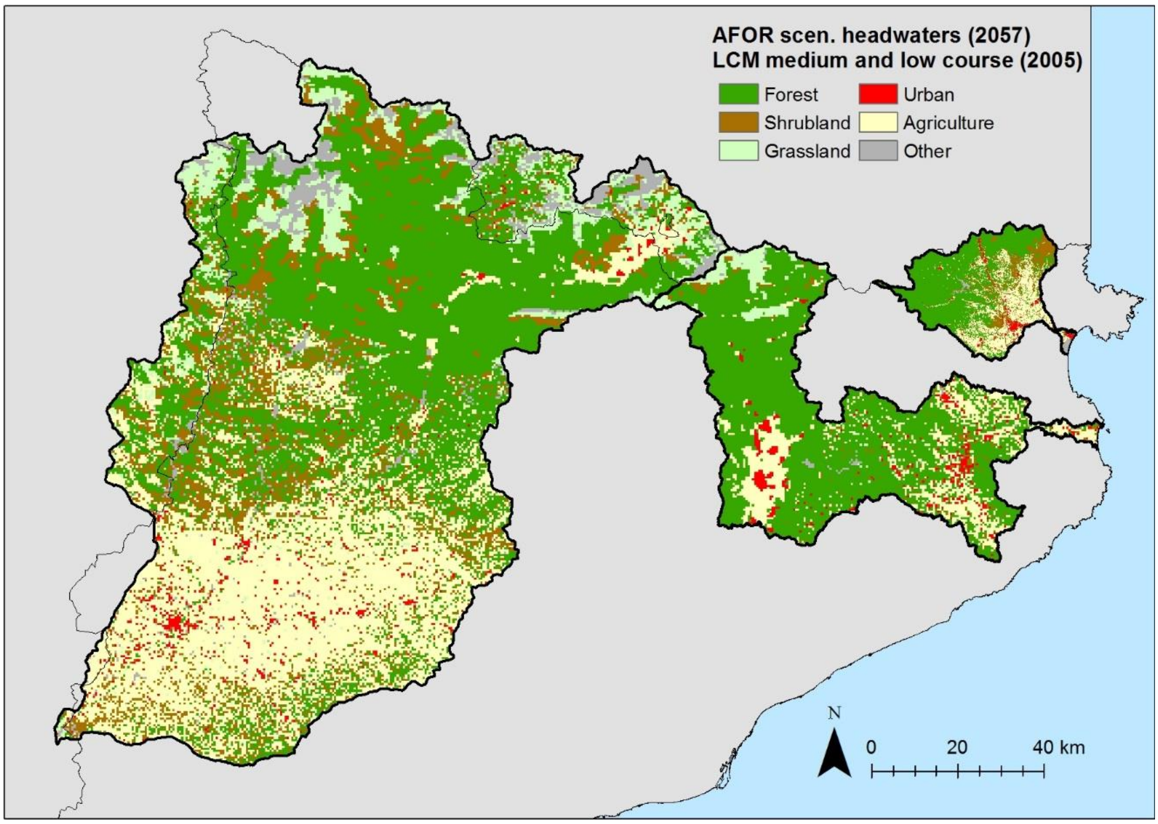


Figure 6. Afforestation scenario (2057) for the case-study basins: Raster developed as combination of the AFOR scenario in the headwaters and the 2005 LCM in the medium and low courses.

	Muga		Ter		Segre	
	Change (%)	**Change (km²)**	**Change (%)**	**Change (km²)**	**Change (%)**	**Change (km²)**
Forest	4.2%	32.2	8.3%	244.5	5.5%	709.8
Shrubland	-3.0%	-23.0	-3.1%	-90.8	-2.4%	-309.3
Grassland	-0.4%	-2.8	-4.5%	-132.0	-2.0%	-261.5
Urban	-0.5%	-4.1	0.1%	2.0	-0.2%	-22.5
Agriculture	-0.4%	-3.1	-0.8%	-22.3	0.2%	22.0
Other	0.1%	0.8	-0.1%	-1.5	-1.1%	-136.8

Table 2. Changes per land cover between the 2005 LCM and 2057 AFOR scenario in percentage and surface (km2) per basin.

3.2.2. Fire scenario (FIREFOR)

This scenario foresees a less forested headwaters by 2050 as a result of an increased incidence of forest fires. Our initial hypothesis is that the fires would affect mainly coniferous forests and shrublands that would be converted by the middle of the 21st century to shrublands and areas regenerated with evergreen forests. The scenario has been generated using the MEDFIRE model (Brotons et al. 2013).

The MEDFIRE model provided a 100m-raster of the 2050 forest landscape for the whole Catalonia, based on the reference fire regime, the climate, the ignition probability or the post-fire regeneration transitions, among other processes. The MEDFIRE model predicted a reduction of the area occupied by conifer forest (959 km^2 surface reduction, a 3% less than in 2010) in Catalonia. This conifer forests reduction favours the expansion mainly of shrublands (610 km^2 and 1.9%), but also of deciduous forest (298 km^2 and 0.9% increase) and evergreen forests (50 km^2 and 0.2% increase) after post-fire regeneration processes (see more details at Pascual et al. 2016).

Hereinafter, we used the 100m-raster of the 2050 forest landscape for drawing the FIREFOR scenario. For this purpose, we had to adapt the MEDFIRE model output with the socioeconomic scenarios defined in the LIFE MEDACC project. Thus, the MEDFIRE 2050 forest landscape raster was used in the headwaters of the case-study basins, meanwhile the LCM 2005 was used in the medium and low courses. After mosaicking both layers, the raster was resampled to 500 m for the Ter and Segre basins. Figure 7 shows the final FIREFOR scenario (2050) for the three basins. The changes with respect to the reference LCM 2005 are more evident in Segre (5.3% conifer forest reduction and 5.5% deciduous forest increase) and Ter (1.6% reduction and 4.5% increase respectively) basins, meanwhile in the Muga basin the opposite trend is expected (0.2% change) (Table 3).

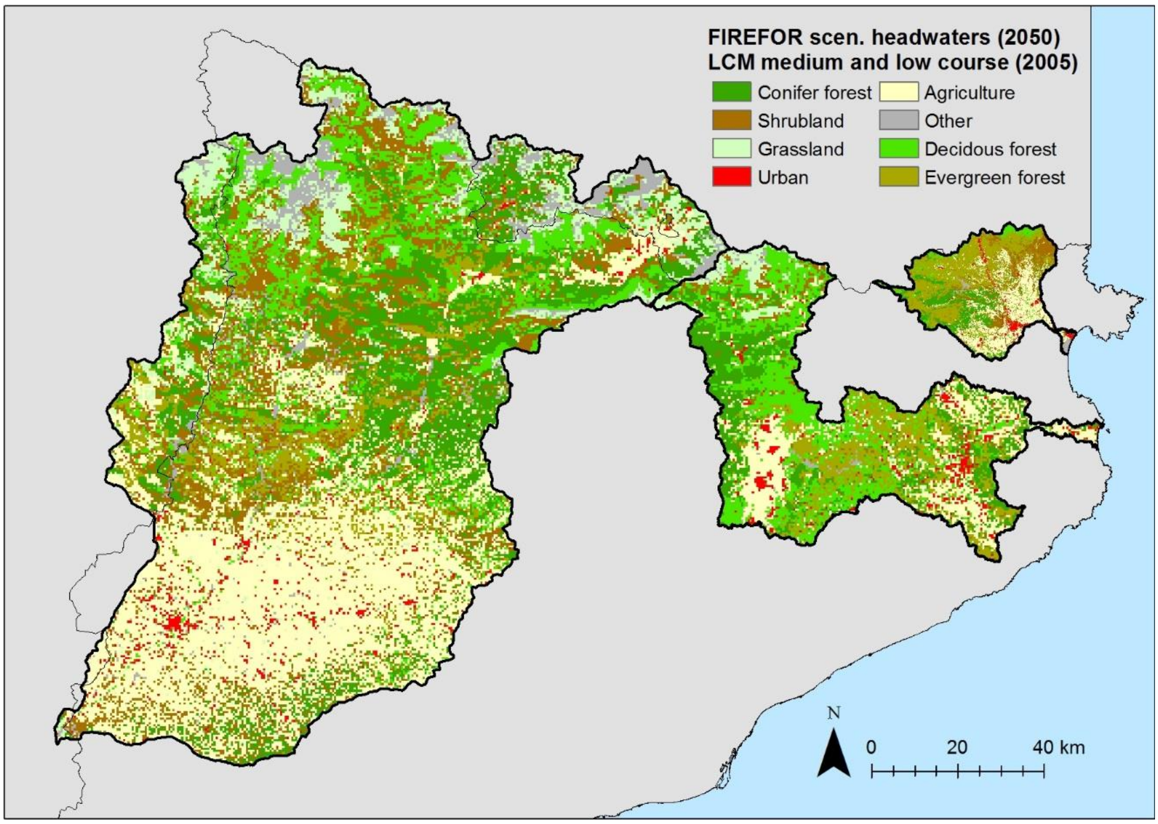


Figure 7. FIREFOR scenario (2050) for the case-study basins: Raster developed as combination of the FIREFOR scenario in the headwaters and the 2005 LCM in the medium and low courses.

	Muga		Ter		Segre	
	Change (%)	Change (km^2)	Change (%)	Change (km^2)	Change (%)	Change (km^2)
Conifer forest	0.2%	1.6	-1.6%	-47.0	-5.3%	-683.0
Deciduous forest	-0.2%	-1.3	4.5%	134.5	5.5%	719.0
Evergreen forest	1.2%	9.2	0.2%	5.0	0.1%	16.8
Shrubland	-0.3%	-2.2	-0.1%	-4.3	1.5%	190.8
Grassland	-0.5%	-4.1	-5.0%	-148.5	-1.8%	-238.5
Urban	-0.5%	-4.0	-0.1%	-4.3	-0.1%	-15.5
Agriculture	0.0%	-0.1	1.8%	52.0	0.9%	115.3
Other	0.1%	0.9	0.4%	12.5	-0.8%	-103.0

Table 3. Changes per land cover between the 2005 LCM and 2050 FIREFOR scenario in percentage and surface (km^2) per basin.

3.2.3. Forest management scenario (MANAGEFOR)

This scenario foresees a change in forest structure (instead of in forest cover area, as previous scenarios) due mainly to forest management and the replacement of species. The aim of the Ministry of Agriculture, Livestock, Fisheries and Food is to increase the current 28% forest area of Catalonia under management to the 50%. We use this target as reference for the scenario: the 50% of the current forest area of the headwaters will be managed, acting first in the more dense forests.

The scenario was built combining the land cover map of 2005 to identify forest areas in the basin headwaters with the Third National Forest Inventory (IFN3) to select the forest areas with higher density (see more details at Pascual et al. 2016). This information was used in the headwaters and mosaic later with the LCM 2005 in the medium and low courses. Figure 8 and Table 5 show the final MANAGEFOR scenario (2050) for the three basins. The managed area in Muga basin (33%) was higher than in Ter and Segre basins, since the Muga headwaters are more forested (63.3%) than the other two (48.3% in Ter and 55.8% in Segre). The forests under management in 2050 will oscillate between the 24 and 33% of the current forest areas. Table 4 shows the managed area per forest type and basin.

	Forest area in the basin (km^2)	Forest area in the headwaters (km^2) (%)	Managed forest area (km^2)	Managed forest related to total forest area in the basin (%)
Muga	403	255 (63.3%)	133	33.0%
Ter	1,782	861 (48.3%)	427	24.0%
Segre	4,527	2,526 (55.8%)	1,261	27.9%

Table 4. Area occupied by forests in the basin and headwaters, and managed area in percentage and surface (km^2) per basin.

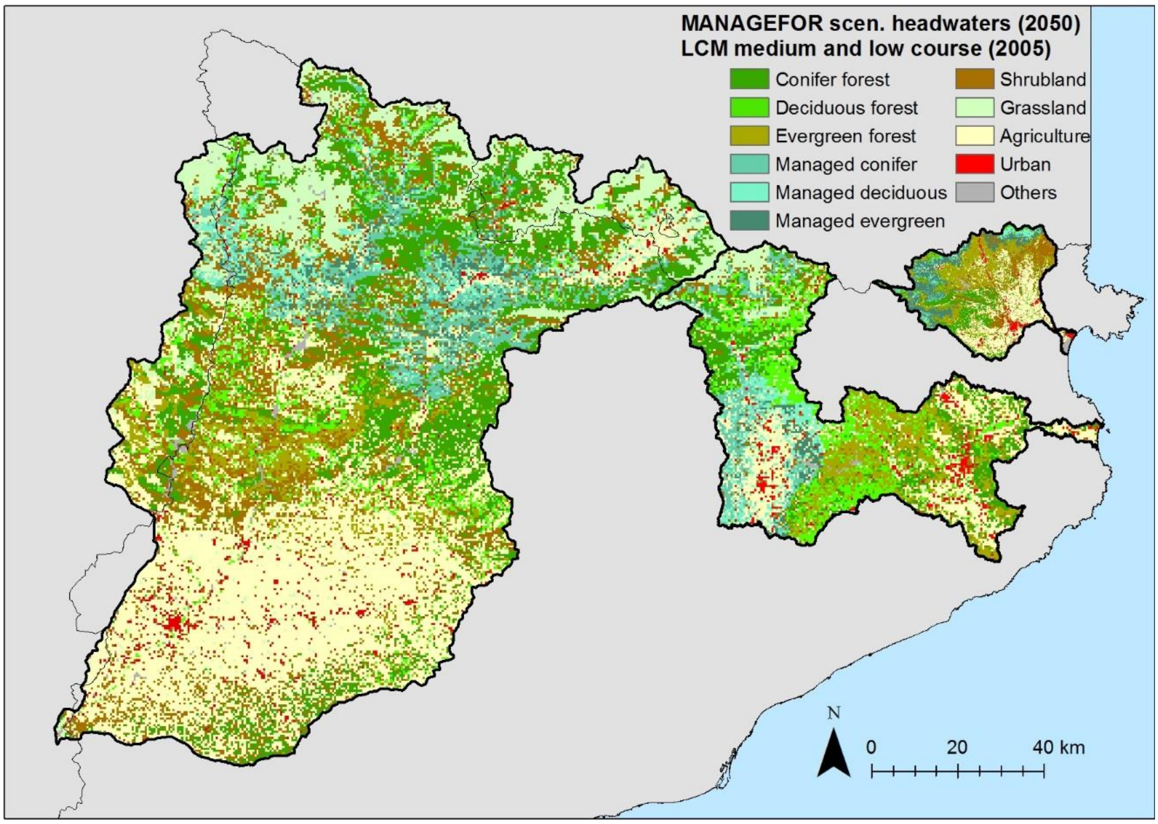


Figure 8. MANAGEFOR scenario (2050) for the case-study basins.

	Muga				Ter			
	LCM 2005	MANAGEFOR scenario 2050			LCM 2005	MANAGEFOR scenario 2050		
	No managed forest (km²)	No managed forest (km²)	Managed forest (km²)	Managed forest (%)	No managed forest (km²)	No managed forest (km²)	Managed forest (km²)	Managed forest (%)
Conifer forest	101	85	16	16%	646	441	205	32%
Deciduous forest	55	31	23	43%	676	507	169	25%
Evergreen forest	248	154	94	38%	461	407	54	12%

	Segre			
	LCM 2005	MANAGEFOR scenario 2050		
	No managed forest (km²)	No managed forest (km²)	Managed forest (km²)	Managed forest (%)
Conifer forest	2,793	2,072	721	26%
Deciduous forest	952	602	350	37%
Evergreen forest	782	592	191	24%

Table 5. Changes per land cover and management between the 2005 LCM and 2050 MANAGEFOR scenario in percentage and surface (km²) per basin.

3.3. Water management scenarios

Water management scenarios were designed for medium and low basins courses, where not significant changes in land cover are expected. Nevertheless, changes in water demands are expected due to the increased pressures on water resources of the agricultural, industrial and touristic sectors.

In comparison with land cover scenarios, the water management scenarios are not represented as maps, but as changes in the magnitude of water extractions. These changes are directly applied to the hydrological models used to evaluate the impacts of the water management scenarios on the water cycle. For this reason, we do not present in this section maps or tables, only the description of the scenarios.

3.3.1. Rational use of water resources scenario (RATUS)

This scenario foresees a reduction in water consumption by 2050 as consequence of using alternative water sources for covering water demands in the case-study basins. The released water is left into the rivers to improve their quality, restore their functionality and recover the provision of environmental services. This scenario has different implications depending on the basin.

Water reuse scenario in the Muga basin

Major water demand pressures in the Muga basin are caused by irrigation (62 hm^3/year, compared with the 147 hm^3/any of Muga renewable water resources). In a basin recurrently affected by water scarcity, this water demand is often difficult to satisfy. Together with a low water contribution and low capacity of water regulation (57 hm^3 in Boadella reservoir), the basin has suffered frequent water restrictions for irrigation, urban (tourism users) and ecological flows. Alternative water sources are key to cover water demands without risking the good ecological status of the river. In this sense, the basin has a high potential for using non-conventional water, mainly from reuse of regenerated water coming for three different treatment plants: Figueres (4.7 hm^3/year), Roses (3.8 hm^3/year) and Empuriabrava (1.1 hm^3/year).

This scenario foresees a reduction of 9.6 hm^3/year in the water abstraction of the Pont de Molins dam. This water abstraction flows into the Right and Left Irrigation channels, which irrigates approximately 4,000 ha and feeds the urban supply of 36,436 to 58,099 inhabitants (Cadaqués, Llançà, Roses, Empuriabrava, Mancomunitat de Pau, Palau Saverdera, Vilajuïga, Garriguella, Pedret and Marzà). The re-used water will directly feed into the irrigation fields, reducing the pressure over the water collection. The reduction of 9.6 hm^3/year in the water abstraction will be applied during the summer period, reducing 3.2 hm^3 in June, July and August, when maximum irrigation demands take place.

Water transfer reduction scenario in the Ter basin

The Ter basin is highly affected by the water transference to the Metropolitan Region of Barcelona, quantified in 160 (5.3 m^3/s) to 210 hm^3/year. Recurrently, the system Ter-Llobregat that supplies Barcelona has not capacity to satisfy the demands, incurring in water restrictions that affect the domestic and industrial consumptions and the maintenance of the ecological flows. Alternative water sources are needed to satisfy current and future water demands without risking the good ecological status of the river. In this sense, the basin has a high potential for finding alternative water sources as a result of the containment of urban demand in the RMB, the total integration of desalinated water produced at La Tordera and Llobregat's ITAMs (Installations for marine water treatment) and the improvement of the efficiency of municipal distribution networks (reduced losses).

This scenario foresees a reduction of 50 hm^3/year in the water transference to the RMB. The reduction will be applied proportionally along the year (4.2 hm^3/month).

Canal d'Urgell modernization scenario

The Segre basin is highly affected by the demand for agriculture irrigation. The two main irrigation channels, Urgell and Segarra-Garrigues (in construction), involves a water demand about 972 hm^3/year to supply 140,000 ha of irrigation. The modernization of the Canal d'Urgell, with more than 150 years, is already planned and its implementation will reduce water consumption in about 150 hm^3/year. This water release is key to achieve a good ecological status of water bodies in the Segre basin, currently affected by contamination and water anoxia.

This scenario foresees a reduction of 150 hm^3/year in the water abstraction of the Canal d'Urgell. The reduction will be applied proportionally along the irrigation months (March, April, May, June, July, August and September), at the rate of 21.4 hm^3/month.

3.3.2. Increased demand scenario (DEMINC)

This scenario foresees an increase in water consumption by 2050 as consequence of not applying measures to reduce the pressures over the water cycle. This scenario puts at risk the good ecological status of the case-study water bodies. This scenario has different implications depending on the basin.

Increase water storage scenario in the Muga basin

The low water regulation capacity of the Muga basin, depending mainly on the Boadella reservoir (57 hm^3), with difficulty can cover irrigation demands (62 hm^3/year) during dry years. The mean water abstraction from the Pont de Molins dam to feed irrigation and urban demands is approximately 28 hm^3/year (mean value for the period 2002-2011 including Canal de la Dreta, Canal de l'Esquerra, Rec del Molí and Costa Brava Consortium – North (CCBN) supply).

This scenario foresees the enlargement of the Boadella reservoir to increase the capacity in 28 hm^3, from the current 57 hm^3 capacity to 85 hm^3 (maximum capacity from 62 to 90 hm^3). This enlargement is as a result of increasing agricultural demands and increasing urban demand (tourism).

Water transfer increase scenario in the Ter basin

The system Ter-Llobregat, which supplies water demand for the metropolitan region of Barcelona (365 hm^3/year), has not enough capacity to supply current urban uses. Once every four years, the demands are higher than available resources, being necessary the use of reservoir storages, which only has capacity to supply demand for one year. Moreover, Ter's river water has a better quality that the Llobregat one, favouring that the processes to make water drinkable be more affordable. This difference increases the pressure over the Ter's resources.

This scenario foresees an increase of 40 hm^3/year in the water transference to the RMB. The increase will be applied proportionally along the year (3.3 hm^3/month).

Canal Segarra-Garrigues development scenario

The Canal Segarra-Garrigues is currently under construction and has an approved water concession of 342 hm^3/year. The objective of the channel is to transform to irrigable land 70,150 ha in Lleida province. Considering the strong pressures over the Segre river, this concession is expected to be extracted from: 100 hm^3/any extracted directly by the river after the Rialb reservoir, 150 hm^3/year obtained from the modernization of the Canal d'Urgell Canal; and a transfer of 92 hm^3/any from the Noguera Pallaresa.

This scenario foresees an extraction of 250 hm^3/year from the Rialb reservoir into the Canal Segarra-Garrigues and a transfer of 92 hm^3/year from the Noguera Pallaresa. This extraction will be applied proportionally along the irrigation months (March, April, May, June, July, August and September), at the rate of 48.9 hm^3/month.

3.4. Conclusions

The socioeconomic scenarios provide different views on the future of a certain area, depending on the demographic, socio-economic and technological driving forces. Climate change and socioeconomic scenarios generally take into account these driving forces to estimate the anthropogenic greenhouse gas emissions that cause climate change, but the processes are developed at global scale. However, when the emphasis need to be taken at local or regional scales, these scenarios may not be adequate.

For Life MEDACC project purposes, we considered key to include not only climate change scenarios but also global change scenarios. We did not find any existent scenario that taken into account the characteristics and dynamics of the case-study basins or that had enough spatial resolution to be appropriate for the project objectives. Therefore, we decided to develop socioeconomic scenarios designed ad hoc for the project.

We have designed five socioeconomic scenarios for 2050: three land cover scenarios for the headwaters (afforestation, fire and forest management scenarios) and two water use scenarios for the medium and low basin courses (rational use of water resources and increased demand scenarios).

The afforestation scenario (AFFOR) maintains the current afforestation trends that have occurred in the basins in the last decades: a 4.1%, 1.6, and 5.2% forest increase in Muga, Ter and Segre basins respectively from 1993 to 2009. In 2005, the forests occupy the 53.1, 60.3 and 34.8% of the Muga, Ter and Segre basins respectively. By 2057, afforestation would occur moderately in the Muga and Segre basins (4.2 and 5.5%-increase) and more noticeable in the Ter basin (8.3%-increase), mainly at the expense of shrublands (2.4-3.1% reduction) and grasslands (0.4-4.5% reduction).

The fire scenario (FIRE) gives unexpected results for the case-study basins. The 2050 forest landscape provided by MEDFIRE model for Catalonia was the expected in our initial hypothesis, with a 3%reduction of the conifer forest area and an expansion of shrublands (1.9%), deciduous forest (0.9% increase) and evergreen forests (0.2% increase) after post-fire regeneration processes. However, the translation of this 2050 forest landscape to the case-study basins was not proportional to the mean observed in Catalonia. In Muga basin, changes between the 2005 and 2057 were almost inappreciable (maximum a 9.2 km^2 increase of evergreen forest). In Ter basin, conifer reduction was not so noticeable (1.6%) than the grassland loss (5.0%), whereas deciduous forest increased a 4.5%. In Segre basin, conifers experimented a 5.3% reduction, whereas shrublands (1.5%) and deciduous forest (5.5%) surface increased.

The forest management scenario (MANAGEFOR) foresees a change in forest structure due mainly to forest management and the replacement of species. The managed area in Muga basin (33%) was higher than in Ter and Segre basins, since the Muga headwaters are more forested (63%) than the other two (48% in Ter and 56% in Segre). A 33.0, 24.0 and 27.9% of forest areas would be under management by 2050 in the Muga, Ter and Segre basins respectively.

The rational use of water resources scenario (RATUS) foresees a reduction in water consumption by 2050 as consequence of using alternative water sources for covering water demands in the case-study basins. In the Muga basin, the use of non-conventional water, mainly from reuse of regenerated water, would reduce in 9.6 hm^3/year the water abstraction in the Pont de Molins dam for irrigation purposes during the summer. In the Ter basin, the current water transference to supply the Metropolitan Region of Barcelona would be reduced in 50 hm^3/year, from the current 160 hm^3/year to 110 hm^3/year. In the Segre basin, the modernization of the Canal d'Urgell irrigation channel would reduce irrigation consumption in 150 hm^3/year. In the three basins, the released water would flow into the rivers to improve their quality, restore their functionality and recover the provision of environmental services.

The increased demand scenario (DEMINC) foresees an increase in water consumption by 2050 as consequence of not applying measures to reduce the pressures over the water cycle. In the Muga basin, the enlargement of the Boadella reservoir from the current 57 hm^3 capacity to 85 hm^3 has the objective to cover future increasing agricultural and urban demands (tourism). In the Ter basin, the current water transference to supply the Metropolitan Region of Barcelona would be increased in 40 hm^3/year, from the current 160 hm^3/year to 200 hm^3/year. In the Segre basin, the consolidation of the Canal Segarra-Garrigues with a concession of 342 hm^3/year for irrigation purposes, would increase the pressures on Segre resources. In the three basins, this scenario puts at risk the good ecological status of the case-study water bodies.

4. How would scenarios impact on hydrology?

4.1. Introduction

Climate change may have a relevant impact on hydrological regimes (e.g. Wang et al. 2012) and water resources (Ludwig et al. 2011) of the Mediterranean region, as consequence of a decreasing precipitation and increasing temperature, and thus increasing potential evapotranspiration (PET). In parallel, changes in land covers and human water demands are increasing the current pressures on a current exposed water resources (Iglesias et al. 2007). These processes, together with an increasing frequency and recurrence of drought episodes in the Mediterranean, aggravate the complexity of water scarcity management, with negative implications for its sustainability (Iglesias et al. 2007).

The vulnerability of the Mediterranean water resources to face these challenges has raised social and political concern in the last decades, promoting the development of strategic policies through integrated water management systems. The design of adaptation strategies needs to be based on research outputs which quantify impacts, identify vulnerable sectors and reduce uncertainty. Throughout the Mediterranean, several studies have assessed climate and global change impacts on local water resources using a variety of projections, models and methodologies (e.g. Avila et al. 1996, ACA 2009, Senatore et al. 2011, Hartmann et al. 2012, Bangash et al. 2013, Koutroulis et al. 2013, Pascual et al. 2015) as key issue to provide water managers and decision makers with useful information to face future threats. These models provide a framework for assessing the relationship between climate, human activities and water resources (Jothityangkoon 2001), applying different hydrological models, input data or downscaling procedures, among others.

One of the LIFE MEDACC project objectives is to evaluate future impacts of climate and global change scenarios on water resources in three case-study basins. This process includes three main steps: 1) calibrating and validating the hydrological models for a historical period with observed stream flow and climate data; 2) generating climatic and socioeconomic scenarios; and 3) incorporating climatic and socioeconomic scenarios into the calibrated and validated hydrological models to evaluate the future effects of the scenarios in the water cycle. The first and second steps have been detailed explained at Pascual et al. (2016). Hereinafter we present the outputs of the third step.

4.2. Impacts of climate and socioeconomic scenarios

4.2.1. *Impacts of climate change scenario*

We introduced the climate change series into the hydrological models. For this simulation exercise, we had to assume that the land use covers were constant throughout the simulations, that water abstractions were equal to the reference period and that the reservoir outflow data was the mean of the monthly output during the reference period (2001-2011). Results were analysed in two time horizons (short term 2021-2030 and long term 2041-2050) and two spatial areas (headwaters and river mouths).

In the case of RHESsys model, although the land use covers are constant in terms of the limit of each class and pursuing the goal of being more realistic, all the simulations were run as a dynamic system to allow vegetation to adapt and respond to seasonal interannual cycles of climate, water redistribution in the system and soil organic matter pools.

Hydrological simulations with climate change scenarios showed a strong alteration in water dynamics in the three basins along the first half of the 21st century. A generalized decrease in water contributions and stream flow is expected.

<u>Effects on the Muga basin – SWAT model</u>

Table 6 shows the mean water contribution (hm^3/year) and its percentages of change at the short and long term and at the headwaters (Boadella Reservoir) and the river mouth (Castelló d'Empúries).

The percentage of change in mean water contributions are estimated with respect to the reference period (2002-2011). The reductions are expected to be more severe at the river mouth, both in the short term (10.1%) and long term (23.9%).

	Mean water contributions per period (hm^3/year)			Changes in mean water contributions respect to 2002-2011 period (%)	
	2002-2011	2021-2030	2041-2050	2021-2030	2041-2050
Boadella Reservoir (Inflow, headwaters)	68.7	64.9	55.6	-5.6%	-19.0%
Castelló d'Empúries (river mouth)	115.1	103.5	87.6	-10.1%	-23.9%

Table 6. Mean water contribution (hm^3/year) and percentage of change in mean water contributions per period (reference, short and long term) at the headwaters and the river mouth.

Changes in mean monthly contributions are shown in Figure 9. In the headwaters (Boadella Reservoir), the contribution are expected to slightly increase during winter season (December-January-February), whereas in spring (March-April-May) and summer (June-July-August) are expected to decrease, especially in April. Fall (September-October-November) does not show changes. In the river mouth (Castelló d'Empúries), the simulation shows a different pattern, with an overall reduction in all months except in February, with a maximum during the spring.

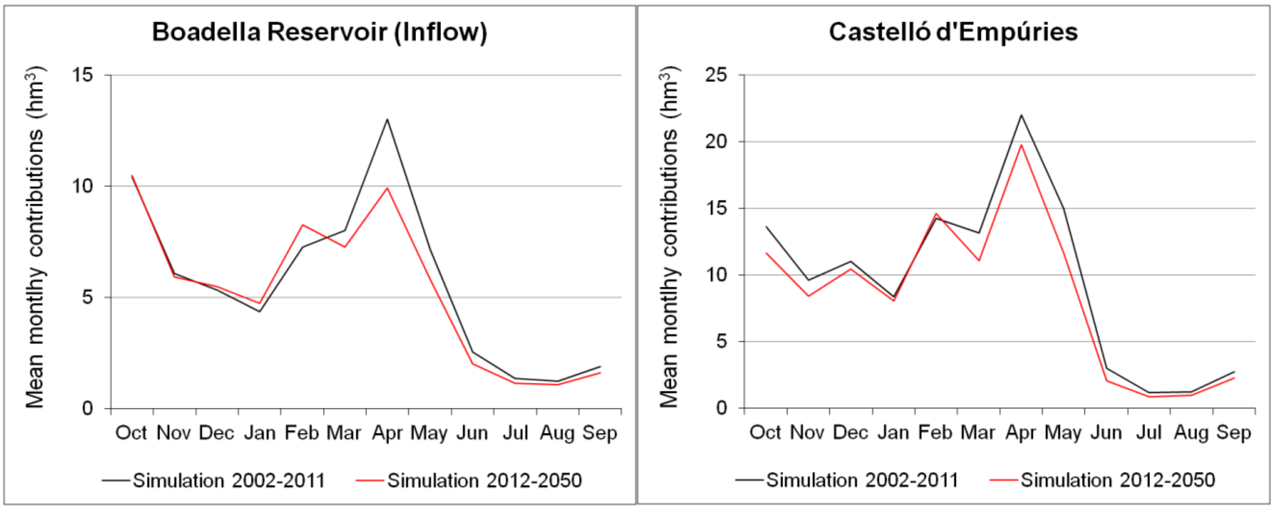


Figure 9. Expected changes in mean monthly contributions (hm^3) per month and location (headwaters and river mouth). Black lines show the mean values of SWAT output for the reference period (2002-2011) and red lines for the 2012-2050 period.

Figure 10 shows the changes in mean season contribution (hm^3/season) for period (short and long terms) and location (headwaters and river mouth). The pattern showed is similar between periods and locations. General reductions are expected in all sessions, expect in the headwaters during winter time. Major reductions are observed in spring and, in less extension, in fall, for both time steps.

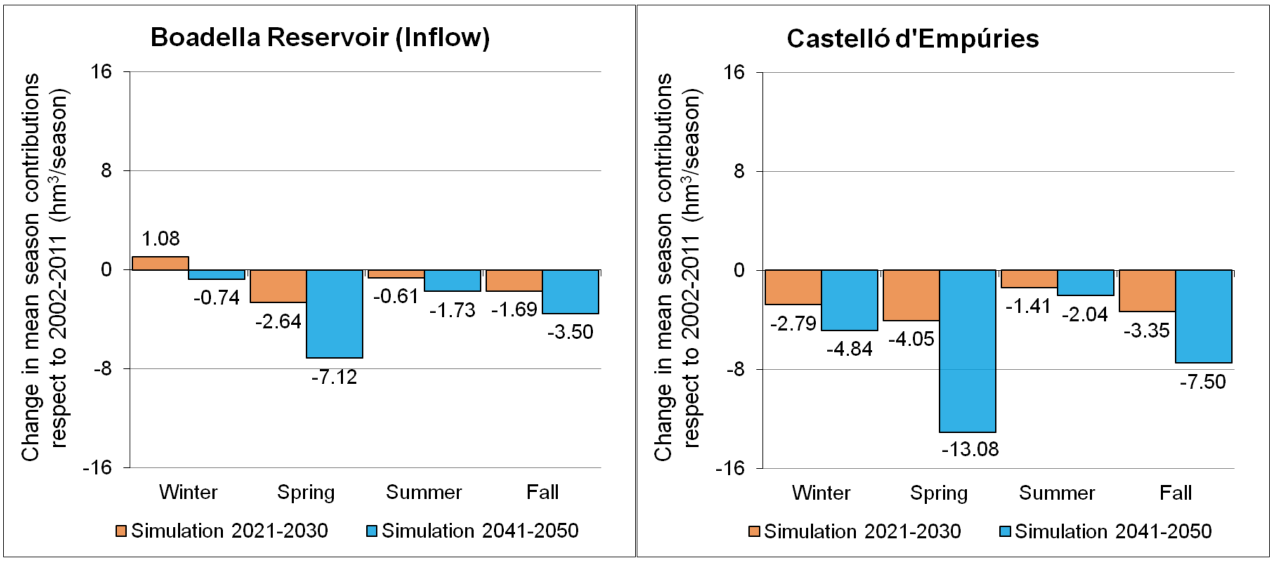


Figure 10. Expected changes in mean contribution per season (hm³/season) for period and location compared to the reference period (2002-2011).

Figure 11 shows the evolution of the stored volume (hm³) in Boadella reservoir. This graphic needs to be contextualised before deducing conclusions. Reservoirs in SWAT has been calibrated to adjust inflows, no stored volumes. Then, this parameter has not been specifically calibrated, although the results were satisfactory. Besides, future simulations included reservoir water abstractions from the reference period (2002-2011), no future ones. In addition, reservoir outflows were included at monthly time step (calibration was done with daily outflows) and monthly values were estimated as the mean outflow value of the reference period (2002-2011). Although this figure may be subjected to high uncertainties, we have included it because it shows if current reservoir management can be maintained in the future and if emergency events, when the reservoir is critically empty , are more frequent or with major intensity and duration in the future. The figure shows a complete emptying during the 2007-2008 drought, and similar events will be repeated from 2027 with similar or higher intensity and duration.

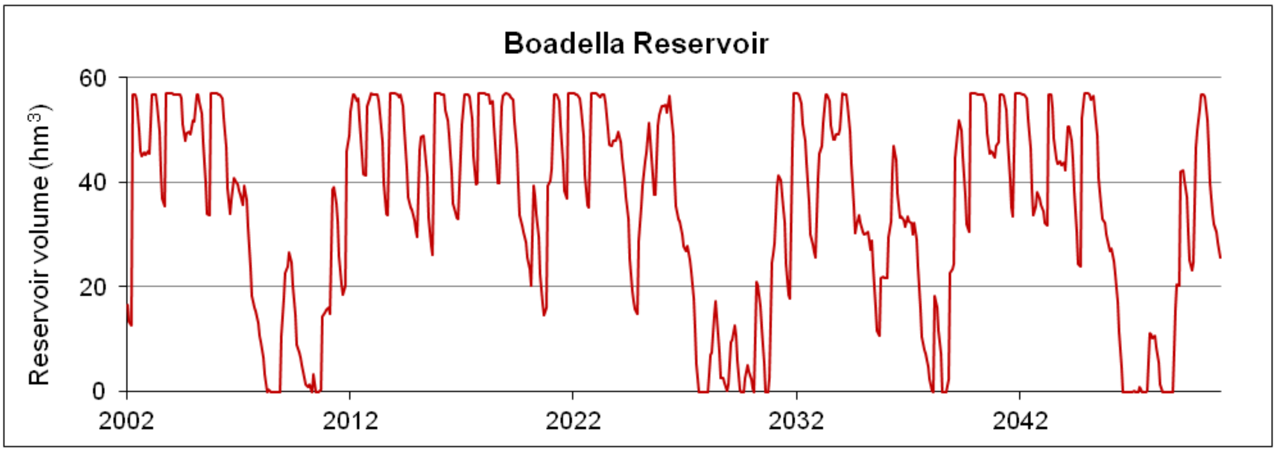


Figure 11. Simulation of reservoir volume (hm³) until 2050.

<u>Effects on the Muga basin – RHESsys model</u>

Table 7 shows the mean water contribution (hm³/year) and its percentages of change at the short and long term and at the headwaters (Boadella Reservoir) and the river mouth (Castelló d'Empúries). The percentage of change in mean water contributions are estimated with respect to the reference period (2002-2011). The reductions are expected to be more quite similar in long term for the two stations (-21% and -19%), while in short term we found more different values between the headwaters (-13%) and river mouth (-7.9 %) and the reduction expected is not as severe as the long term

	Mean water contributions per period (hm³/year)			Changes in mean water contributions respect to 2002-2011 period (%)	
	2002-2011	2021-2030	2041-2050	2021-2030	2041-2050
Boadella Reservoir (Inflow, headwaters)	51.5	44.8	40.3	-13.0%	-21.7%
Castelló d'Empúries (river mouth)	121.9	112.3	98.6	-7.9%	-19.1%

Table 7. Mean water contribution (hm^3/year) and percentage of change in mean water contributions per period (reference, short and long term) at the headwaters and the river mouth.

Changes in mean monthly contributions are shown in Figure 12. In headwaters seems to be a decrease of contributions mainly along the autumn and spring while in summer is showed a very low decrease.

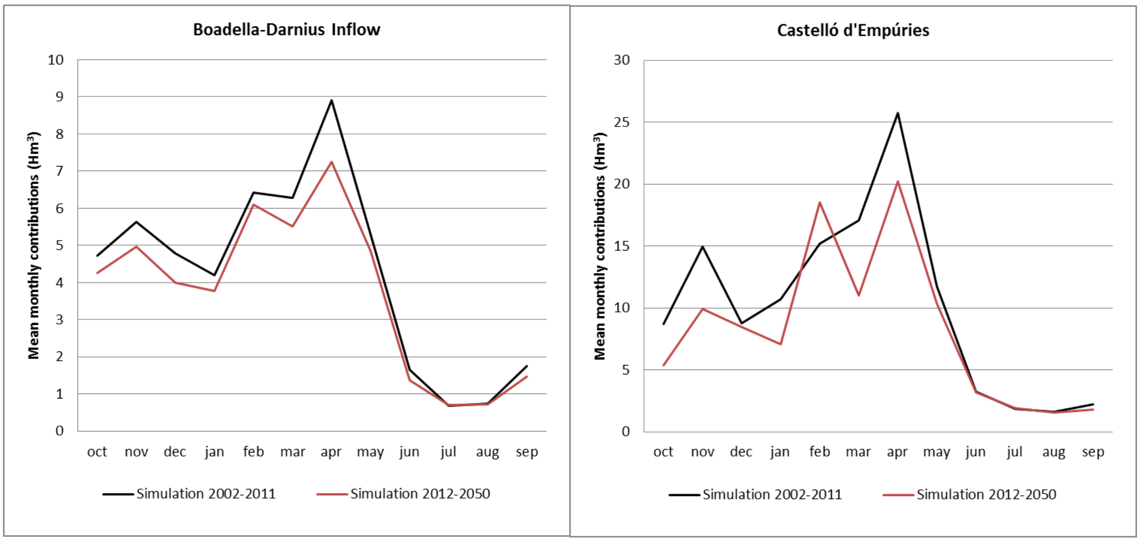
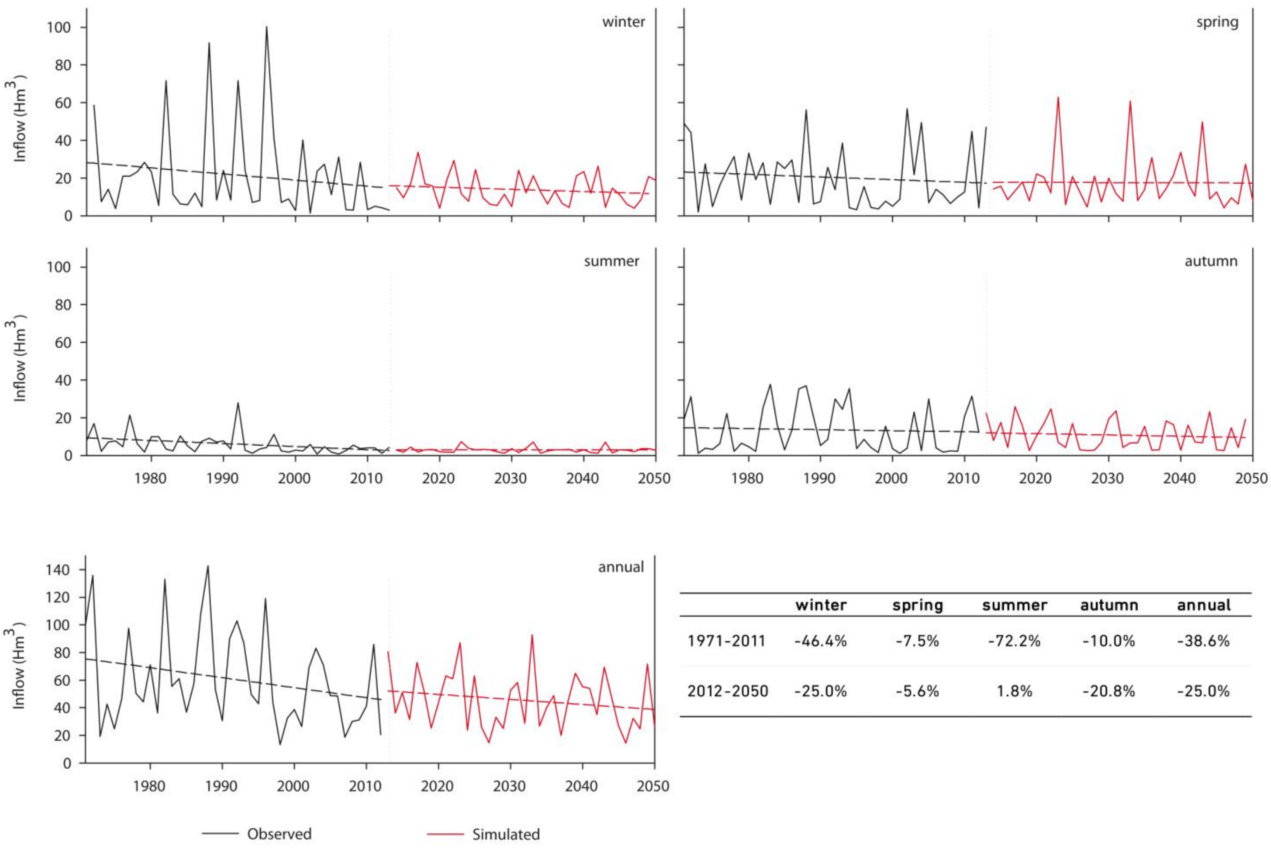


Figure 12. Expected changes in mean monthly contributions (hm^3) per month and location (headwaters and river mouth). Black lines show the mean values of RHESsys output for the reference period (2002-2011) and red lines for the 2012-2050 period.

On Figure 13 we present the seasonal evolution of the inflow in Boadella-Darnius reservoir from its construction in 1971. The observed and simulated inflow are noted in the same graph to compare the observed trend and the changes that can be plausible under climate change conditions. In general terms, the decrease of inflow seems to be slower than in the observed period (1971-2011) where is about -38% while in the simulated period (2012-2050) is -25%. It is remarkable the stronger decrease in the autumn inflow under climate change conditions (-20.8%) being -10% in the observed period. The slight increase in summer is negligible because of the inflow is actually low, representing the real problem.



	winter	spring	summer	autumn	annual
1971-2011	-46.4%	-7.5%	-72.2%	-10.0%	-38.6%
2012-2050	-25.0%	-5.6%	1.8%	-20.8%	-25.0%

Figure 13. Evolution of inflow in Boadella-Darnius reservoir.

Under this conditions and taking into account three aspects involved directly on water management as: i) mean water demand observed in 2002-2011, ii) the minimum ecological flow established by ACA (Agència Catalana de l'Aigüa) and iii) the management of the dam (outflow/storage) as actual, the expected water storage in Boadella-Darnius reservoir can be checked in Figure 14. It is not very encouraging that in at least four periods of time the reservoir would be dried, what suggest a change in the water management of the basin.

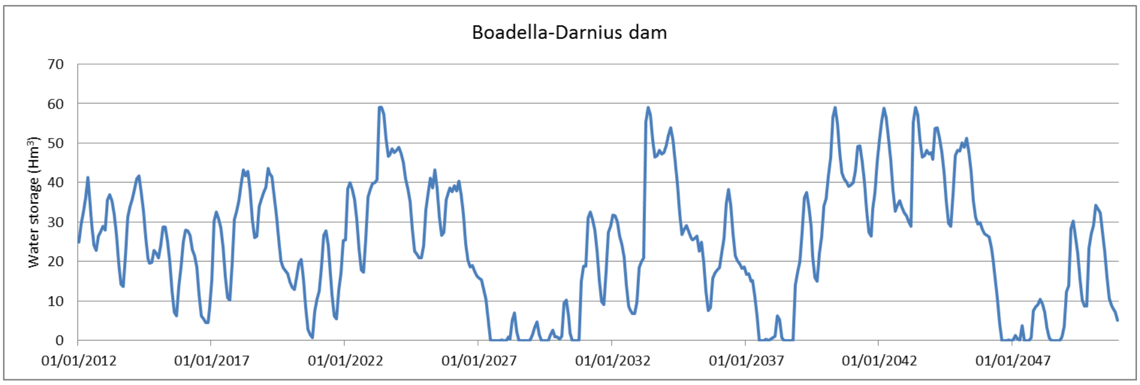


Figure 14. Water storage simulated for the period 2012-2050 in Boadella-Darnius dam.

Effects on the Ter basin – SWAT model

Table 8 shows similar results to the Muga basin, with foreseen reductions more severe at the river mouth, both in the short term (20.6%) and long term (31.1%). Nevertheless, changes are also more severe in Ter than in Muga basin, with maximum values oscillating between 23.9% at Muga river mouth and 31.1% at Ter river mouth.

	Mean water contributions per period (hm³/year)			Changes in mean water contributions respect to 2002-2011 period (%)	
	2002-2011	2021-2030	2041-2050	2021-2030	2041-2050
Roda de Ter (headwaters)	398.9	343.7	314.9	-13.8%	-21.1%
Torroella de Montgrí (river mouth)	338.4	268.8	233.3	-20.6%	-31.1%

Table 8. Mean water contribution (hm^3/year) and percentage of change in mean water contributions per period (reference, short and long term) at the headwaters and the river mouth.

Changes in mean monthly contributions are shown in Figure 15. In the headwaters (Roda de Ter), an overall reduction is expected except in January. Major reduction are observed during the spring. In the river mouth (Torroella de Montgrí), the simulation shows a different pattern, with an important reduction from October to December and in spring. The effect of reservoir management and water abstraction may cause these differences.

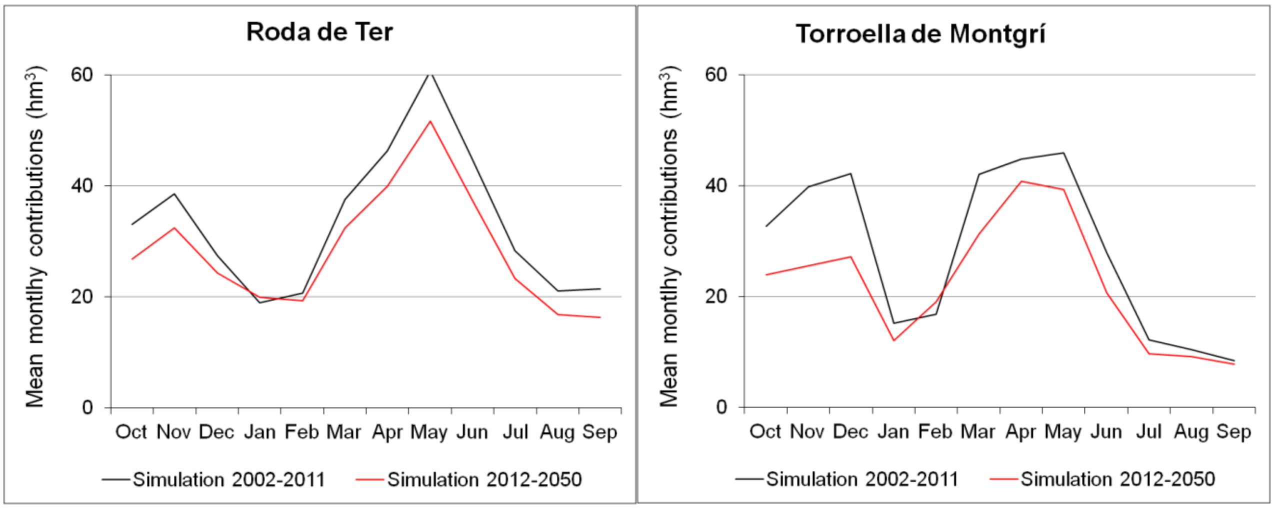


Figure 15. Expected changes in mean monthly contributions (hm^3) per month and location (headwaters and river mouth). Black lines show the mean values of SWAT output for the reference period (2002-2011) and red lines for the 2012-2050 period.

Figure 16 shows the changes in mean season contribution (hm^3/season) for period (short and long terms) and location (headwaters and river mouth). General reductions are expected in all sessions, especially in spring.

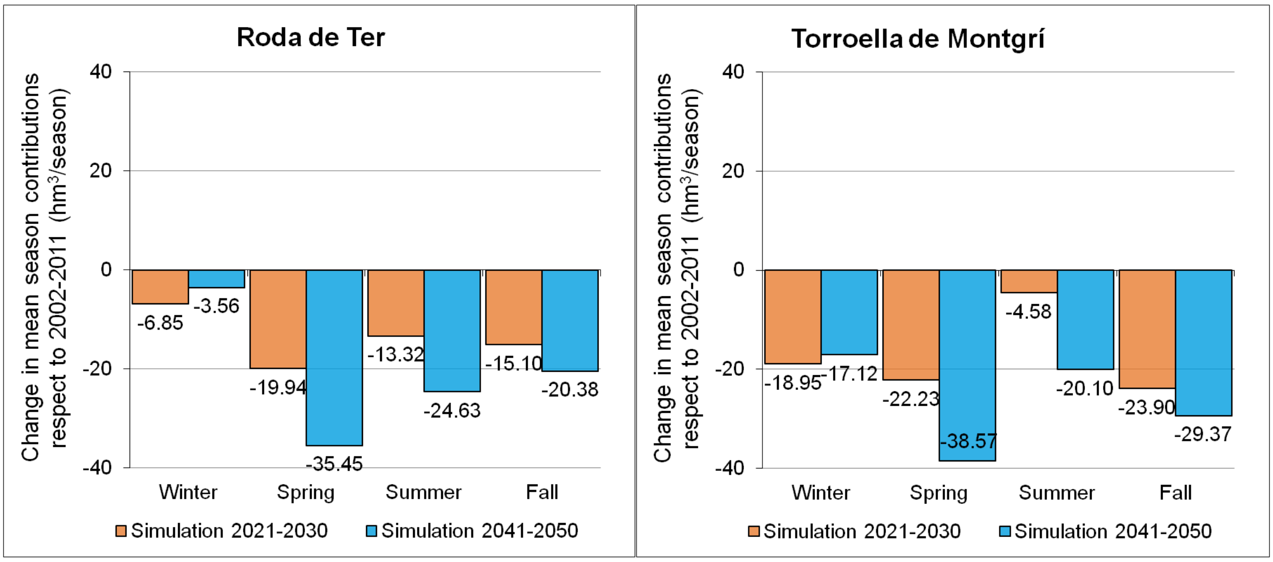


Figure 16. Expected changes in mean contribution per season (hm^3/season) for period and location compared to the reference period (2002-2011).

Figure 17 shows the evolution of the stored volume (hm³) in Sau and Susqueda reservoirs. Similar to the Muga basin, this graphic needs to be contextualised before deducing conclusions (see previous section). The Sau Reservoir's figure shows the effects of 2004-05 and 2007-08 droughts in the stored water of the reservoir. Similar to Muga basin, emptying events are more frequent and intense from 2027 (also there is an isolated event in 2013 and 2021). The evolution of Susqueda's volume also shows the effect of the 2007-08 drought. From 2027 to 2050, the reservoir with difficulty will arrive to its maximum stored capacity and emptying events will have longer effects.

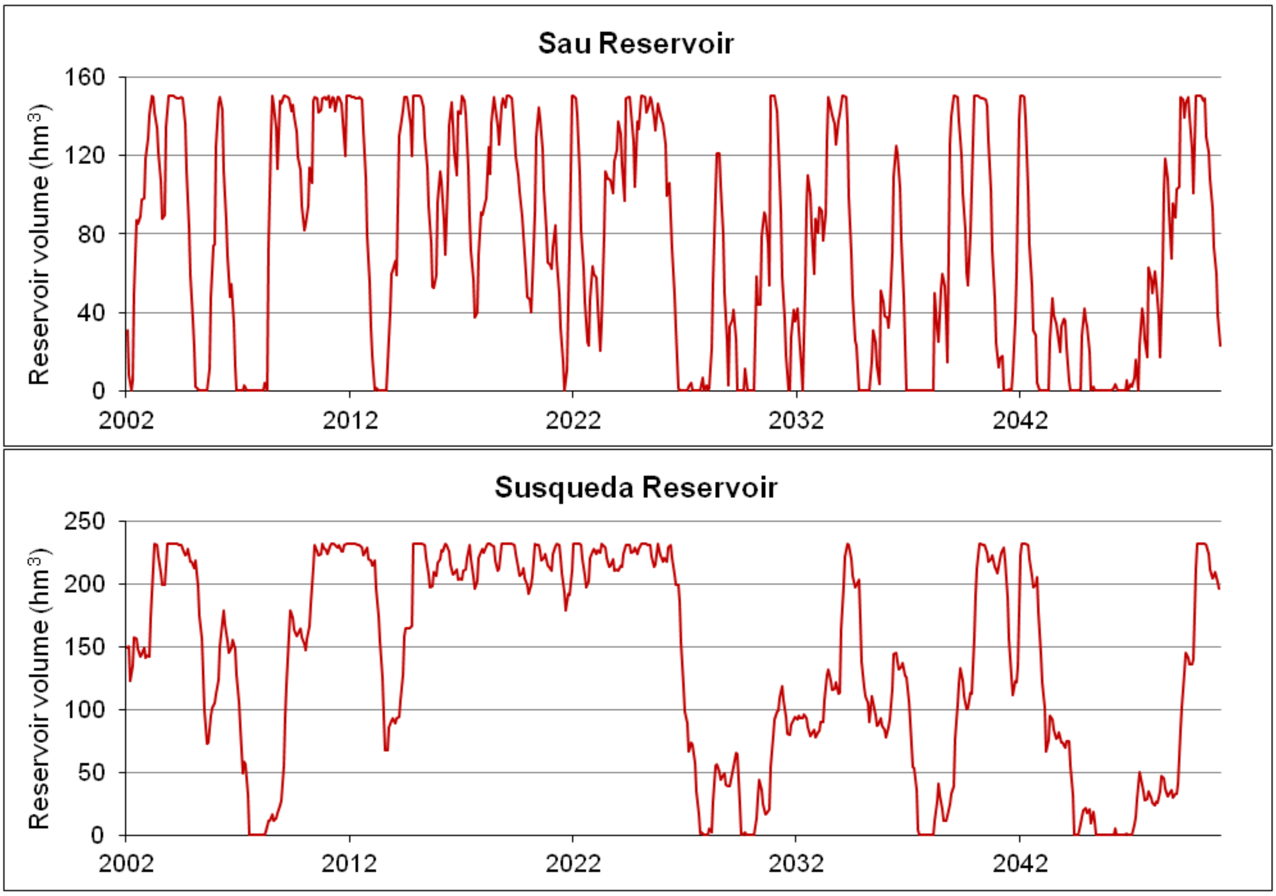


Figure 17. Simulation of reservoir volumes (hm³) until 2050.

<u>Effects on the Ter basin – RHESsys model</u>

Table 9 shows a sever decrease on Roda de Ter gauging station (-34% for short term and -36.6% for long term). As is exposed in Figure 18, the simulation show an important decrease along the year and a slight increase in winter. The snow melt process is expected to be early along the year because of the increment of temperature. In the case of Torroella de Montgrí gauging station, the decrease is quite similar to the previous station, -38.8 % in 2021-2030 and – 36.2% in 2041-2050.

	Mean water contributions per period (hm³/year)			Changes in mean water contributions respect to 2002-2011 period (%)	
	2002-2011	2021-2030	2041-2050	2021-2030	2041-2050
Roda de Ter (headwaters)	410.8	264.9	276.2	-35.5%	-32.8%
Torroella de Montgrí (river mouth)	457	279.8	291.4	-38.8%	-36.2%

Table 9. Mean water contribution (hm^3/year) and percentage of change in mean water contributions per period (reference, short and long term) at the headwaters and the river mouth.

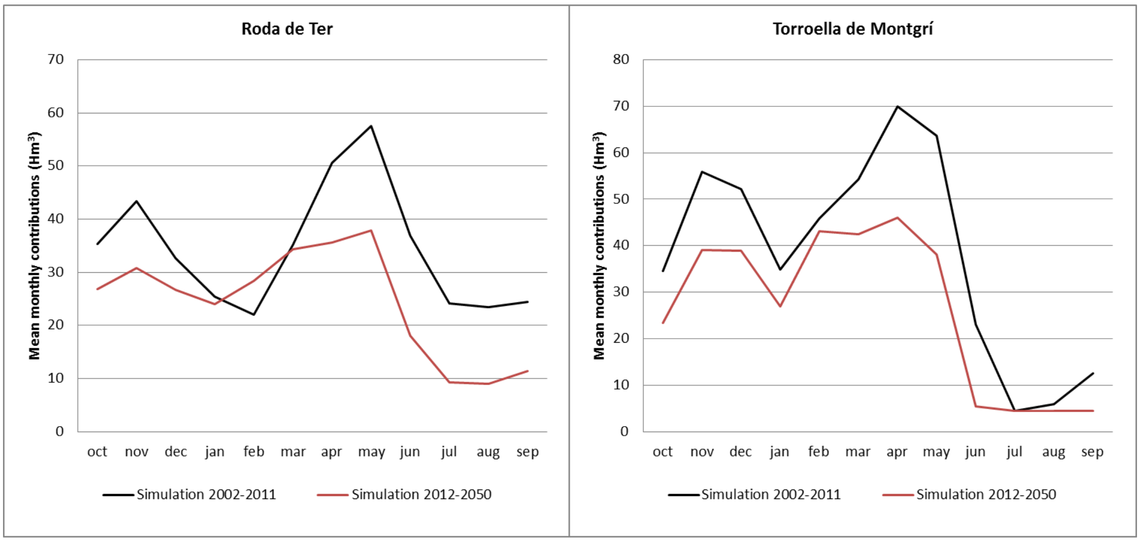


Figure 18. Expected changes in mean monthly contributions (hm^3) per month and location (headwaters and river mouth). Black lines show the mean values of RHESsys output for the reference period (2002-2011) and red lines for the 2012-2050 period.

As explained in Figure 14 for Boadella-Darnius dam and taking into account the same conditions (water demand, minimum ecological flow and dam management), in Figure 19 is showed the water storage simulated for the period 2012-2050 in the system Sau-Susqueda. The scenario is not as good as showed in Figure 17 but it is maintained a clear negative trend in terms of amount of water supply. Along the first decade, the system could be maintained but from 2022 the storage gets down dramatically until the end of decade of 2030, when seems to be a slight improvement.

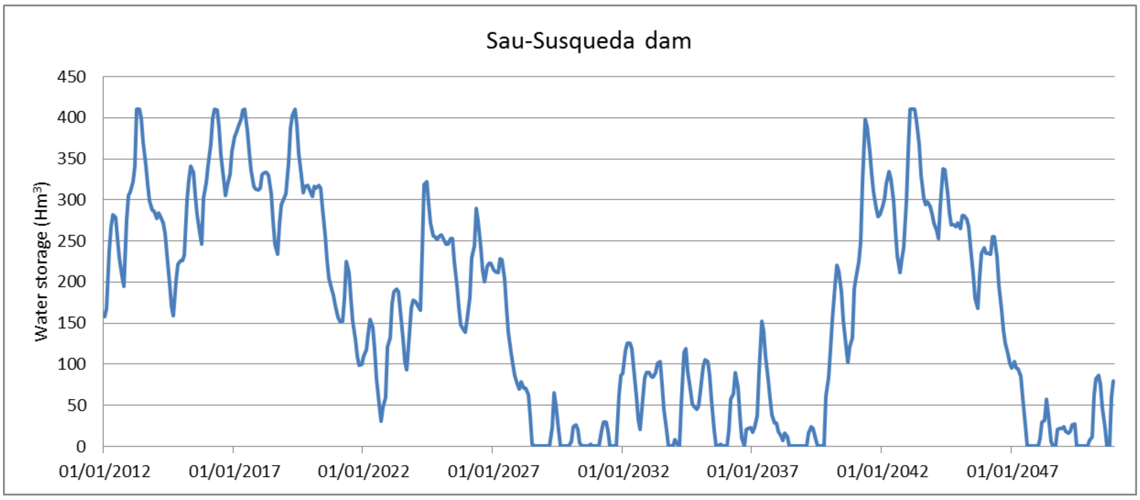


Figure 19. Water storage simulated for the period 2012-2050 in Sau-Susqueda system.

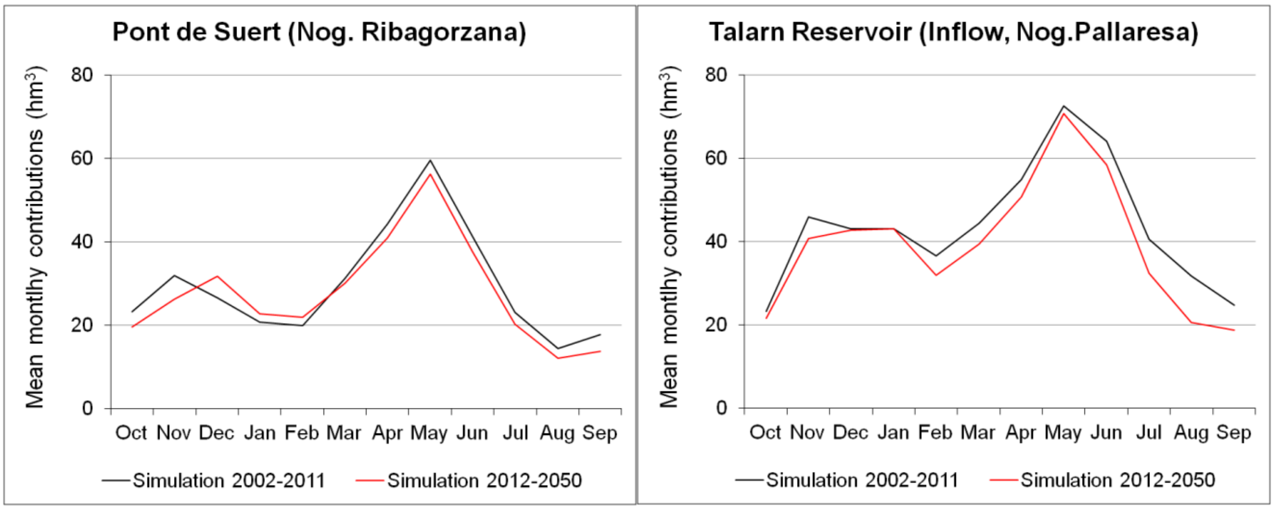
<u>Effects on the Segre basin – SWAT model</u>

Table 10 shows the mean water contribution (hm³/year) and its percentages of change at the short and long term and at three points of the Segre headwaters (Pont de Suert, Talarn Reservoir and Organyà) and the river mouth (Seròs). At the short term (2021-2030), contribution reduction are similar in percentage to the Muga basin, more noticeable in the headwaters (from 5.6 to 9.1%) than in the river mouth (3.0%). At the long term, the reductions are similar in all river courses, but less severe than in Muga basin (from 19% to 24%-reduction) and much less than in Ter basin (from 21.1 to 31.1%-reduction).

	Mean water contributions per period (hm³/year)			Changes in mean water contributions respect to 2002-2011period (%)	
	2002-2011	2021-2030	2041-2050	2021-2030	2041-2050
Pont de Suert (Noguera Ribagorzana headwaters)	353.5	333.6	312.1	-5.6%	-11.7%
Talarn Reservoir Inflow (Noguera Pallaresa headwaters)	521.4	474.1	450.9	-9.1%	-13.5%
Organyà (Segre headwaters)	660.7	625.9	598.2	-5.3%	-9.5%
Seròs (river mouth)	1,539.7	1,493.9	1,351.0	-3.0%	-12.3%

Table 10. Mean water contribution (hm³/year) and percentage of change in mean water contributions per period (reference, short and long term) at three points of the headwaters and the river mouth.

Changes in mean monthly contributions are shown in Figure 20. Future simulations show a similar trend to the reference ones (2002-2011) and the reductions are more moderate than in Muga and Ter basins. In the Noguera Ribagorzana headwaters (Pont de Suert), winter contributions are expected to increase whereas in spring, summer and especially in fall, contributions will slightly decrease. In the Noguera Pallaresa headwaters (Talarn Reservoir inflow), reductions are foreseen in all seasons, more severe during the summer. In the Segre headwaters (Organyà), moderate changes are expected, more noticeable along spring and summer. In the river mouth (Seròs), reductions are foreseen along fall, winter and spring, whereas in summer reductions are more moderate. The effect of reservoir management and water abstraction may cause these difference in the river mouth.



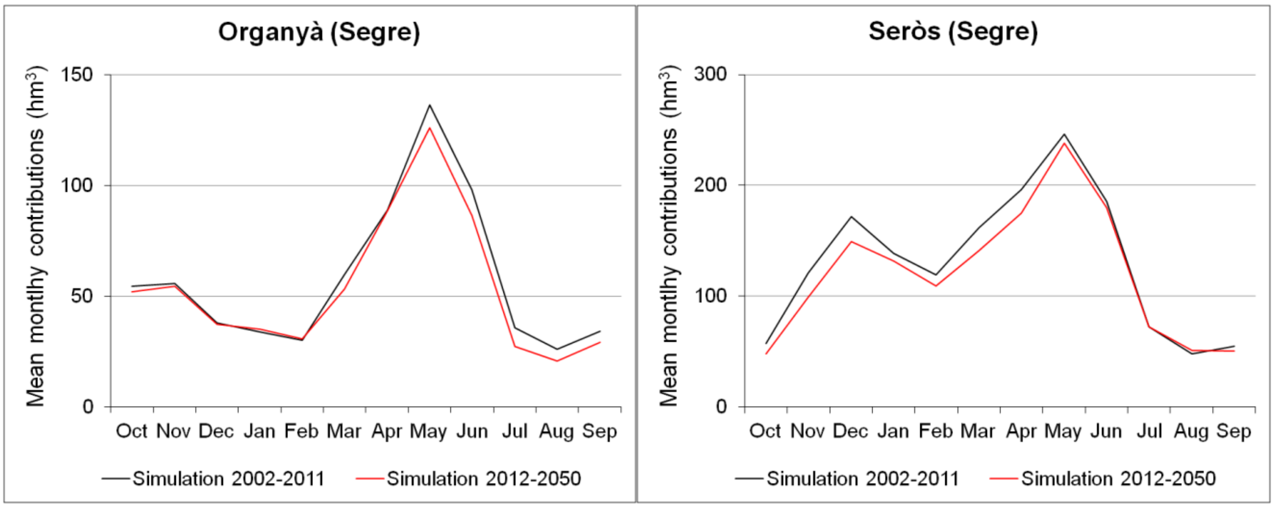
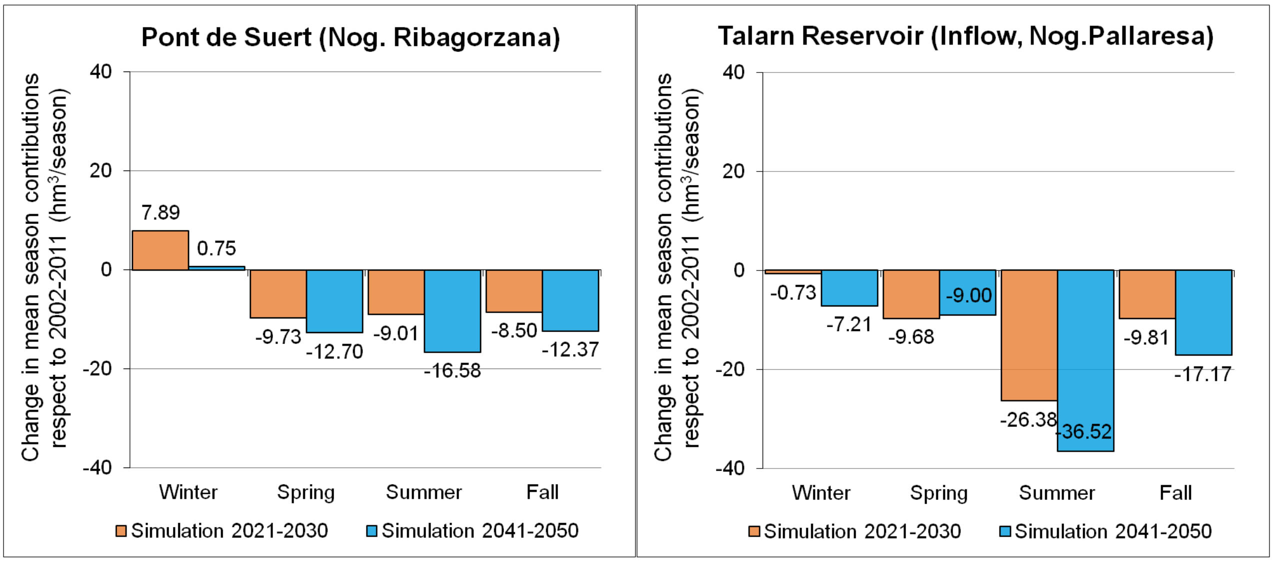


Figure 20. Expected changes in mean monthly contributions (hm³) per month and location (headwaters and river mouth). Black lines show the mean values of SWAT output for the reference period (2002-2011) and red lines for the 2012-2050 period.

Figure 21 shows the changes in mean season contribution (hm³/season) for period (short and long terms) and location (headwaters and river mouth). The Segre headwaters show a similar trend, with important reductions in spring, followed by summer and fall, and small or absence of reductions in winter (an increase in winter contributions is foreseen in the Noguera Ribagorzana and Segre headwaters, both at short and long term). Segre river mouth (Seròs) show a different pattern, with maximum reductions in spring, followed by winter and fall, and moderate reductions in summer (with a possible increase at short term). The effects of river regulation and water abstraction may contribute to this differentiate trend.



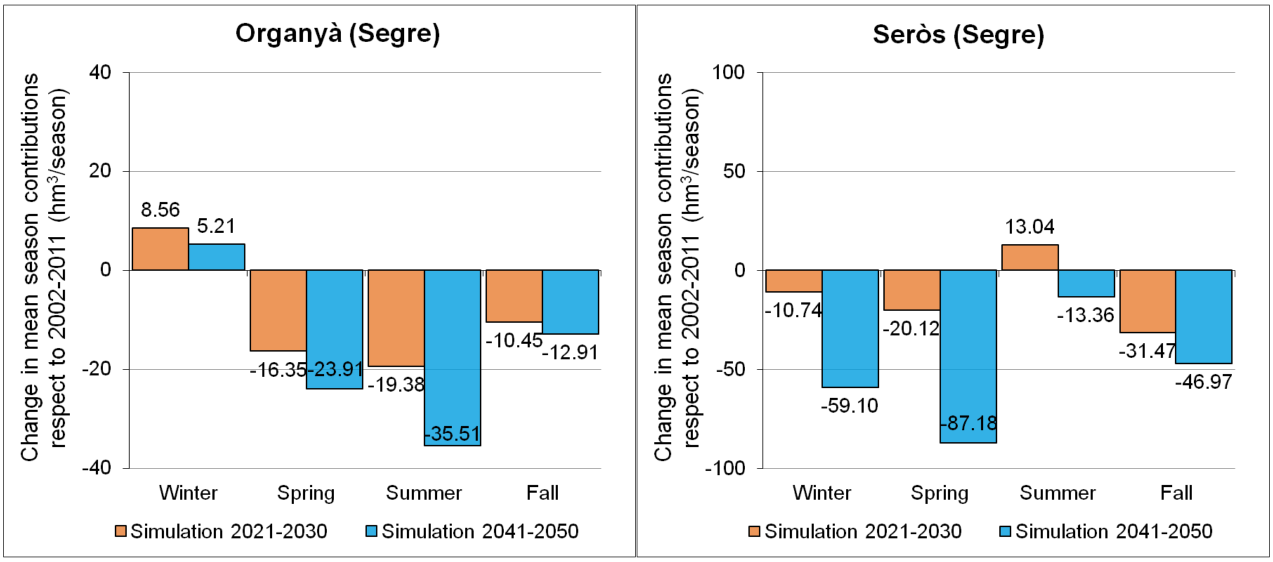
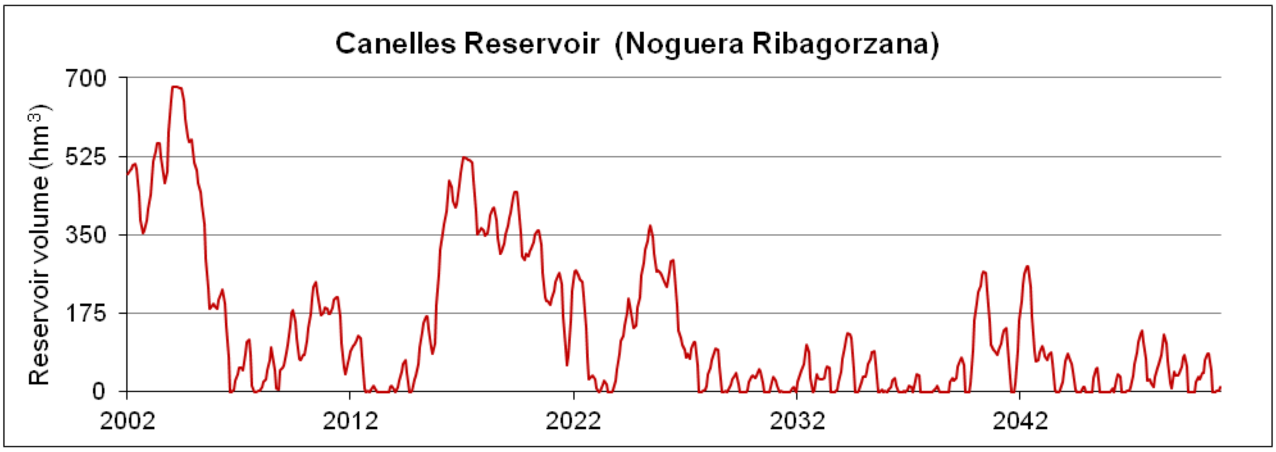


Figure 21. Expected changes in mean contribution per season (hm^3/season) for period and location compared to the reference period (2002-2011).

Figure 23 shows the evolution of the stored volume (hm^3) in Canelles, Camarassa and Rialb reservoirs. We only show here one reservoir per river, but similar results are obtained in the other four reservoirs. Similar to the Muga basin, this graphic needs to be contextualised before deducing conclusions (see previous section). The Camarassa Reservoir's figure shows the effects of 2007-08 droughts in the stored water. Similar to Muga and Ter basins, emptying events are more frequent and intense from 2027. The evolution of Rialb's volume follows the same trend than Camarassa, but emptying events seem to be more intense and long. The Canelles Reservoir presents the most important reduction, being alarming the situation after 2027 when almost every year the reservoir empties completely at least one month per year.



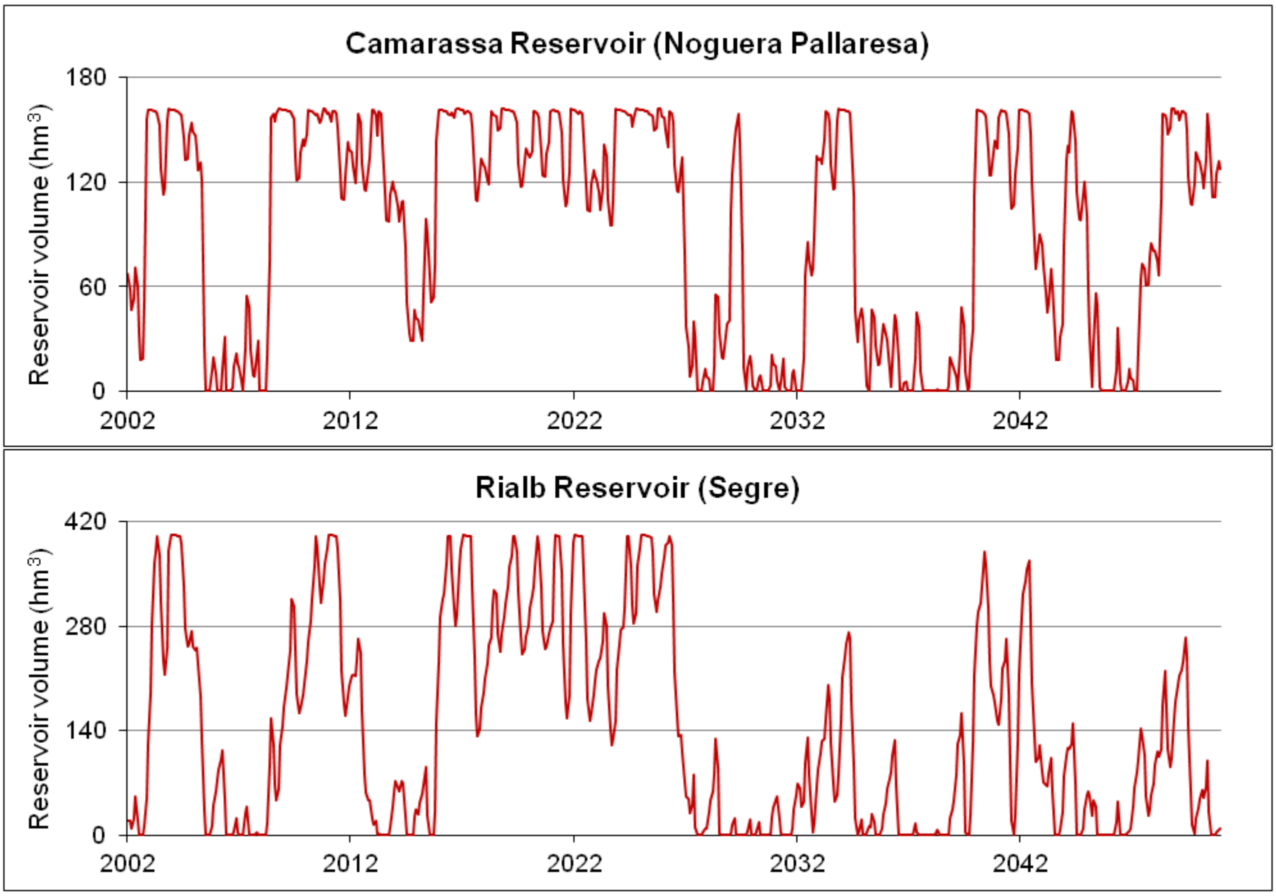


Figure 22. Simulation of reservoir volumes (hm³) until 2050.

Effects on the Segre basin – RHESsys model

The Table 11 explains the mean water contribution and percentage of change in each studied periods. As is showed, in headwaters there is a common pattern of decrease, excepting in Escaló where there is a slight increase in short term of 2.3%. The rest of them note a decrease around 7%. In the long term period all the values are normalized around -20%. In the river mouth case (Seròs gauging station) shows a slight decrease (-1.6%) for 2021-30 period while for the 2041-50 period is about -13%.

	Mean water contributions per period (hm³/year)			Changes in mean water contributions respect to 2002-2011 period (%)	
	2002-2011	2021-2030	2041-2050	2021-2030	2041-2050
Valira (headwaters)	103.9	96.9	79.0	-6.7%	-24.0%
Escalés Reservoir (Inflow, headwaters)	345.3	323.7	277.7	-6.3%	-19.6%
Escaló (headwaters)	171.1	175.0	135.3	2.3%	-20.9%
Organyà (headwaters)	833.5	765.8	649.9	-8.1%	-22.0%
Seròs (river mouth)	1,510.5	1,486.6	1,311.6	-1.6%	-13.2%

Table 11. Mean water contribution (hm³/year) and percentage of change in mean water contributions per period (reference, short and long term) at three points of the headwaters and the river mouth.

In Figure 23 are represented the expected changes in mean monthly contributions for the headwaters gauging stations (Valira, Escalés, Escaló, Organyà and Seròs) due to climate change. They show a similar pattern: no changes or slight increase in autumn/winter and a higher decrease between April and June. As noted in previous section about Ter river, this is because the snow melting process starts early along the year.

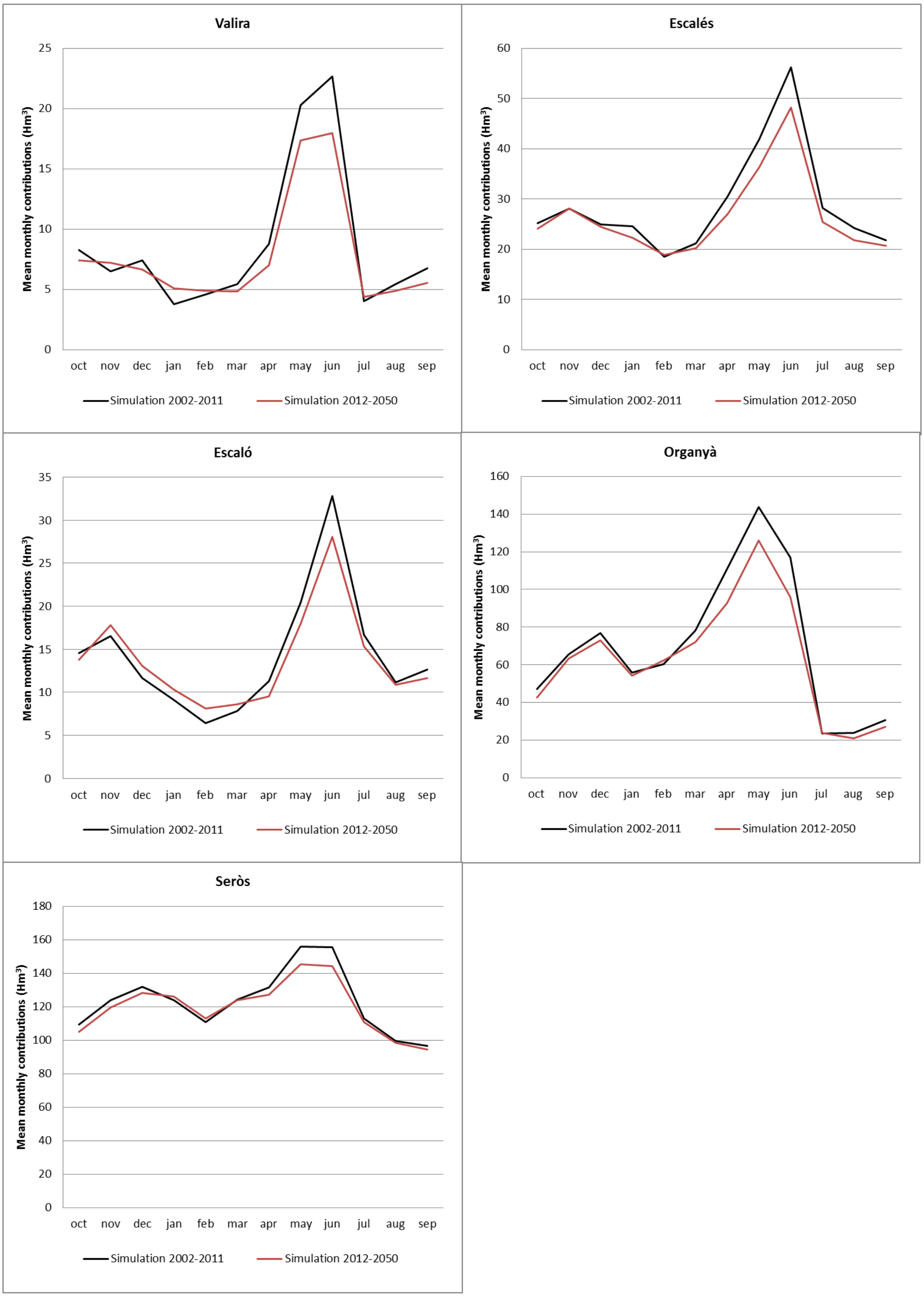


Figure 23. Expected changes in mean monthly contributions (hm^3) per month and location (headwaters and river mouth). Black lines show the mean values of RHESsys output for the reference period (2002-2011) and red lines for the 2012-2050 period.

In a same way as in Figure 14 and Figure 19 we have simulated the water storage in Oliana and Camarassa reservoirs and the result can be checked in Figure 24. As it is showed, the alternation dry/wet years changes along the time increasing the moments where the actual dam management could lead to increase drought events.

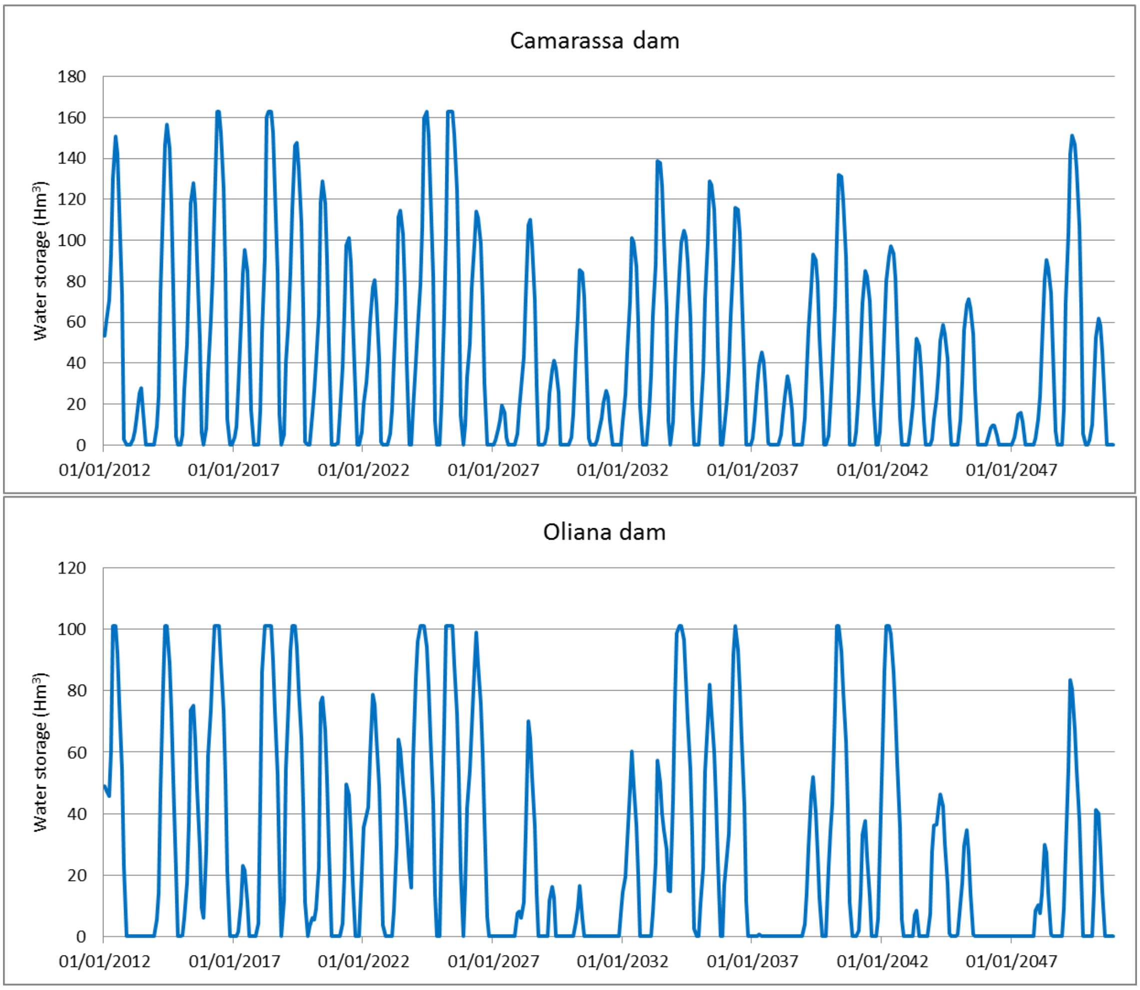


Figure 24. Simulation of reservoir volumes (hm^3) until 2050.

4.2.2. Impacts of climate and land cover scenarios

For this simulation exercise, we combined the climate change scenario with the land cover scenarios exposed in section 3.2. We had to assume that water abstractions were equal to the reference period and that the reservoir outflow data was the mean of the monthly output during the reference period (2001-2011). Results were analysed in two time horizons (short term 2021-2030 and long term 2041-2050) and two spatial areas (headwaters and river mouths).

Simulations with SWAT only included AFOR and FIREFOR scenarios. MANAGEFOR scenario implies to modify the vegetation input parameters in the model in a way not possible with SWAT. This scenario will be analysed with RHESsys model, where is possible to add a layer as input of percentage of occupation. Thus, the selected areas for forest management where reclassified to be 50% of occupation, while the rest are as actual (100%).

In AFOR and FIREFOR scenarios, we made the following assumptions. In the AFOR scenario, forest is all included in the same category, without distinction between conifers, evergreen and deciduous forest. In order to perform the simulations, we assigned the same vegetation parameters than conifer forests to the forest category. In FIREFOR, we did not need to make the same assumption since forests were divided in the three categories. In both AFOR and FIREFOR scenarios, agriculture area was included in the same category, without distinction between woody crops, herbaceous group and irrigated herbaceous crops. In order to perform the simulations, we assigned the same crops parameters than herbaceous crops (the majoritarian one) to the crops category in AFOR and FIREFOR scenarios.

	Ter basin	Muga basin	Segre basin			
	Roda de Ter	Boadella Darnius	Valira	Escalés	Escaló	Organyà
Managed area (Forest)	72.3	45.3	24.5	64.5	21.5	45.6
Managed area (Total)	25.2	41.6	12.1	21.9	7.9	22.9

Table 12. Managed area (in %) for each sub-basin.

In Table 12 is showed the managed area for each sub-basin where the MANAGEFOR scenario has been implemented. From one hand, the managed area for the headwater sub-basins varies from 21% in Escaló to 72% in Roda de Ter, regarding to the Forest land use (Deciduous broadleaf forest, and Evergreen Needle/Deciduous forest). From the other hand, the managed area regarding to the total area of the basins has also a high variability (7.9% in Escaló to 41.6% in Boadella-Darnius). Thus, the expected results of simulations may be different apart from RHESsys model is highly sensitive to vegetation changes.

<u>Effects on the Muga basin – SWAT model</u>

Table 13 shows the percentages of change at the short and long term and at the headwaters (Boadella Reservoir) and the river mouth (Castelló d'Empúries) for the climate scenario (RCP4.5) and the combination between the climate and AFOR scenarios (RCP4.5+AFOR) and between the climate and FIREFOR scenario (RCP4.5+FIREFOR). The percentage of change are estimated with respect to the reference period (2002-2011) for the RCP4.5 scenario. All scenarios foresee a notable reduction of water contributions, higher when the land cover scenarios are included. Differences are more noticeable in the river mouth and the AFOR, where the RCP4.5 estimated reductions about 11.6 and 15.9 hm^3/year at the short and long term, meanwhile contribution reductions are about 21.9 and 36.8 hm^3/year in the AFOR scenario. AFOR scenarios foresees major water contribution reductions caused by the increase of the vegetation evapotranspiration originated in a higher forest surface. Contrarily, differences between RCP4.5 and FIREFOR scenarios are less appreciable. This is caused by the land change cover scenario that, as was shown in Figure 25, only foresees small changes in land cover in Muga basin (maximum increase is a 1.2% of evergreen forests and maximum lost is 0.5% of grasslands). Nevertheless, the differences among land cover scenarios are not so evident, especially in the headwaters, where the changes in land cover occur (reductions about 4.6 and 3.7 hm^3/year at the short term and 14.5 and 13.0 hm^3/year at the long term for AFOR and FIREFOR respectively).

	Changes in mean water contributions respect to 2002-2011 period (%)					
	RCP4.5		RCP4.5 + AFOR		RCP4.5 + FIREFOR	
	2021-2030	2041-2050	2021-2030	2041-2050	2021-2030	2041-2050
Boadella Reservoir (Inflow, headwaters)	-5.6%	-19.0%	-6.7%	-21.1%	-5.4%	-18.9%
Castelló d'Empúries (river mouth)	-10.1%	-23.9%	-19.1%	-31.6%	-11.3%	-25.0%

Table 13. Percentage of change in mean water contributions per period (reference, short and long term) at the headwaters and the river mouth per scenario (RCP4.5, RCP4.5+AFOR, RCP4.5+FIREFOR) compared with the reference period (2002-2011 for the RCP4.5 scenario).

Changes in mean monthly contributions are shown in Figure 25. All scenarios foresee a notable reduction of water contributions, with similar patterns depending on the locations. In the headwaters, there is an important reduction of the spring peak and appears a new peak in February. Afforestation produces more water during winter time, but this pattern is not observed in the fire scenario. In the river mouth, general reductions are observed all the year, being more notable along the summer and fall. AFOR scenario causes lower water contribution during fall, winter and the beginning of the spring compared with the climate scenario (RCP4.5). Differences between FIREFOR and RCP4.5 scenarios are inappreciable.

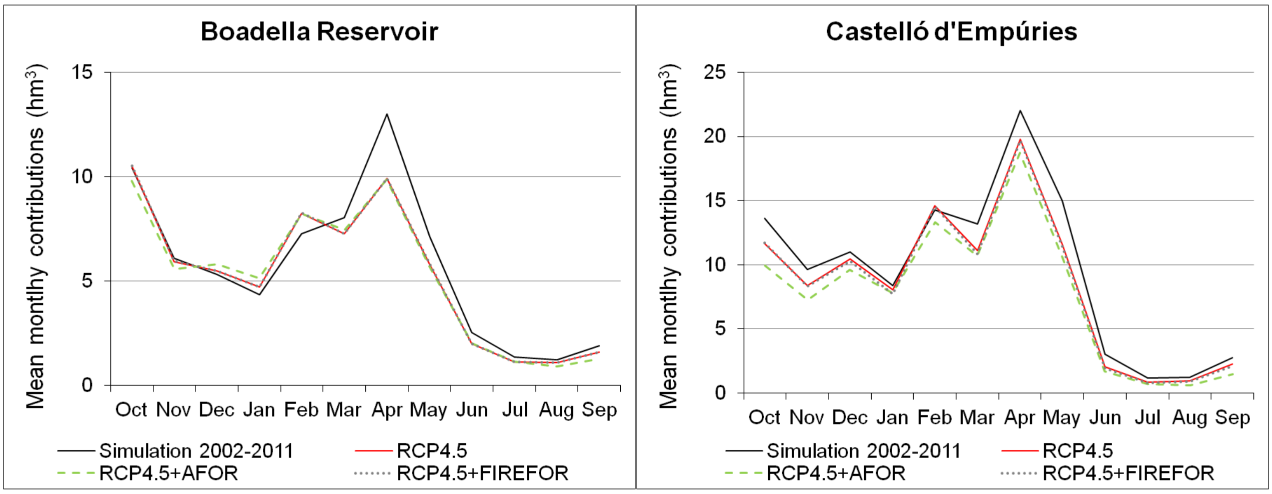
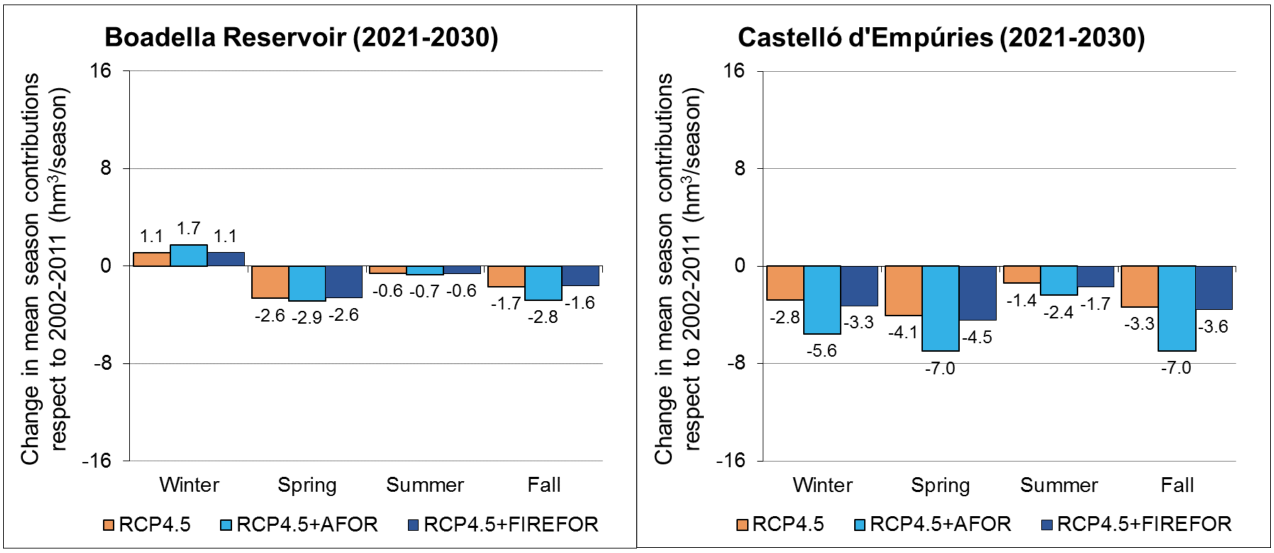


Figure 25. Expected changes in mean monthly contributions (hm^3) per month, location (headwaters and river mouth) and scenario (RCP4.5, RCP4.5+AFOR, RCP4.5+FIREFOR) compared with the reference period (2002-2011 for the RCP4.5 scenario) (black lines).

Figure 26 shows the changes in mean season contribution (hm^3/season) for period (short and long terms), location (headwaters and river mouth) and scenario (RCP4.5, RCP4.5+AFOR, RCP4.5+FIREFOR). All scenarios showed similar patterns and magnitude orders depending on the location and the period, with maximum reduction in spring and, in less quantity, in fall. Between the headwaters and the river mouth, differences were observed in winter time, with slight increases at short time and small decreases at long time in the headwaters, compared with the river mouth (similar to the results obtained in Figure 10).



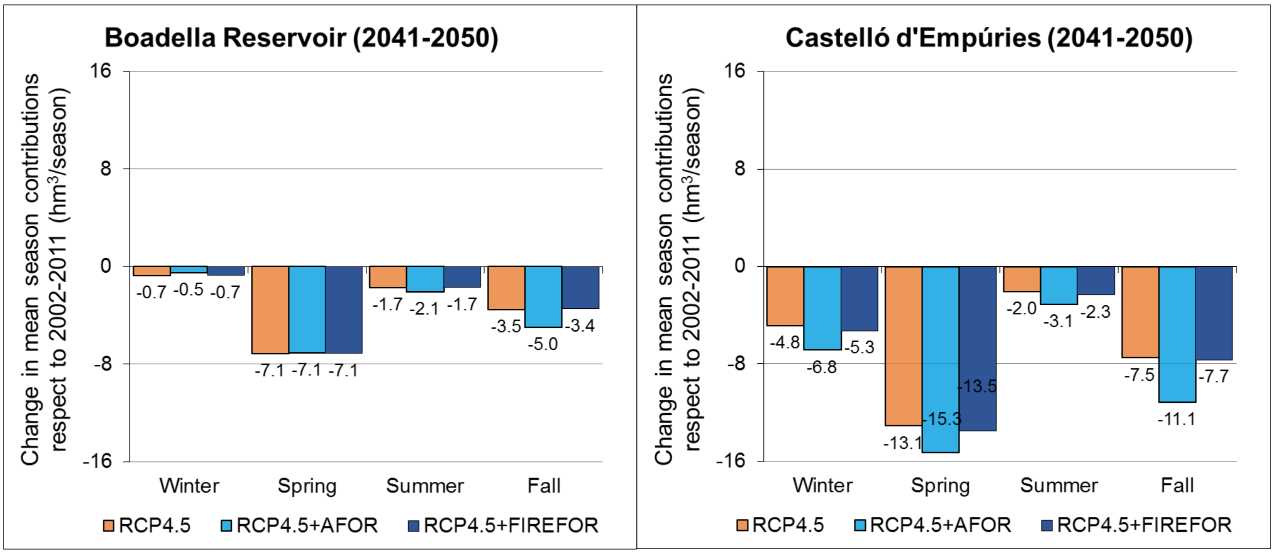


Figure 26. Expected changes in mean contribution per season (hm³/season) for period, location and scenario (RCP4.5, RCP4.5+AFOR, RCP4.5+FIREFOR) compared with the reference period (2002-2011 for the RCP4.5 scenario).

Figure 27 shows the evolution of the stored volume (hm3) in Boadella reservoir per scenario. The figure shows that there are not notable changes in the number, frequency and intensity of the emptying events among scenarios.

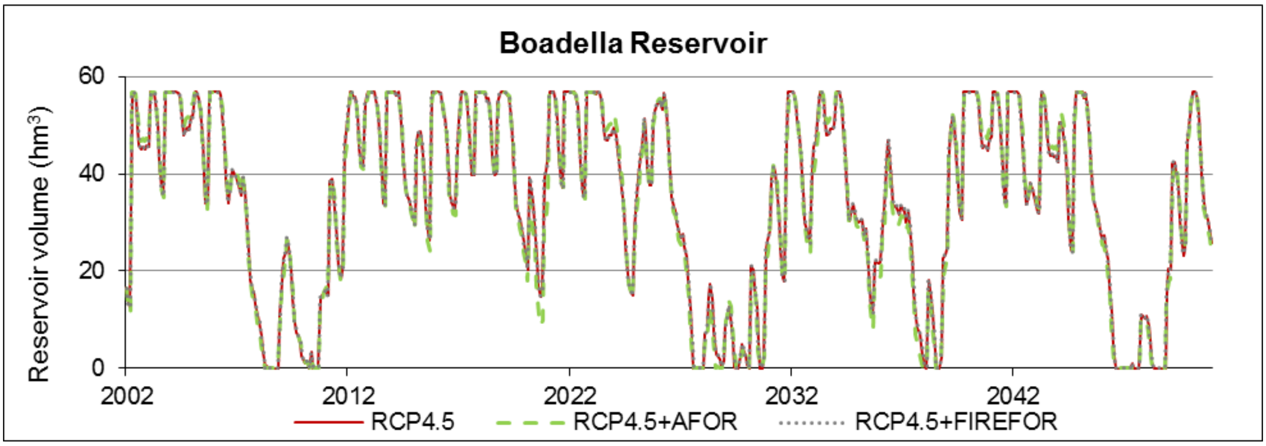


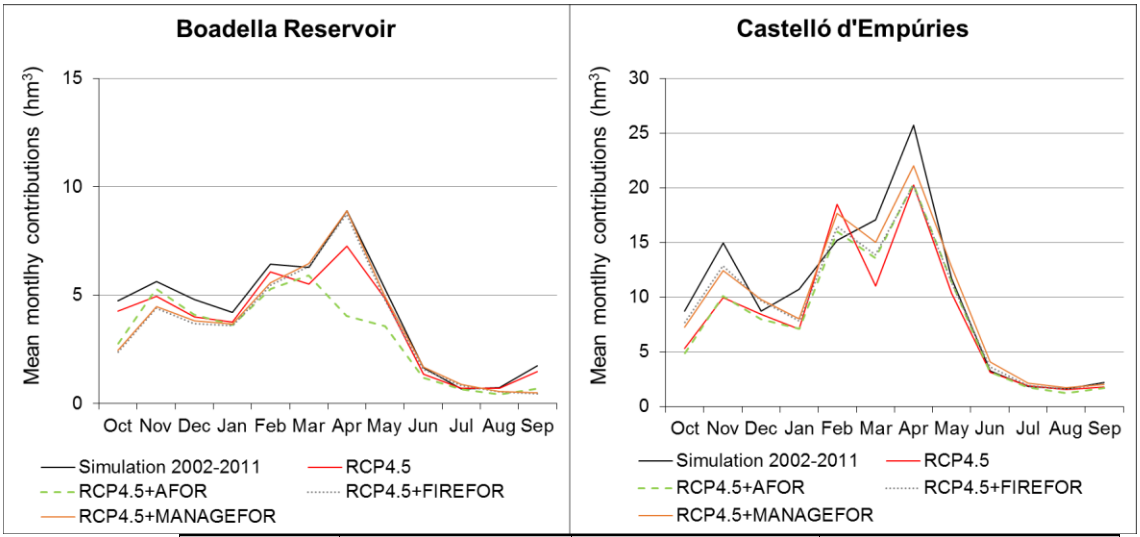
Figure 27. Simulation of reservoir volumes (hm³) until 2050 per scenario.

<u>Effects on the Muga basin – RHESsys model</u>

As is explained at the beginning of section 4.2.2., we have included the land cover scenario MANAGEFOR for the simulations with RHESsys model. In Figure 28 is observed the effect of the climate and the combined action of the climate and the land cover changes on the mean monthly contributions in Boadella-Darnius inflow and Castelló d'Empúries gauging stations. As expected, the AFOR scenario has a stronger impact than the rest of the land use scenarios representing a strong decrease, -26.3% for headwaters and -18.5% for river mouth. We can observe that if the forest area is managed, the decrease can be smoothed.

The seasonal changes are more or less linear in both stations and all the land cover scenarios excepting in the case of AFOR in Boadella-Darnius inflow contribution, where a drastically drop is observed in spring months. It may be due to an increment of the Leaf Area Index or to a growth of the vegetation and its relation with evapotranspiration.

In both cases the summer streamflow does not register any changes with the different climate and land cover scenarios applied.



	RCP4.5	RCP4.5+AFOR	RCP4.5+FIREFOR	RCP4.5+MANAGEFOR
Boadella	-12.0%	-26.3%	-16.2%	-10.1%
Castelló	-18.4%	-18.5%	-10.3%	-5.6%

Figure 28. Expected changes in mean monthly contributions (hm^3) per month, location (headwaters and river mouth) and scenario (RCP4.5, RCP4.5+AFOR, RCP4.5+FIREFOR, RCP4.5+MANAGEFOR) compared with the reference period (2002-2011 for the RCP4.5 scenario) (black lines).

In the Figure 29 are plotted the simulations of reservoir volumes of Boadella-Darnius dam for each scenario. Although the differences are negligible, the MANAGEFOR scenario slightly improves the water storage and in some years delay the storage drops. Anyway, the times when water scarcity exits are the same in all the scenarios.

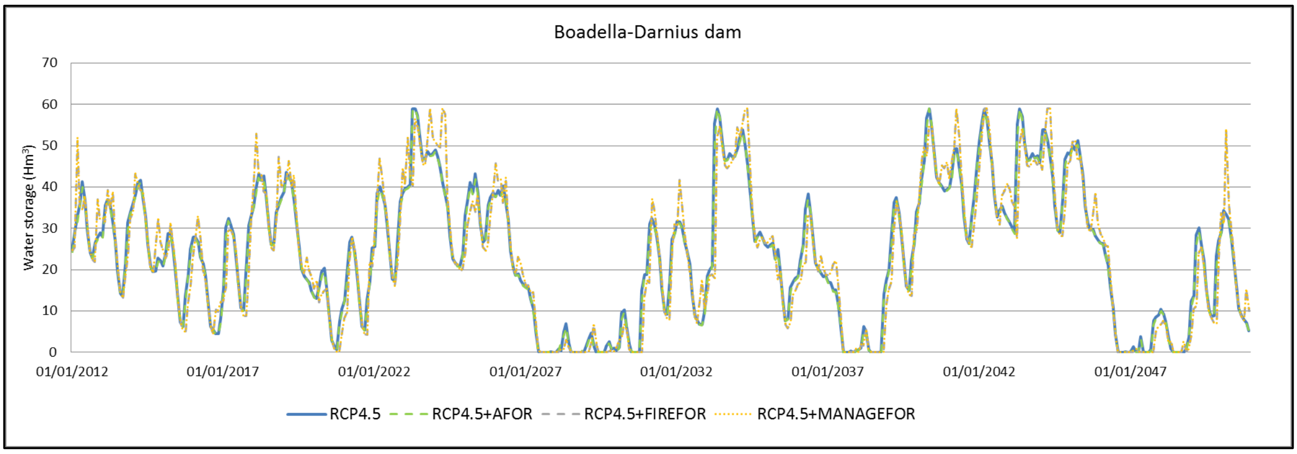


Figure 29. Simulation of reservoir volumes (hm^3) until 2050 per scenario

<u>Effects on the Ter basin – SWAT model</u>

Table 14 shows the percentages of change at the short and long term and at the headwaters and the river mouth for each scenario. All scenarios foresee a notable reduction of water contributions, but differences among scenarios are hardly appreciable.

	Changes in mean water contributions respect to 2002-2011 period (%)					
	RCP4.5		RCP4.5 + AFOR		RCP4.5 + FIREFOR	
	2021-2030	2041-2050	2021-2030	2041-2050	2021-2030	2041-2050
Roda de Ter (headwaters)	-13.8%	-21.1%	-14.4%	-20.3%	-15.1%	-22.1%
Torroella de Montgrí (river mouth)	-20.6%	-31.1%	-22.3%	-31.0%	-20.8%	-31.5%

Table 14. Percentage of change in mean water contributions per period (reference, short and long term) at the headwaters and the river mouth per scenario (RCP4.5, RCP4.5+AFOR, RCP4.5+FIREFOR) compared with the reference period (2002-2011 for the RCP4.5 scenario).

Changes in mean monthly contributions are shown in Figure 30. In the headwaters, all scenarios foresee a similar reduction of water contributions in spring and fall. Differences among scenarios are visible mainly in winter, where the AFOR scenario predicts higher contributions than the RCP4.5 and FIREFOR scenarios and the reference simulation (2002-2011), similar to the results obtained in Muga basin. In the river mouth, all the scenarios are similar in trend and magnitude, except in a lower contribution in fall in the afforestation scenario. In the river mouth, the scenarios show a different pattern compared to the headwaters, with an important reduction from October to December and in spring. The effect of reservoir management and water abstraction may cause these differences.

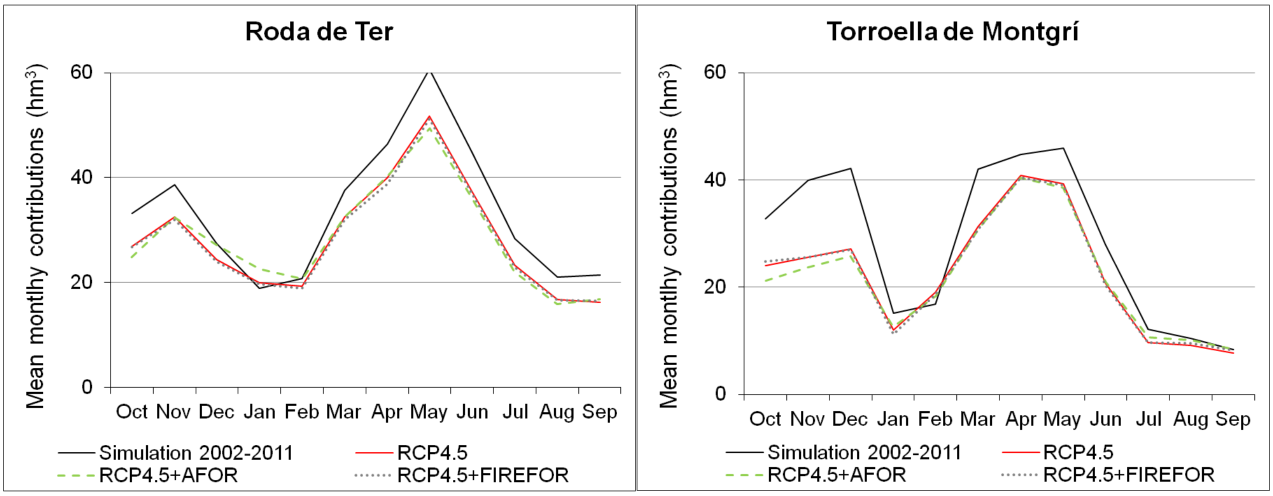


Figure 30. Expected changes in mean monthly contributions (hm^3) per month, location (headwaters and river mouth) and scenario (RCP4.5, RCP4.5+AFOR, RCP4.5+FIREFOR) compared with the reference period (2002-2011 for the RCP4.5 scenario) (black lines).

Figure 31 shows the changes in mean season contribution (hm^3/season) for period (short and long terms), location (headwaters and river mouth) and scenario (RCP4.5, RCP4.5+AFOR, RCP4.5+FIREFOR). All scenarios showed similar patterns and magnitude orders depending on the location and the period. Two differences between locations are visible: in the headwaters, changes in winter contributions are slightly negative in the climate and FIREFOR scenario and are positive in AFOR scenario. Meanwhile, winter reductions are notable in all scenarios in the river mouth. The second difference falls to the fact that, in the headwater, the reduction of summer contribution is notable and, in some scenarios, higher than expected fall reduction. Contrarily, summer reductions are low at the short term and moderate at the long term in the river mouth compared with the headwaters. One possible explanation is the paper of reservoir regulation in Torroella de Montgrí contributions.

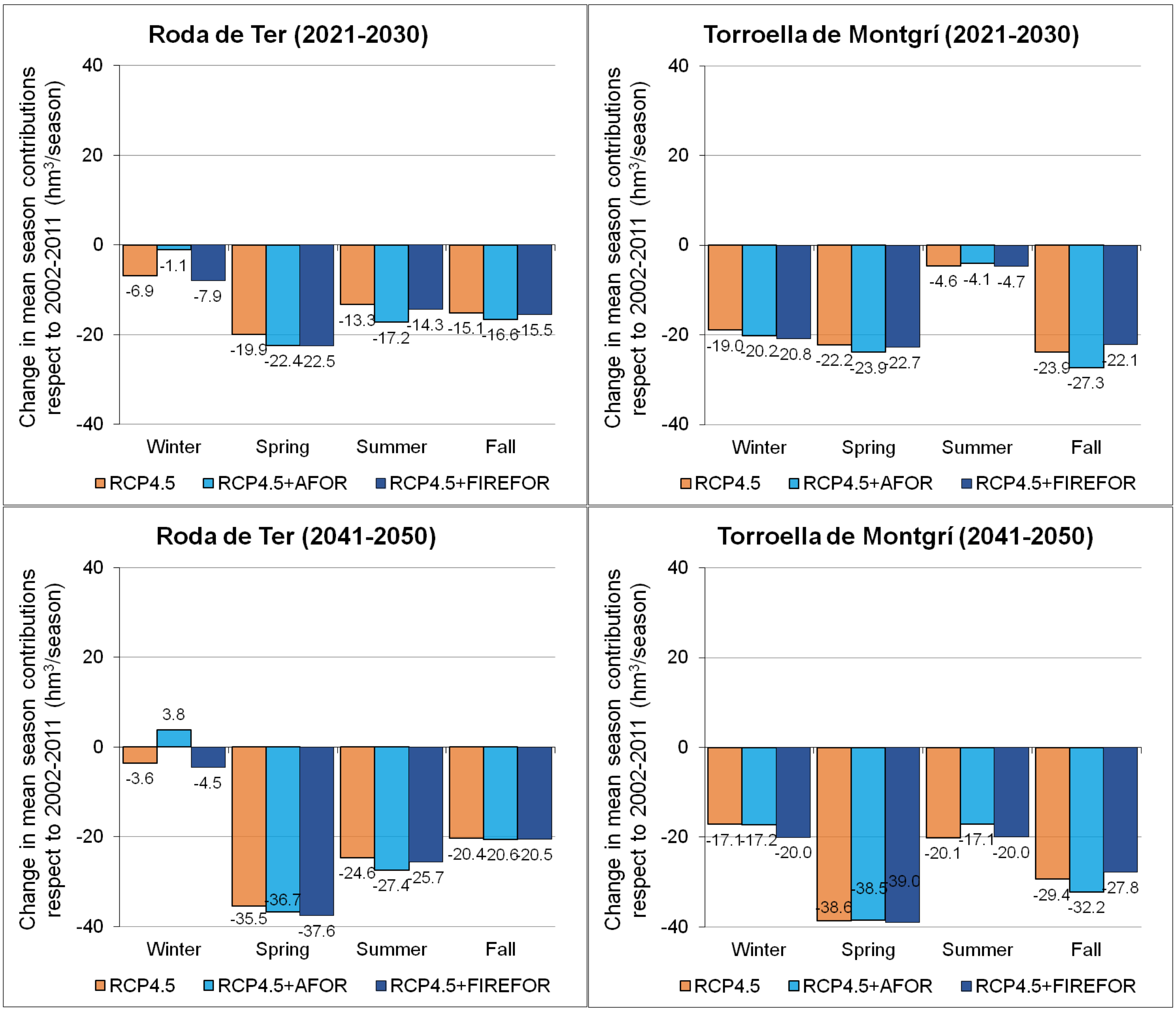
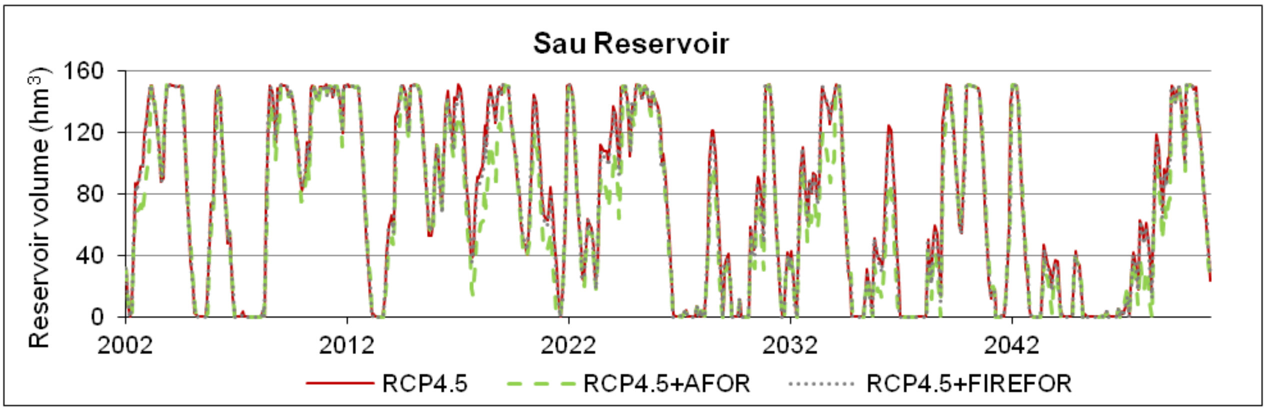


Figure 31. Expected changes in mean contribution per season (hm³/season) for period, location and scenario (RCP4.5, RCP4.5+AFOR, RCP4.5+FIREFOR) compared with the reference period (2002-2011 for the RCP4.5 scenario).

Figure 32 shows the evolution of the stored volume (hm³) in Sau and Susqueda reservoirs per scenario. AFOR scenario shows lower water storages compared with the climate and FIREFOR scenarios, especially in Susqueda reservoir. Nevertheless, there are not notable changes in the number, frequency and intensity of the emptying events among scenarios.



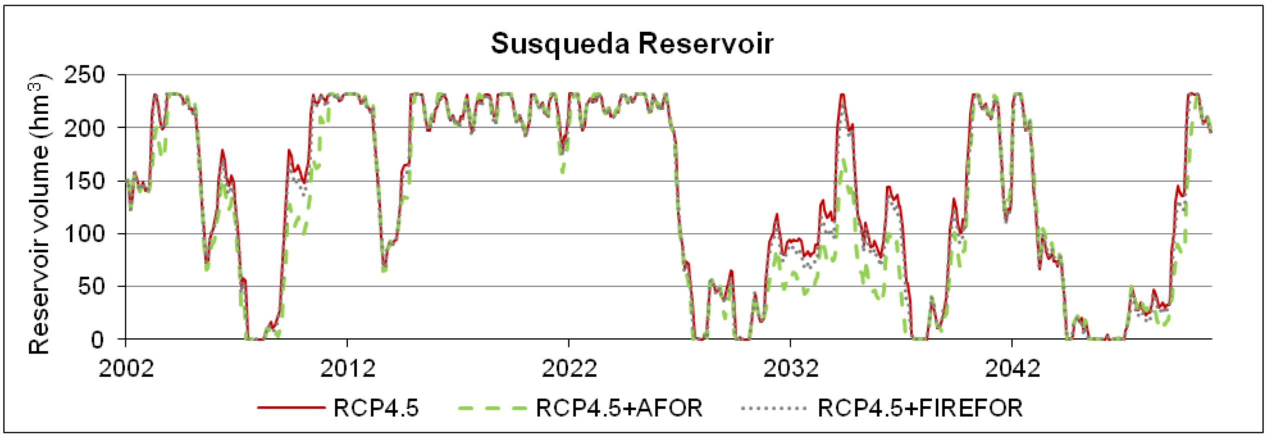
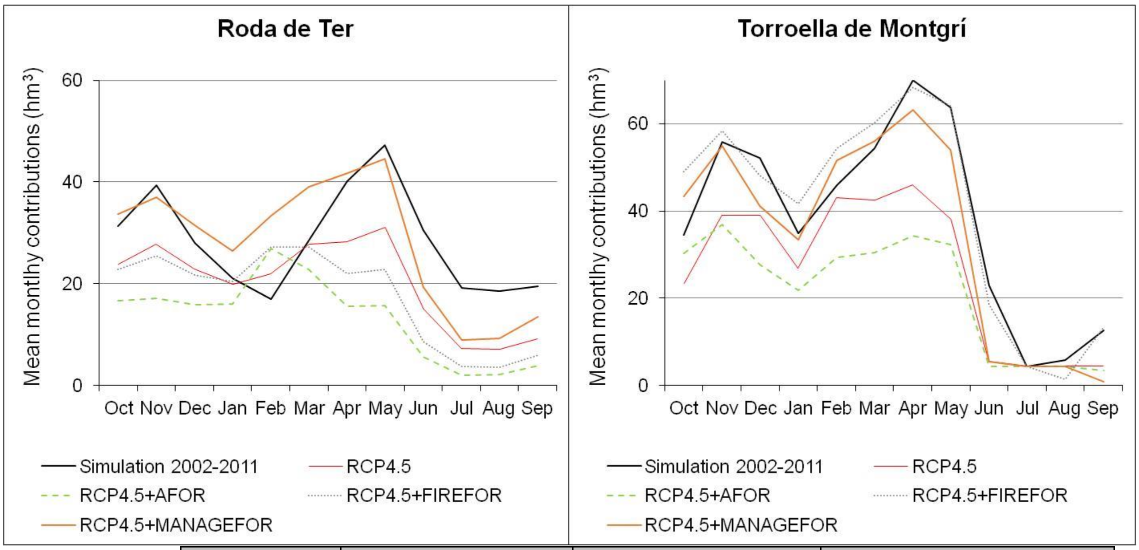


Figure 32. Simulation of reservoir volumes (hm3) until 2050 per scenario.

Effects on the Ter basin – RHESsys model

The simulations in Ter basin vary hugely between the different climate and land cover scenarios. The Figure 33 shows the mean monthly contributions and its percentage of change. The simulations show that this basin is very sensitive to any change, may be too high (the decrease with RCP4.5+AFOR reaches to 52.8% in Roda de Ter and 43.2% in Torroella de Montgrí). In the case of Roda de Ter, the seasonal regime is changed may due to the snow melt process, which is expected to be early. As in the previous basin analysed, the MANAGEFOR scenario improve the forecast of streamflow decrease, being negligible in Roda de Ter (-0.6%) and substantially less than in AFOR scenario (9.7%)



	RCP4.5	RCP4.5+AFOR	RCP4.5+FIREFOR	RCP4.5+MANAGEFOR
Roda	-28.9%	-52.8%	-37.8%	-0.6%
Torroella	-30.7v	-43.2%	5.5%	-9.7%

Figure 33. Expected changes in mean monthly contributions (hm³) per month, location (headwaters and river mouth) and scenario (RCP4.5, RCP4.5+AFOR, RCP4.5+FIREFOR, RCP4.5+MANAGEFOR) compared with the reference period (2002-2011 for the RCP4.5 scenario) (black lines).

As is noted for Boadella-Darnius dam, in Figure 34 where is showed the simulation of Sau-Susqueda system reservoir volumes for each scenario, there is not many changes about the drought periods its severity, frequency and duration.

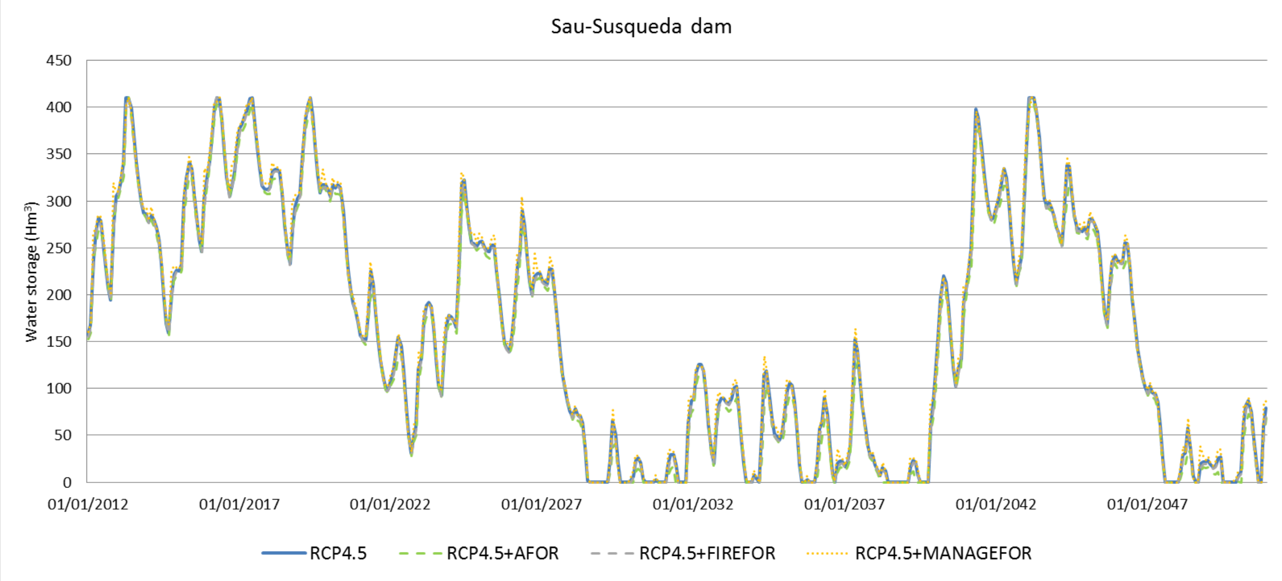


Figure 34. Simulation of reservoir volumes (hm^3) until 2050 per scenario.

<u>Effects on the Segre basin – SWAT model</u>

Table 15 shows the percentages of change at the short and long term and at the headwaters and the river mouth for each scenario. All scenarios foresee a notable reduction of water contributions, but differences among scenarios are almost inappreciable. In the Noguera Ribagorzana and Pallaresa headwaters, land use scenarios slightly worsen the effects of climate change. In Organyà headwaters the basin behaviour is the opposite, showing contrasted improvements when land cover scenarios take part, especially in the FIREFOR scenario. In the river mouth, the changes in water contributions among scenarios are very similar, with a reduction between 32.6 and 45.8 hm^3/year at the short term and between 187.5 and 193.9 hm^3/year at the long term.

	Changes in mean water contributions respect to 2002-2011 period (%)					
	RCP4.5		**RCP4.5 + AFOR**		**RCP4.5 + FIREFOR**	
	2021-2030	**2041-2050**	**2021-2030**	**2041-2050**	**2021-2030**	**2041-2050**
Pont de Suert (Noguera Ribagorzana headwaters)	-5.6%	-11.7%	-6.4%	-12.3%	-6.5%	-12.4%
Talarn Reservoir Inflow (Noguera Pallaresa headwaters)	-9.1%	-13.5%	-9.9%	-14.3%	-9.8%	-14.2%
Organyà (Segre headwaters)	-5.3%	-9.5%	-3.3%	-7.7%	-0.7%	-5.1%
Seròs (river mouth)	-3.0%	-12.3%	-2.8%	-12.6%	-2.1%	-12.2%

Table 15. Percentage of change in mean water contributions per period (reference, short and long term) at the headwaters and the river mouth per scenario (RCP4.5, RCP4.5+AFOR, RCP4.5+FIREFOR) compared with the reference period (2002-2011 for the RCP4.5 scenario).

Changes in mean monthly contributions are shown in Figure 35. In the Noguera Ribagorzana headwaters (Pont de Suert), winter contributions are expected to increase whereas in spring, summer and especially in fall, contributions will slightly decrease. Land change scenarios differentiate slightly from climate change scenario (RCP4.5), with higher reductions in winter and spring but higher contributions along August and fall. In the Noguera Pallaresa headwaters (Talarn Reservoir inflow), reductions are foreseen in all seasons, more severe during the summer. Differences among land change and climate scenarios are not appreciable. In the Segre headwaters (Organyà), moderate changes are expected, more noticeable along spring and summer. Land change scenarios foresees higher contributions during winter and spring, but differences are low. In the river mouth (Seròs), reductions are foreseen along fall, winter and spring, whereas in summer reductions are more moderate. The effect of reservoir management and water abstraction may cause these difference in the river mouth. Differences among land change and climate scenarios are not appreciable.

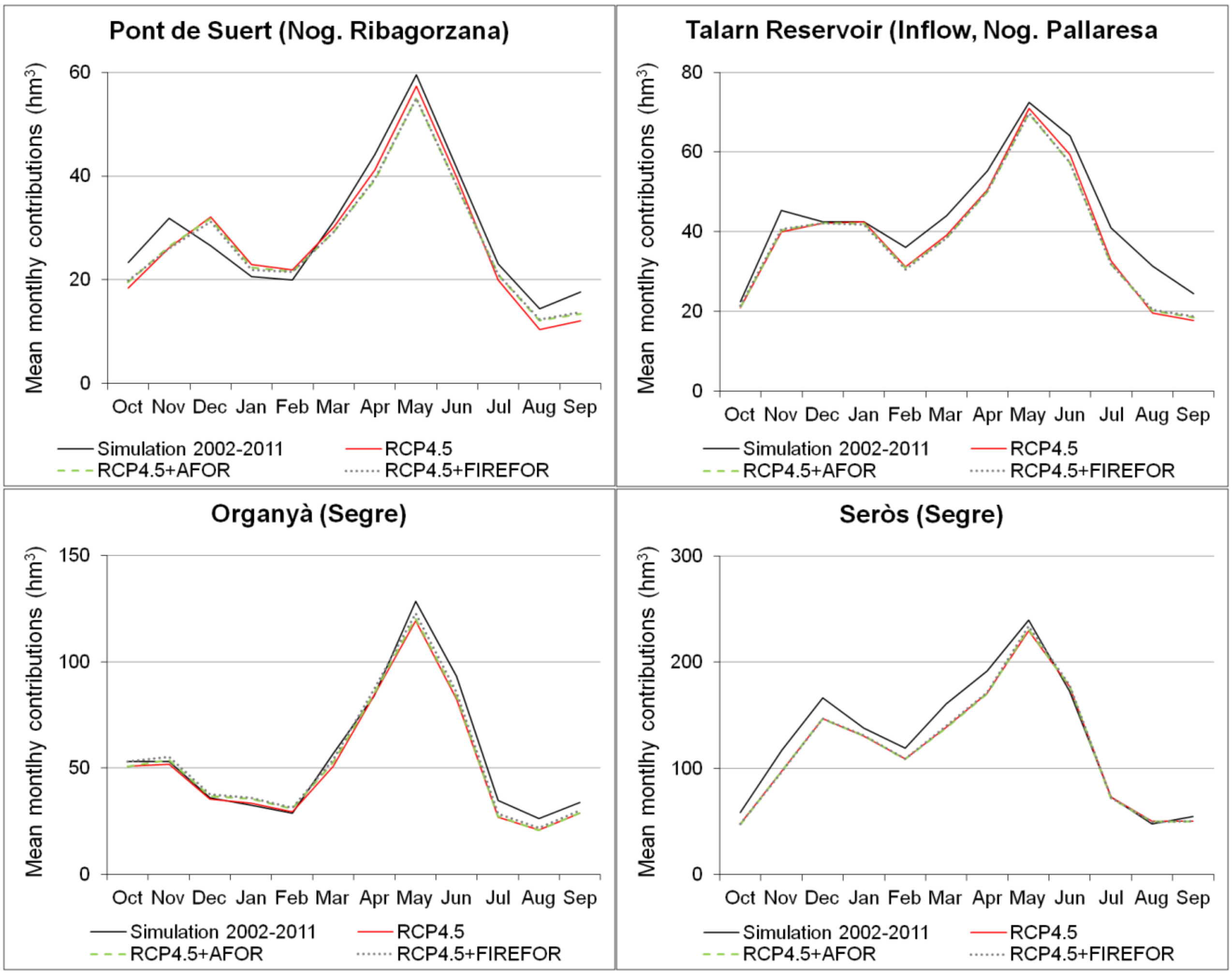
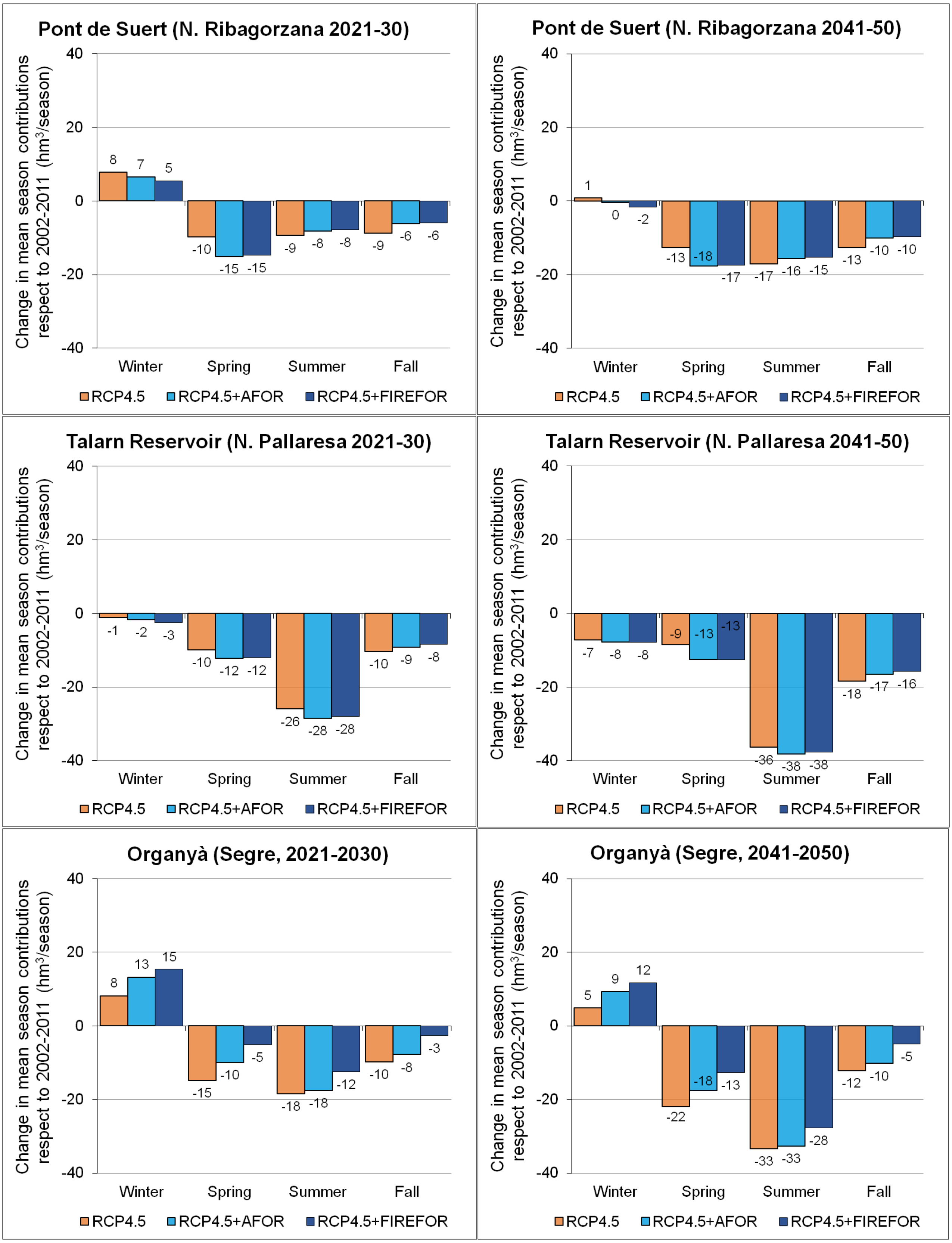


Figure 35. Expected changes in mean monthly contributions (hm³) per month, location (headwaters and river mouth) and scenario (RCP4.5, RCP4.5+AFOR, RCP4.5+FIREFOR) compared with the reference period (2002-2011 for the RCP4.5 scenario) (black lines).

Figure 36 shows the changes in mean season contribution (hm³/season) for period (short and long terms), location (headwaters and river mouth) and scenario (RCP4.5, RCP4.5+AFOR, RCP4.5+FIREFOR). Two differences between locations are visible: in the headwaters, changes in winter contributions are slightly negative in all scenarios at Talarn (Noguera Pallaresa) and positive in the majority of scenarios at Pont de Suert and Organyà (Noguera Ribagorzana and Segre). Meanwhile, winter reductions are notable in all scenarios in the river mouth, especially at the long term (55-56 hm³). The second difference falls to the fact that, in the headwaters, the reduction of summer contribution is notable and higher than any other season. Contrarily, mean contributions increase in summer at the short term and slightly decrease at the long term in the river mouth compared with the headwaters. The same patterns was observed in Ter basin. One possible explanation is the paper of reservoir regulations in Seròs contributions. At the river mouth, strong reductions are observed in spring, winter and fall.


Pont de Suert (N. Ribagorzana 2021-30)
Change in mean season contributions respect to 2002-2011 (hm³/season)
40
20
0
-20
-40
8 7 5
-10 -15 -15
-9 -8 -8
-9 -6 -6
Winter
Spring
Summer
Fall
RCP4.5
RCP4.5+AFOR
RCP4.5+FIREFOR
Pont de Suert (N. Ribagorzana 2041-50)
Change in mean season contributions respect to 2002-2011 (hm³/season)
1 0 -2
-13 -18 -17
-17 -16 -15
-13 -10 -10
Winter
Spring
Summer
Fall
RCP4.5
RCP4.5+AFOR
RCP4.5+FIREFOR
Talarn Reservoir (N. Pallaresa 2021-30)
Change in mean season contributions respect to 2002-2011 (hm³/season)
-1 -2 -3
-10 -12 -12
-26 -28 -28
-10 -9 -8
Winter
Spring
Summer
Fall
RCP4.5
RCP4.5+AFOR
RCP4.5+FIREFOR
Talarn Reservoir (N. Pallaresa 2041-50)
Change in mean season contributions respect to 2002-2011 (hm³/season)
-7 -8 -8
-9 -13 -13
-36 -38 -38
-18 -17 -16
Winter
Spring
Summer
Fall
RCP4.5
RCP4.5+AFOR
RCP4.5+FIREFOR
Organyà (Segre, 2021-2030)
Change in mean season contributions respect to 2002-2011 (hm³/season)
8 13 15
-15 -10 -5
-18 -18 -12
-10 -8 -3
Winter
Spring
Summer
Fall
RCP4.5
RCP4.5+AFOR
RCP4.5+FIREFOR
Organyà (Segre, 2041-2050)
Change in mean season contributions respect to 2002-2011 (hm³/season)
5 9 12
-22 -18 -13
-33 -33 -28
-12 -10 -5
Winter
Spring
Summer
Fall
RCP4.5
RCP4.5+AFOR
RCP4.5+FIREFOR

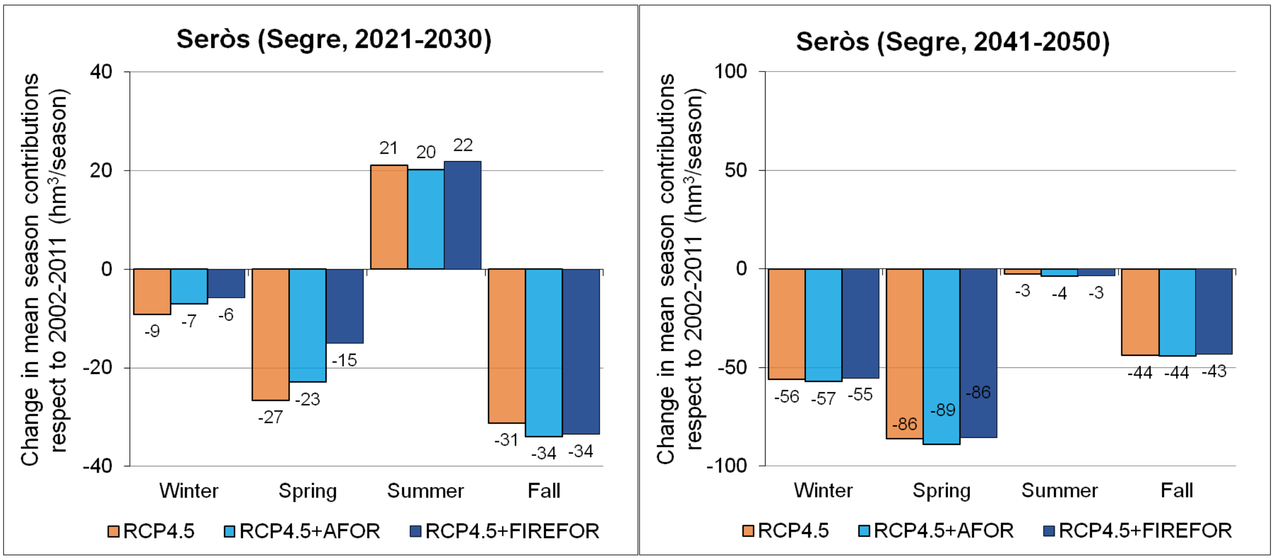
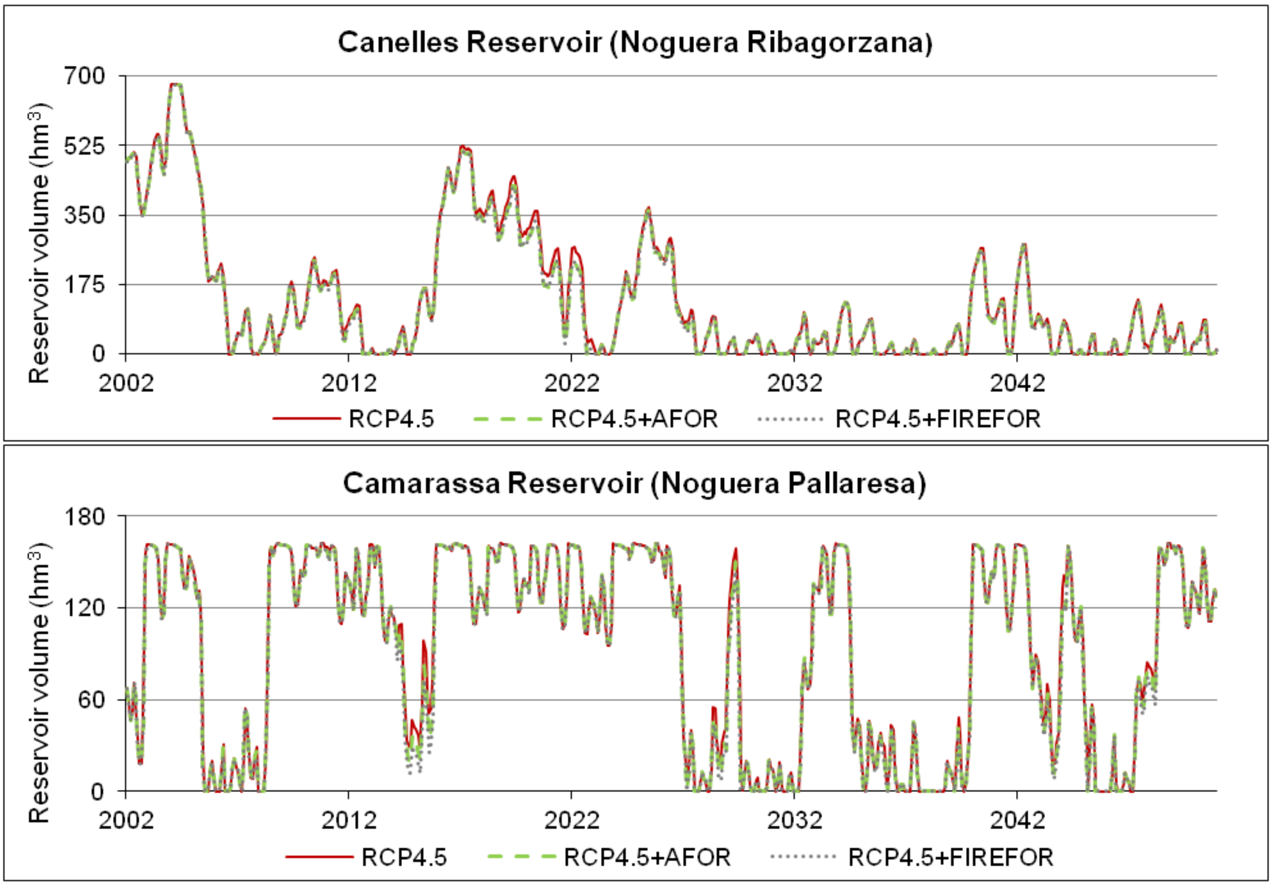


Figure 36. Expected changes in mean contribution per season (hm^3/season) for period, location and scenario (RCP4.5, RCP4.5+AFOR, RCP4.5+FIREFOR) compared with the reference period (2002-2011 for the RCP4.5 scenario).

Figure 37 shows the evolution of the stored volume (hm3) in Canelles, Camarassa and Rialb reservoirs per scenario. In Canelles and Camarassa reservoirs, land change scenarios show slightly lower stored volumes than the climate change scenario. However, no differences are observed in the number, frequency and intensity of the emptying events among scenarios. Contrarily, land change scenarios shows higher stored volumes in Rialb reservoir, more accentuated in the FIREFOR scenario. This fact corroborates the changes observed in previous figures in Organyà, where the FIREFOR scenario showed the lowest reductions in water contributions.



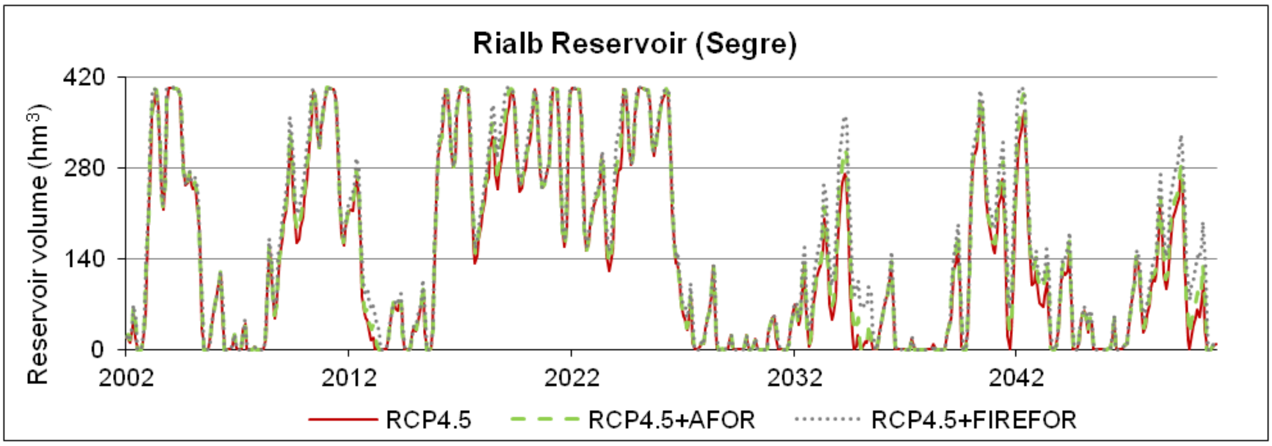


Figure 37. Simulation of reservoir volumes (hm^3) until 2050 per scenario.

<u>Effects on the Segre basin – RHESys model</u>

The Figure 38 and Table 16 show the expected changes in mean monthly contributions and the percentage of change (respectively) for the different climate and land cover scenarios in the Segre basin (Valira, Escalés, Organyà and Seròs gauging stations). The results show differences between headwaters (Valira, Escalés and Organyà) and mouth river (Seròs). The action of climate change in headwaters implies a decrease around -7% while in mouth river is -2.7%. The combined action of climate and land cover changes show more variability. While in Escaló and Organyà the decrease is around -20% (-19.6% and -25% respectively) in Valira and Seròs are -8.5% and -9%. The FIREFOR and MANAGEFOR scenarios show a streamflow increase in Valira (+6% and +10%) but a decrease in the rest of gauging stations except in Organyà with MANAGEFOR where the increment is about 2%.

The seasonal changes are mainly linear and similar to the rest of the basins, except in Valira sub-basin, where the spring streamflow (May/June) is highest than expected. This is because is a forested area where the changes in canopy for FIREFOR and MANAGEFOR has been significant. The pattern observed in Ter basin (changes in regime) is not showed in Segre basin, may be due to the different forest spatial distribution and its reflect into different changes in the land cover scenarios.

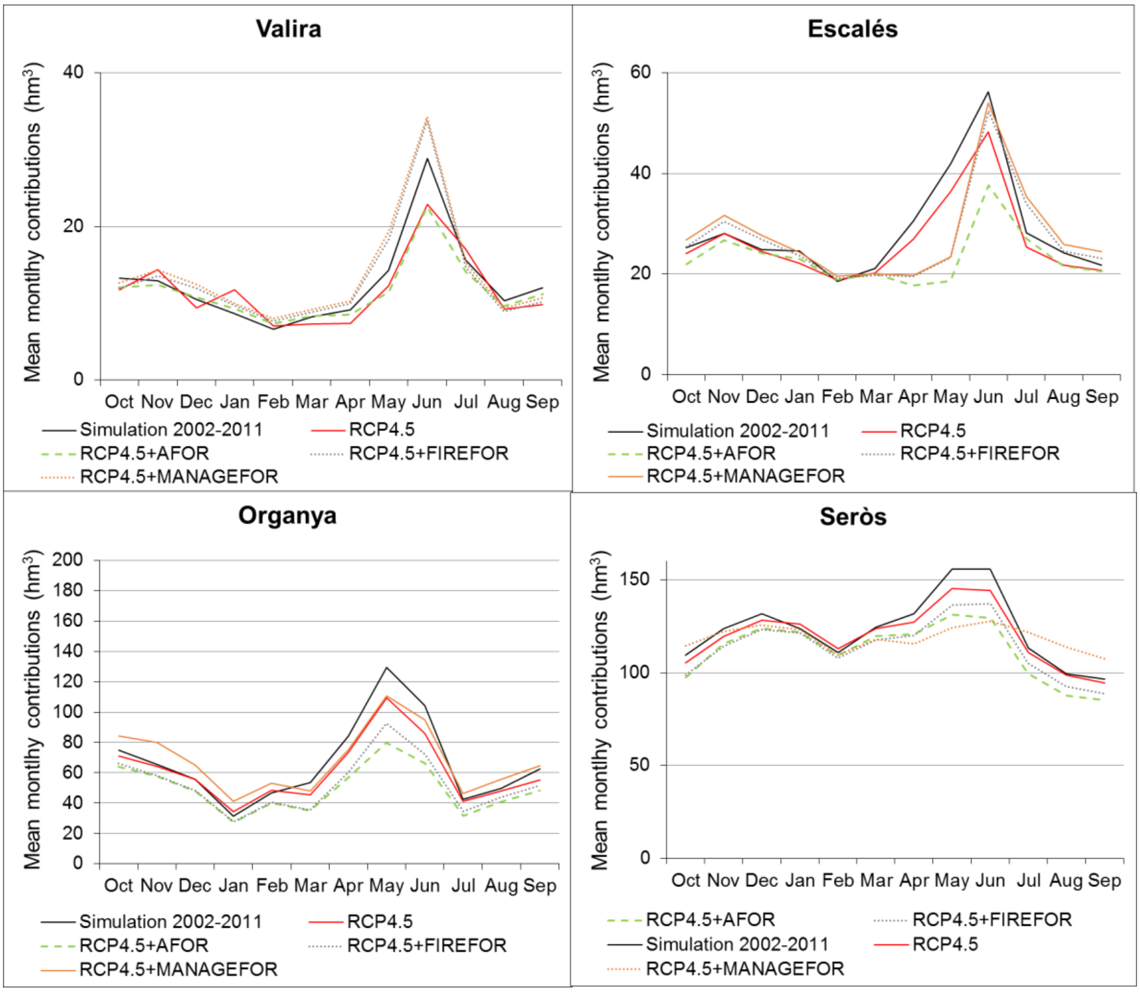


Figure 38. Expected changes in mean monthly contributions (hm³) per month, location (headwaters and river mouth) and scenario (RCP4.5, RCP4.5+AFOR, RCP4.5+FIREFOR) compared with the reference period (2002-2011 for the RCP4.5 scenario) (black lines).

	RCP4.5	RCP4.5+AFOR	RCP4.5+FIREFOR	RCP4.5+MANAGEFOR
Valira	-6.7%	-8.5%	6.0%	10.2%
Escaló	-8.1%	-19.6%	-6.6%	-3.5%
Organyà	-8.5%	-25.6%	-21.1%	2.3%
Seròs	-2.7%	-9.1%	-7.6%	-3.6%

Table 16. Percentage of change in mean water contributions per period (reference, short and long term) at the headwaters and the river mouth per scenario (RCP4.5, RCP4.5+AFOR, RCP4.5+FIREFOR, RCP4.5+MANAGEFOR) compared with the reference period (2002-2011 for the RCP4.5 scenario).

In Figure 39 is plotted the simulation of Oliana reservoir for the different climate and land use scenario. The variations between RCP4.5 scenario and RCP4.5+AFOR and RCP4.5+FIREFOR are linear and negligible. However the simulations with RCP4.5+MANAGEFOR shows a slight improvement of the storages forecasted: shorter periods of drought, drop of storage not as strong as other scenarios, etc.

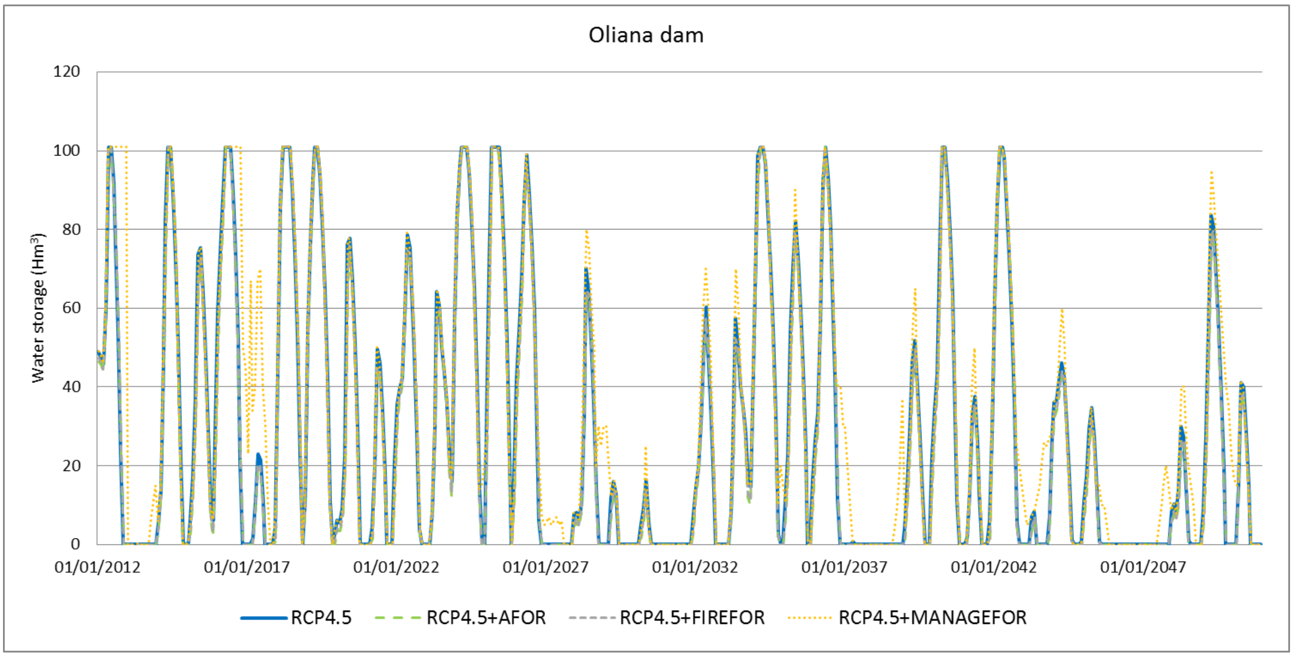


Figure 39. Simulation of reservoir volumes (hm^3) until 2050 per scenario.

4.2.3. Impacts of climate and socioeconomic scenarios

For this simulation exercise, we combined the climate change scenarios with the land cover and water management scenarios explained in section 3.3. Water abstractions were then modified depending on water management scenarios. In contraposition, reservoir outflow data was the mean of the monthly output during the reference period (2001-2011). Results were analysed in two time horizons (short term 2021-2030 and long term 2041-2050) and two spatial areas (headwaters and river mouths).

Simulations with SWAT only included AFOR and FIREFOR scenarios. MANAGEFOR scenario implies to modify the vegetation input parameters in the model in a way not possible with SWAT. This scenario will be analysed with RheSSys model.

In AFOR and FIREFOR scenarios, we made the following assumptions. In the AFOR scenario, forest is all included in the same category, without distinction between conifers, evergreen and deciduous forest. In order to perform the simulations, we assigned the same vegetation parameters than conifer forests to the forest category in AFOR scenario. In FIREFOR, we did not need to make the same assumptions since forests were divided in the three categories. In both AFOR and FIREFOR scenarios, agriculture area was included in the same category, without distinction between woody crops, herbaceous group and irrigated herbaceous crops. In order to perform the simulations, we assigned the same crops parameters than herbaceous crops (the majoritarian one) to the crops category in AFOR and FIREFOR scenarios.

<u>Effects on the Muga basin – SWAT model</u>

Table 17 shows the percentages of change at the short and long term and at the headwaters and the river mouth for each scenario. There are not foreseen changes in the headwaters among socioeconomic scenarios, since the water management scenarios increase/decrease water abstractions in the Ponts de Molins dam, after the headwaters. The RATUS scenario foresees a reduction 9.6 hm^3/year in the water abstraction of the Pont de Molins dam, applied during the summer period, reducing 3.2 hm^3 in June, July and August, when maximum irrigation demands take place. For this reason, the reduction in water contribution notable decrease, from a 19.1-31.6% in the AFOR scenario (21.9 to 36.4 hm^3/year) at the short and long term, to a 11.7-24.6% in the AFOR+RATUS scenario (13.4 to 28.3 hm^3/year). Curiously, the combination of the RCP4.5, AFOR and RATUS scenarios show a results very similar to the climate scenario (RCP4.5), as if the rational use of water resources can counterbalance the effects of afforestation. Decreases are similar in the FIREFOR scenarios (from 13.0-28.7 hm³/year in FIREFOR scenario to 4.5-21 hm³/year when including RATUS). The release of water into the river will improve the ecological status of the river.

On the contrary, DEMINC scenario foresees the enlargement of the Boadella reservoir to increase the capacity in 28 hm³, from the current 57 hm³ capacity to 85 hm³ (maximum capacity from 62 to 90 hm³). This scenario does not influence on water contributions, since water abstractions are not modified. Changes in reservoir water storage are shown in Figure 42 and explained later in this section.

	Changes in mean water contributions respect to 2002-2011 period (%)							
	RCP4.5		**RCP4.5 + AFOR**		**RCP4.5+AFOR+RATUS**		**RCP4.5+AFOR+DEMINC**	
	2021-2030	**2041-2050**	**2021-2030**	**2041-2050**	**2021-2030**	**2041-2050**	**2021-2030**	**2041-2050**
Boadella (headwaters)	-5.6%	-19.0%	-6.7%	-21.1%	-6.7%	-21.2%	-6.7%	-21.1%
Castelló (river mouth)	-10.1%	-23.9%	-19.1%	-31.6%	-11.7%	-24.6%	-18.5%	-31.3%
	RCP4.5		**RCP4.5 + FIREFOR**		**RCP4.5+FIREFR+RATUS**		**RCP4.5+FIREFR+DEMINC**	
	2021-2030	**2041-2050**	**2021-2030**	**2041-2050**	**2021-2030**	**2041-2050**	**2021-2030**	**2041-2050**
Boadella (headwaters)	-5.6%	-19.0%	-5.4%	-18.9%	-5.4%	-18.9%	-5.4%	-18.9%
Castelló (river mouth)	-10.1%	-23.9%	-11.3%	-25.0%	-3.9%	-18.3%	-10.7%	-24.4%

Table 17. Percentage of change in mean water contributions per period (reference, short and long term) at the headwaters and the river mouth per scenario compared with the reference period (2002-2011 for the RCP4.5 scenario).

Changes in mean monthly contributions are shown in Figure 40. Only changes are shown for the river mouth, since the headwaters remain the same as the section 4.2.2. The socioeconomic scenarios show the same patterns as when including only land change scenarios, except in RATUS scenarios. RATUS scenario causes that, during the summer, water contributions increase as result of reducing water abstractions. The DEMINC scenario does not modify water contributions.

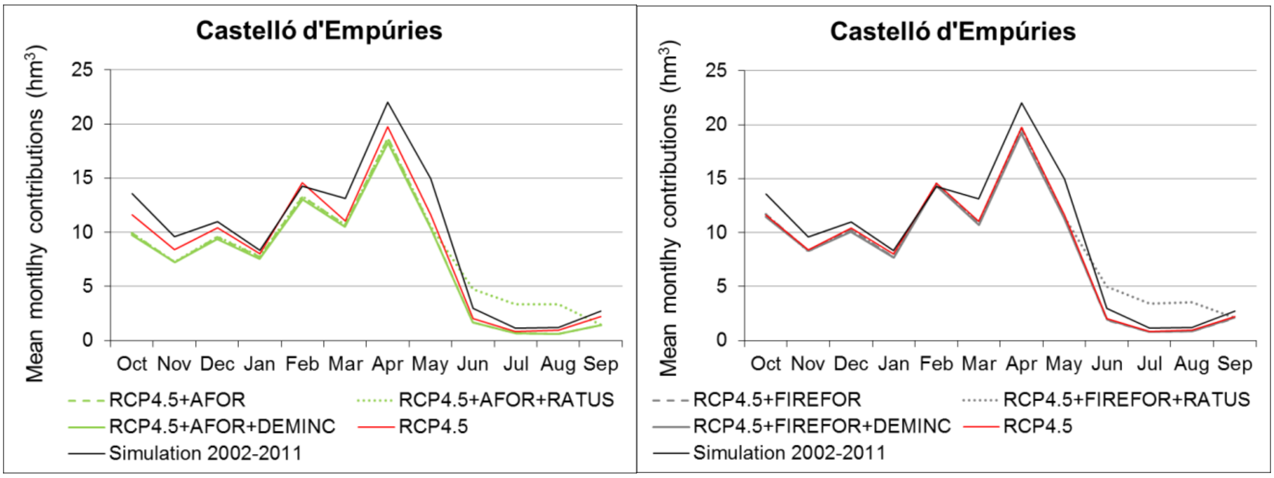


Figure 40. Expected changes in mean monthly contributions (hm³) per month and scenario at the river mouth compared with the reference period (2002-2011 for the RCP4.5 scenario) (black lines).

Figure 41 shows the changes in mean season contribution (hm³/season) for period and scenario at the river mouth. Similar to the previous figure, RATUS scenario favours the increase of streamflows during the summer meanwhile the DEMINC scenario does not modify water contributions.

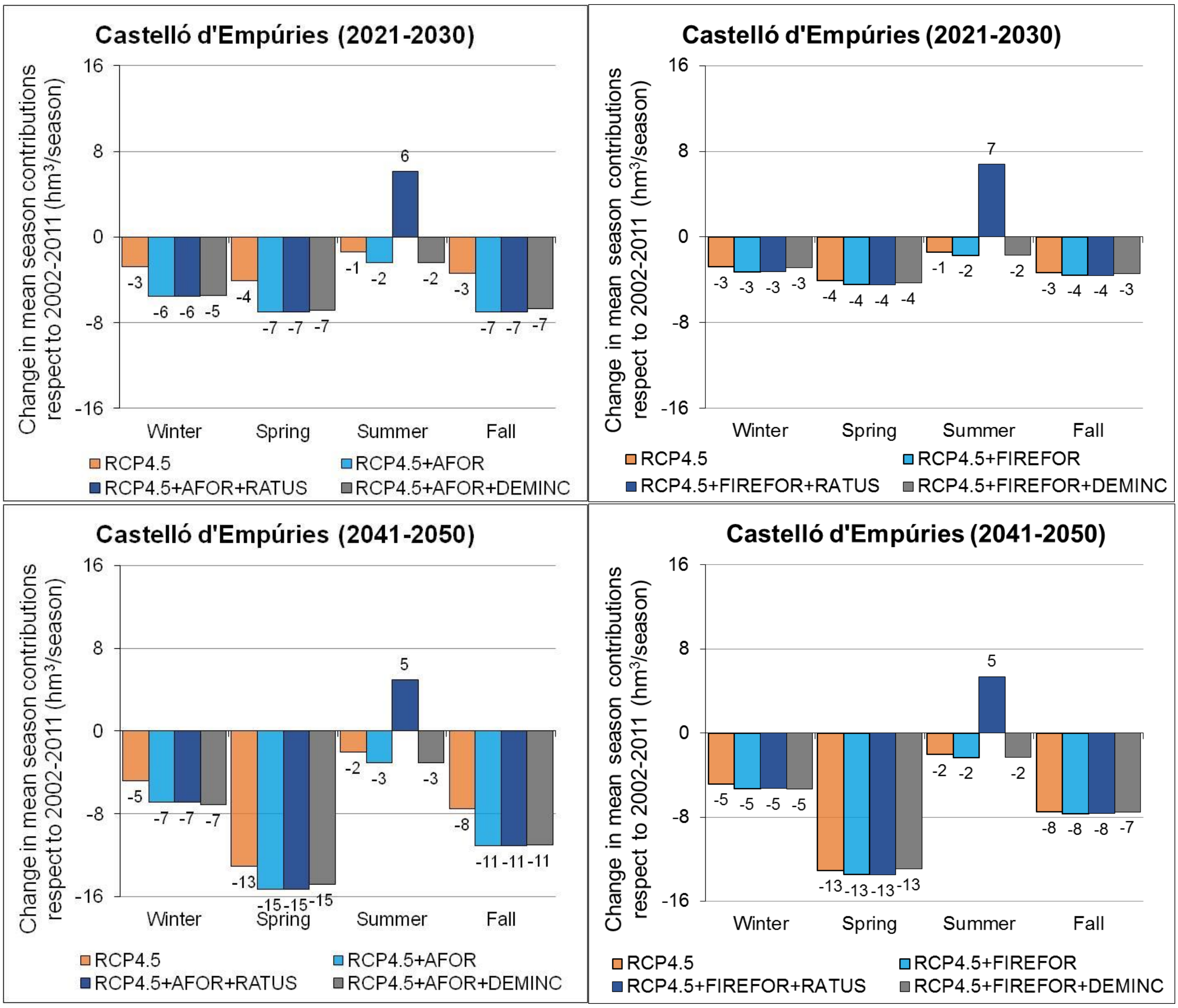


Figure 41. Expected changes in mean contribution per season (hm³/season) for period and scenario at the river mouth compared with the reference period (2002-2011 for the RCP4.5 scenario).

Figure 42 shows the evolution of the stored volume (hm³) in Boadella reservoir per DEMINC scenario. Although the reservoir has a major storage capacity than in RCP4.5 scenario, there are not that notable changes in the number and frequency of the emptying events, except that the reservoir takes more months to become empty and that there are some events in which the reservoir does not empty completely. But with this figure we can conclude that the enlargement of the Boadella reservoir may not be the most adequate adaptation measure to reduce the vulnerability of the Muga basin.

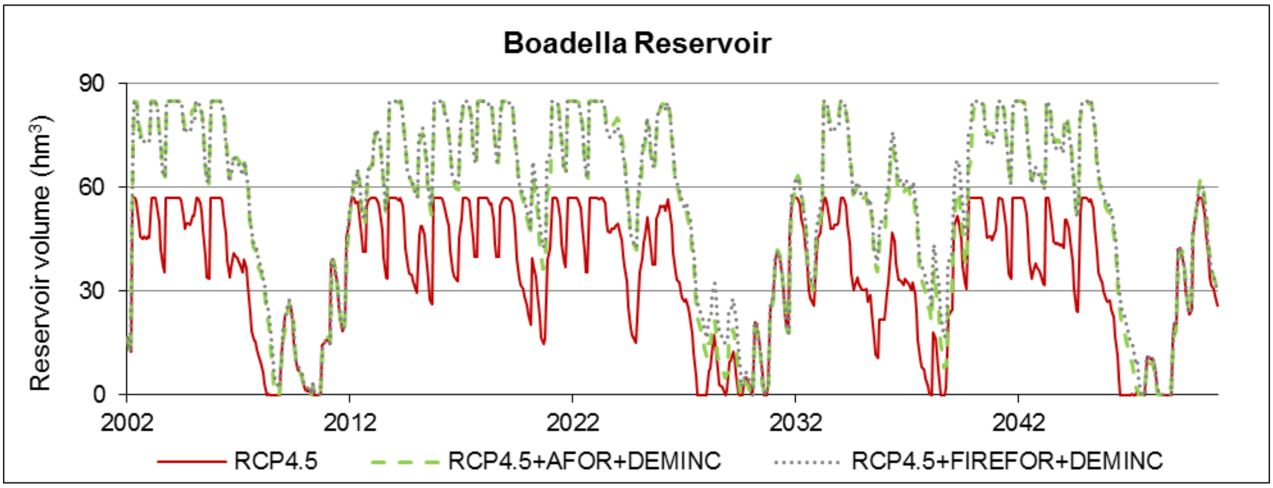


Figure 42. Simulation of reservoir volumes (hm³) until 2050 per scenario.

Effects on the Muga basin – RHESsys model

The effects of the different socioeconomic scenarios on the Muga basin has been evaluated on the water availability. As the Boadella-Darnius reservoir works as the main water storage for the basin, the evaluation has been done on its management, trying to quantify the changes under the different conditions defined by the climate, land cover and socioeconomic scenarios.

On section 4.2.1. we explain the way to simulate the expected storage based on the actual water demand, minimum ecological streamflow and own water management of Boadella-Darnius reservoir. Thus, in Figure 43 we show the mean monthly regime for inflow, outflow and storage under land use change scenarios and RATUS socioeconomic scenario, which implies a reduction of water consumption for summer months (June, July and August) of – 3.2 Hm³.

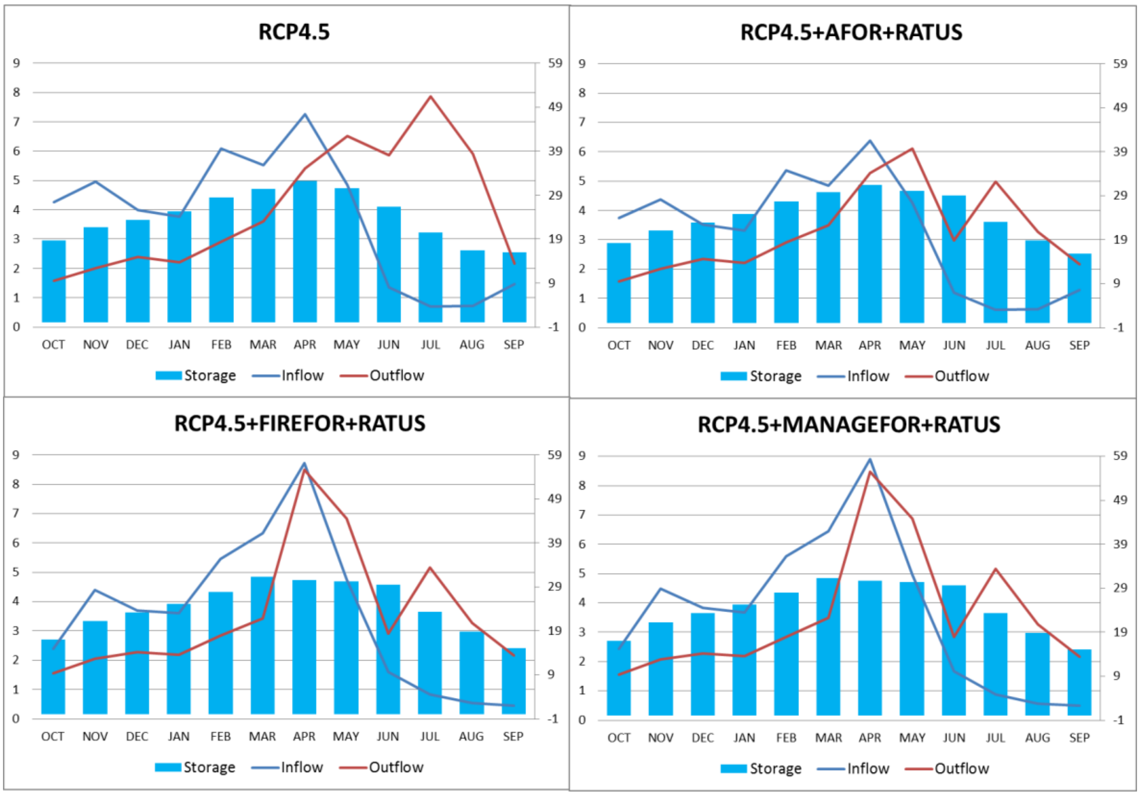


Figure 43. Mean monthly Inflow, Outflow and Storage for different socioeconomic scenarios.

The simulation shows how the storage is maintained at a half capacity for at least 4 months (March to June), while in RCP4.5 scenario and under actual water demand conditions the storage reaches to half capacity only for 2/3 months and the seasonal decrease is earlier and more pronounced.

	RCP4.5+AFOR	RCP4.5+FIREFOR	RCP4.5+MANAGEFOR
Inflow	-11.96%	-4.76%	-2.20%
Outflow	-0.87%	4.79%	5.06%
Storage	-1.68%	-1.30%	-0.96%
	RCP4.5+AFOR+RATUS	**RCP4.5+FIREFOR+RATUS**	**RCP4.5+MANAGEFOR+RATUS**
Inflow	-11.96%	-4.76%	-2.20%
Outflow*	-18.88%	-10.91%	-10.87%
Storage	1.08%	1.19%	1.54%

Table 18.Mean changes (%) in Boadella-Darnius reservoir management under different scenarios

The Table 18 shows the changes of the water management system comparing the combined action of climate-land cover changes and climate-land cover-socioeconomic changes, showing a slight increase on the storage of the dam. The decrease noted in outflow is due to the forcing to the dam management in the last decades; we have maintained the same operational regime between ecological flow, outflow and inflow. Table 18 makes clear the importance of the climate and land cover effects on dam inflow.

The DEMNIC scenario in Muga basin does not include an increment of water consumption, but an increment of the capacity of storage. The reduction of the inflow showed in Table 18 is significant enough to not being able to fill the dam.

<u>Effects on the Ter basin – SWAT model</u>

Table 19 shows the percentages of change at the short and long term and at the headwaters and the river mouth for each scenario. There are not foreseen changes in the headwaters among socioeconomic scenarios, since the water management scenarios increase/decrease water abstractions in the Pasteral dam, after the headwaters. The RATUS scenario foresees a reduction of 50 hm^3/year in the water transference to the RMB from the Ter basin, proportionally along the year (4.2 hm^3/month). For this reason, the reduction in water contribution notable decrease, from a 20.6-31.1% in the RCP4.5 scenario (69.6 to 105.1 hm^3/year) at the short and long term, to a 7.0-16.7% in the AFOR+RATUS scenario (23.7 to 56.4 hm^3/year). Decreases are similar in the FIREFOR scenarios (19.5 to 58.8 hm^3/year). The release of water into the river will improve the ecological status of the river.

On the contrary, DEMINC scenario foresees an increase of 40 hm^3/year in the water transference to the RMB, proportionally along the year (3.3 hm^3/month). This causes notable water contribution decreases that exceeds the 42% of the reference period for the long term (143.2 to 144.5 hm3/year in the AFOR+DEMINC and FIREFOR+DEMINC scenarios respectively).

	Changes in mean water contributions respect to 2002-2011 period (%)							
	RCP4.5		RCP4.5 + AFOR		RCP4.5+AFOR+RATUS		RCP4.5+AFOR+DEMINC	
	2021-2030	2041-2050	2021-2030	2041-2050	2021-2030	2041-2050	2021-2030	2041-2050
Roda (headwaters)	-13.8%	-21.1%	-14.4%	-20.3%	-14.4%	-20.3%	-14.4%	-20.3%
Torroella (river mouth)	-20.6%	-31.1%	-22.3%	-31.0%	-7.0%	-16.7%	-34.4%	-42.3%
	RCP4.5		RCP4.5 + FIREFOR		RCP4.5+FIREFR+RATUS		RCP4.5+FIREFR+DEMINC	
	2021-2030	2041-2050	2021-2030	2041-2050	2021-2030	2041-2050	2021-2030	2041-2050
Roda (headwaters)	-13.8%	-21.1%	-15.1%	-22.1%	-15.1%	-22.1%	-15.1%	-22.1%
Torroella (river mouth)	-20.6%	-31.1%	-20.8%	-31.5%	-5.8%	-17.4%	-32.8%	-42.7%

Table 19. Percentage of change in mean water contributions per period (reference, short and long term) at the headwaters and the river mouth per scenario compared with the reference period (2002-2011 for the RCP4.5 scenario).

Changes in mean monthly contributions are shown in Figure 44. Expected changes in mean monthly contributions (hm^3) per month and scenario at the river mouth compared with the reference period (2002-2011 for the RCP4.5 scenario) (black lines).. Only changes are shown for the river mouth, since the headwaters remain the same as the section 4.2.2. The socioeconomic scenarios show the same patterns as when including only land change scenarios, since the increase/decrease water abstractions in the Pasteral dam are proportional all months. The RATUS scenario reduce the impacts of the climate scenario, maintaining water contributions in spring and summer, but does not prevent fall reductions. The DEMINC scenario accentuates the negative impacts of climate and land change scenarios.

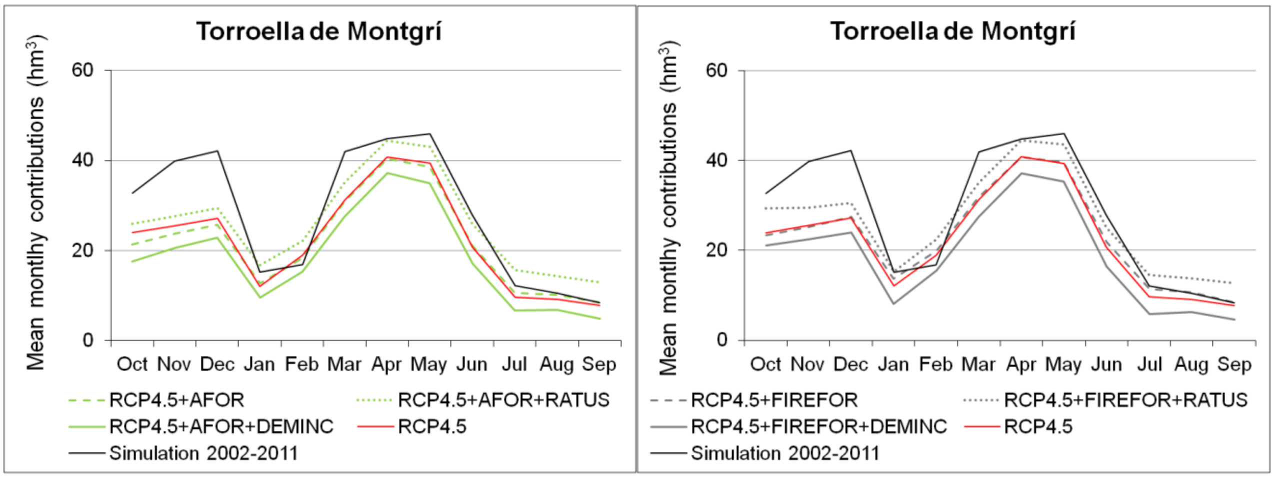


Figure 44. Expected changes in mean monthly contributions (hm^3) per month and scenario at the river mouth compared with the reference period (2002-2011 for the RCP4.5 scenario) (black lines).

Figure 45 shows the changes in mean season contribution (hm^3/season) for period and scenario at the river mouth. Similar to the previous figure, the DEMINC scenario accentuate the negative impacts of climate and land change scenarios, with notable reduction in all seasons that can arrive up to 49 hm^3 in summer or 42 hm^3 in fall. RATUS scenario attenuates the impacts, and foresees an improvement in summer contribution at the short term.

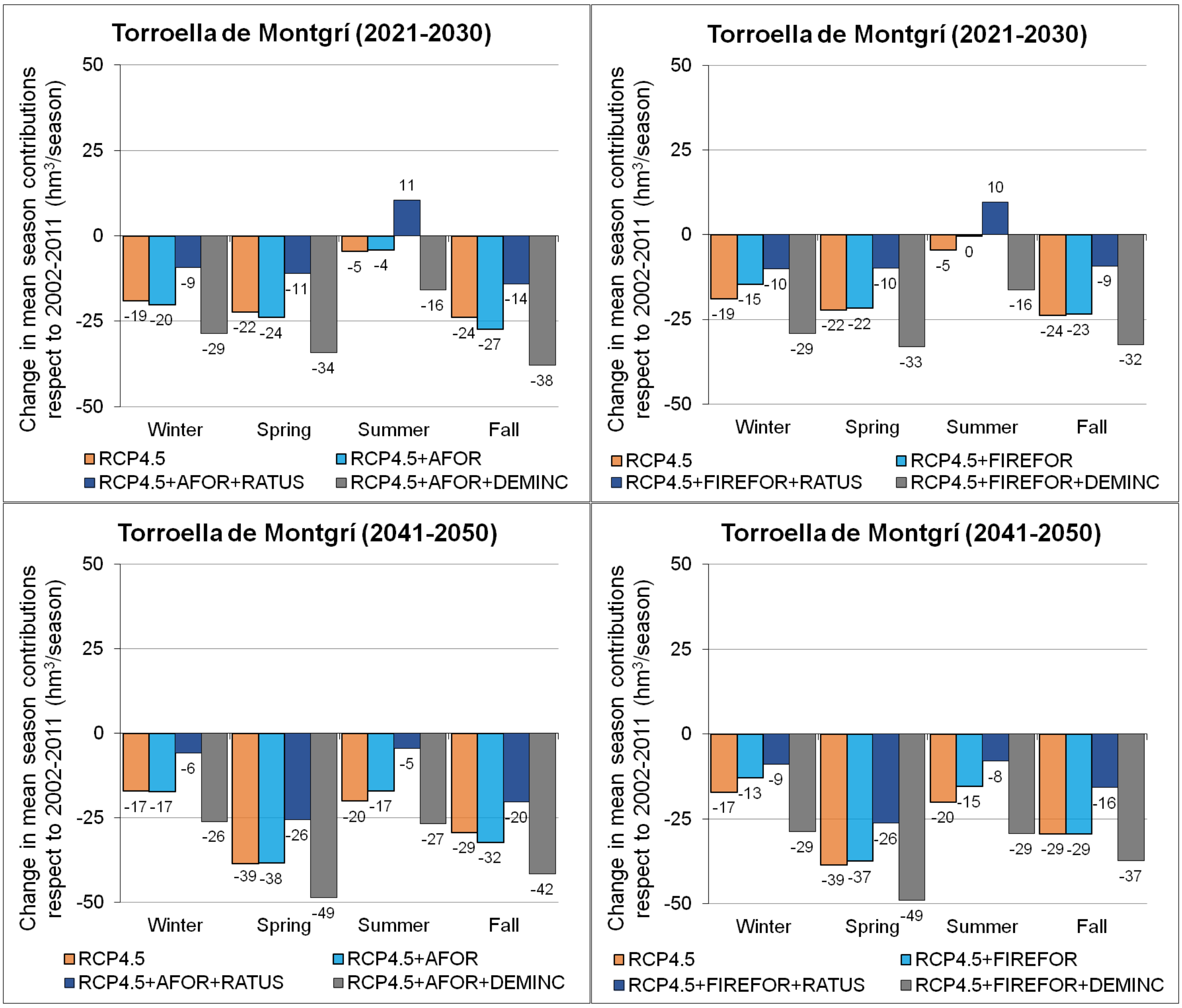


Figure 45.Expected changes in mean contribution per season (hm³/season) for period and scenario at the river mouth compared with the reference period (2002-2011 for the RCP4.5 scenario).

There are not foreseen changes in the stored volume (hm³) in Sau and Susqueda reservoirs since the water management scenarios increase/decrease water abstractions in the Pasteral dam, after the reservoirs, without influencing the storage.

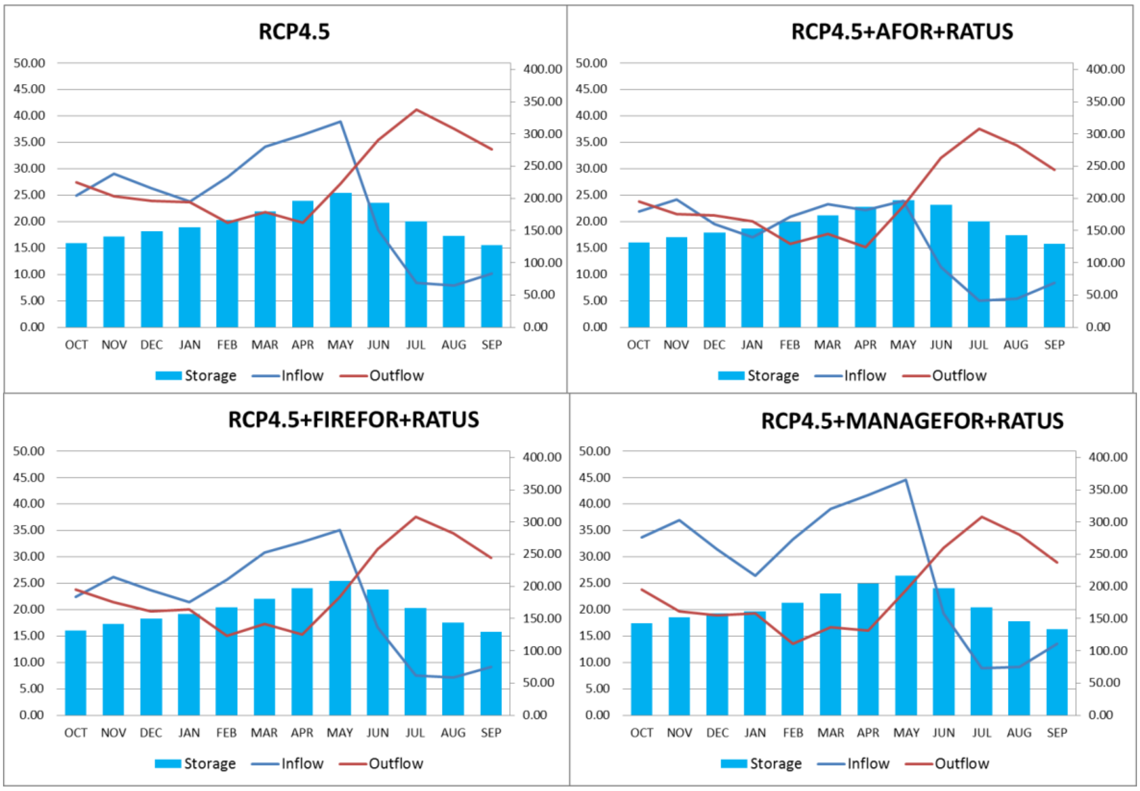
<u>Effects on the Ter basin – RHESsys model</u>

The evaluation of effects in streamflow in Ter basin are showed in Figure 46 and Table 20. As in previous section, the dams Sau and Susqueda are considered as a system. The mean monthly dam management is plotted to observe the plausible changes in each land cover and socioeconomic scenario under RCP4.5 climate scenario. It is noted how the water storage capacity improves with RATUS scenario the storage capacity goes from -4.8% in RCP4.5+AFOR to -1.82% if the RATUS scenario is added. This changes are also noticeable for FIREFOR and MANAGEFOR scenarios and their simulations with RATUS scenario.

The DEMNIC scenario implies an extraction of water (as explain before) what has its impact in the water storage. What is striking is that the storage capacity has a higher decrease if DEMNIC storage is not applied. The reason is explained with the outflow. As this simulations were made taking into account the general management of the reservoirs, it needs lower outflow trying to maintain the same water storage, what is not a plausible solution if the ecological flow has to be maintained.

	RCP4.5+AFOR	RCP4.5+FIREFOR	RCP4.5+MANAGEFOR
Inflow	-29.20%	-10.00%	17.84%
Outflow	1.72%	0.06%	-1.03%
Storage	-4.08%	-1.34%	2.31%
	RCP4.5+AFOR+RATUS	**RCP4.5+FIREFOR+RATUS**	**RCP4.5+MANAGEFOR+RATUS**
Inflow	-29.20%	-10.00%	17.84%
Outflow*	-13.22%	-14.29%	-15.60%
Storage	-1.82%	0.87%	4.61%
	RCP4.5+AFOR+DEMNIC	**RCP4.5+FIREFOR+DEMNIC**	**RCP4.5+MANAGEFOR+DEMNIC**
Inflow	-29.20%	-10.00%	17.84%
Outflow*	-1.59%	-2.24%	-3.67%
Storage	-3.59%	-0.91%	2.81%

Table 20. Mean changes (%) in Boadella-Darnius reservoir management under different scenarios



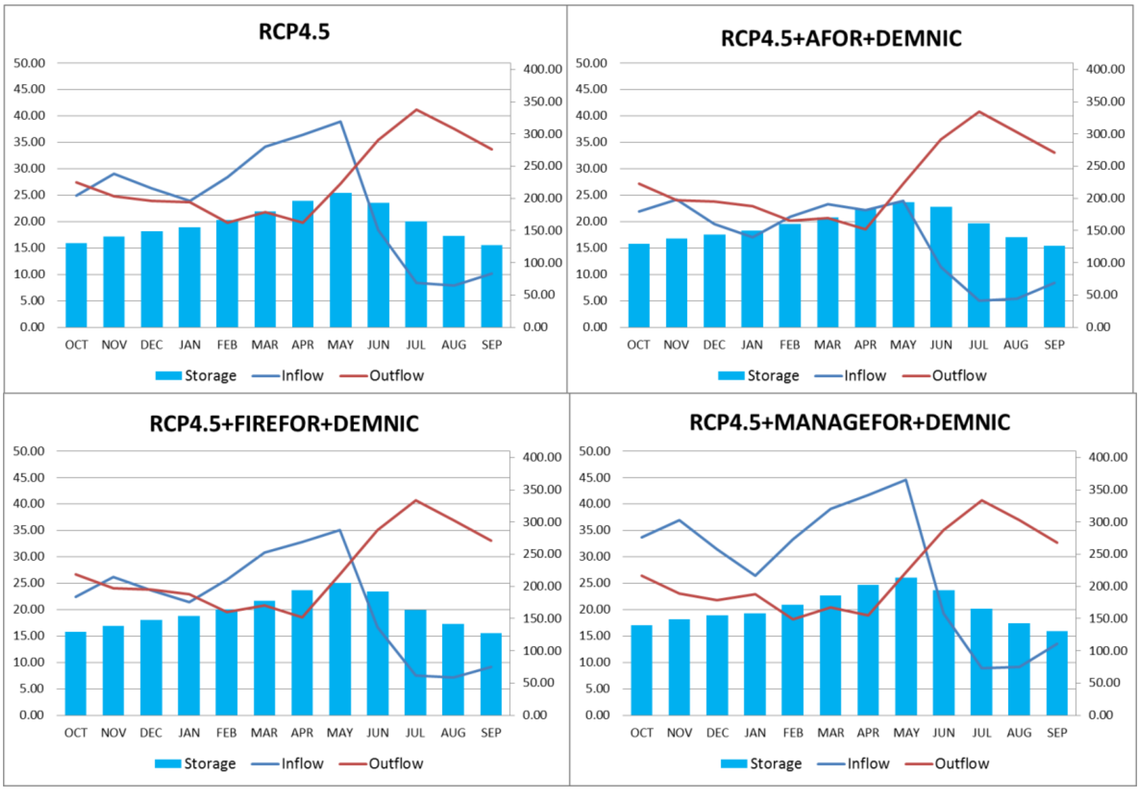


Figure 46. Mean monthly Inflow, Outflow and Storage for different socioeconomic scenarios.

Effects on the Segre basin – SWAT model

Table 21 shows the percentages of change at the short and long term and at the headwaters and the river mouth for each scenario. There are not foreseen changes in the headwaters among socioeconomic scenarios, since the water management scenarios increase/decrease water abstractions in the Canal d'Urgell water collection (RATUS) or in Camarassa and Rialb reservoirs (DEMINC). The RATUS scenario foresees a reduction of 150 hm^3/year in the water abstraction of the Canal d'Urgell, proportionally along the irrigation months (March, April, May, June, July, August and September, at the rate of 21.4 hm^3/month). For this reason, the reduction in water contribution notable decrease, from a 3.0-12.3% in the RCP4.5 scenario (45.8 to 188.7 hm^3/year) at the short and long term, to a 1%-increase and 8.7%-decrease in the AFOR+RATUS scenario (increase 15.7 and decrease 134.6 hm^3/year at the short and long term respectively). Changes are lower at the FIREFOR scenario (increase 27.1 and decrease 127.7 hm^3/year at the short and long term respectively). The release of water into the river will improve the ecological status of the river.

On the contrary, DEMINC scenario foresees the consolidation of the Canal Segarra-Garrigues, with a water concessions of 342 hm^3/year: 250 hm^3/year are taken from the Rialb reservoir and 92 hm^3/year from the Noguera Pallaresa at the Camarassa reservoir. The distribution along the year of this 342 hm^3 uptake is proportional to the current water abstraction for the Canal d'Urgell. The scenario also considers the Canal d'Urgell modernization, reducing in 150 hm^3/year in the water abstraction of the channel. This scenario causes notable water contribution decreases at the short term but no changes at the long term (from 45.8 (RCP4.5) to 119.7 (AFOR and FIREFOR) hm^3/year at the short term and from 188.7 (RCP4.5) to 195.2 (FIREFOR) and 198.2 (AFOR) hm^3/year at the long term compared with the RCP4.5 scenario).

	Changes in mean water contributions respect to 2002-2011 period (%)							
	RCP4.5		RCP4.5 + AFOR		RCP4.5+AFOR+RATUS		RCP4.5+AFOR+DEMINC	
	2021-2030	2041-2050	2021-2030	2041-2050	2021-2030	2041-2050	2021-2030	2041-2050
Pont de Suert (headwaters)	-5.6%	-11.7%	-6.4%	-12.3%	-6.4%	-12.3%	-6.4%	-12.3%
Talarn (headwaters)	-9.1%	-13.5%	-9.9%	-14.3%	-9.9%	-14.3%	-9.9%	-14.3%
Organyà (headwaters)	-5.3%	-9.5%	-3.3%	-7.7%	-3.3%	-7.7%	-3.3%	-7.7%
Seròs (river mouth)	-3.0%	-12.3%	-2.8%	-12.6%	1.0%	-8.7%	-7.8%	-12.9%
	RCP4.5		RCP4.5 + FIREFOR		RCP4.5+FIREFR+RATUS		RCP4.5+FIREFR+DEMINC	
	2021-2030	2041-2050	2021-2030	2041-2050	2021-2030	2041-2050	2021-2030	2041-2050
Pont de Suert (headwaters)	-5.6%	-11.7%	-6.5%	-12.4%	-6.5%	-12.4%	-6.5%	-12.4%
Talarn (headwaters)	-9.1%	-13.5%	-9.8%	-14.2%	-9.8%	-14.2%	-9.8%	-14.2%
Organyà (headwaters)	-5.3%	-9.5%	-0.7%	-5.1%	-0.7%	-5.1%	-0.7%	-5.1%
Seròs (river mouth)	-3.0%	-12.3%	-2.1%	-12.2%	1.8%	-8.3%	-7.8%	-12.7%

Table 21. Percentage of change in mean water contributions per period (reference, short and long term) at the headwaters and the river mouth per scenario compared with the reference period (2002-2011 for the RCP4.5 scenario).

Changes in mean monthly contributions are shown in Figure 47. Only changes are shown for the river mouth, since the headwaters remain the same as the section 4.2.2. The RATUS scenario reduce the impacts of the climate scenario from April to August, when the water abstraction of the Canal d'Urgell is reduced in 150 hm^3. For the rest of the year, water contributions are the same than the climate change scenario. The DEMINC scenario accentuates the negative impacts of climate and land change scenarios.

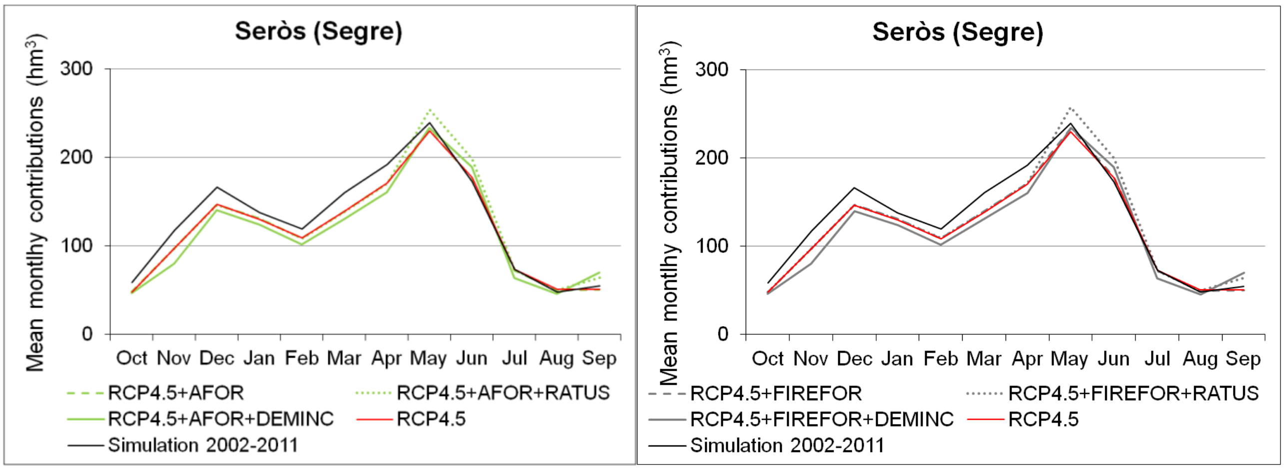


Figure 47. Expected changes in mean monthly contributions (hm^3) per month and scenario at the river mouth compared with the reference period (2002-2011 for the RCP4.5 scenario) (black lines).

Figure 48 shows the changes in mean season contribution (hm^3/season) for period and scenario at the river mouth. Similar to the previous figure, the RATUS scenario attenuates the impacts of climate and land change scenarios at the short and long term. The scenario also foresees an improvement in summer contribution. Contrarily, the DEMINC scenario accentuate the negative impacts of climate and land change scenarios, with notable reductions in all seasons except in summer, that can arrive up to 89 hm³ in spring or 73 hm³ in winter at the long term. The improvement in summer's contributions is result of the modernization of the Canal d'Urgell.

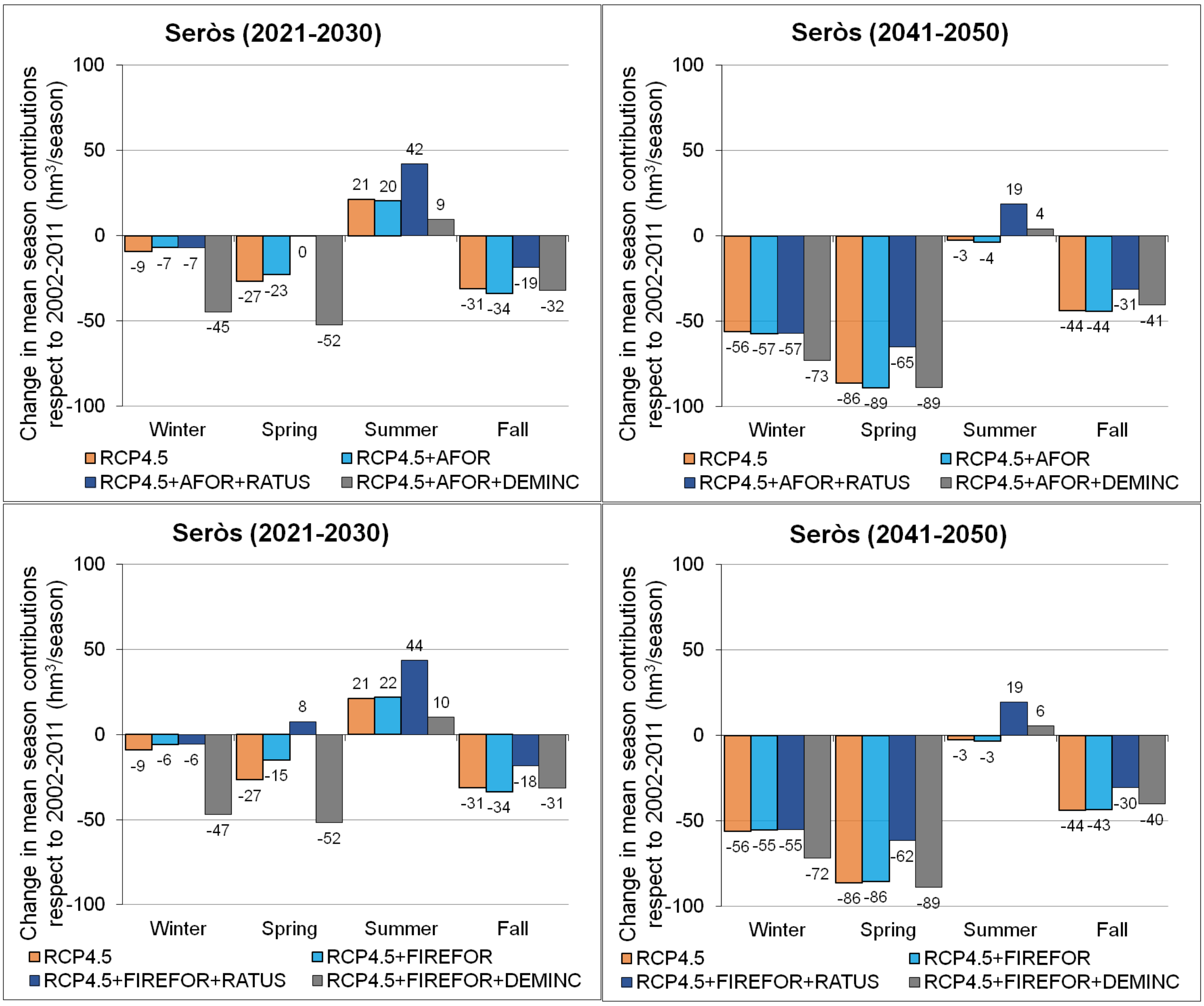


Figure 48. Expected changes in mean contribution per season (hm³/season) for period and scenario at the river mouth compared with the reference period (2002-2011 for the RCP4.5 scenario).

Figure 49 shows the evolution of the stored volume (hm³) in Canelles, Camarassa and Rialb reservoirs per DEMINC scenario. In Canelles reservoir, no changes are observed when DEMINC scenario is included. However, Camarassa and Rialb reservoirs show important changes with respect to the climate change scenario. In the Camarassa reservoir, 92 hm³/year are derived from the Noguera Pallaresa to the Canal Segarra-Garrigues. This water derivation causes notable reductions in the stored water, with an increase in the number, frequency and intensity of the emptying events. But the most important effect of the DEMINC scenario is shown in the Rialb reservoir, where water abstraction arrives to 250 hm³/year to feed the channel. Since 2005, the emptying events are recurrent and the situation is alarming after 2027 when almost every year the reservoir empties completely at least one month per year. Besides, after 2027, the stored volume never achieves the maximum capacity of the reservoir.

Although the Table 21 showed similar contribution reductions among scenarios in the river mouth at the long term (12.3% in RCP4.5, 12.6% in AFOR, 12.2% in FIREFOR, 12.9% in AFOR-DEMINC and 12.7% in FIREFOR-DEMINC), the effects of DEMINC scenario are clearly identified in Figure 48. The scenario increases the number, frequency and intensity of the emptying events and is especially relevant in Rialb reservoir considering that the reservoir would be empty or within emergency thresholds nearly one month per year.

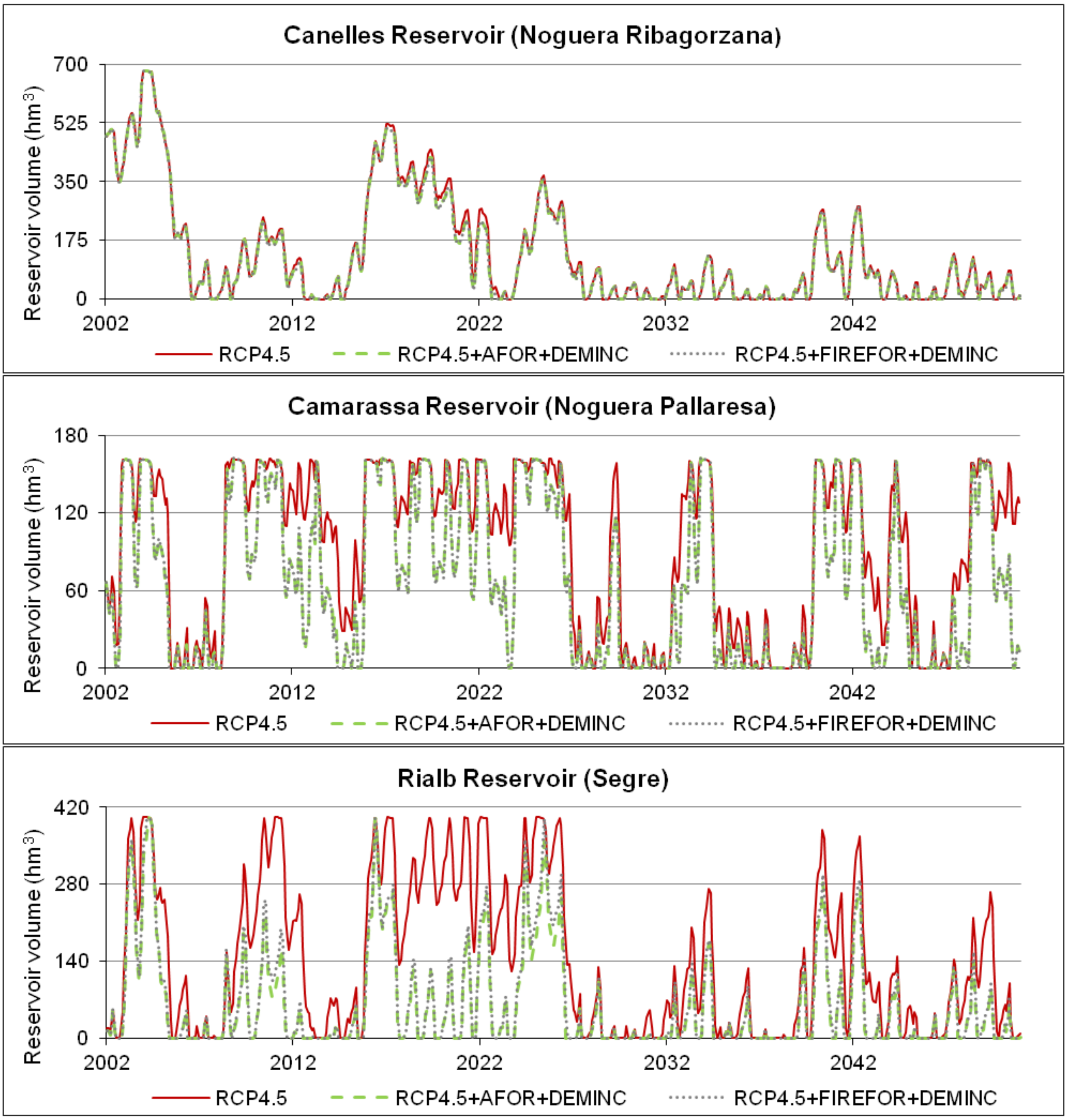


Figure 49. Simulation of reservoir volumes (hm^3) until 2050 per scenario.

Effects on the Segre basin – RHESsys model

In this case, as plotted in Figure 50, the expected changes in mean monthly storages of Camarassa reservoir are showed. It is showed also the mean monthly observed storage for the period 2002-2011 (black dotted line) to be comparable to the simulated one (black line). In spite of the complexity of the basin and the difficulties that RHESsys model has to simulate reservoirs and artificial flows, the result is good. In red, the simulation of storage for the period (2012-2050), which shows how the capacity to dam water decrease in spring (-4.8%), winter (-1.5%) and summer (-1.8%) but it is compensated in spring (+4.5%).

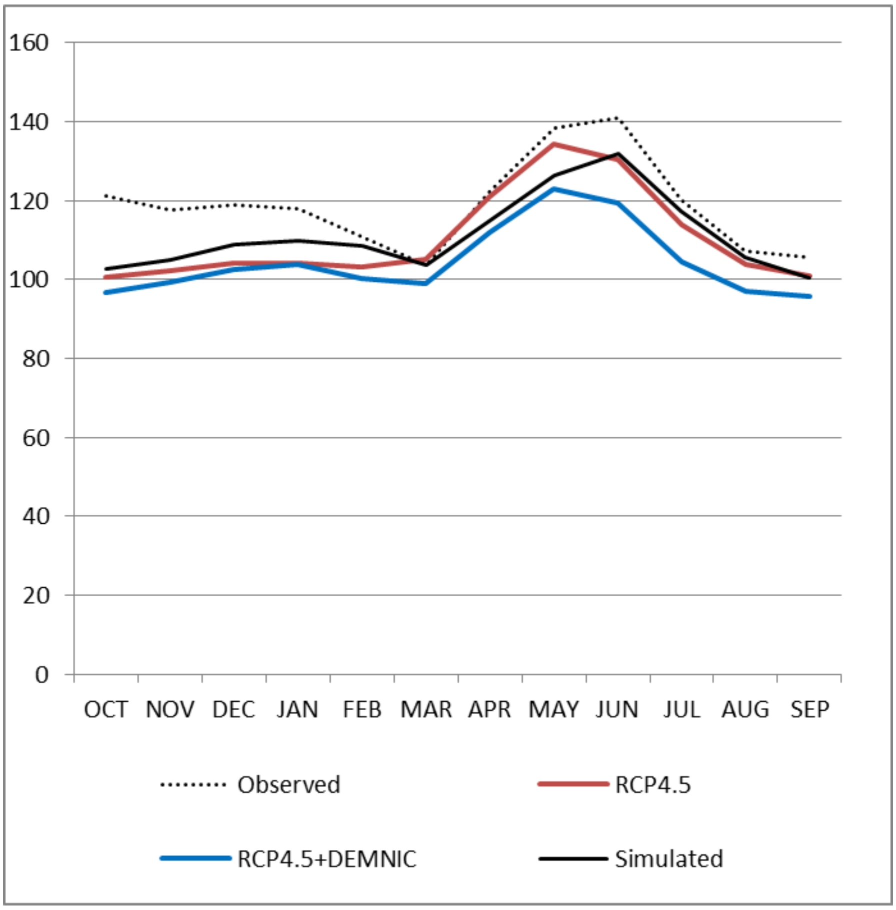


Figure 50. Expected changes in mean monthly storages (hm^3).

The simulation under the conditions by DEMNIC socioeconomic scenario (an extraction of 93 hm3 from Camarassa dam) shows higher decrease. The seasonal higher change is in summer (-9.4%) while in winter and autumn are around -6%.

4.3. Conclusions

We have assessed the impacts of climate and global change on water resources in three case-study basins: Muga, Ter and Segre. To do so, we have incorporated climate and socioeconomic scenarios into two calibrated and validated hydrological models (SWAT and RHESSys). We have analysed the results in two time horizons (short term 2021-2030 and long term 2041-2050) and two spatial areas (headwaters and river mouths).

Hydrological simulations with SWAT and climate change scenarios (RCP4.5) showed a strong alteration in water dynamics in the three basins along the first half of the 21st century. A generalized decrease in water contributions is expected, from 9.5 to 21.1% in the headwaters and from 12.3% to 31.1% in the river mouth at the long term. RHESsys results shows a major decrease, in the headwaters around -20% except in Ter basin (-32%) and in river mouth is -19% in Muga basin, -36% in Ter Basin and -13.2% in Segre basin.

Comparing among basins, Ter basin showed the most severe reduction in water contributions, both in the headwaters and the river mouth at the short and long term. Besides, the reductions were more severe at the river mouth of the Muga and Ter basins than the headwaters, both at the short (10.1 and 20.6% respectively) and long term (23.9 and 31.1% respectively). Segre basin showed a different hydrological behaviour, with higher reductions in the headwaters (from 5.3 to 9.1% at the short and 9.5 to 13.5% at the long term) than in the river mouth (3.0 and 12.3% respectively). Segre basin is highly regulated and the effects of reservoir management and water abstraction may cause these difference in the river mouth. Changes in mean monthly and season contributions showed strong reductions in spring and fall in Muga and Ter basin, whereas in Segre basin major reductions were observed in summer in the headwaters and in spring in the river mouth. The evolution of the stored volume in the reservoirs showed than the number, frequency and intensity of emptying events increase along the 21st century, especially after 2027.

Similar water contribution reductions have been predicted for the 21st century in other Mediterranean basins. Thus, Senatore et al. (2011) estimated 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 the Eastern shore of the Mediterranean region, in Jordan, Hartmann et al. (2012) estimated a 15 to 30% reduction in water availability for the period 2068-2099. In Catalonia, north-eastern Spain, the Catalan Water Agency (2009) estimated a 16% to 28% reduction of the mean annual stream flows of the Catalan basins. Pascual et al. (2015) assessed the impacts of B1 and A2 IPCC emission scenarios in three Catalan basins (Fluvià, Tordera and Siurana). They obtained large reduction (34%) in mean streamflows by 2076–2100 in the headwaters of the two wettest basins, while lower decreases (25% of mean value for 2076–2100) were obtained in the drier basin.

Hydrological simulations with SWAT and land cover scenarios (RCP4.5+AFOR and RCP4.5+ FIREFOR) showed also a strong alteration in water dynamics in the three basins along the first half of the 21st century. AFOR scenarios foresaw major reductions in water contribution than FIREFOR or RCP4.5 in Muga basin, caused by the increase of the vegetation evapotranspiration originated in a higher forest surface (31.6%-reduction in AFOR river mouth compared with a 23.9% in RCP4.5 and 25% in FIREFOR). The distinctive effect of land cover scenarios on mean water contributions were hardly appreciable in Ter and Segre basins. Changes in mean monthly contributions showed a different pattern between land change scenarios in Muga and Ter headwaters. In both basins, the AFOR scenario predicted more water during winter time. In the river mouth, general reductions were observed all the year in both basins and in all scenarios, being more notable in fall in the AFOR scenario. In the Segre basin, all land change scenarios showed a similar pattern to the climate change scenario, in trend and magnitude. All reservoirs showed a slightly lower stored volumes than the climate change scenario, but without differences in the number, frequency and intensity of the emptying events among scenarios. In conclusion, land cover scenarios did not show remarkable changes with respect the climate change scenario alone (RCP4.5). One explanation can be that the changes in land cover were not so significant in the scenarios to have a relevant influence in the water cycle. Also the basins are highly forested and forests act as regulator of the water dynamics. Another reason can be the higher sensitivity of SWAT model to climate change scenarios than to changes in land cover documented by Morán-Tejeda et al. (2014) in the Pyrenees (Spain). They found also that SWAT had a linear response to changes in land cover.

Hydrological simulations with RHESsys and land cover scenarios (AFOR, FIREFOR and MANAGEFOR) shows similar trends: high decrease with AFOR (Headwaters: from -8.5% to -26%; Mouth river: from -9% to -52%) and FIREFOR (Headwaters: from +6% to -37%; Mouth river: from +5% to -37%) scenarios and a slight improvement with MANAGEFOR scenario (Headwaters: from +10% to -10%; Mouth river: from – 5% to -9.7%). The Ter basin shows a very high decrease what suggest that the vegetation processes in RHESsys excessively sensitive to changes in canopy structure and spatial distribution of the vegetation classes.

Hydrological simulations with SWAT and socioeconomic scenarios (RCP4.5+AFOR+RATUS, RCP4.5+AFOR+DEMINC, RCP4.5+FIREFOR+RATUS and RCP4.5+FIREFOR+DEMINC) showed also a strong alteration in water dynamics in the three basins along the first half of the 21st century, although the impact could be minimised if measures that encourage the rational use of water resources are taken. In the Muga basin, the re-use of regenerated water (RATUS) showed a results very similar to the climate scenario (RCP4.5), as if the rational use of water resources can counterbalance the effects of afforestation (AFOR). At monthly time step, contributions did not show changes among scenarios, except in a summer increase in the RATUS scenario as a consequence of reducing water abstractions for irrigation purposes. The enlargement of the Boadella reservoir (DEMINC) did not influence the changes on water contributions but also did not show an improvement in reducing the number, frequency or intensity of the emptying events, and may not be an adequate adaptation measure to reduce the vulnerability of the basin. In the Ter basin, the changes in the water transference to the Metropolitan Region of Barcelona causes, in one hand, an important improvement of water contributions in the RATUS scenario (16.7-17.4% reduction compared with 31.1% in the RCP4.5 at the long term), but in the other hand, a more than a 42%-reduction of water contributions in the DEMINC scenario. At monthly time step, the RATUS scenario reduce the impacts of the climate change scenario, maintaining water contributions in spring and summer as the reference period, but does not prevent fall reductions. Contrarily, the DEMINC scenario accentuates the negative impacts of climate and land change scenarios. In the Segre basin, the modernization of the Canal d'Urgell (reducing water abstraction in 150 hm^3/year) improves water contributions in the RATUS scenario (1.0-1.8% increase and 8.3-8.7% decrease compared with the 12.3% in the RCP4.5 at the long term). The consolidation of the Canal Segarra-Garrigues, with a water concession of 342 hm^3/year, causes notable water contribution decreases at the short term (from 3.0% in the RCP4.5 to 7.8% in both DEMINC scenarios) but no changes at the long term (12.3% in RCP4.5, 12.6% in AFOR, 12.2% in FIREFOR, 12.9% in AFOR-DEMINC and 12.7% in FIREFOR-DEMINC). However, effects of DEMINC scenario are notable in the evolution of the stored water in Camarassa and Rialb reservoir, where water abstraction takes place. The stored water in both reservoirs notably reduced when comparing with the climate change scenario, and there is an increase in the number, frequency and intensity of the emptying events. The most remarkable effect occurs in Rialb reservoir, where emptying events are recurrent since 2025 and the situation is alarming after 2027 when almost every year the reservoir empties completely at least one month per year. Besides, after 2027, the stored volume never achieves the maximum capacity of the reservoir.

Hydrological simulations with RHESsys and socioeconomic scenarios (different combinations between RCP4.5, AFOR, FIREFOR and MANAGEFOR with RATUS and DEMNIC) show expected results in terms of water storage improvement with RATUS scenario and clear decrease in water availability in DEMNIC scenario. In Muga basin is plotted an improvement of capacity to fill Boadella-Darnius if RATUS scenario is applied: from a decrease of -1.3 % with RCP4.5+AFOR to +1.08% if RATUS scenario is involved, -1.3% RCP4.5+FIREFOR to +1.19% with RATUS and -0.96% for RCP4.5+MANAGEFOR to +1.54% with RATUS. The results are quite similar in Ter basin, as explained before. In this case also is included the simulations with DEMNIC scenario. As expected, the storages decrease -3.6% with AFOR, -0.91% with FIREFOR and with MANAGEFOR + 2.81%. In the case of Segre basin it has been noted a decrease in the capacity of water reservoir (Camarassa dam) of -9.4% in summer apart from a reduction of 6% in winter and in autumn and a slight improvement in spring.

This section provides important information for water and land managers to understand, locate and quantify the impacts of climate and global 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 case-study basins.

5. How would scenarios impact on agriculture?

5.1. Introduction

Agriculture is sensitive to variations in biotic and abiotic environmental conditions, such as weather and climate as crop growth and development depend on factors such as temperature, irradiation or precipitation. Thus, it can be expected to be markedly influenced by climate change, and the suitability of crops for a specific area could be expected to evolve with it. On the other hand, assessing which crops are adequate for the climate of a given area appears essential for planners, land managers, farmers and plant breeders.

The Mediterranean region is potentially highly vulnerable to existing adverse trends of warming and rainfall reduction and would likely be the region within Europe to firstly experience severe economical and sociological consequences from climate change.

This section presents estimated net irrigation requirements (NIR) and a set of agroclimatic parameters of major crops (see section 5.2.1) in the three basins for the reference period and two future periods under climate change conditions. These parameters can be used to assess the impacts of climate and global change in the LIFE MEDACC case study basins, and can then be used to propose and apply adaptation strategies to improve and sometimes maintain agriculture in some regions.

5.2. Impact of climate scenarios on agriculture

5.2.1. Describing the current agriculture land use

For the three basins, crop maps were built as a first step to assess agriculture in the reference period and under climate change scenarios. After the maps were established, assessment of impacts on agriculture only considered crops occupying >1% of surface of the agriculture land at the sub-basin level (from now on, major crops). Figure 51, Figure 52 and Figure 53 show crop distribution along the basins.

Agriculture in Muga basin is basically occupying middle and lower basin segments. It is characterized by a concentration of maize in the lower part and the widespread distribution of winter cereals in the lower and middle parts of the basin. Fodder and woody crops, such as olives and vines, are general in the middle part of the basin. Percentage of irrigated and rainfed surface for major crops is shown in Table 29 in Annex 1 for the Muga basin. The irrigated land in this basin is mostly occupied by maize and alfalfa (highly widespread) or fruit orchard such as apple or peach (little widespread). Winter cereals are mostly rainfed, except wheat in the lower basin, for which as much as 43% of its surface is irrigated. Olive and grapevine are mostly rainfed.

Agriculture in Ter basin is basically occupying lower and middle basin. The lowest part of the lower Ter is characterized by two important crops: apple and maize, which are, in fact, the two most irrigated crops in the basin (Table 30, Annex 1). The rest of the lower Ter is composed by herbaceous crops such as winter cereals, sorghum, sunflower, rape, etc. and some woody crops such as hazel. In the middle Ter agriculture is mostly located around Vic, following the Gurri river (a Ter tributary) and the middle Ter itself, and is mainly composed by herbaceous crops such as winter cereals, maize, sorghum, rape and fodder crops.

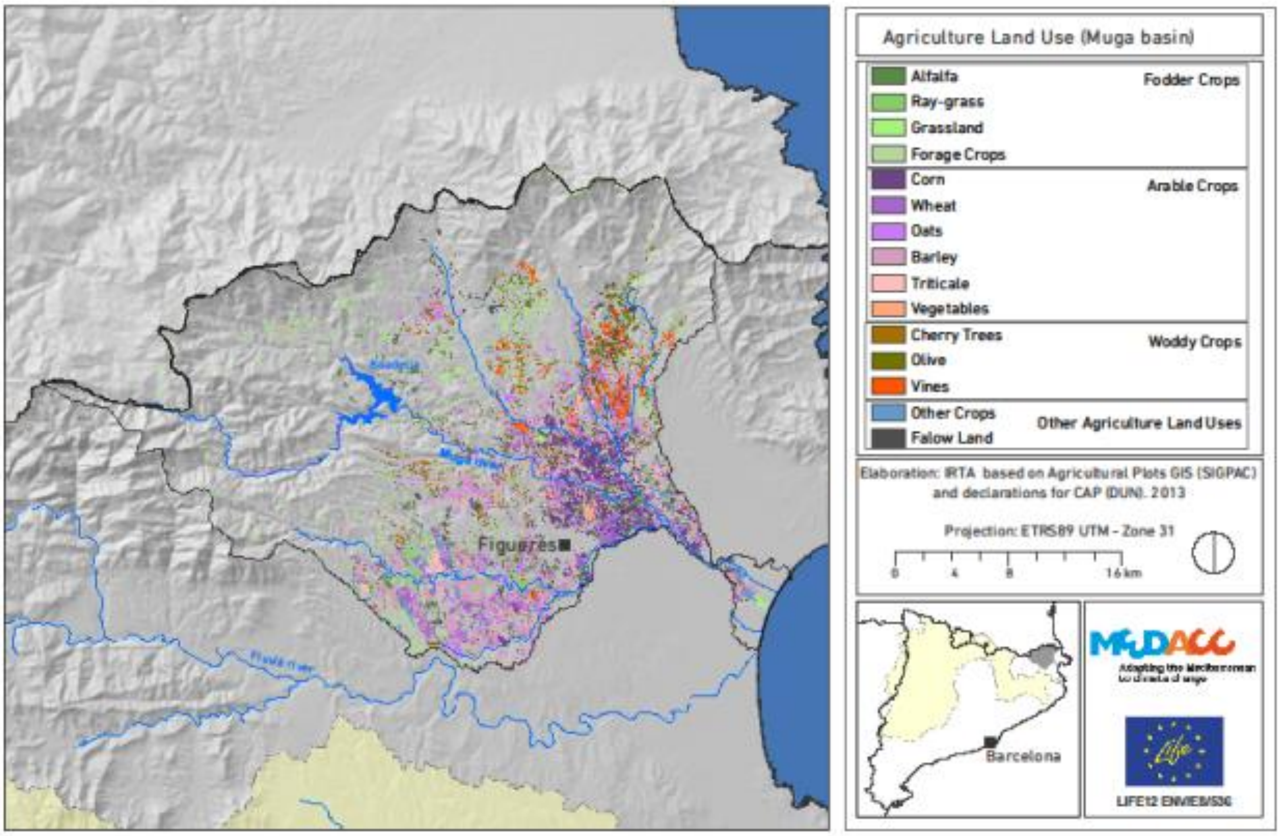


Figure 51. Agriculture land use map of Muga basin. This map was built based, basically, on the Catalan Agricultural plot GIS (SIGPAC) for the year 2013 and farmer declarations for CAP (DUN) for the year 2013.

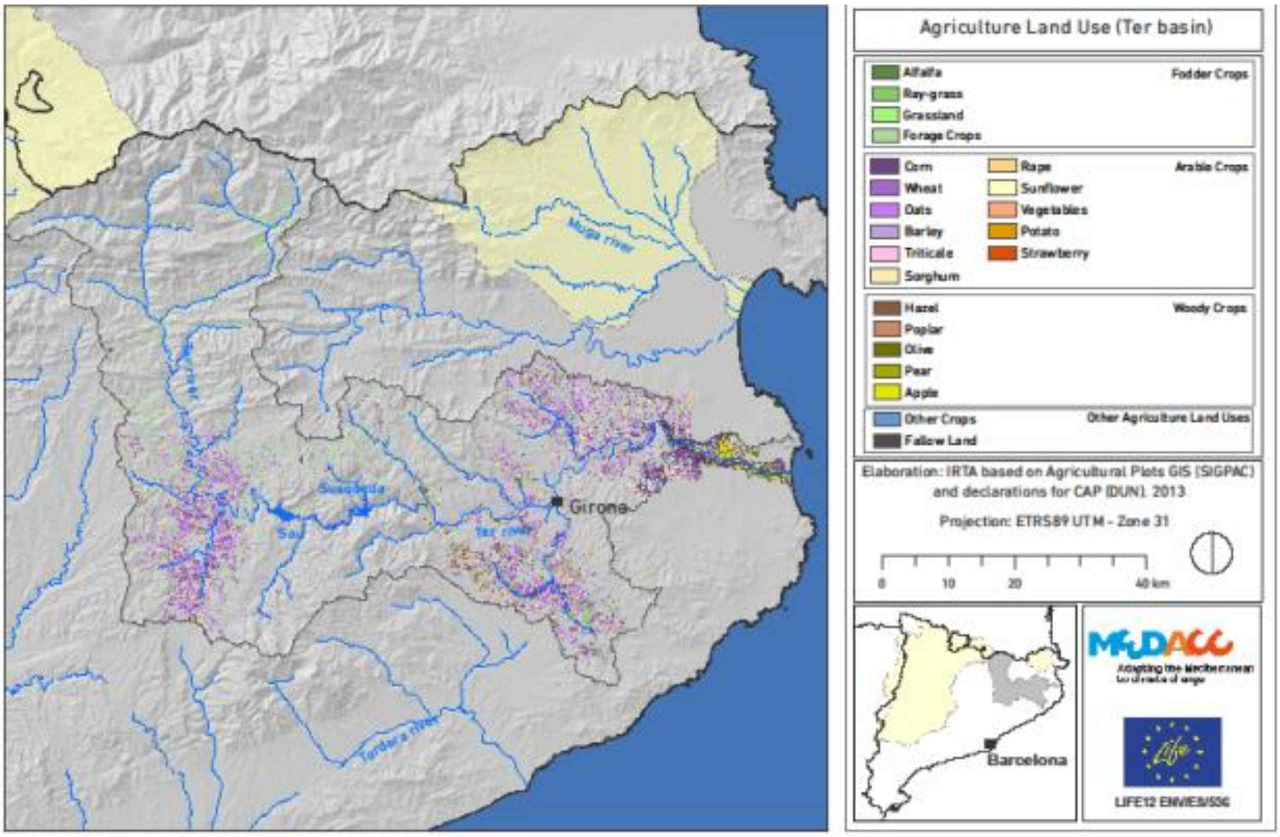


Figure 52. Agriculture land use map of Ter Basin. This map was built based, basically, on Catalan Agricultural plot GIS (SIGPAC) for the year 2013 and farmer declarations for CAP (DUN) for the year 2013.

Most crops in Segre basin occupy the lower basin and tend to concentrate by crop typology. The main crops of this lower basin are basically winter cereals (wheat, barley, oats, triticale, etc.) locating mainly at the right part of the lower basin and even extending to the middle basin. The central part of this lower basin (the valley of Lleida) is dominated by maize, fruit orchards and alfalfa. In the left part of the lower basin agriculture land is dominated by nectarines or peach trees. There are several important areas of grapevine production: on the one hand subzones of Costers del Segre Denomination of Origin (D.O.): Raimat, Garrigues and Valls del Riu Corb as a representation of the lower Segre and, on the other hand, Artesa de Segre and the altitude vineyards of Pallars Jussà as a representation of the middle Segre. Finally, the south part is basically composed by woody rainfed crops such as olives and almonds. The crops consuming most water per hectare in this basin are maize, all the fruit orchards (peach, nectarines, apple, pear, etc.), alfalfa and ryegrass. More than 40% of the grapevine surface is irrigated in the lower Segre. In general, winter cereals are mainly rain fed (Table 31, Annex1).

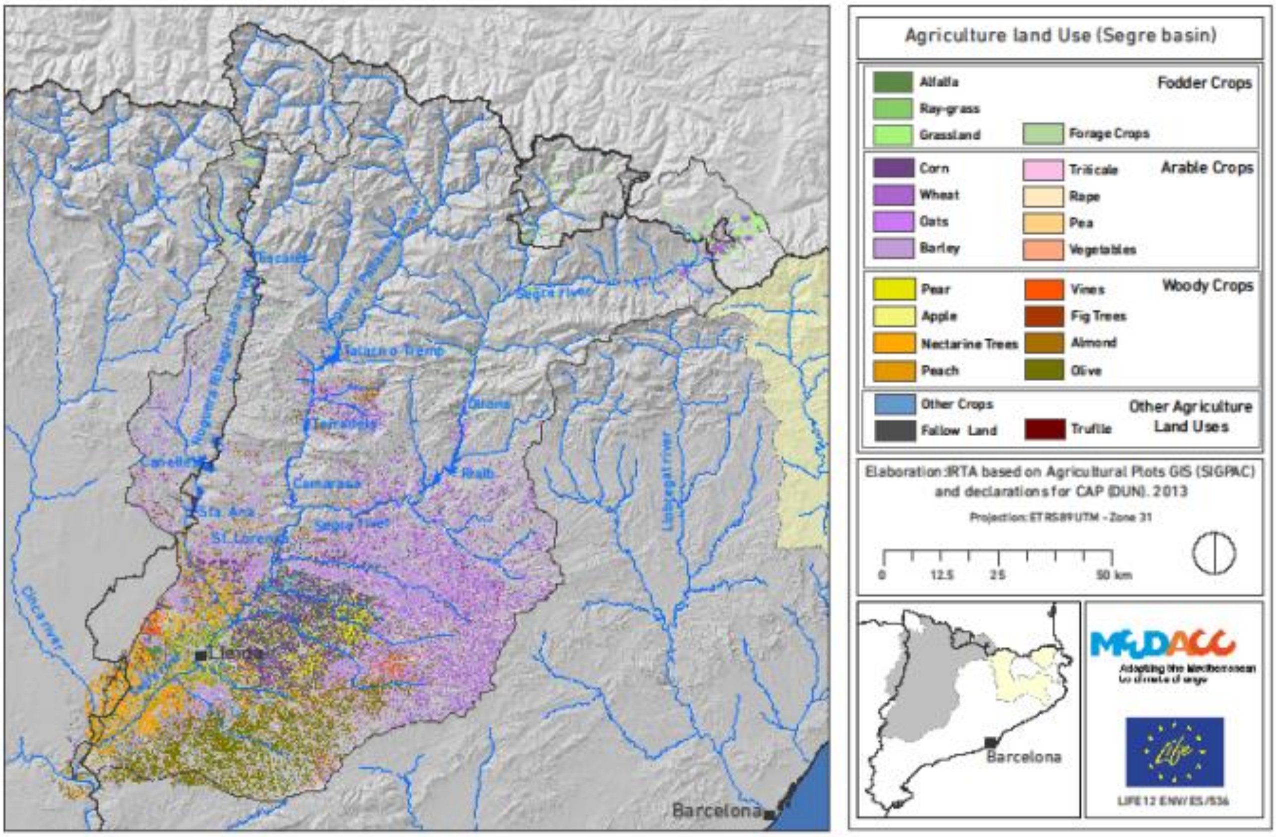


Figure 53. Agriculture land use map of Segre basin. This map was built based, basically, on the Aragon and Catalan Agricultural plot GIS (SIGPAC) for the year 2013 and farmer declarations for CAP (DUN) for the year 2013.

Major crops supposed 21% of total surface in Muga basin, 18% in Ter basin and 28% in Segre basin. Table 29 to Table 31 (Annex 1) show surface distribution of major crops along the three basins and the percentage of the cropland under irrigated or rainfed conditions.

5.2.2. Assessing maximum soil water capacity (SWCmax) of agriculture soils

For the three basins, soils were classified in 5 soil water capacity (SWC) groups.

In Muga basin, cropland is distributed on the two highest classes (Figure 54), as agriculture is growing over the best soils, those with the highest capacity to store water.

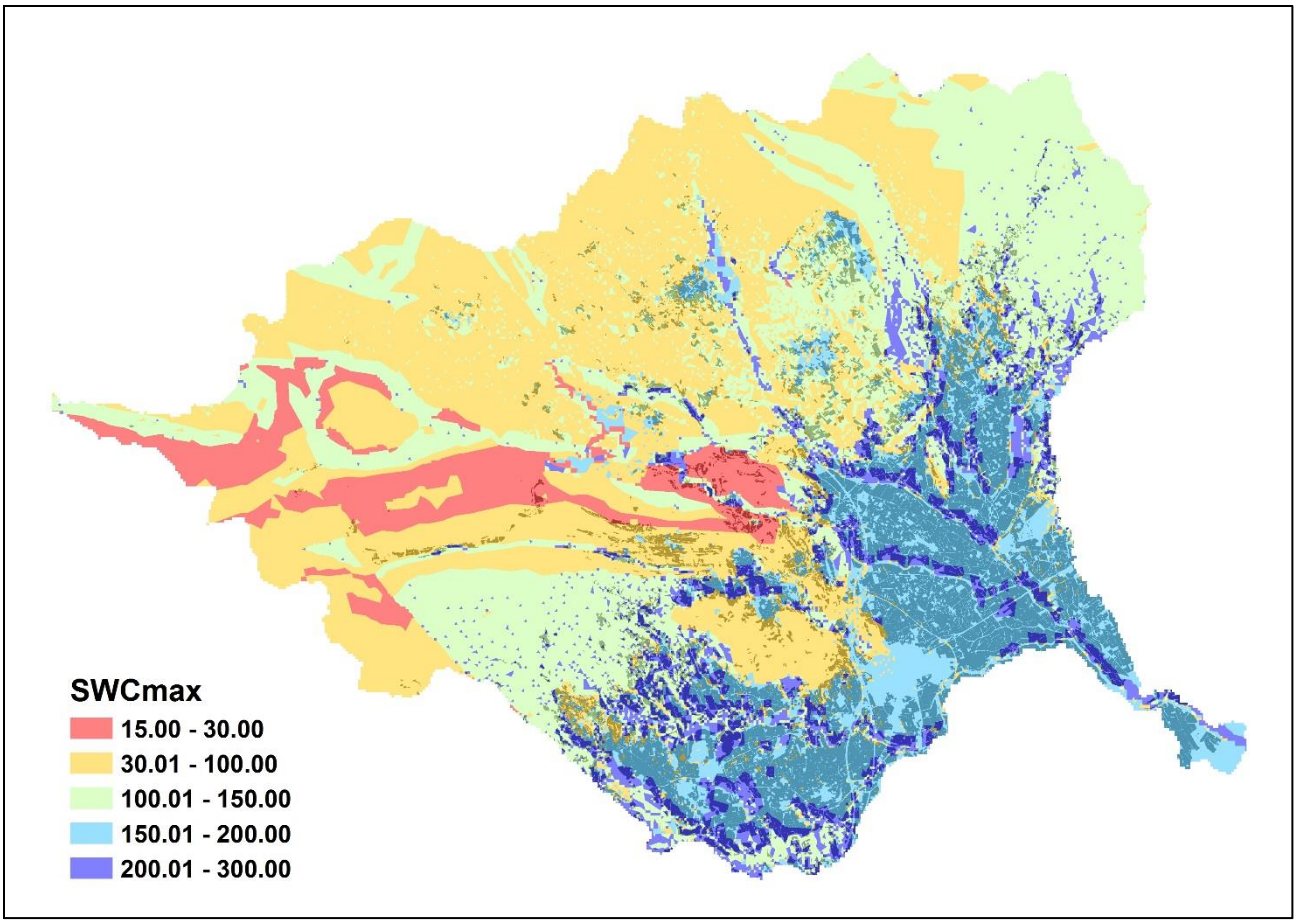


Figure 54. Map of maximum soil water capacity (mm) of Muga basin. Shades under colours represent agriculture land.

In Ter basin, cropland is distributed over the three highest classes (Figure 55). As in the Muga basin, the reason is that agriculture is generally growing on the best soils, those with the highest capacity to store water. However, agriculture land in the Middle Ter occupies soils with lower SWC than in lower Ter.

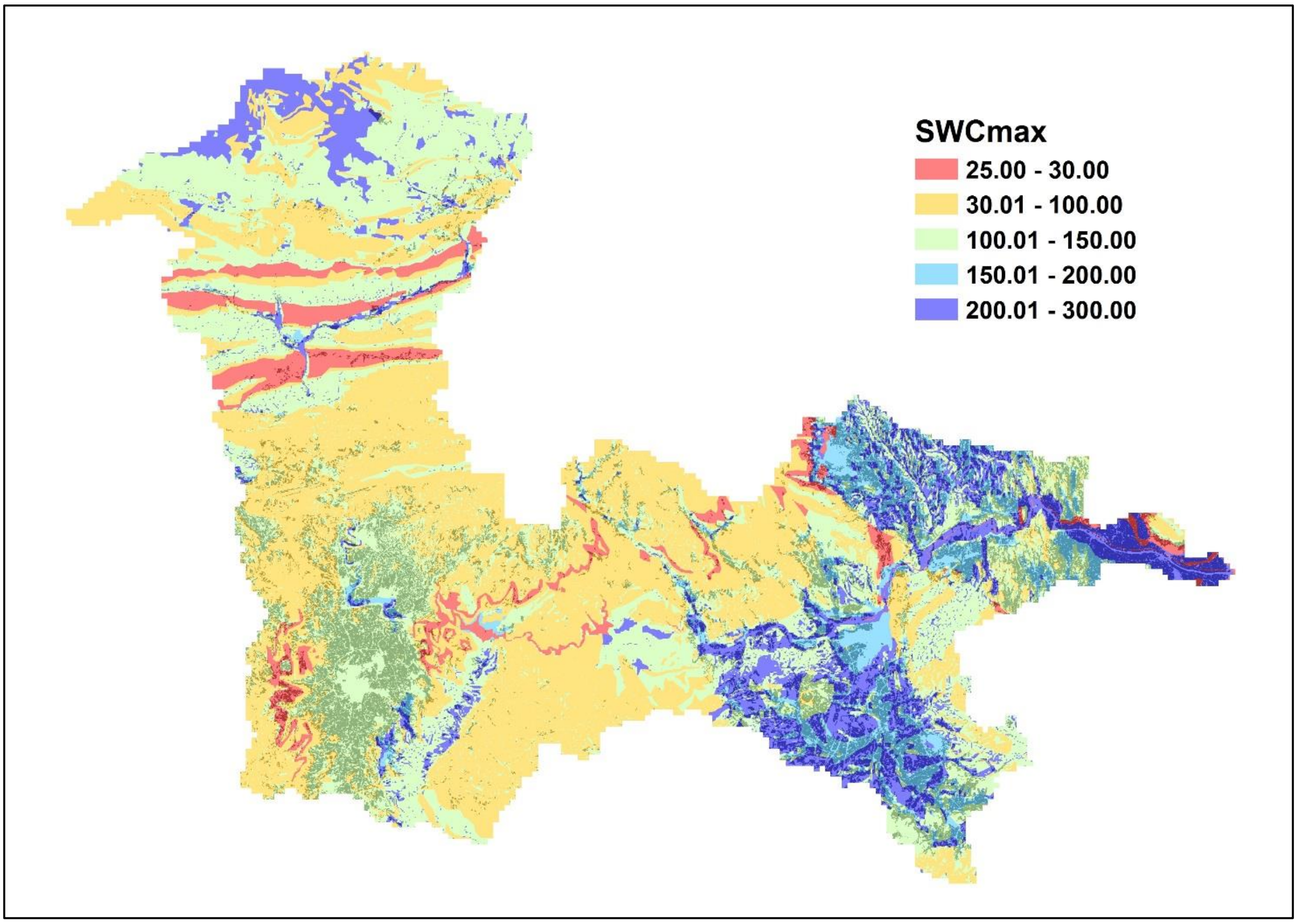


Figure 55. Map of maximum soil water capacity (mm) of Ter basin. Shades under colours represents agriculture surface.

In Segre, agriculture land is distributed in the lower Segre irrespective of the SWC soil group (Figure 56), although crops with higher water requirements such as maize, alfalfa or fruit orchards occupy the soils with highest SWC, leaving the soils with less SWC to crops such as winter cereals and rainfed woody crops such as olives or almonds.

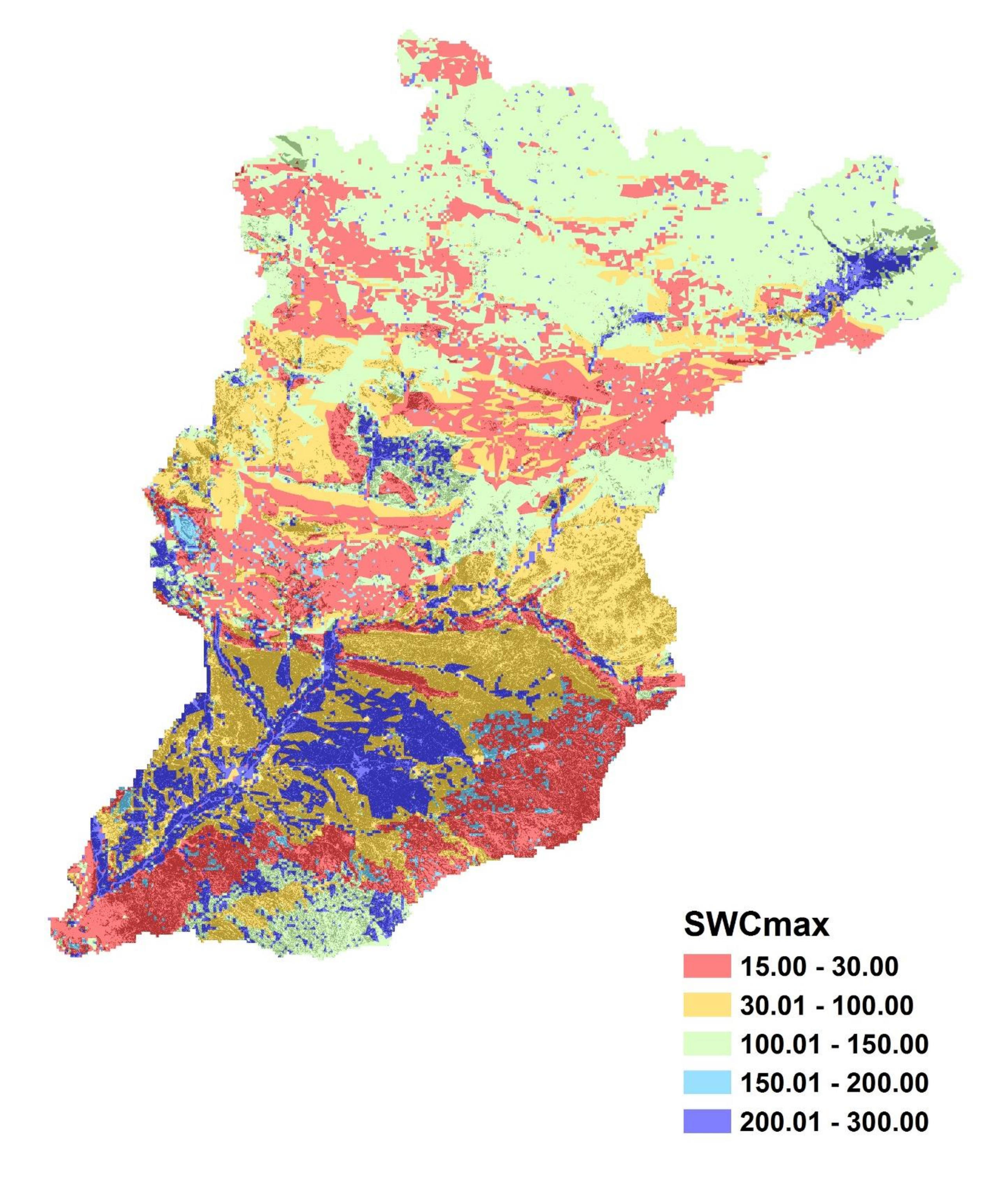


Figure 56. Map of maximum soil water capacity (mm) of Segre basin. Shades under colours represents agriculture surface.

To calculate and present the results regarding the impacts of climate scenarios on agriculture the three basins were divided in three segments: Upper, Middle and Lower Basin (Figure 57), and three periods were considered: the reference period (2002-2011), the short (2021-2030) and the long term (2041-2050).

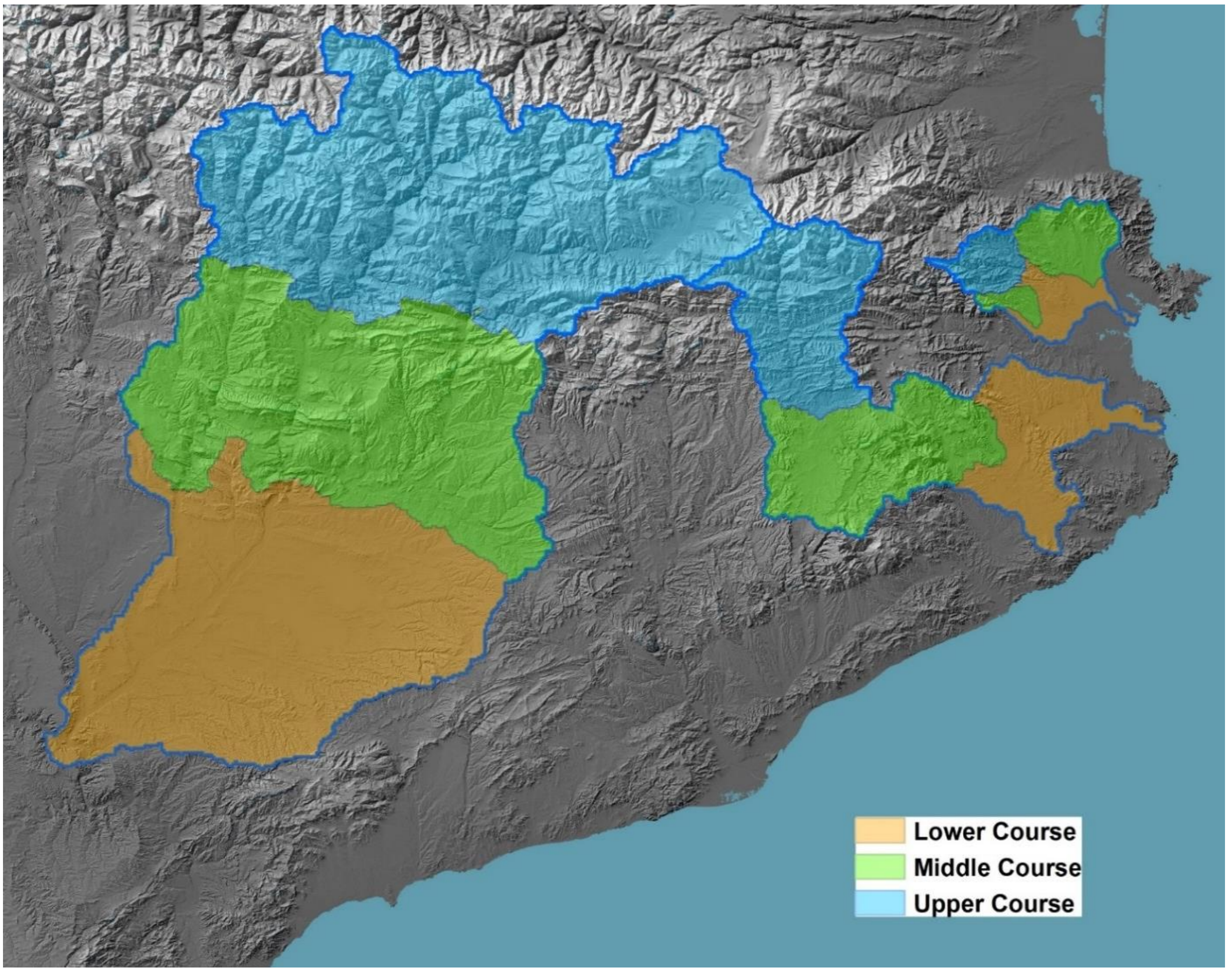


Figure 57. Segments basin delineation for the three basins.

5.2.3. Current and Future Net Irrigation Requirements (NIR) of major crops

The basin theoretical total annual NIR in Muga basin is about 15.58 hm^3 $year^{-1}$ in average for the reference period (2002-2011), showing an increase of 0.1% in the short term (2021-2030) and an increase of 3.9% in the long term (2041-2050) under RCP4.5 climate change scenario, both respect to the reference period.

The basin theoretical total annual NIR in Ter basin is about 64 hm^3 $year^{-1}$ in average for the reference period (2002-2011), showing an increase of 2.4% in the short term (2021-2030) and an increase of 10.2 % in the long term (2041-2050) under RCP4.5 climate change scenario, both respect to the reference period.

The basin theoretical total annual NIR in Segre basin is about 799.7 hm^3 $year^{-1}$ in average for the reference period (2002-2011), showing an increase of 6.6% in the short term (2021-2030) and an increase of 6.7% in the long term (2041-2050) under RCP4.5 climate change scenario, both respect to the reference period.

Annual average values of total and basin segment (lower, middle and upper) theoretical NIR (absolute values in hm^3 $year^{-1}$ for the whole basin) of major crops in each basin are shown in Table 22. These values consider both rainfed and irrigated cropland theoretical NIR of major crops (those occupying more than 1% of cropland) in each basin. Moreover, these values are net requirements implying that water losses by irrigation system or water distribution inefficiencies are not considered, i.e., only plant level water requirements are considered.

Crop	Basin Segment	Surface (ha)	ETa (mm) Reference Period	ETa (mm) Short term	ETa (mm) Long Term	NIR (mm) Reference Period	NIR (mm) Short term	NIR (mm) Long Term
Triticale	Lower Course	3125	238.3	238.9	240.5	200.6	208.6	201.4
	Middle Course	1093	340.4	324.8	316.2	150.9	163.0	157.0
	Upper Course	393	305.7	288.2	276.8	1.7	1.1	0.0
Winter cereal Fodder	Lower Course	1582	249.2	245.6	248.2	194.6	203.4	195.2
	Middle Course	2709	355.3	337.1	330.0	144.1	159.2	152.9
	Upper Course	1259	271.1	273.6	266.6	24.6	13.3	9.6
Pear	Lower Course	11996	249.3	244.4	238.9	315.6	329.0	335.1
Apple	Lower Course	7202	228.2	223.5	215.0	328.3	352.1	362.6
	Middle Course	94	187.4	202.1	210.9	0.0	0.0	0.0
Rye-grass	Lower Course	1243	76.2	71.8	71.5	136.8	146.9	149.4
	Middle Course	187	273.8	254.0	252.6	60.2	93.6	97.8
	Upper Course	25	433.5	444.6	449.8	0.0	0.0	0.0
Rapeseed	Lower Course	1871	125.3	126.6	124.8	79.2	83.1	77.4
	Middle Course	1223	237.3	224.0	232.5	56.2	65.3	65.4
Vegetables	Lower Course	917	20.2	19.3	18.8	38.0	37.5	37.1
	Middle Course	187	143.6	136.0	132.9	66.5	82.6	86.3
	Upper Course	69	253.9	272.6	280.8	2.9	0.9	1.6
Rye	Lower Course	57	238.4	235.8	239.5	197.5	211.1	202.6
	Middle Course	154	372.1	354.9	346.2	127.3	142.6	136.7
	Upper Course	514	293.9	282.3	272.1	2.6	1.1	0.2

Basin	Basin Segment	Total Basin NIR (hm^3) Reference Period	Total Basin NIR (hm^3) Short Term	Total Basin NIR (hm^3) Long term	% changes* Short Term	% changes* Long term
Muga	Lower basin	10.7	10.6	10.9	-0.4	1.9
	Middle basin	4.6	4.7	5.0	1.6	9.0
	Upper basin	0.28	0.27	0.28	-4.2	-0.5
	Total basin	**15.6**	**15.6**	**16.2**	**0.1**	**3.9**
Ter	Lower basin	36.2	36.7	39.0	1.3	7.6
	Middle basin	24.2	24.8	27.1	2.4	12.1
	Upper basin	3.6	4.1	4.4	13.5	23.2
	Total basin	**64.0**	**65.6**	**70.6**	**2.4**	**10.2**
Segre	Lower basin	695.8	739.6	742.8	6.3	6.8
	Middle basin	98.9	109.1	106.8	10.3	8.1
	Upper basin	4.98	3.89	3.88	-21.8	-22.1
	Total basin	**799.7**	**852.5**	**853.6**	**6.6**	**6.7**

* % change respect reference period

Table 22. Annual average values of total and basin segment (lower, middle and upper) theoretical NIR (absolute values in hm3 year-1 for the whole basin) of major crops in each basin for the Reference period (2002-2011) and both future periods under RCP4.5 climate change scenario: short term (2021-2030) and long term (2030-2050). Relative change (%) with respect to the reference period is also presented.

To better understand NIR increases or decreases during both future periods, annual NIR and their monthly distribution were analysed for the most represented crops. Annual NIR and ET_a of other major crops in the three basin are presented in Table 32 to

Table 34 in Annex 1.

<u>Annual NIR (mm year-1) of major crops</u>

Table 23 to Table 25 present actual evapotranspiration (ETa) and net irrigation requirements (NIR) of major crops in the three basins of the study. In general, reference evapotranspiration (ET0) increases, and crop evapotranspiration (ET_c), also increases in most cases. ET_c was calculated according to FAO methodology, and can be seen as ET_c=ET_a+ NIR (annual ET_c values are shown in Annex 1, Table 35). Indeed, ET_a also increases in the upper course. ET_a limits evapotranspiration to the amount of water available in the soil, plus rain. However, ET_a tends to decrease in the middle and lower course of the basins as less runoff from the upper course reaches them, maybe also reflecting lower rainfall during the crop growth cycle, meaning earlier soil water depletion (see mean annual values of P_{ef} and ET_0 per basin segment and time period: Annex 1, Table 36).

Most crops in the Muga basin (Table 23) follow an increasing trend from the reference period to the short and the long term periods, except for grassland and winter cereals. Grassland present a considerable increase in the short term, higher than for the other crops, but its relatively small representation in the Muga basin results in a negligible effect on NIR at basin level, consistently with a much higher weight of winter cereals, which present a decrease in NIR in the short term which moderates the not-so-high increase in all other crops, resulting in a slight increase for the basin in the short term. Olive would present a consistent NIR increase in the lower and middle basin, up to 24% of increase in the long term in the middle basin, where this crop is highly widespread. The reasons for the behaviour of winter cereals are presented below, when monthly NIR of major crops is considered (Figure 60).

The Ter basin presents the most variable response of the three basins (Table 24). Annual NIR could increase in most of the major crops in both periods and all over the basin, except for winter cereals of which annual NIR could decrease in both periods in the lower basin, although showing some recovery in the long term. Annual NIR of Maize could increase up to 9% and 14% in the long term in the lower and middle basins, respectively. Alfalfa annual NIR could increase up to 14% and 17% in the long term in the lower and middle basins, respectively. Winter cereals follow the same pattern: in the lower basin annual theoretical NIR could decrease up to 9% in the short term and 5% in the long term as a consequence of growing cycle shortening (see next section about distribution of monthly NIR). However, in middle and upper basin theoretical annual NIR could increase around 10% in the long term. Finally, apple trees could increase their annual NIR in the lower basin around 3% and 9% with respect to the reference period in the short and long terms, respectively. The Apple annual NIR in the middle basin could increase up to 10% and 24% with respect to the reference period in the short and long terms, respectively.

			ET_a (mm year^{-1})			NIR (mm year^{-1})		
Crop	Basin Segment	Surface (ha)	Reference Period	Short term	Long term	Reference period	Short term	Long term
Maize	Lower Course	1517	237.3	236.5	231.7	233.6	235.7	235.6
	Middle Course	387	253.2	249.6	241.4	219.7	224.1	228.3
Alfalfa	Lower Course	644	452.6	461.1	451.6	391.7	402.7	424.6
	Middle Course	363	497.8	503.4	493.5	306.7	313.9	340.6
	Upper Course	41	499.1	503.9	501.3	247.3	255.6	272.5
Wheat	Lower Course	1360	322.5	326.0	321.1	60.1	56.5	57.2
	Middle Course	294	342.8	348.0	337.9	51.0	47.8	51.5
Grassland	Middle Course	1942	656.2	622.9	622.6	147.6	214.4	220.6
	Upper Course	5003	405.0	416.4	417.9	37.2	32.7	34.3
Olive	Lower Course	482	447.7	454.6	448.9	119.2	122.3	133.4
	Middle Course	981	473.2	475.9	469.1	86.4	94.4	107.3
Grapevine	Middle Course	857	263.8	268.0	268.5	7.3	7.8	8.0

Table 23. Actual Evapotranspiration (ETa) and Net Irrigation Requirements in 5 representative crops in the three segments of Muga basin during the reference period (2002-2011) and in short (2021-2030) and long term (2041-2050)

	ET_a (mm)	NIR (mm)

Crop	Basin Segment	Surface (ha)	Reference period	Short term	Long term	Reference period	Short term	Long term
Maize	Lower Course	4447	282.9	269.1	256.3	219.0	227.3	238.8
	Middle Course	983	333.4	317.0	302.8	212.9	229.4	242.5
	Upper Course	64	208.2	272.0	303.5	0.0	0.0	0.7
Alfalfa	Lower Course	1503	492.7	492.7	483.6	201.0	209.0	229.1
	Middle Course	314	517.9	510.5	499.0	232.2	248.4	272.5
	Upper Course	71	561.0	565.9	570.4	71.6	81.9	88.0
Wheat	Lower Course	6078	339.1	344.6	336.4	88.56	80.04	84.03
	Middle Course	6319	346.9	338.7	323.2	115.94	116.11	127.10
	Upper Course	412	386.9	372.6	360.2	89.86	93.25	98.90
Apple	Lower Course	923	320.7	319.1	311.7	207.4	213.5	225.0
	Middle Course	58	431.8	421.7	407.6	143.3	158.1	178.0

Table 24. Actual Evapotranspiration (ETa) and Net Irrigation Requirements in 4 most representative crops in the three segments of Ter basin during the reference period (2002-2011) and in short (2021-2030) and long term (2041-2050).

All crops in the Segre basin (Table 25) are expected to experience a significant increase in the short term that slows down in the long term, irrespective of the segment of the river, which explains the expected behaviour of the NIR for the basin. Typical rainfed crops such as grapevine and almond could present an increase in NIR in the long term of around 15% and olive of up to 17% for the lower basin, where agriculture is concentrated. In general, winter cereals would show an increase of around 10% in the short term, and a subsequent slow down, as for the general basin pattern. This would result in a NIR increase of only 6% in the long term in relation to the reference period, with barley even presenting a decrease in the same period, not only in relation to the short term, but also compared to the reference period in the case of the lower course. Maize NIR would increase up to 5% in the long term in the lower basin and up to 12% in the middle basin. NIR of fruit orchards such as apple would increase in the long term up to 10% in the lower basin but nectarines and peach less than 3%. Finally, grassland in middle Segre would increase up to 45% in the short term and almost 50% in the long term.

			ET_a (mm)			NIR (mm)		
Crop	Basin Segment	Surface (ha)	Reference period	Short term	Long term	Reference period	Short term	Long term
Maize	Lower Course	30401	195.5	182.5	173.7	453.6	472.6	474.5
	Middle Course	1317	189.4	189.8	187.3	157.4	172.1	177.4
	Upper Course	378	114.8	137.4	151.4	0.0	0.0	0.0
Alfalfa	Lower Course	18135	320.3	299.4	297.3	432.0	479.7	489.3
	Middle Course	2669	483.3	478.5	481.5	190.1	215.3	219.5
	Upper Course	566	308.5	313.7	316.1	0.0	0.0	0.0
Grassland	Middle Course	1942	656.2	622.9	622.6	147.6	214.4	220.6
	Upper course	5003	405.0	416.4	417.9	37.2	32.7	34.3
Wheat	Lower Course	30121	230.7	229.0	231.3	211.6	220.7	212.8
	Middle Course	19110	322.3	310.4	300.1	156.2	169.0	166.0
	Upper Course	1585	283.1	274.7	264.1	2.4	0.7	0.8
Barley	Lower Course	79141	231.9	225.2	224.7	145.7	152.1	144.0
	Middle Course	39805	305.4	292.8	284.8	106.5	116.3	112.1
	Upper Course	256	273.9	268.0	260.3	0.4	1.3	1.1
Olive	Lower Course	36740	331.5	312.4	309.3	293.7	334.8	344.8
	Middle Course	1929	387.1	399.1	401.6	163.1	170.8	173.7
	Upper Course	97	254.1	259.8	262.5	0.0	0.0	0.0
Grapevine	Lower Course	3370	204.0	205.3	200.6	70.2	75.6	81.1
	Middle Course	458	201.0	211.7	212.7	36.4	39.4	41.1
Almond	Lower Course	14067	236.8	228.1	220.0	410.5	435.2	445.5
	Middle Course	24067	335.7	340.6	345.3	194.4	217.7	223.5
Peach	Lower Course	13430	253.4	246.5	240.7	360.1	365.8	370.9
	Middle Course	94	252.3	253.4	250.2	271.6	267.5	267.9

Table 25. Actual Evapotranspiration (ETa) and Net Irrigation Requirements in 9 most representative crops in the three segments of Segre basin during the reference period (2002-2011) and in short (2021-2030) and long term (2041-2050)

Monthly NIR (mm month^{-1}) of major crop

The following pages present the expected ET_a and NIR monthly behaviour of some major crops in the different basin and segments. In general, an earlier rise of ET_a in the year is observed, but it is only reflected in an increase in NIR if the phenology of the crop admits it. Also, in a number of crops and basin segments, a NIR increase in the early growing cycle is balanced by a reduced NIR later in the cycle for phenological reasons, even if ET_c is still higher than in the reference period (data not shown). Several pattern examples follow.

Muga

Maize presents a simple NIR pattern (Figure 58): ET_a increases in June but NIR does not as water soil content still suffices to provide for such an increase. However, as the season advances, ET_a is limited in both the short and the long term, and NIR consistently increases. An earlier finalization of the crop cycle reduces NIR in August and September, but in the lower basin this is not enough to compensate earlier increases in June and July resulting in noticeable annual NIR increases for both periods.

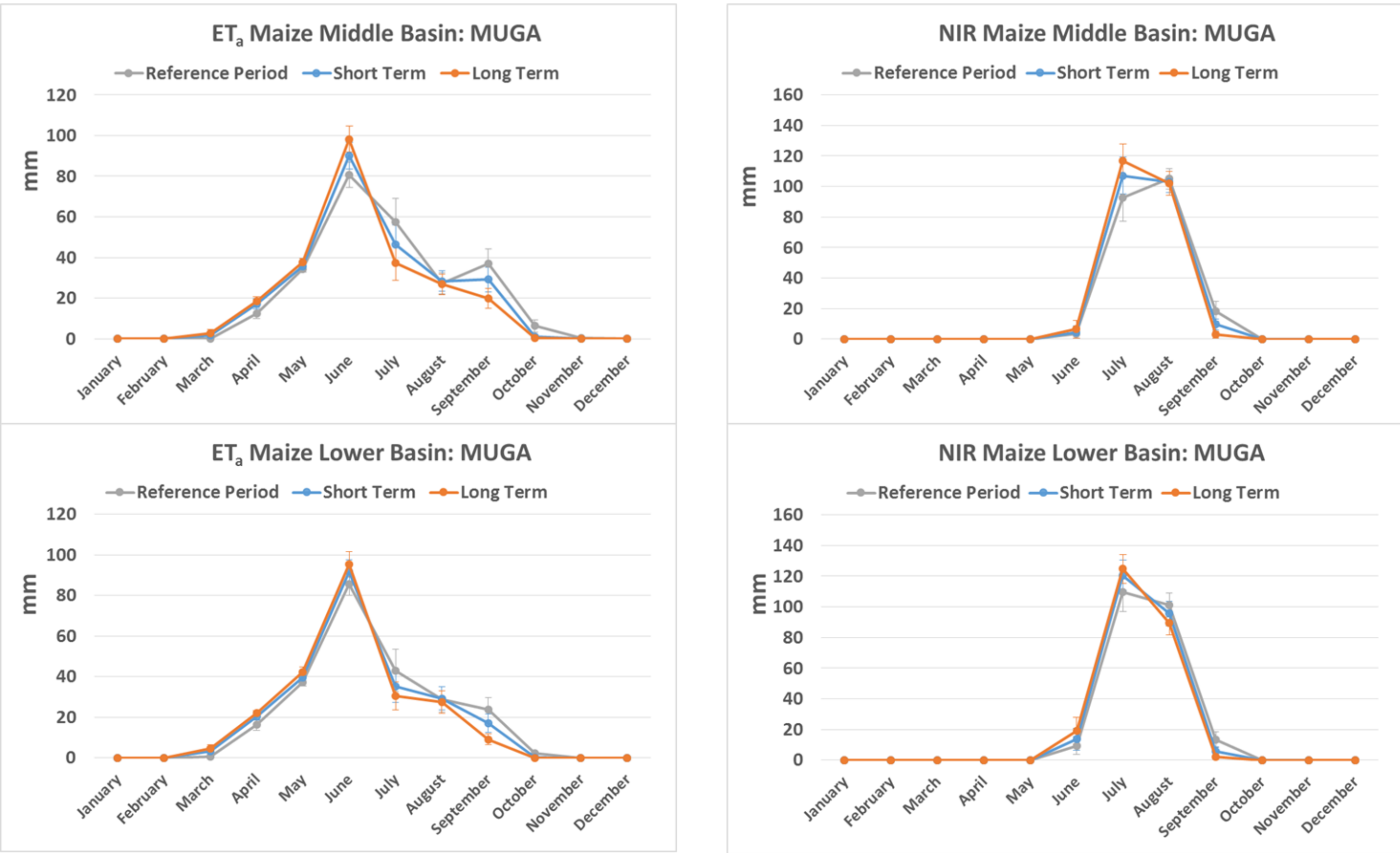


Figure 58. Monthly net irrigation requirements (left) and actual evapotranspiration (right) of maize in the middle and lower Muga basin and in the three studied periods: reference period (2002-2011) and in short (2021-2030) and long Term (2041-2050).

In the Muga basin, alfalfa (Figure 59) presents a sustained increase in NIR. ET_a is already very limited in the reference period from May on, resulting in limited NIR increases, as reflected in a limited annual NIR increase (Table 23).

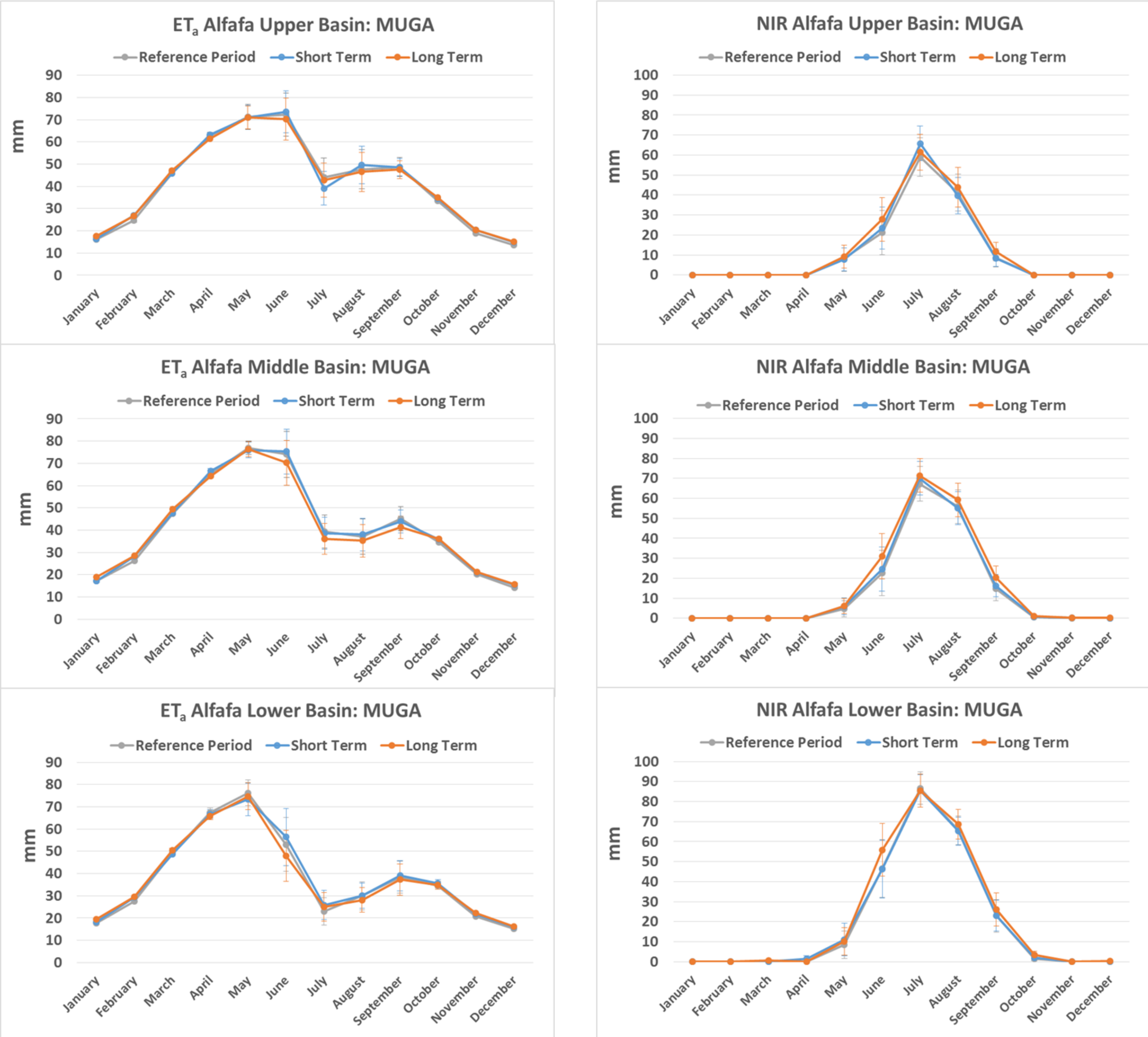


Figure 59. Monthly net irrigation requirements (left) and actual evapotranspiration (right) of Alfalfa in the upper, middle and lower Muga basin and in the three studied periods: reference period (2002-2011) and in short (2021-2030) and long term (2041-2050).

Wheat in the Muga basin (Figure 60) presents an interesting monthly pattern: in the middle course, ET_a increases beginning in January, both for the short and the long term compared to the reference period, resulting in no NIR till May. There, NIR increases slightly in the short term and much more in the long term. However, due to growing cycle shortening, NIR is reduced in June both in the short and the long term, overcompensating the earlier increase. As a result, the annual short and long-term NIR is reduced with respect to the reference period, as referred in the previous section. In the lower course the pattern is similar, but temperature rise advances the pattern, so first changes are observed in April, with higher NIR for both periods with respect to the reference, a stabilisation in May, and lower NIR in June: this again overcompensates the earlier increase, but only in the short term period, whereas in the long term a minor increase in annual NIR is finally observed.

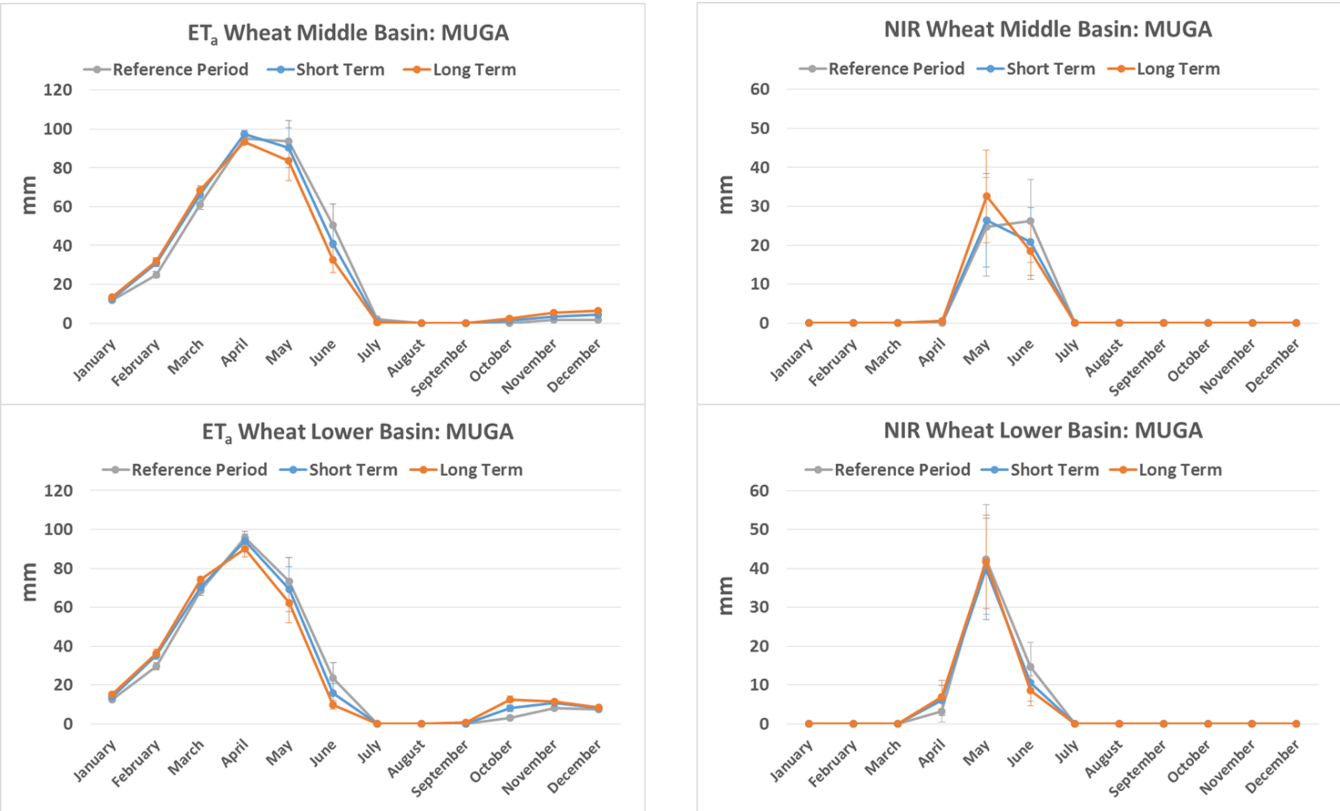


Figure 60. Monthly net irrigation requirements (left) and actual evapotranspiration (right) of wheat in the middle and lower Muga basin and in the three studied periods: reference period (2002-2011) and in short (2021-2030) and long term (2041-2050).

Olive pattern (Figure 61) in La Muga is the simplest: NIR increase all over the growing season. It is to be noted that, in the long term, even if ET_a increases in June in all basin segments, a NIR increase can also be observed, as ET_a has reached soil water capacity, hence implying a need for irrigation to reach ET_c.

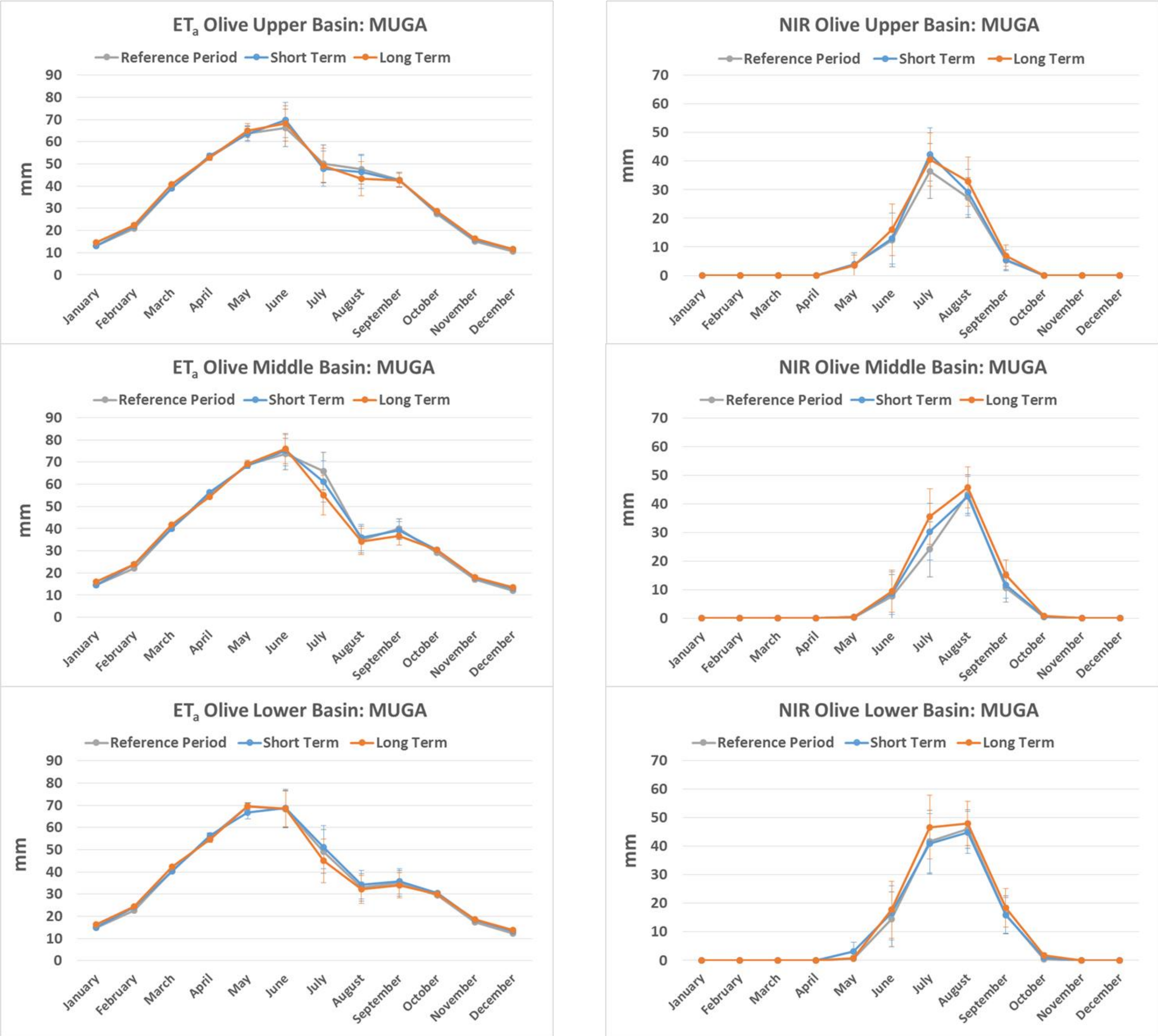


Figure 61. Monthly net irrigation requirements (left) and actual evapotranspiration (right) of olive in the upper, middle and lower Muga basin and in the three studied periods: reference period (2002-2011) and in short (2021-2030) and long term (2041-2050).

Ter

Maize (Figure 62) located in the upper basin would present no NIR despite ET_a is higher during all the growing cycle in both future periods (ET_a=ET_c), as there is enough water stocked in the soil. In the middle basin maize would present the same pattern as in Muga: in both future periods, NIR increases in the month (July) were ET_a begins to decrease as a consequence of limited soil water content. In the lower segment, NIR decreases are more evident during the cycle ending, but not enough to compensate NIR increases of July which would explain annual NIR increase of around 10% in the long term in relation to the reference period (Table 24).

Figure 62. Monthly net irrigation requirements (left) and actual evapotranspiration (right) of maize in the upper, middle and lower Ter basin and in the three studied periods: reference period (2002-2011) and in short (2021-2030) and long term (2041-2050).

Alfalfa in the upper Ter basin (Figure 63) presents noticeable increases during June, July and August in both future periods in relation to the reference period, resulting in annual NIR increases in both future periods Lower and middle course would show similar patterns: small NIR increases for the short term and higher increases during the long term.

Figure 63. Monthly net irrigation requirements (left) and actual evapotranspiration (right) of alfalfa in the upper, middle and lower Ter basin and in the three studied periods: reference period (2002-2011) and in short (2021-2030) and long term (2041-2050).

Wheat in the Ter basin (Figure 64) presents the same monthly winter cereals-pattern that occurs in la Muga: in the first part of the year (from January until April in the upper segment or March in the middle and lower segments), ET_a increases with no limitations both for the short and the long term compared to the reference period (growth cycle start), resulting in no NIR. From there, NIR increases in the short term and much more in the long term for about two months. Then, due to growing cycle shortening, NIR is reduced both in the short and in the long term, partially compensating (upper and middle basins) or overcompensating (lower basin) the earlier increase. As a result, the annual short and long-term NIR in the lower basin could be reduced with respect to the reference period, as referred in the previous section concerning annual NIR: experimenting always in the long term NIR would recover in relation to the short term, but would never reach reference period level.

Figure 64. Monthly net irrigation requirements (left) and actual evapotranspiration (right) of wheat in the upper, middle and lower Ter basin and in the three studied periods: reference period (2002-2011) and in short (2021-2030) and long term (2041-2050).

Apple orchards in Ter basin (Figure 65) are limited to lower and middle segments. General NIR increases would happen during late spring and summer months, both in the short and long terms; however, in the lower basin September values would be lower than the reference, slightly compensating earlier increases. In general, long term values would be more extreme (highest or lowest). As a result, annual NIR would notably increase in relation to the reference period, particularly in the long term, where it could present up to a 24% increase in the middle basin (Table 24).

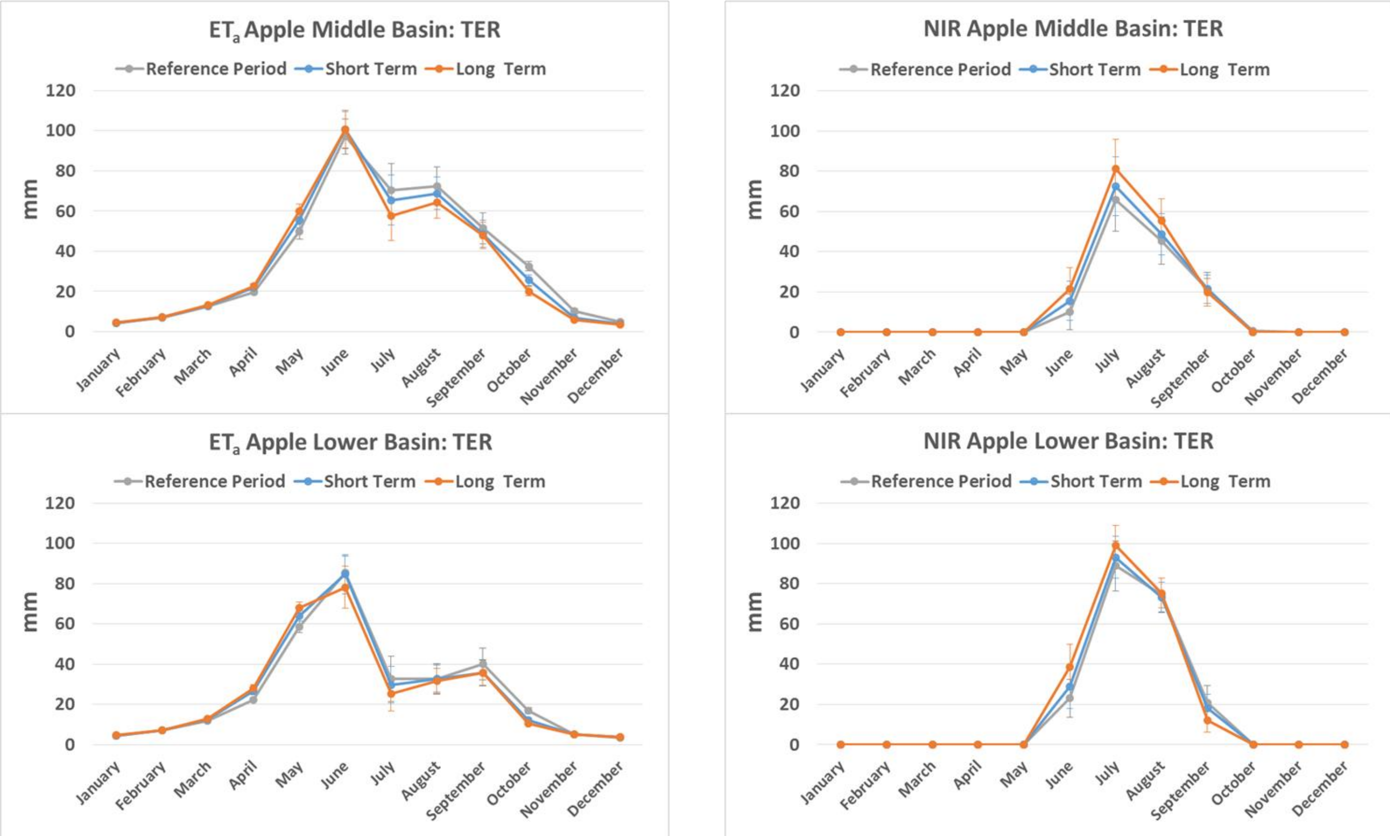


Figure 65. Monthly net irrigation requirements (left) and actual evapotranspiration (right) of apple in the middle and lower Ter basin and in the three studied periods: reference period (2002-2011) and in short (2021-2030) and long term (2041-2050).

Segre

Maize pattern in Segre middle and lower course is as described for Muga, although with contrasting NIR in the middle and lower courses: higher NIR for the lower basin in relation to Muga, and lower for the Segre in the middle basin. To understand this, it has to be considered that the lower Muga course corresponds to the vicinity of the sea, were temperatures are moderated by sea buffer, while for the Segre basin, lower course corresponds to inland, as it is a tributary of the Ebro river.

Figure 66. Monthly net irrigation requirements (left) and actual evapotranspiration (right) of maize in the upper, middle and lower Segre basin and in the three studied periods: reference period (2002-2011) and in short (2021-2030) and long term (2041-2050).

Almond trees also present a maize-like pattern, with an increase mostly all over the growth cycle except by the end, were NIR decreases but does not compensate earlier increases. However, in this case, being a woody crop, the reason is not the end of plant life, but a reduction of plant demand after fruit harvest based on agronomic considerations.

Figure 67. Monthly net irrigation requirements (left) and actual evapotranspiration (right) of almond in the upper, middle and lower Segre basin and in the three studied periods: reference period (2002-2011) and in short (2021-2030) and long term (2041-2050).

Barley in the Segre basin (Figure 68) presents a monthly pattern similar to other winter cereals such as wheat in the Muga or Ter basins: from January to February (Middle and Lower segment) ET_a increases both for the short and the long term compared to the reference period, resulting in no NIR till March. In both cases (lower and middle), monthly NIR increases in the short term at the beginning of the growth cycle and declines at the cycle ending as a consequence of the cycle shortening. As presented in the previous section (Table 25), barley would present a decrease in NIR in the long term in relation to the short term for both the middle and the lower course. And, for the lower course, long term NIR would decrease even compared to the reference period. With the general shortening of the growth cycle as a most probable explanation, this result can be followed in figure 47: in the middle basin, long and short term NIR remain the same and above the reference period along the crop cycle except for the end of the cycle (June), where the long term NIR decreases with respect the other two periods, resulting in an annual decrease; in the lower course, long term NIR would be mostly below short term NIR, and even below or similar to the reference period, except for the very beginning of the cycle, thus resulting in a long term annual NIR decrease with respect to the other two periods.

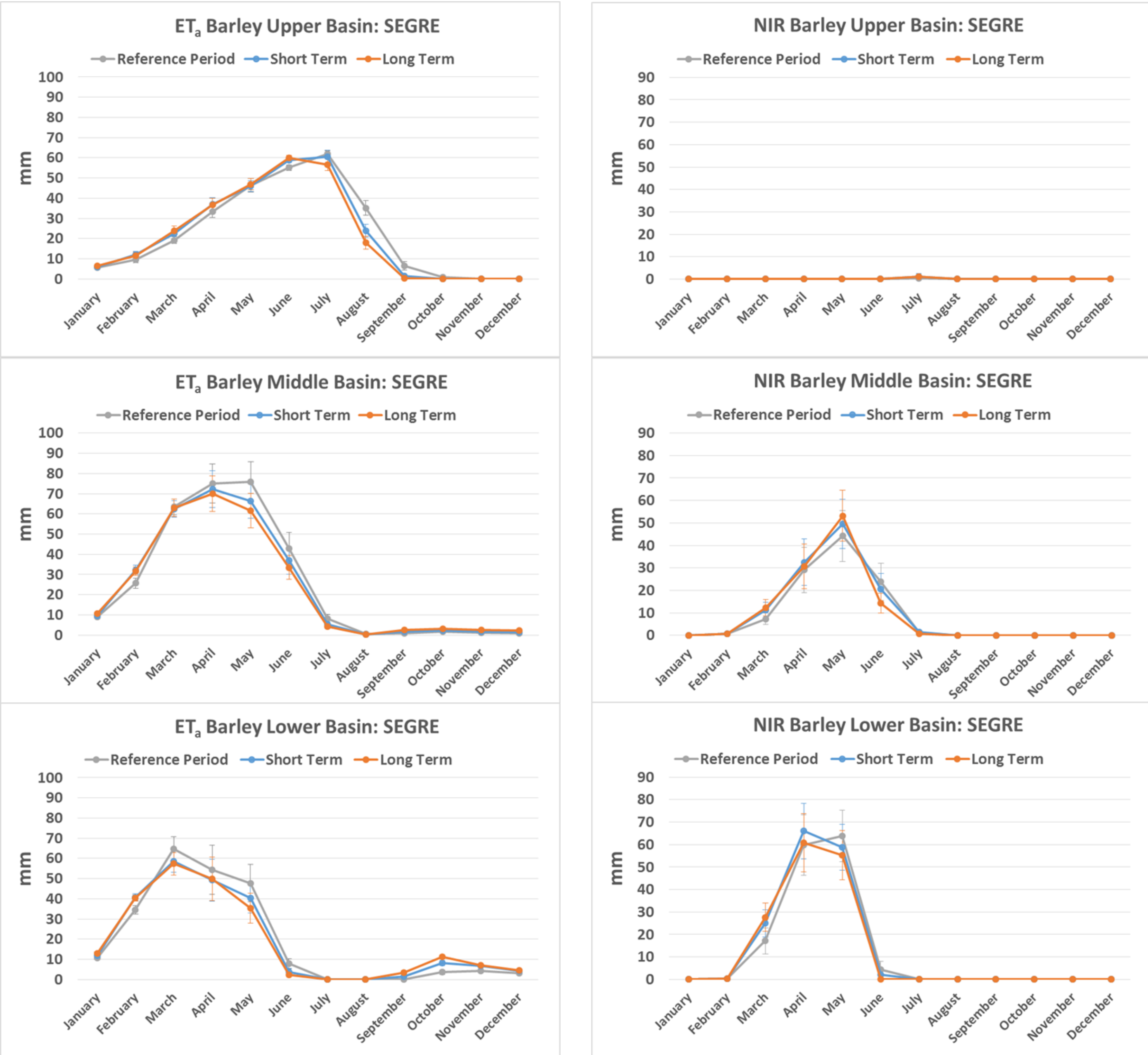


Figure 68. Monthly net irrigation requirements (left) and actual evapotranspiration (right) of barley in the upper, middle and lower Segre basin and in the three studied periods: reference period (2002-2011) and in short (2021-2030) and long term (2041-2050).

Peach in the middle Segre presents the following pattern: slightly NIR increases during May and June and decrease in August for short and long term with respect to the reference period. These decreases in August balance increases in May and June resulting in a slightly decrease in the annual NIR (Table 25). In contrast, peach NIR increases in the lower segment in May and especially in June; although NIR decreases in August as in the middle course, it is not enough to compensate increases in the previous months, resulting in an increase of annual NIR (Table 25) in this segment of the basin. July represents the inflection point between NIR increases and decreases, and remains constant along time in both basin segments.

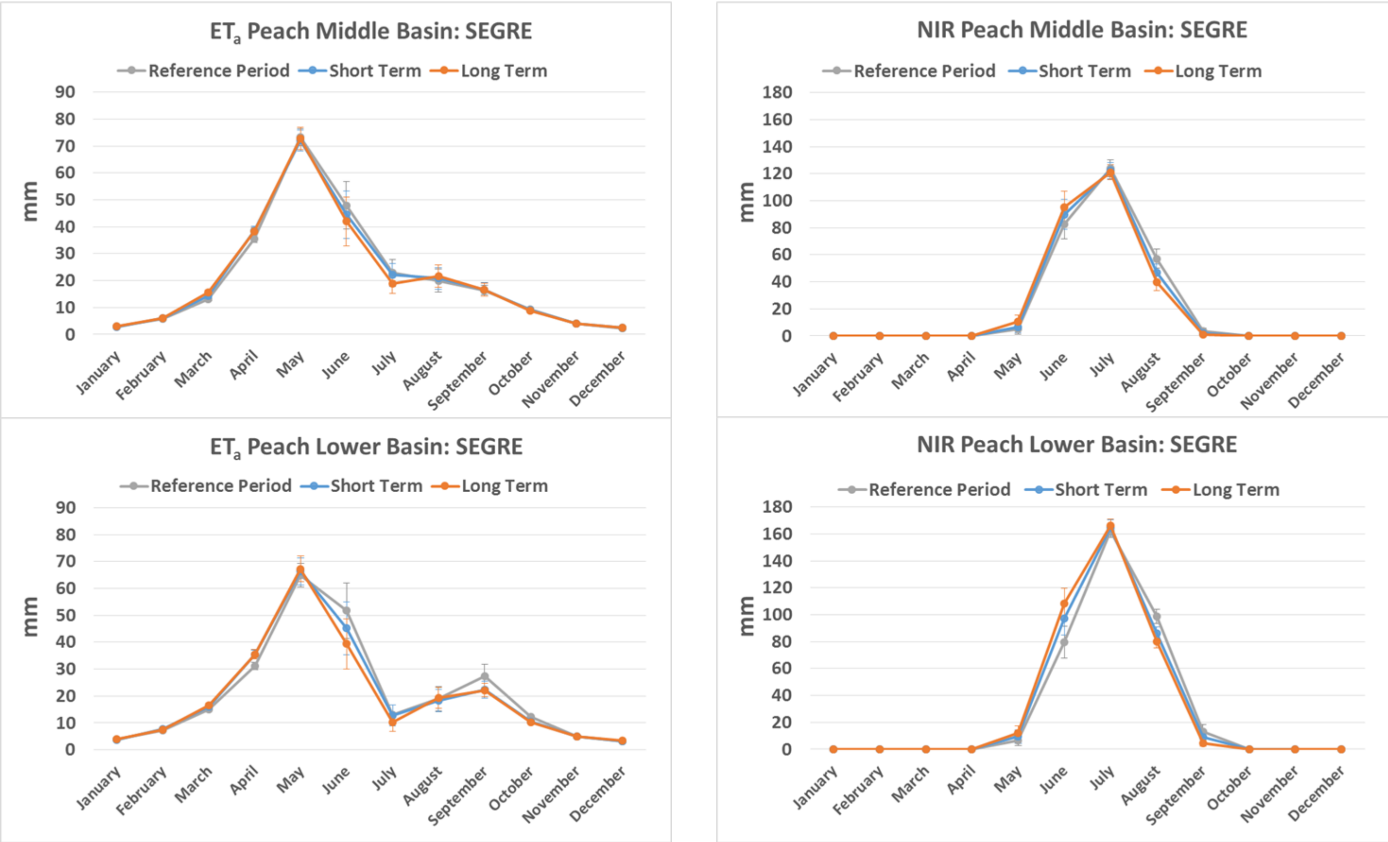


Figure 69. Monthly net irrigation requirements (left) and actual evapotranspiration (right) of peach in the middle and lower Segre basin and in the three studied periods: reference period (2002-2011) and in short (2021-2030) and long term (2041-2050).

Grassland NIR (Figure 70) in the upper basin hardly experiment any changes in both future periods and NIR is always low. However, in the middle basin NIR would experiment an important increase at both periods with respect to the reference (but not between them) from April to September. As a hypothetical grass reference is used for the calculation of ET_0 (Allen et al. 1998), grassland NIR pattern is useful to understand how ET_0 would perform in both future periods.

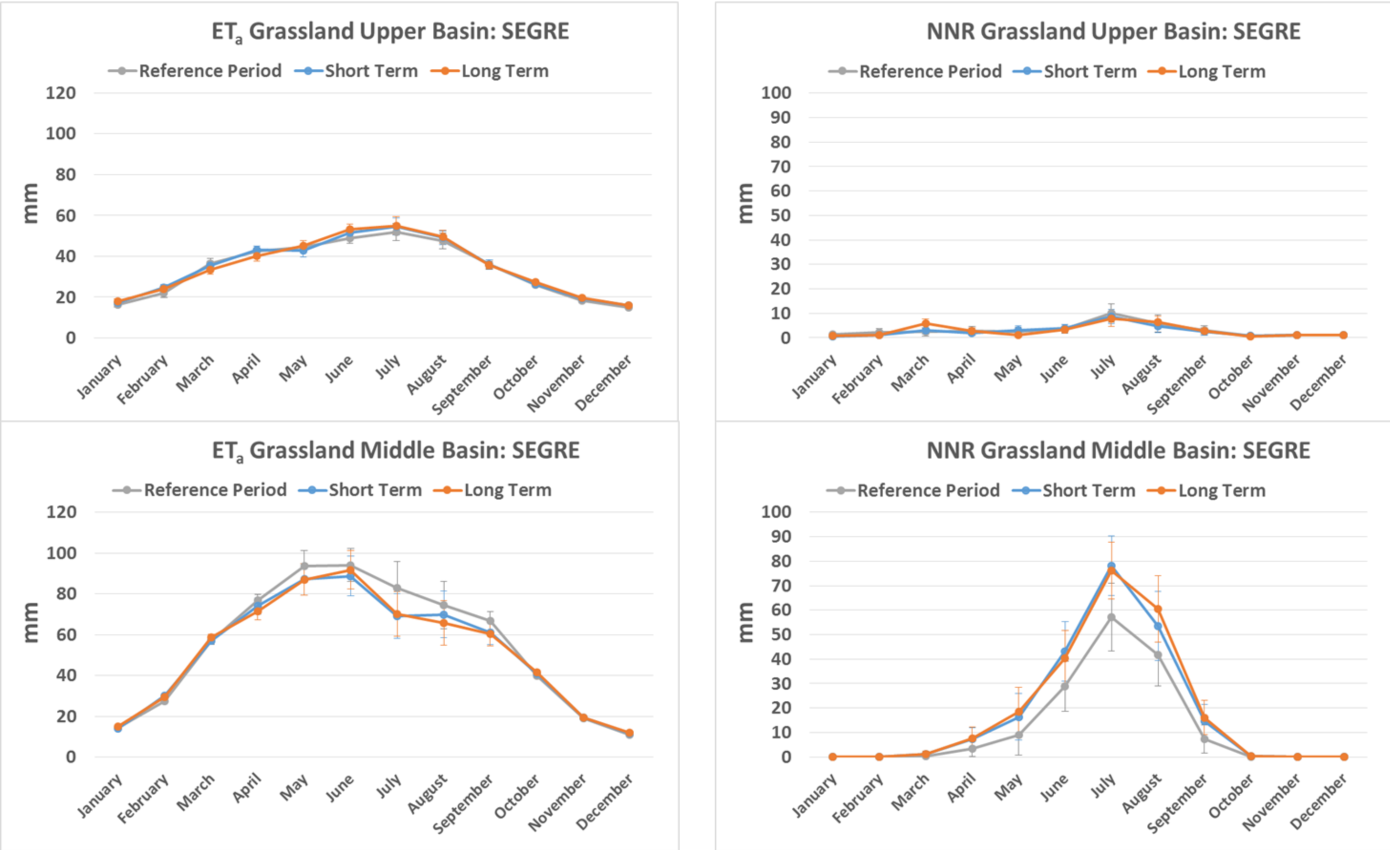


Figure 70. Monthly net irrigation requirements (left) and actual evapotranspiration (right) of grassland in the upper and middle Segre basin and in the three studied periods: reference period (2002-2011) and in short (2021-2030) and long term (2041-2050).

Olive NIR (Figure 71) presents the same general pattern as in Muga, with NIR increases in both future periods with respect to the reference period along the growing cycle: June, July and August in the middle segment and from May to August in the lower basin, resulting in increases for annual NIR (Table 25).

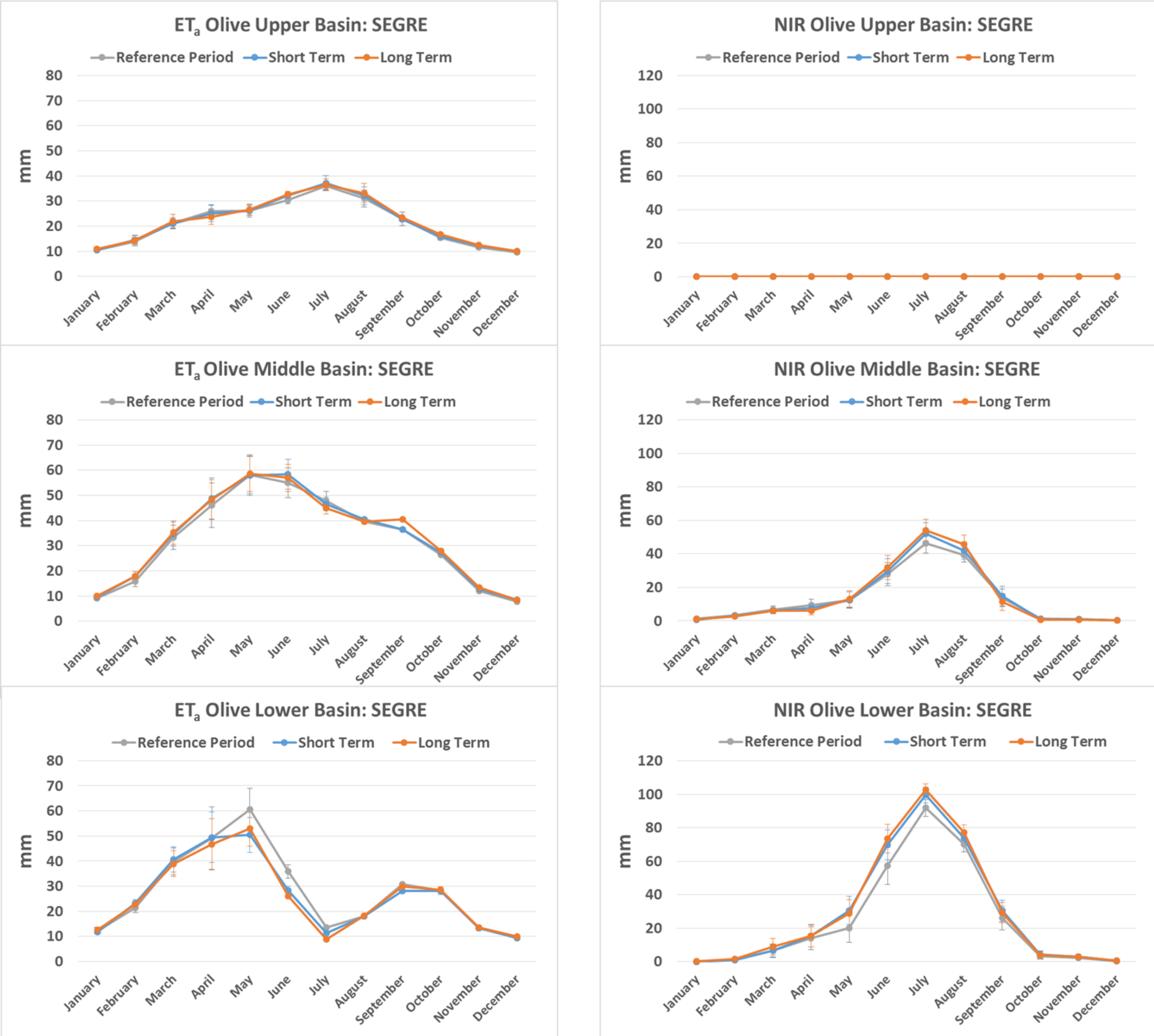


Figure 71. Monthly net irrigation requirements (left) and actual evapotranspiration (right) of olive in the upper, middle and lower Segre basin and in the three studied periods: reference period (2002-2011) and in short (2021-2030) and long term (2041-2050).

5.2.4. Assessing agriculture suitability using agroclimatic indicators

To assess the suitability of present day crops to expected conditions in the short and the long terms, a set of general agroclimatic indicators was calculated. These agroclimatic indicators affect different phases of the growing cycle of some crops: number of frost days in March and April could affect germination of cereals and flowering of woody crops; *day of year* T_{mean} *> 10℃* corresponds to the day in which daily mean temperature exceeds that value, which is a general threshold for the beginning of the growth cycle of many crops; extreme temperatures (heat) during summer affect grain formation in maize or fruit orchards so the *number of days with* T_{max}*>30ºC* and the *number of days with* T_{max}*>35ºC* were calculated; finally, some crop-specific indicators based on growing degree days (GDD) accumulated from 1st January were estimated for some of the most relevant major crops, such as the day when 2076 GDD and 2126 GDD are reached (Tbase=10ºC) to assess the cycle duration of FAO cycle grain maize varieties of 600 and 700, respectively, days from 1st January needed to accumulate a certain number of GDD required to reach each phenological stage for grapevine according to different phenological records made in Catalonia by IRTA Environmental Horticulture program (Tbase=10ºC; Budbreak: 71 GDD; Bloom: 319 GDD; Fruitset: 429 GDD; Berry at pea size: 429 GDD; Veraison: 221 GDD; Harvest: 1857 GDD; Leaf Fall: 2163 GDD), or for wheat according to different phenological records made in Catalonia By IRTA Field Crops Program (Tbase=5ºC; Spike: 714 GDD; Anthesis: 1295 GDD; Maturation: 1956 GDD), or flowering time estimation for Apple, following Funes et al., (2016).

<u>Muga</u>

Agroclimatic indicators for the Muga basin are shown in Table 26. Number of frost days in March and April decreases all over the basin, being that decrease higher in the upper basin. This does not necessarily mean a reduction or disappearance of frost risk because of the advancement of crop cycle, as can be seen in the indicator *Day of Year* T_{mean} *> 10℃*, that indicates an advancement of growing cycle of up to 12, 10 or 5 days in the lower, middle and upper basin, respectively, in the long term.

			Upper Basin			Middle Basin			Lower Basin		
			Reference Period	Short term	Long term	Reference Period	Short term	Long term	Reference Period	Short term	Long term
Agroclimatic Indicators (in general for all crops)	Number of days T_{min}<0ºC	March	8.4	7.4	6.3	2.7	2.7	2.6	1.7	1.6	1.3
		April	1	0.7	0.4	0	0	0	0	0	0
	Number of days T_{max}>30ºC	July	9.0	11.1	12.9	12.9	14.8	16.8	13.8	16.4	17.7
		August	5.5	7.3	9.2	11.0	13.2	15.6	11.8	14.5	16.4
	Number of days T_{max}>35ºC	July	0.4	0.8	1.3	0.5	1.0	1.4	1.2	1.6	2.2
		August	0.5	0.9	1.05	1.3	1.5	2.0	1.0	1.8	2.5
	Day of Year (DOY) T_{mean}>10ºC		107	106	102	79	74	69	70	63	58
Maize	Day of Year (DOY) when GDD= 2076* (600 FAO cycle grain maize varieties)		†	†	†	299‡	288‡	277‡	284	270	261
	Day of Year (DOY) when GDD=2126* (700 FAO cycle grain maize varieties)		†	†	†	303‡	283‡	295‡	289	275	266

**Growing degree days counted from 1st January.*

†Maize does not represents a major crop in this segment to perform calculations

‡Sub-basin n. 11 was excluded from these calculations as required GDD are not attained all years, at least in the reference period.

Table 26.Agroclimatic indicators for growth and development of crops in general and maize in particular in the upper, middle and lower Muga basin in the three studied periods: reference period (2002-2011) and in short (2021-2030) and long term (2041-2050).

Number of days with T_{max}*>30ºC* increases all over the basin for the long term compared to the reference period: 4 days both for July and August in the upper and middle basins, and 4 and 5 days (July and August, respectively) in the lower basin. *Number of days with* T_{max}*>35ºC* would roughly double all over the basin in the long term in relation to the reference period, which is consistent with an increase of heat effects currently observed such as heat stroke in apples affecting fruit quality (http://www.irta-rdi.info/els-estudis-sobre-mesures-dadaptacio-al-canvi-climatic-en-la-pomera-de-girona-es-donen-a-coneixer-a-tv3/).

The two indicators related to the celerity of growing cycle accomplishment of maize show that it could be shortened in the long term compared to the reference period: 22 days shorter in the middle basin and 23 in the lower basin for 600 FAO cycle grain maize varieties; 16 days in the middle basin and 23 days in the lower basin for 700 FAO cycle grain maize varieties.

Figure 72 shows a time-sequence of the most important phenological stages in grapevine growing cycle, representing days passing from 1st January to reach each phenological phase. This agroclimatic indicator for grapevine was only calculated for middle Muga basin were this crop is highly widespread (D.O. Empordà-Costa Brava). The beginning of the cycle (budbreak) would advance 10 days in the short term and 13 days in long term with respect to the reference period. The duration on the cycle (195 days from budbreak to harvest in the reference period) would be shortened up to 2 days in the short term and 7 days at long term, as a consequence of shorter time from veraison to harvest, and to some extent form pea size to veraison; this contrasts with a retardation in the duration of the blooming phase. Finally, the shortening of the growing cycle would result in an earlier harvest time of about 12 days in the short term and 20 days in the long term.

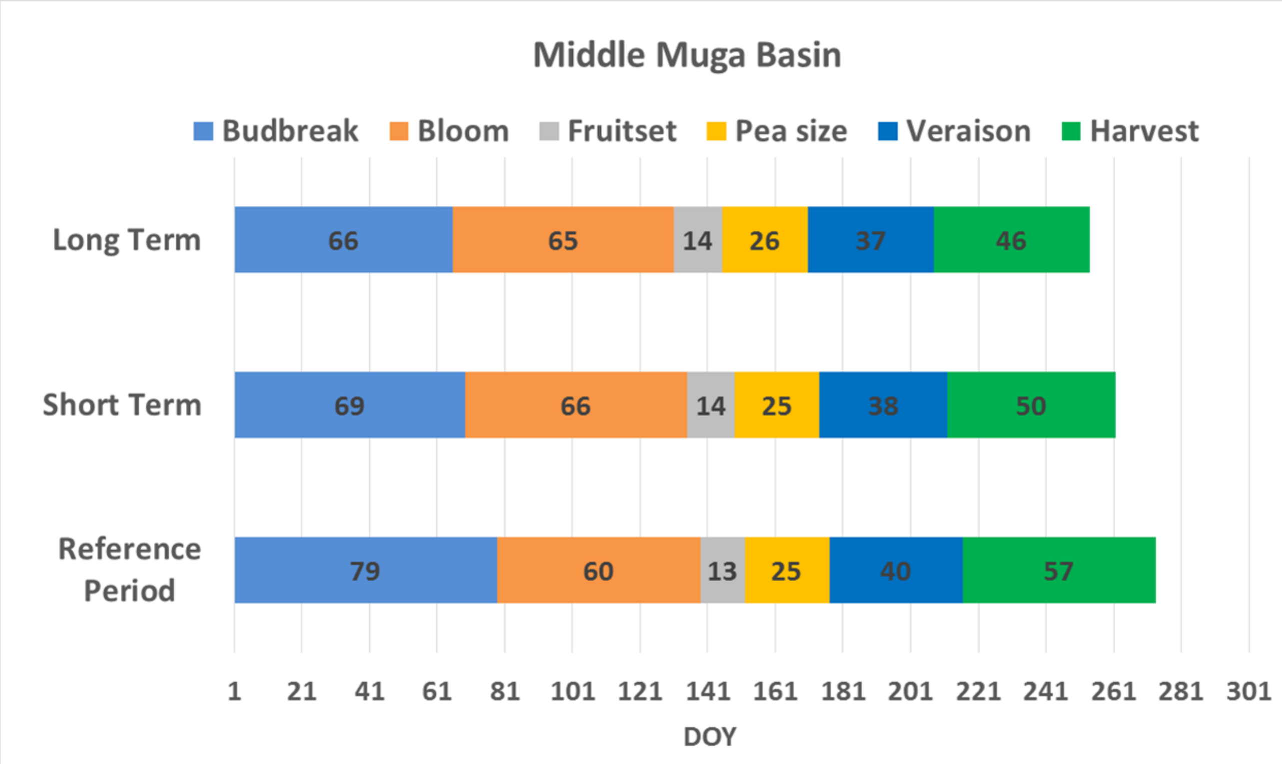


Figure 72. Time-sequence representation of different stages of vine growth from 1st October in the middle Muga Basin. Numbers inside each bar, are number of days in reach each phenological stage. All data are averaged through the corresponding term: short term (2021-2030), long term (2041-2050) and reference period (2002-2011).

For wheat (Figure 73), the phenological phases (spike, anthesis and grain maturation) would advance, particularly the spike phase (about a week in the long term), which determines the beginning of growing cycle.

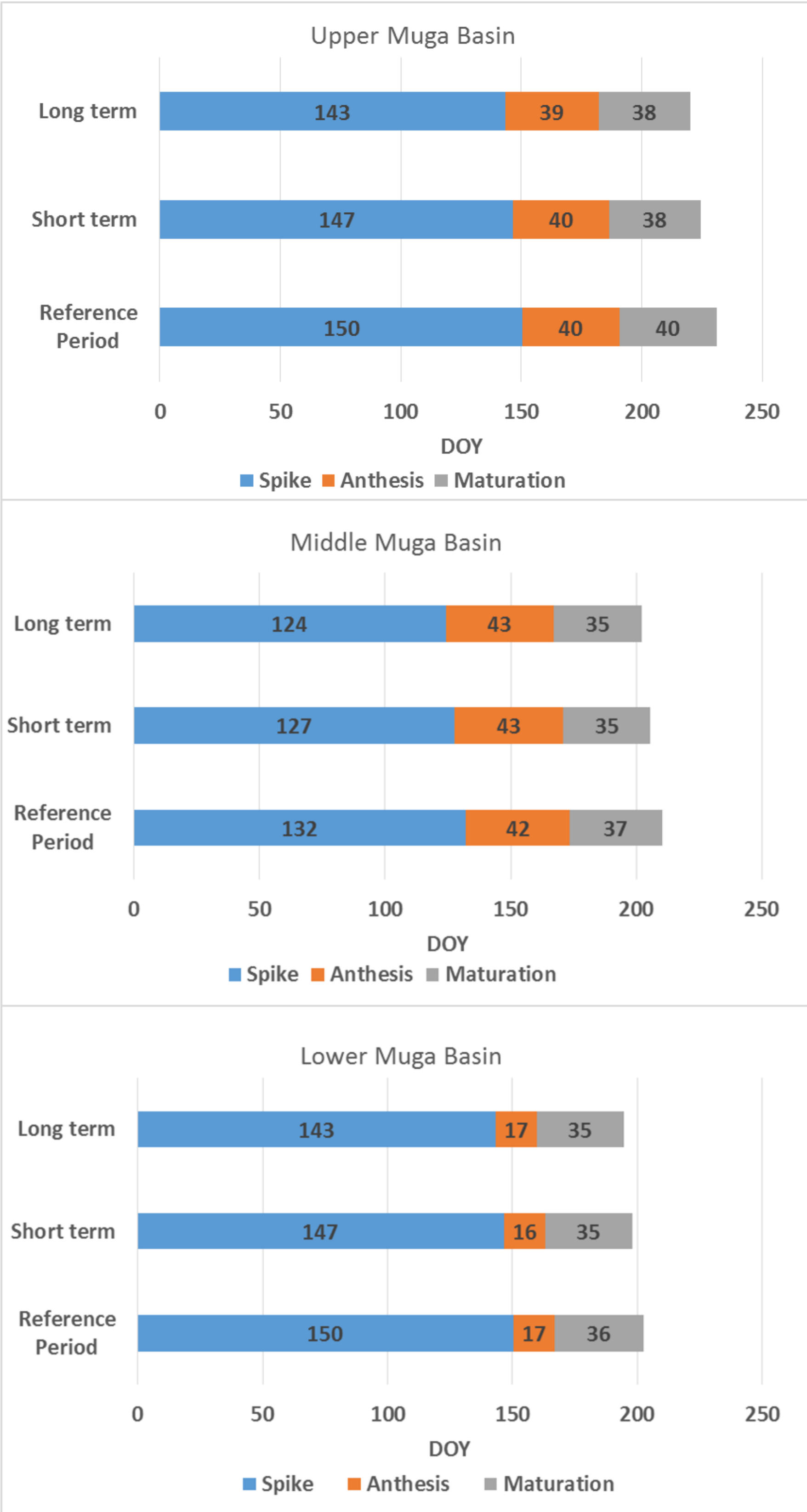


Figure 73. Time-sequence representation of different stages of wheat growth cycle (spike, anthesis and maturation) from 1st October in the upper, middle, lower Muga Basin. Numbers inside each bar, are number of days in reach each phenological stage. All data are averaged through the corresponding term: short term (2021-2030), long term (2041-2050) and reference period (2002-2011).

Ter

Table 27 shows the agroclimatic indicators for the Ter basin. Number of frost days in March and April decreases all over the basin, being that decrease higher in the upper and middle basin segments. As for the Muga, growing cycle advancement may counterbalance this reduction, thus it is not clear than frost risk would diminish. Indeed, *Day of Year Tmean > 10℃*, indicating the beginning of the growing cycle, show acycle advancement in 7-8 days along the basin in the long term.

Number of days with Tmax>30℃ increases all over the basin for the long term compared to the reference period: almost 5 days for July and August in the upper basin, 5 days for both months in the middle basin and 3 and 4 days (July and August, respectively) in the lower basin. Consistently, *Number of days Tmax>35℃* also increases greatly in relative and absolute terms all over the basin, particularly in the middle and lower basins. Again, this is consistent with the currently observed heat effects we mention above in the Muga basin section.

About maize specific indicators, both show a shortening of the growing cycle in the long term with respect to the reference period: 24 and 27 days shorter in lower basin for 600 and 700 FAO cycle grain maize varieties, respectively.

			Upper Basin			Middle Basin			Lower Basin	
		Reference Period	Short term	Long term	Reference Period	Short term	Long term	Reference Period	Short term	Long term
Agroclimatic Indicators (in general for all crops)	Number of days T_{min}<0ºC									
	March	17.3	16.1	15.0	7.8	6.9	5.9	6.5	6.2	5.7
	April	7.1	6.1	5.4	0.8	0.7	0.3	0.5	0.4	0.2
	Number of days T_{max}>30ºC									
	July	4.4	7.3	9.4	14.1	16.9	18.9	17.6	19.1	20.5
	August	3.5	5.8	8.0	10.6	13.4	15.6	15.3	17.3	19.3
	Number of days T_{max}>35ºC									
	July	0.04	0.26	0.44	1.2	2.2	3.1	2.8	4.1	5.2
	August	0.26	0.58	0.82	1.5	2.1	3.0	3.7	4.4	5.5
	Day of Year (DOY) T_{mean}>10ºC	131	127	123	101	97	93	80	79	73
Maize	Day of Year (DOY) when GDD= 2076* (600 FAO cycle grain maize varieties)	†	†	†	‡	‡	‡	299	285	275
	Day of Year (DOY) when GDD=2126* (700 FAO cycle grain maize varieties)	†	†	†	‡	‡	‡	307	288	280

**Growing degree days counted from 1st January.*

† Maize does not represents a major crop in this segment to perform calculations

‡Calculations not performed as required GDD are not attained all years in most of the subbasins, at least in the reference period.

Table 27. Agroclimatic indicators for growth and development of crops in general and maize in particular in the upper, middle and lower Ter basin in the three studied periods: reference period (2002-2011) and in short (2021-2030) and long term (2041-2050).

Apple flowering time in lower Ter for the eight apple cultivars studied was analysed following Funes et al. 2016. Figure 74 shows the time-sequence representation of the chilling and heat phases to F2 flowering stage. Flowering time would suffer no changes in the short or long terms: in spite of a delay in the beginning of chill accumulation of almost 10 days already in the short term, an equivalent, counterbalancing effect is observed during the heat accumulation phase and no changes would happen during the chilling phase.

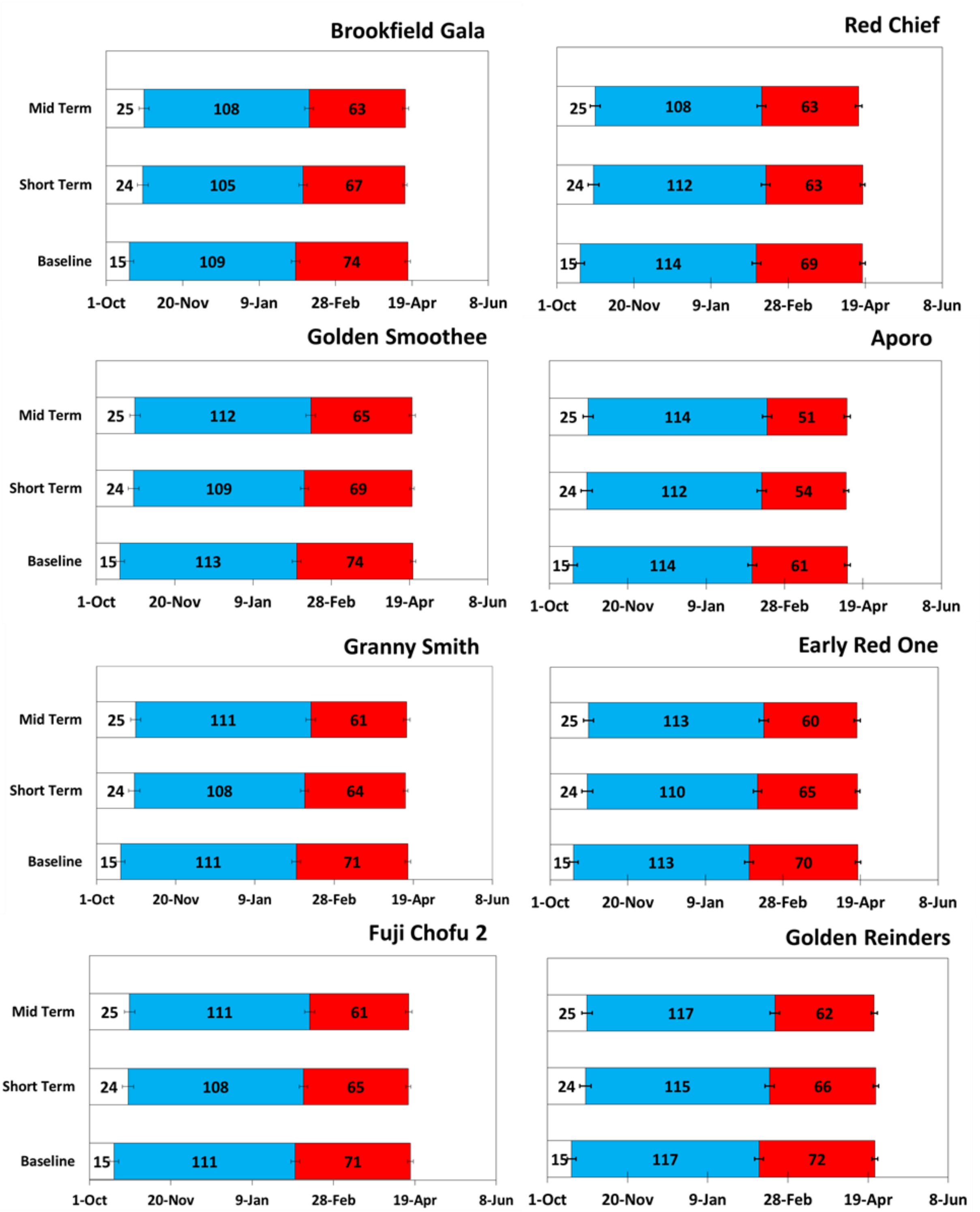


Figure 74. Time-sequence representation of the chilling and heat phases to F2 flowering stage (anthesis of 50% of the flowers). Numbers represent duration of each phase. Days to beginning of chill phase are counted from 1st October. Data from Funes et al. 2016 in a RCP4.5 climate change scenario (IPCC, 2014) for the lower Ter basin segment. All data are averaged through the corresponding term: short term (2021-2030), long term (2041-2050) and reference (2002-2011). Bars at the end of each strip represent standard error of the mean, representing variability in each period in completing each phase. These bars do not represents the phenology model RMSE or uncertainties related to climate projections.

Figure 75 shows a time-sequence of the most important phenological stages in wheat growing cycle, representing days passing from 1st January to reach spike, anthesis and wheat grain maturation. In general, the phenological phases would advance mainly because of the spike phase, which determines an advancement of growing cycle between 8 and 17 days in the long term, but already from 4 to 13 days in the short term. The more upstream in the basin, the higher the advancement.

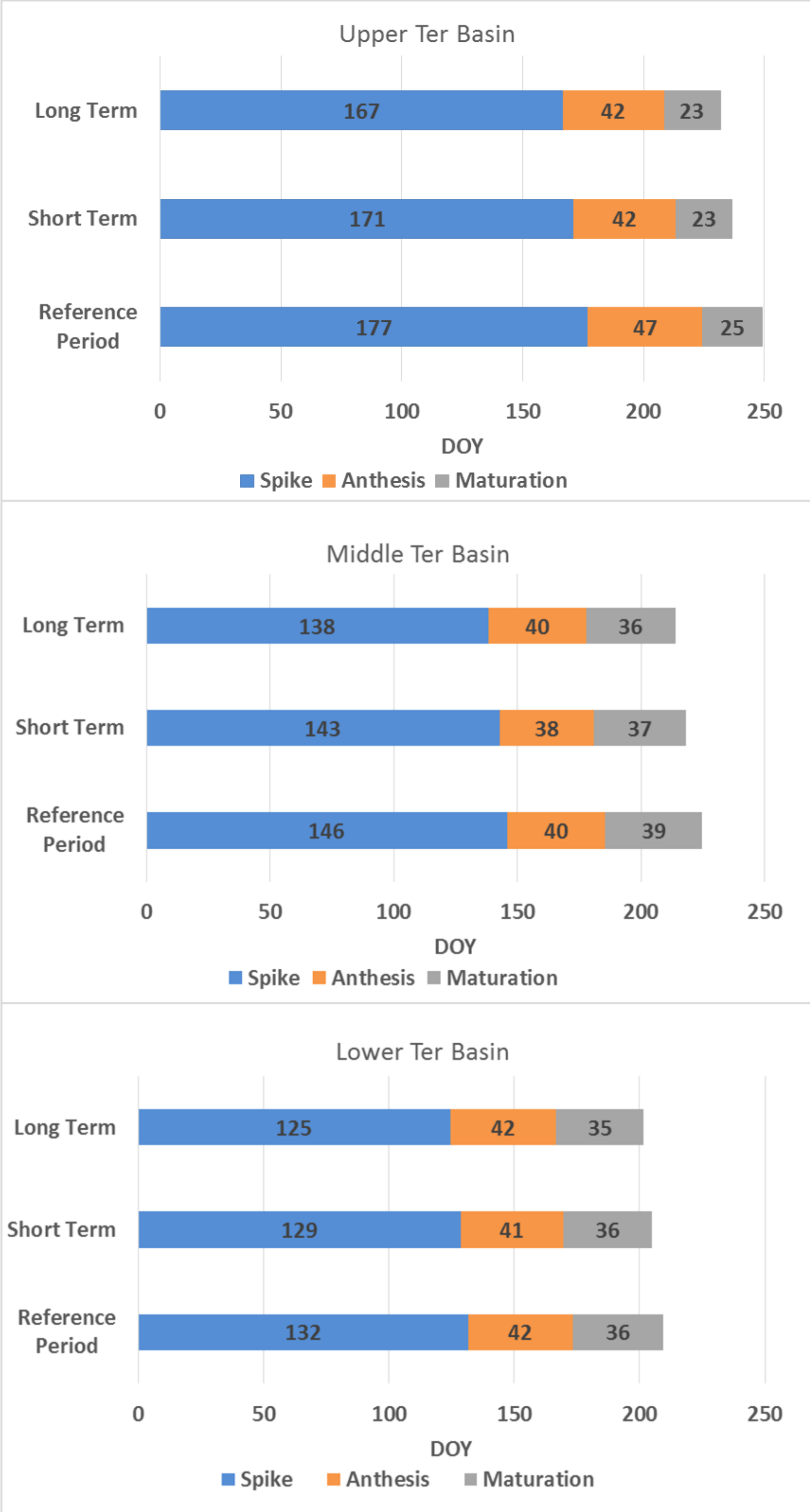


Figure 75. Time-sequence representation of wheat growth cycle stages (spike, anthesis and maturation) from 1st October in the upper, middle, lower Ter Basin. Numbers in each bar, are days to reach each phenological stage. Data are averaged through the corresponding term: short term (2021-2030), long term (2041-2050) and reference period (2002-2011).

Segre

Agroclimatic indicators for the Segre basin are presented in Table 28. Number of frost days in March and decreases all over the basin, as in Muga and Ter basins, being the decrease higher in upper and middle basin segments. As in Muga and Ter basins, frost risk would not necessarily diminish or disappear, as these results will be counterbalanced by growth cycle advancement, pointed out by the lower values in the *Day of Year Tmean > 10℃*, that implies the beginning of cycle of many crops. Beginning cycle advancement would be up to 11 days in the lower, 7 days in the middle and 5 days in upper basins in the long term.

Number of days with Tmax>30℃ increases all over the basin for the long term period in relation to the reference period: days would more than double for July and August in the upper basin, and would increase in 5 days both months in the middle basin and around 4 days both months in the lower basin. *Number of days with Tmax>35℃,* also increases all over the basin both proportionally and in absolute terms, particularly in the middle and lower basin, doubling in the long term: in the lower basin days with extreme temperatures would increase more than 5 days in July. As noted for the other two basins, this last indicator could be reflecting some heat effects that are currently being observed such as heat stroke in apples, which affects fruit quality.

Maize specific indicators show shorter growing cycle in the long term compared to the reference period in the lower basin: 22 days for 600 FAO cycle grain maize varieties and 20 days for 700 FAO cycle grain maize varieties.

			Upper Basin			Middle Basin			Lower Basin	
		Reference Period	Short term	Long term	Reference Period	Short term	Long term	Reference period	Short term	Long term
Agroclimatic Indicators (in general for all crops)	Number of days T_{min}<0ºC									
	March	19.6	19.2	18.2	13.3	12.7	11.5	5.4	5.0	4.0
	April	19.6	11.8	11.0	4.6	4.1	3.6	0.4	0.3	0.2
	Number of days T_{max}>30ºC									
	July	0.7	1.3	1.6	13.6	16.5	18.5	22.1	24.8	26.1
	August	0.7	1.1	1.5	11.5	14.2	16.3	19.2	22.3	23.6
	Number of days T_{max}>35ºC									
	July	0.01	0.03	0.03	2.4	3.9	5.6	5.1	8.4	10.7
	August	0.00	0.02	0.03	2.4	3.3	4.8	4.2	6.1	8.0
	Day of Year (DOY) T_{mean}>10ºC	150	148	145	108	104	101	82	77	71
Maize	Day of Year (DOY) when GDD= 2076* (600 FAO cycle grain maize varieties)	†	†	†	‡	‡	‡	282	269	260
	Day of Year (DOY) when GDD=2126* (700 FAO cycle grain maize varieties)	†	†	†	‡	‡	‡	285	274	265

**Growing degree days counted from 1st January.*

† Maize does not represents a major crop in this segment to perform calculations

‡Calculations not performed as required GDD are not attained all years in most of the subbasins, at least in the reference period.

Table 28. Agroclimatic indicators for growth and development of crops in general and maize in particular in the upper, middle and lower Segre basin in the three studied periods: reference period (2002-2011) and in short (2021-2030) and long term (2041-2050).

The time-sequence for wheat main phenological stages is presented in Figure 76: as described for the other two basins, spike phase shows the highest advancements, from 7 to 13 days in the long term, but, in contrast with the other two basins, the shortening in number of days to reach the other two phenological phases are also significant: up to 7 days for anthesis (upper Segre), 2 to 5 for maturation, resulting in growing cycles 10 to 25 days shorter in the long term, but already 4 to 16 days shorter in the short term.

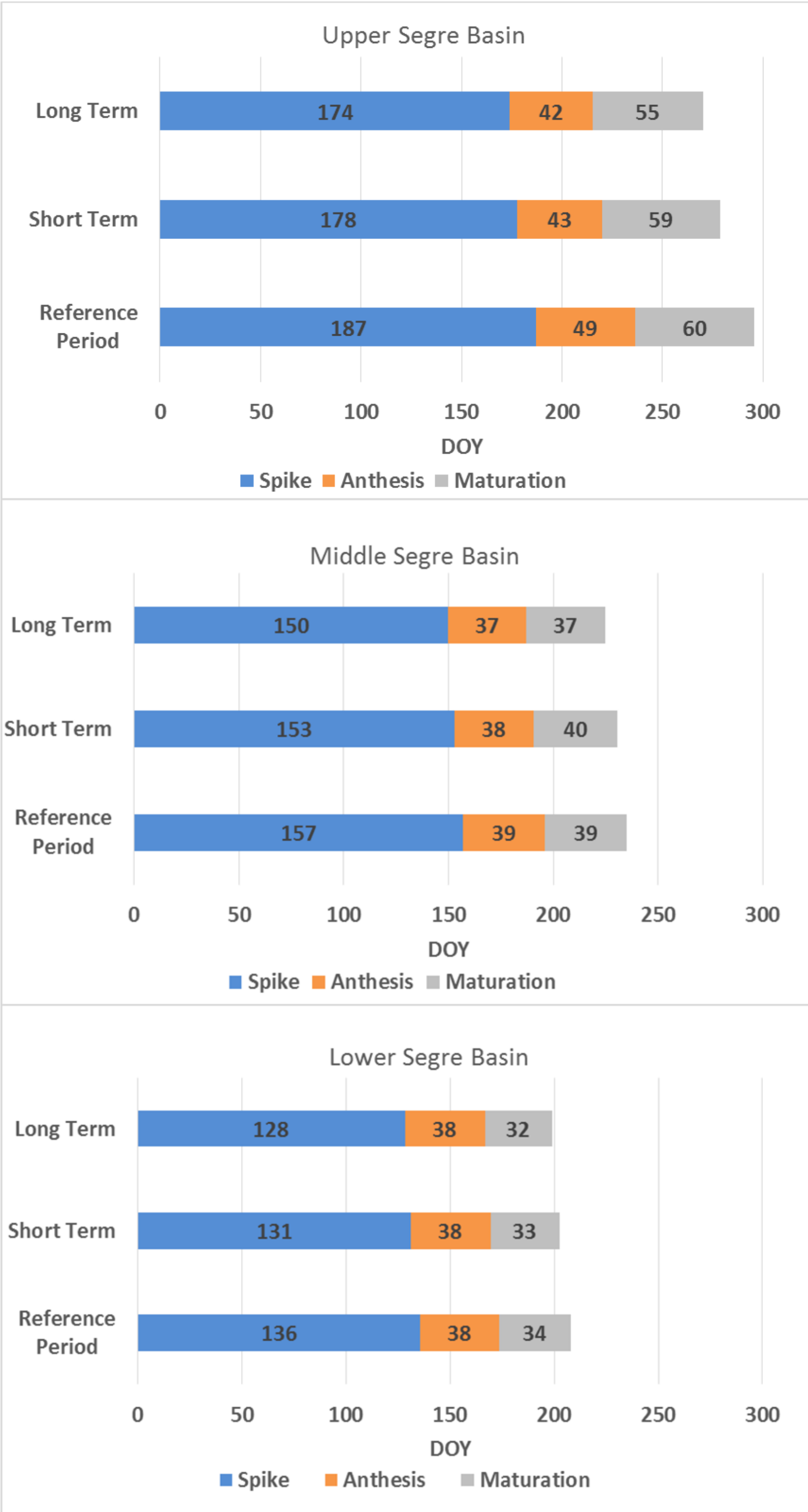


Figure 76. Time-sequence representation of different stages of wheat growth cycle (spike, anthesis and maturation) from 1st January in the upper, middle, lower Segre Basin. Numbers inside each bar, are number of days in reach each phenological stage. All data are averaged through the corresponding term: short term (2021-2030), long term (2041-2050) and reference period (2002-2011).

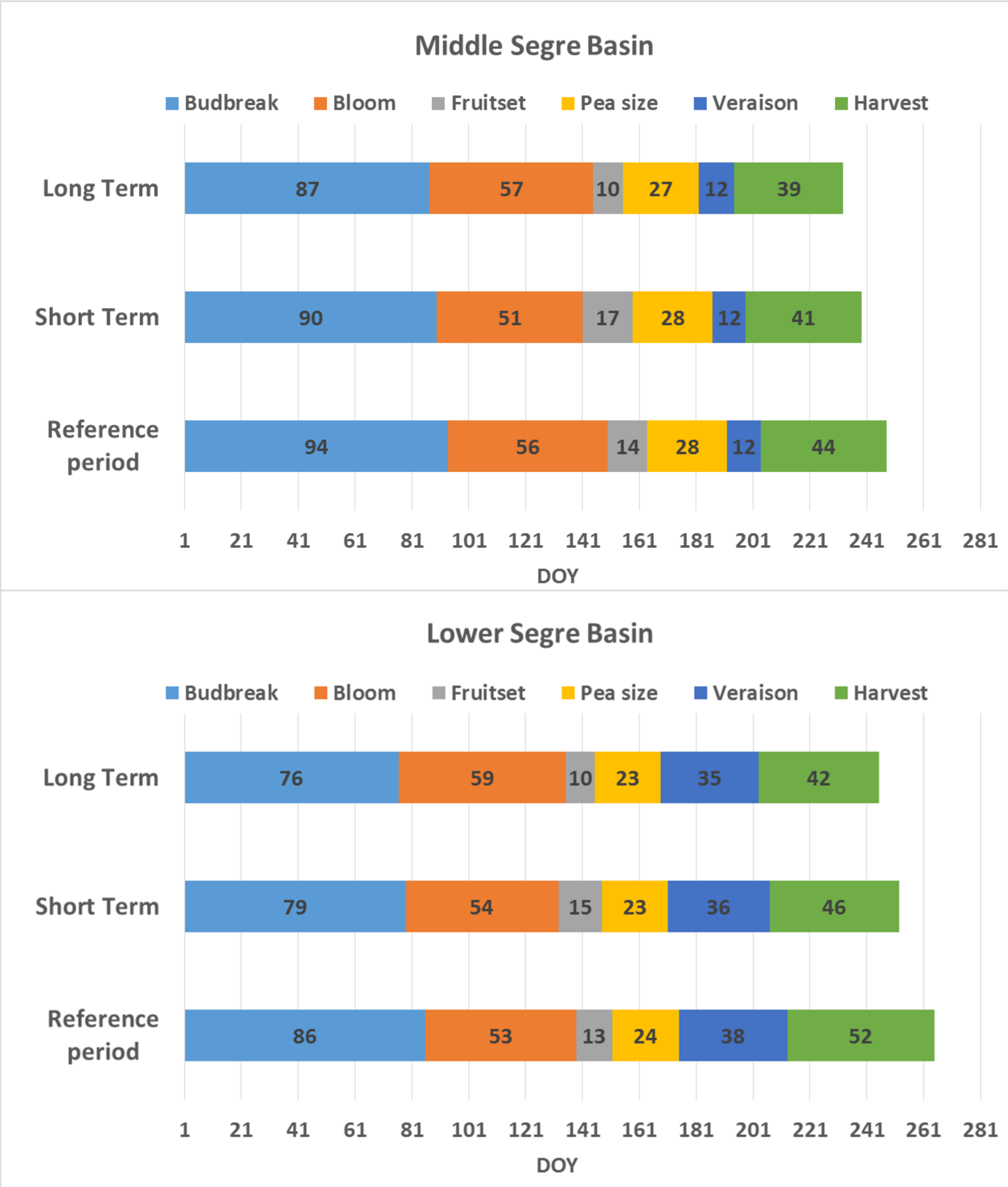


Figure 77. Time-sequence representation of different stages of vine growth from 1st October in the middle and lower Segre Basin. Numbers inside each bar, are number of days in reach each phenological stage. All data are averaged through the corresponding term: short term (2021-2030), long term (2041-2050) and reference period (2002-2011).

Figure 77 shows a time-sequence of the most important phenological stages in grapevine growing cycle. This agroclimatic indicator for grapevine was calculated for middle and lower Segre, were this crop is present: on the one hand subzones of Coster de Segre D.O.: Raimat, Garrigues and Valls del Riu Corb as representation of the lower Segre and, on the other hand, Artesa de Segre and the altitude vineyards of Pallars Jussà as representation of the middle Segre. **In the middle Segre**: the cycle beginning (budbreak) would advance 4 days in the short term and 7 days in the long term with respect to the reference period. The duration on the cycle, 154 days from budbreak to harvest in the reference period, would be shortened up to 5 days in the short term and 9 days in the long term, mainly as a consequence of a shortening in the fruitset and harvest phases; in contrast, blooming phase would not be shortened (although bloom date would, because of earlier budbreak), and veraison and pea size phases would suffer no significant changes (in terms of number of days to reach each phase from previous phase, although the date would advance because of the general advancement of growing cycle or the shortening of previous phases). Summing up all phases, harvest time would be advanced about 9 days in the short term and 16 days in the long term. **In the lower Segre**: budbreak time would be reached 7 days before in the short term and 10 days in the long term compared to the reference period. The duration on the cycle (180 days from budbreak to harvest in the reference period) would be shortened up to 6 days in the short term and 11 days in the long term, mainly as a consequence of shortening in all phases after blooming, particularly from veraison to harvest. Although blooming phase would last up to 6 days longer in the long term, blooming date would be slightly advanced because of earlier budbreak. Finally, the shortening of the growing cycle would result in an earlier harvest time of about 13 days in the short term and 20 days in the long term.

5.3. Conclusions

The results of this study show the effects of climate change to be expected along the first half of the 21st century on vegetative, reproductive and productive characteristics of crops nowadays present in the Muga, Ter and Segre basins. These effects are based on climate projections of the RCP 4.5 scenario, regionalized to a high spatial resolution, and on phenological and agroclimatic models that are valid in the reference period and are assumed to be valid for the next 50 years. This is the first reason to take these results carefully, as they are just showing tendencies, not exact predictions. The second reason is that crop performance will be affected by agronomical practices, local edaphic conditions and production needs, i.e., the market. Moreover, this study has focused on the expected conditions for current crops in the basins were they are currently produced: from the results in this study, conclusions could be derived about increasing or decreasing difficulties for those crops to be productive in their current locations. However, to generate recommendations about the suitability of crops for any of those locations, a range of climatic tolerance for each crop would be required, which falls beyond the scope of this work.

A clear result is that, in general, NIR would grow, ranging from small to moderate increases in the short term and from moderate to high in the long term. Dynamics would be different for the three basins: a continuous increase for the Muga and Ter basins, and an initial increase that then would stop in the Segre basin. These general trends vary from crop to crop. Anyway, a generalized NIR increase together with lower water availability restraining irrigation could become very limiting for crop productivity.

Phenological changes could be a more relevant constraint for crop productivity: in general, frost days will decrease in the three basins and extremely hot days will increase, but growth cycle will begin earlier and be shorter for all crops; hence, it is not clear if frost risk would really decrease or heat damages would really increase. General changes in blossom date could result in a disynchrony with pollinators, and harvest advances could affect differently alcoholic and phenolic maturation in grapevine or pulp and skin maturation in apples, pears or stones fruits, for instance.

Upper segments of basins would suffer the most important climatic changes because they are the coldest and wettest. However, effects on crop production would be higher in the middle and lowest segments of basins, as most of the cropland is there. The coastal effect produces clear differences between the lower basin and the rest of the watershed, except in the Segre basin as this is a tributary river and its lower course is clearly inland.

In general, the three basins included in this study would suffer noticeable impacts of climate change, which can result in significant limitations for crops if adaptive strategies beyond irrigation are not applied.

6. How would scenarios impact on forests?

6.1. Introduction

Currently, forests are experiencing changes in the abiotic environment much faster than during the past several hundred years. Abiotic factors determining forest dynamics range from temperature limitations in northern boreal and high mountain elevations, to water limitation in the continental and Mediterranean contexts, and include large-scale disturbances such as wind throw, insect infestations and fires. Changes in the climate may therefore have a wide range of effects across Europe (Lindner et al., 2010). Forest management across such large geographical scales thus needs to be adaptive to changing conditions. It is essential to develop and use tools able to explore forest ecosystems' responses to different climate change projections.

Several previous studies (e.g. Vayreda et al. 2012) remark than, despite Mediterranean forests are, in general, currently performing as carbon sinks, during the second half of this century, some of them may become net carbon sources. The main cause of this change would be driven by an increased aridity according to climate change scenario projections. Furthermore, for the same reason, the relative amount of evapotranspiration will be also increased due to a rising atmospheric evaporative demand. However, adaptive forest management to climate change would help to increase water use efficiency by forests, as well as to maintain positives its carbon balances.

In the other hand, one of the most important regional vulnerabilities of Mediterranean forests is the fire risk. Observational studies have found very consistent correlations between climatic variables and the rate of forest fire risk and the number of fires and burned area (Piñol et al. 1998). Future climate scenarios foreseen an increase in forest fire risks (Moriondo et al. 2006).

In this work we used GOTILWA+ model (Gracia et al. 2004), a forest growth process-based model that allows to explore the effects of different climate change scenarios on forests. The main aim is to explore the functional response until 2050 horizon of the MEDACC forest species using this modelling tool. We also have used the Drought Code (DC) index of the Canadian Forest Fire Weather Index System to assess future fire risk in the forests of the three case-study basins.

6.2. Impact of climate scenarios on forests

The impacts of climate change on forests were evaluated inducing climate change into the GOTILWA+ model and estimating future daily DC values per sub-basin for the climate series. Results were analyzed for the reference period (2002-2011) and for two time horizons (short term 2021-2030 and long term 2041-2050). The methodology followed and the input data are detailed explained at Pascual et al. (2016).

6.2.1. GOTILWA+ model

The forest functional GOTILWA+ model has been applied in order to assess the effects of climate change on the forest of the pilot plots (demonstrative activities) of the LIFE MEDACC case-study basins. A set of simulation experiments have been designed based on the methodological approach defined in the section 6 of the Deliverable 13 (Pascual et al. 2016). The GOTILWA+ model was calibrated with a benchmarking exercise with reference data. Then, a set of simulation experiments was defined using the climate change scenarios (RCP4.5).

The simulations were done for each pilot plots (demonstrative activities) of the LIFE MEDACC case-study basins. The pilots were established in three sites: a *Quercus ilex* forest at Requesens (Muga basin), a *Pinus sylvestris* forest at Montesquiu (Ter basin) and, finally, a *Pinus nigra* forest at Solsonès (Segre basin). The details of the pilot plots can be consulted at Savé et al. (2014) and Savé et al. (2015a and 2015b). Climate projections of the RCP4.5 climate scenario were used, as explained at Pascual et al. (2016). The projections extend from 2002 to 2050.

The initial structure of the forest comes from initial inventories in the three pilot sites. They are described at Savé et al. (2015b). The simulated species are the dominant ones in each pilot (*Quercus ilex* at Requesens site, *Pinus sylvestris* at Montesquiu site and *Pinus nigra* at Solsonès site). The soil data have been provided by the maps created ad hoc by LIFE MEDACC and initial surveys in these areas (Vicente-Serrano et al. 2014).

Simulations have been designed and performed without forest management, therefore, they reproduce spontaneous forest dynamics and tree mortality associated with diffuse and episodic events (self-thinning). The variables analysed in this study were the leaf area index (LAI), actual evapotranspiration (AET), net primary production (NPP), net ecosystem carbon exchange (NEE), wood production (WP), water stored in soil (WS) and volume of dead wood (DWV).

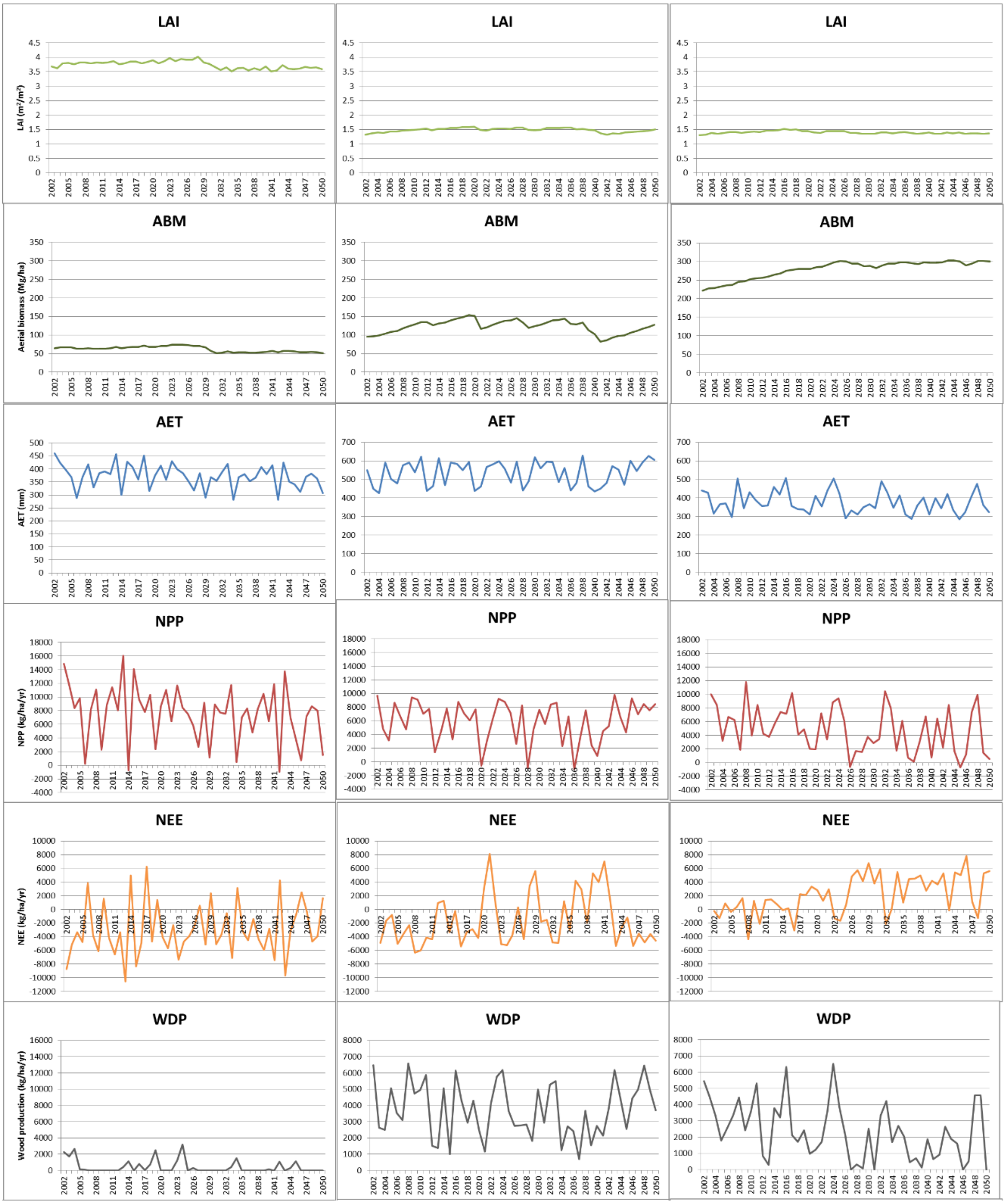
Results show different patterns in relation to each species and each site (Figure 78) but there are several common features with the future climatic conditions: in all the cases, forests species show mortality episodes in specific moments of the next four decades, especially at the end of the simulation period. The most relevant case is *Pinus sylvestris* at Montesquiu, with a large number of episodes and intensity. In this last case, they are distributed along of the simulation period. *Quercus ilex* at Requesens shows the most distinctive pattern among the simulated forests. It is located in a high slope site with very poor quality conditions (thin soil, high volume of stones, highly windy zone). In this situation, forest accumulates less biomass and remains without growth in a vegetative way. Defoliation can occur but it usually doesn't imply tree mortality. However, in these cases, forest fire risk could be remarkably increased in addition of the general drought conditions of the area.

In general, forests lose vigour in growth. Variables such as net primary production NPP and wood production WDP are good indicators of that. The net ecosystem exchange NEE is closely related to the dynamics of soil carbon. Negative values indicate net capture of atmospheric carbon and positive values indicate emission. In general, the carbon sequestration capacity of forests is declining throughout the century and the second half of the century forests which are currently sinks could reduce their sequestration capacity. This change is determined by the reduction of carbon sequestration rates (as a consequence of forest decline) and an increase in respiration rates (resulting from temperature increase and necromass increase) which could have a consequently reduction of the effect of forest sink (Gracia et al. 2010).

Water stored in soil WS shows a high variability in the simulation outcomes but it doesn't show a clear and significant decrease pattern. Forest decline (self-thinning processes) could buffer soil water decrease in a less precipitation scenario. Actual evapotranspiration AET shows a similar pattern which could be strongly related to defoliation and tree mortality episodes.

From a structural point of view, *Pinus nigra* at Solsonès seems to stabilize biomass along the simulation. It shows tree mortality episodes in the last part of the simulation period, but it doesn't imply significant biomass decrease. Nevertheless, forest functioning would be clearly worst. In this situation, forest fire risk will remarkably increase.

Quercus ilex (Muga) | *P. sylvestris* (Ter) | *P. nigra* (Segre)



Quercus ilex (Muga) *P. sylvestris* (Ter) *P. nigra* (Segre)

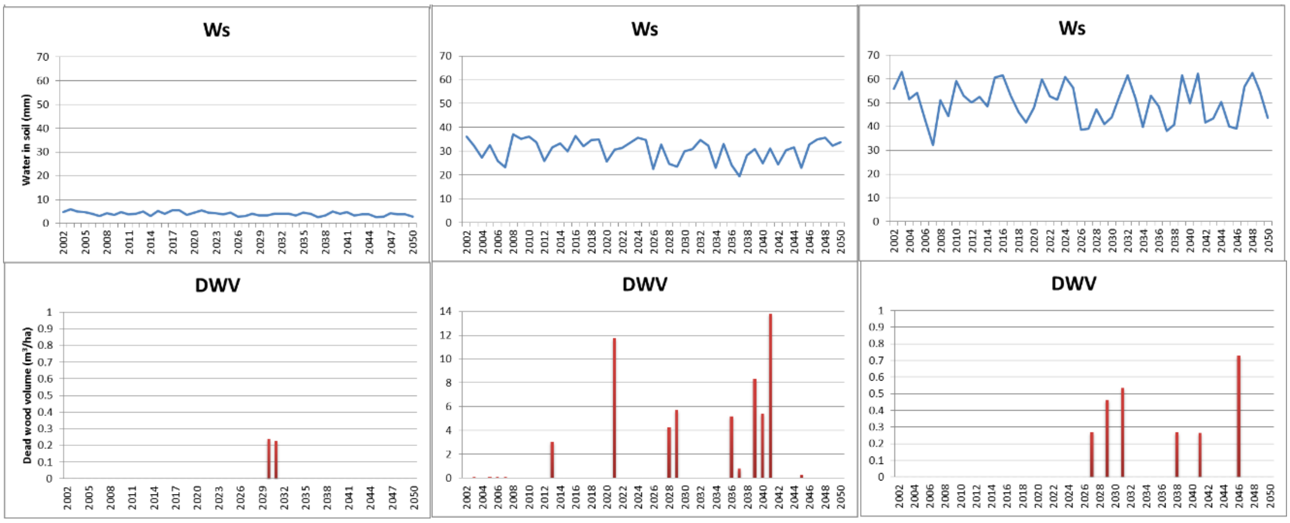


Figure 78. GOTILWA+ results for the forest species in each simulated site for the 2002-2050 period. The represented variables are: Leaf Area Index (LAI), Aboveground biomass (ABM), Actual evapotranspiration (AET), Net Primary Production (NPP), Net Ecosystem Exchange (NEE), Wood Production (WDP), Water stored in soil (WS) and Dead wood volume (DWV).

6.2.2. Meteorological fire risk

We have estimated the DC values for each sub-basin of the case-study basins, using as input data the RCP4.5 scenario. We obtained then daily DC values per subbasin. Afterwards, we have calculated the number of days per year and sub-basin with DC values higher than 800, when a risk of large fires exists. We have then calculated the mean number of days per year with DC>800 per sub-basin for three periods: reference (2002-2011), short term (2021-2030) and long term (2041-2050). Finally, we have assigned these mean values to the forest land cover existent in 2005 per sub-basin.

Figure 79 shows the distribution of the number of days per year with high fire meteorological risk for the reference period (2002-2011), short term (2021-2030) and long term (2041-205) for Muga and Ter basins. The headwaters of both basins show a low number of days per year in which the possibility of having forest fires is high (less than 7 days per year). This situation is maintained at the short and long term, with not changes by 2050. The medium and low courses of Muga basin present a major number of days with risk for the reference period (from 6 to 15 in the medium basin and less than 22 in the river mouth). This situation is worsened at the short and long term, increasing to 16-25 days/year with high fire risk in the medium basin and to 38-41 days/year in the river mouth. Ter medium course is similar to the headwaters, and changes at short and long term are not expected. Contrarily, Ter river mouth shows an increasing trend to higher number of days per year with high fire risk at the short and long term, until a maximum of 13-18 days/year. It is worthy to highlight that the most populated areas are located in the sub-basins with a higher fire risk.

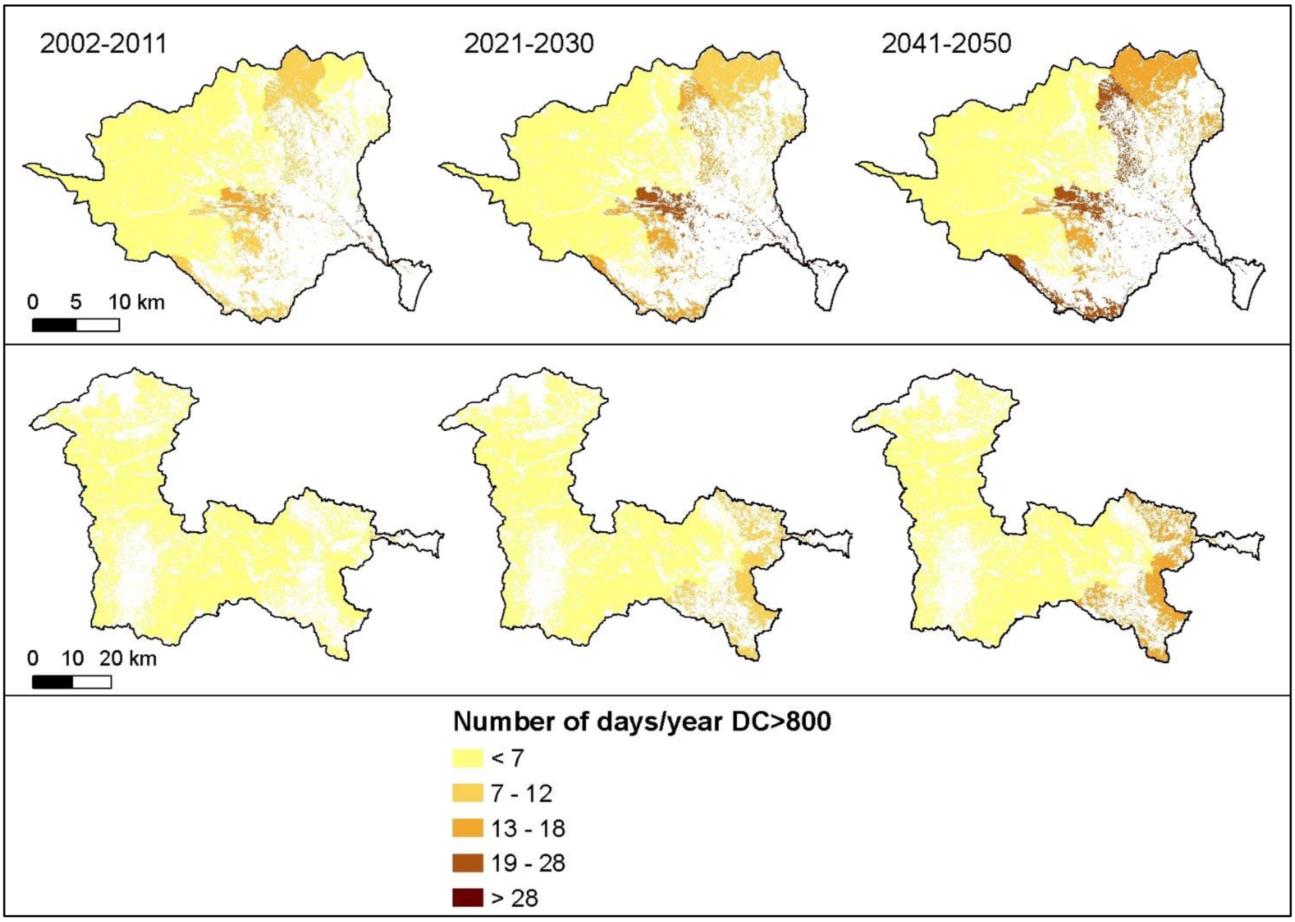


Figure 79. Distribution of the number of days per year with high fire meteorological risk for the reference period (left, 2002-2011), short term (middle, 2021-2030) and long term (right, 2041-205) for Muga (up) and Ter (down) basins.

Figure 80 shows the same outputs for Segre basin. Similar to Muga and Ter basin, the Segre headwaters show a low number of days per year in which the possibility of having forest fires is high (the mostly of sub-basins has no days/year with DC>800). This situation is also maintained at the short and long term, with not changes by 2050. The medium and low courses present a major number of days with risk for the reference period (from 20 to 90, although two sub-basins overpass 100 days/year and the last sub-basin in the river mouth arrives to 141). The analysis at the short and long term does not show major differences with the reference period; noticeable changes are observed at the SE part of the basin, where the number of days/year increase in about 20 to 30.

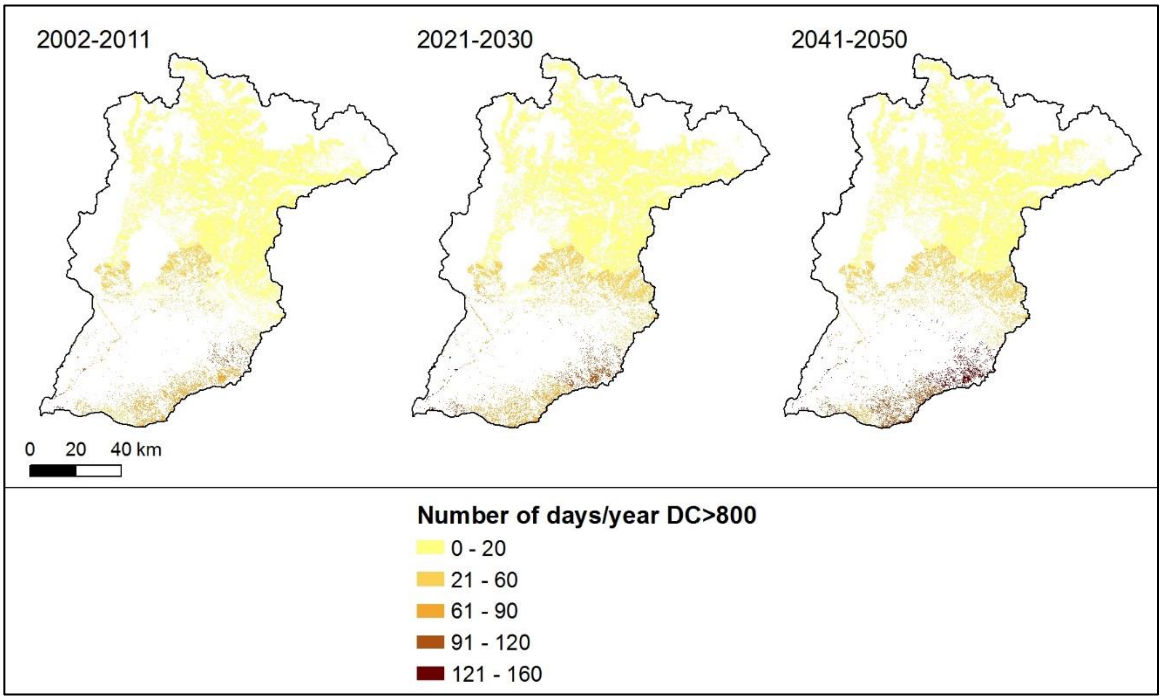


Figure 80. Distribution of the number of days per year with high fire meteorological risk for the reference period (left, 2002-2011), short term (middle, 2021-2030) and long term (right, 2041-205) for Segre basin.

6.3. Conclusions

Forests are one of the systems which could potentially be more vulnerable to climate change, either by decreasing water availability (effects of water stress) or either by increasing fire risk. These changes will affect forest functioning and structure. In general, we expect a decline in forest productivity and, consequently, a decrease in carbon sink capacity. We also expect an increase in frequency and intensity of mortality episodes of some species. It is the case of *Pinus sylvestris* in the studied area.

Some previous works remark that the increase in atmospheric CO_2 concentration can lead to a transitory increase in forest production in the immediate next decades in non-water-limited forests. In accordance to our simulations, the projected aridity increase at the end of the simulation (rainfall decrease and temperature increase) can be more important than the effect of fertilization, especially in the simulated Mediterranean forests. Consequently, forest production could decrease.

Mediterranean forests are currently water-limited. Climate change is accelerating relative water loss from the system (evapotranspiration increase and less water incomes). As a consequence, Mediterranean forests species will suffer water stress, with a large number of multi-scale implications:

- Changes in species suitability and landscape changes (not assessed in this project). More resistant species could replace more sensitive species in certain areas in a progressive transition.
- Fire risk increment may aggravate forest vulnerability.
- Forest diseases and pests could be aggravated as a consequence of warmer conditions and forest decline (fragility).

Adaptive forest management can reduce water competition among trees and increase climate change resilience. Adaptive forest management must consider water limitations of Mediterranean forests and must take into account forest water balance (besides carbon balance).

Simulation tools like GOTILWA+ model can allow us to explore the effects of climate change projection in forests, to detect forest management opportunities and to assess the effects of forest management in the future.

7. Conclusions

The assessment of climate and global change impacts on the environmental, hydrological and agriculture systems in the LIFE MEDACC case study basins ends with the following conclusions:

How would be the climate?

- Climate projections foresee a general warming in Catalonia in all the climatic areas (Pyrenees, Inland and Coast) and in all the temporal horizons (from 2000 to 2050). The foreseen changes in temperature oscillate from +0.8 to +1.4 ºC for 2012-2020 and 2031-2050 periods, respectively, being 1971-2000 the control period.
- Average annual precipitation in Catalonia is expected to decrease by roughly 9% (Pyrenees: -9.9%, Inland: -7.7%, Coast: -8.9%). A great decrease is foreseen in autumn and spring, when the largest amount of precipitation is expected.
- The foreseen climate in Catalonia goes towards more frequent, longer and stronger drought episodes by 2050.

How would be the territory?

- The socioeconomic scenarios provide different views on the future of a certain area, depending on the demographic, socio-economic and technological driving forces.
- We have designed five socioeconomic scenarios for 2050: three land cover scenarios for the headwaters (afforestation, fire and forest management scenarios) and two water use scenarios for the medium and low basin courses (rational use of water resources and increased demand scenarios).
- The afforestation scenario (AFFOR) maintains the current afforestation trends that have occurred in the basins in the last decades. By 2057, afforestation would occur moderately in the Muga and Segre basins (4.2 and 5.5%-increase) and more noticeable in the Ter basin (8.3%-increase), mainly at the expense of shrublands (2.4-3.1% reduction) and grasslands (0.4-4.5% reduction).
- The fire scenario (FIRE) foreseen inappreciable changes in Muga basin between 2005 and 2057. In Ter basin, conifer reduction was not so noticeable (1.6%) than the grassland loss (5.0%), whereas deciduous forest increased a 4.5%. In Segre basin, conifers experimented a 5.3% reduction, whereas shrublands (1.5%) and deciduous forest (5.5%) surface increased.
- The forest management scenario (MANAGEFOR) foresees a change in forest structure due mainly to forest management and the replacement of species. A 33.0, 24.0 and 27.9% of forest areas would be under management by 2050 in the Muga, Ter and Segre basins respectively.
- The rational use of water resources scenario (RATUS) foresees a reduction in water consumption by 2050 as consequence of using alternative water sources for covering water demands in the case-study basins.
- The increased demand scenario (DEMINC) foresees an increase in water consumption by 2050 as consequence of not applying measures to reduce the pressures over the water cycle.

How would scenarios impact on hydrology?

- Climate change may have a relevant impact on hydrological regimes and water resources of the Mediterranean region, as consequence of a decreasing precipitation and increasing temperature.
- Hydrological models such as SWAT and RHESsys can predict the impacts of different scenarios on water cycle such as changes in vegetation, climate and water management.
- The use of two different hydrological models reduces the uncertainty of this kind of tools and makes results more robust.

- RHESsys model is highly sensitive to changes in vegetation. On the contrary, SWAT model is highly sensitive to climate change scenarios. Besides, SWAT model can simulate in a very good way the reservoir management.
- The work with SWAT and RHESsys makes visible the importance of vegetation and soils parametrization to improve the results and to avoid uncertainty.
- Hydrological simulations with climate, land cover and socioeconomic scenarios showed a strong alteration in water dynamics in the three basins along the first half of the 21st century.
- The results about simulations under different scenarios provides important information for water and land managers to understand, locate and quantify the impacts of climate and global change on water resources.

<u>How would scenarios impact on agriculture?</u>

- The results of this study show the effects of climate change to be expected along the first half of the 21st century on vegetative, reproductive and productive characteristics of crops nowadays present in the Muga, Ter and Segre basins. These effects are based on climate projections of the RCP 4.5 scenario, regionalized to a high spatial resolution, and on phenological and agroclimatic models that are valid in the reference period and are assumed to be valid for the next 50 years. This is the first reason to take these results carefully, as they are just showing tendencies, not exact predictions. The second reason is that crop performance will be affected by agronomical practices, local edaphic conditions and production needs, i.e., the market. Moreover, this study has focused on the expected conditions for current crops in the basins were they are currently produced: from the results in this study, conclusions could be derived about increasing or decreasing difficulties for those crops to be productive in their current locations. However, to generate recommendations about the suitability of crops for any of those locations, a range of climatic tolerance for each crop would be required, which falls beyond the scope of this work.
- In general, the net irrigation requirements (NIR) would grow in the first half of the 21st century, ranging from small to moderate increases in the short term and from moderate to high in the long term. Dynamics would be different for the three basins: a continuous increase for the Muga and Ter basins, and an initial increase that then would stop in the Segre basin. These general trends vary from crop to crop. Anyway, a generalized NIR increase together with lower water availability restraining irrigation could become very limiting for crop productivity.
- Phenological changes could be a more relevant constraint for crop productivity: in general, frost days will decrease in the three basins and extremely hot days will increase, but growth cycle will begin earlier and be shorter for all crops; hence, it is not clear if frost risk would really decrease or heat damages would really increase. General changes in blossom date could result in a disynchrony with pollinators, and harvest advances could affect differently alcoholic and phenolic maturation in grapevine or pulp and skin maturation in apples, pears or stones fruits, for instance.
- Upper segments of basins would suffer the most important climatic changes because they are the coldest and wettest. However, effects on crop production would be higher in the middle and lowest segments of basins, as most of the cropland is there. The coastal effect produces clear differences between the lower basin and the rest of the watershed, except in the Segre basin as this is a tributary river and its lower course is clearly inland.
- In general, the three basins included in this study would suffer noticeable impacts of climate change, which can result in significant limitations for crops if adaptive strategies beyond irrigation are not applied.

<u>How would scenarios impact on forests?</u>

- Forests are one of the systems which could potentially be more vulnerable to climate change, either by decreasing water availability (effects of water stress) or either by increasing fire risk. These changes will affect forest functioning and structure.

- A decrease of forest productivity and, consequently, a decrease in carbon sink capacity is expected.
- An increase in the frequency and intensity of mortality episodes of some species is also expected.
- Adaptive forest management can reduce water competition among trees and increase climate change resilience.
- Adaptive forest management must consider water limitations of Mediterranean forests and must take into account forest water balance (besides carbon balance).
- Simulation tools like GOTILWA+ model can allow us to explore the effects of climate change projection in forests, to detect forest management opportunities and to assess the effects of forest management in the future.

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9. Annexes

9.1. Annex 1. Tables for agriculture modelling

Major Crops	Basin Segment	Surface (ha)	% irrigated land	% rainfed land
Alfalfa	Lower	644	60.2	39.8
	Middle	363	14.3	85.7
	Upper	41	19.2	80.8
Maize	Lower	1517	92.3	7.7
	Middle	387	80.9	19.1
Wheat	Lower	1360	43.3	56.7
	Middle	294	30.9	69.1
Cherry Tree	Lower	184	35.2	64.8
	Middle	11	59.6	40.4
Oats	Lower	975	22.5	77.5
	Middle	945	4.8	95.2
	Upper	58	19.4	80.6
Rapeseed	Lower	140	26.5	73.5
	Middle	28	66.1	33.9
Winter cereals fodder	Lower	389	23.5	76.5
	Middle	726	11.7	88.3
	Upper	121	19.4	80.6
Sunflower	Lower	111	45.0	55.0
	Middle	18	38.0	62.0
Olive	Lower	482	3.1	96.9
	Middle	981	0.2	99.8
	Upper	3	0.0	100.0
Barley	Lower	2757	22.9	77.1
	Middle	916	18.9	81.1
	Upper	59	25.6	74.4
Grassland	Lower	45	24.6	75.4
	Middle	105	17.0	83.0
	Upper	11	24.7	75.3
Apple	Lower	96	86.9	13.1
	Middle	17	84.2	15.8
Peach	Lower	3	60.7	39.3
	Middle	39	43.8	56.2
Rye-grass	Lower	478	27.1	72.9
	Middle	301	7.5	92.5
Sorghum	Lower	88	16.6	83.4
	Middle	64	34.8	65.2
	Upper	2	0.0	100.0
Triticale	Lower	206	32.2	67.7
	Middle	128	19.1	80.9
Grapevine	Lower	32	3.1	96.9
	Middle	857	4.6	95.4
	Upper	1	0.0	100.0

Table 29. Surface of major crops in the upper, middle and lower Muga basin and % of surface under irrigated and rainfed conditions.

Major Crops	Basin Segment	Surface (ha)	% irrigated land	% rainfed land
Alfalfa	Lower	1503	36	64
	Middle	314	8.7	91.3
	Upper	71	2.0	98.0
Maize	Lower	4447	73.9	26.1
	Middle	983	13.3	86.7
	Upper	64	3.8	96.2
Wheat	Lower	6078	25.3	74.7
	Middle	6319	4.2	95.8
	Upper	412	9.7	60.3
Hazel	Lower	557	50.4	49.6
	Middle	218	40.6	59.4
Oats	Lower	1390	17.3	82.7
	Middle	592	4.8	95.2
	Upper	85	1.5	98.5
Rapeseed	Lower	1565	23.7	76.3
	Middle	1245	6.5	93.5
	Lower	10	0.0	100.0
Winter cereals fodder	Lower	864	14.3	85.7
	Middle	3358	4.6	95.4
	Upper	1081	2.6	97.4
Sunflower	Lower	556	21.0	79.0
	Middle	25	0.0	100.0
Olive	Lower	233	7.3	92.7
	Middle	3	47.1	52.9
Barley	Lower	7198	22.2	77.8
	Middle	4010	11.3	88.7
	Upper	202	12.2	87.8
Grassland	Lower	174	11.8	88.2
	Middle	1147	4.7	95.3
	Upper	1599	2.1	97.9
Apple	Lower	923	95.1	4.9
	Middle	58	68.7	31.3
	Upper	9	81.8	18.2
Pear	Lower	488	86.3	13.7
	Middle	197	86.3	13.7
Rye-grass	Lower	1955	25.7	74.3
	Middle	1249	9.0	91.0
	Upper	126	3.5	96.5
Sorghum	Lower	245	17.0	83.0
	Middle	70	5.9	94.1
	Upper	24	0.0	100.0
Triticale	Lower	475	19.4	80.6
	Middle	253	2.1	97.9
	Upper	34	3.6	96.4
Grapevine	Lower	56	6.2	93.8
	Middle	15	1.7	98.3

Table 30. Surface of major crops in the upper, middle and lower Ter basin and % of surface under irrigated and rainfed conditions.

Major Crops	Basin Segment	Surface (ha)	% irrigated land	% rainfed land
Alfalfa	Lower	18135	97.6	2.4
	Middle	2669	15.9	84.1
	Upper	566	22.7	77.3
Maize	Lower	30401	98.6	1.4
	Middle	1317	92.0	8.0
	Upper	378	84.3	15.7
Wheat	Lower	30121	29.2	70.8
	Middle	19110	3.1	96.9
	Upper	1585	28.9	71.1
Almond	Lower	14067	11.6	88.4
	Middle	2469	4.2	95.8
	Upper	15	3.7	96.3
Oats	Lower	3833	20.4	79.6
	Middle	2653	12.5	87.5
	Upper	271	12.6	87.4
Rapeseed	Lower	1871	11.0	89.0
	Middle	1223	5.2	94.8
	Lower	55	65.8	34.2
Winter cereals (fodder)	Lower	1582	74.8	25.2
	Middle	2709	6.3	93.7
	Upper	1259	25.3	74.7
Vegetables	Lower	917	98.8	1.2
	Middle	187	75.6	24.4
	Upper	69	64.4	35.6
Olive	Lower	36740	11.8	88.2
	Middle	1929	0.4	99.6
	Upper	97	5.1	94.9
Barley	Lower	79414	17.4	82.6
	Middle	39805	6.0	94.0
	Upper	256	6.5	93.5
Grassland	Lower	2339	97.4	2.6
	Middle	1942	5.7	94.3
	Upper	5003	26.7	73.3
Apple	Lower	7202	96.4	3.6
	Middle	94	55.1	44.9
	Upper	45	75.8	24.2
Pear	Lower	11996	97.1	2.9
	Middle	5	59.8	40.2
Rye-grass	Lower	1243	98.2	1.8
	Middle	187	5.0	95.0
	Upper	25	49.7	50.3
Rye	Lower	57	13.9	86.1
	Middle	154	7.1	92.9
	Upper	514	28.5	71.5
Triticale	Lower	3125	24.4	75.6
	Middle	1093	12.9	87.1
	Upper	393	28.1	71.9
Grapevine	Lower	3370	40.7	59.3
	Middle	458	10.1	89.9
	Upper	13	23.4	76.6
Apricot	Lower	914	98.5	1.5
Cherry Tree	Lower	924	86.3	13.7
	Middle	159	64.0	36.0
Fig Tree	Lower	242	93.9	6.1
Nectarine	Lower	9639	99.0	1.0
Walnut	Lower	252	79.1	20.9
	Middle	68	34.9	65.1
Peach	Lower	13430	93.3	6.7
	Middle	94	51.2	48.8

Table 31. Surface of major crops in the upper, middle and lower Segre basin and % of surface under irrigated and rainfed conditions. The irrigated and rainfed land in The Segre basin is not considering the cropland from the French territory as this kind of information is lacking in the information source: The numbers in this table only take into consideration the part of the basin from Catalonia, Aragon and Andorra.

Crop	Basin Segment	Surface (ha)	ET_a (mm)			NNR (mm)		
			Reference Period	Short term	Long Term	Reference Period	Short term	Long Term
Triticale	Lower Course	206	324.4	327.6	323.7	57.7	54.5	54.7
	Middle Course	128	341.6	346.8	337.0	48.9	46.3	50.4
Winter Cereal Fodder	Lower Course	389	324.4	327.9	323.2	58.9	55.1	56.5
	Middle Course	726	332.6	337.8	328.9	54.1	51.2	57.1
	Upper Course	121	332.2	339.6	324.0	95.6	85.9	91.0
Barley	Lower Course	2757	298.1	292.0	290.3	18.5	16.0	14.3
	Middle Course	916	310.0	307.2	300.8	17.6	14.8	15.6
	Upper Course	59	306.8	308.6	293.6	51.0	46.3	54.3
Oats	Lower Course	975	297.9	292.0	289.7	19.1	16.7	15.2
	Middle Course	945	305.1	302.1	296.2	19.3	16.2	17.4
	Upper Course	58	308.3	309.6	294.7	50.8	46.0	53.6
Sunflower	Lower Course	111	217.0	222.2	220.7	234.3	233.3	227.8
	Middle Course	18	284.6	273.3	262.1	176.9	187.0	190.3
Grassland	Middle Course	105	527.3	534.1	516.9	324.7	334.9	361.4
	Upper Course	11	572.1	579.1	569.6	244.3	251.4	267.8
Peach	Middle Course	39	326.3	332.2	327.0	205.6	208.3	212.0
Apple	Lower Course	96	304.7	307.1	299.9	230.2	234.7	240.0
Rye-grass	Lower Course	478	494.6	500.6	486.2	380.6	389.8	412.9
	Middle Course	301	565.9	577.4	561.3	277.5	283.5	305.3
Sorghum	Lower Course	88	247.9	248.0	240.5	182.9	180.3	184.5
	Middle Course	64	310.0	295.9	279.1	132.0	143.3	153.9
Cherry tree	Lower Course	184	319.8	324.4	319.6	211.3	214.1	217.4
Rapeseed	Lower Course	140	388.8	389.2	389.0	5.8	17.2	38.1
	Middle Course	28	342.7	353.3	370.5	0.0	0.0	0.0

Table 32. Actual Evapotranspiration (ETa) and Net Irrigation Requirements in other major crops in the three segments of Muga basin during the reference period (2002-2011) and in Short (2021-2030) and Long Term (2041-2050)

Crop	Basin Segment	Surface (ha)	ET_a (mm) Reference Period	ET_a (mm) Short term	ET_a (mm) Long Term	NIR (mm) Reference Period	NIR (mm) Short term	NIR (mm) Long Term
Triticale	Lower Course	475	338.8	345.3	335.8	98.9	88.0	92.3
	Middle Course	253	346.9	340.0	327.0	110.4	111.5	121.2
	Upper Course	34	381.5	366.8	355.9	95.5	100.1	103.2
Winter cereal Fodder	Lower Course	864	337.5	342.5	334.5	82.1	74.6	79.0
	Middle Course	3358	352.3	344.7	330.5	107.6	107.9	116.5
	Upper Course	1081	389.1	373.7	362.0	93.1	98.0	101.8
Barley	Lower Course	7198	320.4	315.0	311.1	37.1	32.5	32.3
	Middle Course	4010	323.0	312.9	304.3	56.7	56.3	60.6
	Upper Course	202	359.4	345.9	335.6	55.8	56.3	60.0
Oats	Lower Course	1390	320.4	315.0	311.1	30.3	26.5	26.3
	Middle Course	592	323.0	312.9	304.3	46.0	44.9	47.8
	Upper Course	85	359.4	345.9	335.6	58.1	60.2	63.4
Sunflower	Lower Course	556	249.5	247.1	235.4	233.2	231.6	242.1
Olive	Lower Course	233	454.4	457.8	451.9	102.1	107.1	121.2
	Middle Course	3	478.4	478.0	476.8	107.5	117.0	125.5
Hazel	Lower Course	557	330.0	329.9	320.8	92.0	92.3	104.7
	Middle Course	218	363.4	357.2	352.7	49.0	57.6	66.6
Grassland	Lower Course	174	553.0	532.7	515.9	349.3	377.9	412.5
	Middle Course	1147	621.2	622.5	607.3	283.4	296.6	328.1
	Upper Course	1599	656.1	652.1	649.8	110.2	133.9	150.0
Pear	Lower Course	488	362.4	361.0	348.9	198.1	200.4	215.7
	Middle Course	197	406.3	396.0	386.7	141.3	155.5	168.8
Rye-grass	Lower Course	1955	557.0	546.7	533.2	376.9	394.6	420.4
	Middle Course	1249	592.7	589.9	573.1	315.6	334.9	365.4
	Upper Course	126	648.4	645.4	645.4	169.1	193.7	206.2
Sorghum	Lower Course	245	279.5	263.1	255.7	170.5	181.6	192.0
	Middle Course	70	286.4	272.9	260.7	225.6	233.7	246.6
Vines	Middle Course	56	297.0	299.2	301.8	4.6	5.3	5.5
Rapeseed	Lower Course	1565	378.5	381.5	393.7	1.2	6.8	15.3
	Middle Course	1245	343.1	363.5	375.3	11.9	10.2	16.7

Table 33. Actual Evapotranspiration (ETa) and Net Irrigation Requirements in other major crops in the three segments of Ter basin during the reference period (2002-2011) and in Short (2021-2030) and Long Term (2041-2050).

Crop	Basin Segment	Surface (ha)	ET_a (mm) Reference Period	Short term	Long Term	NIR (mm) Reference Period	Short term	Long Term
Triticale	Lower Course	3125	238.3	238.9	240.5	200.6	208.6	201.4
	Middle Course	1093	340.4	324.8	316.2	150.9	163.0	157.0
	Upper Course	393	305.7	288.2	276.8	1.7	1.1	0.0
Winter cereal Fodder	Lower Course	1582	249.2	245.6	248.2	194.6	203.4	195.2
	Middle Course	2709	355.3	337.1	330.0	144.1	159.2	152.9
	Upper Course	1259	271.1	273.6	266.6	24.6	13.3	9.6
Pear	Lower Course	11996	249.3	244.4	238.9	315.6	329.0	335.1
Apple	Lower Course	7202	228.2	223.5	215.0	328.3	352.1	362.6
	Middle Course	94	187.4	202.1	210.9	0.0	0.0	0.0
Rye-grass	Lower Course	1243	76.2	71.8	71.5	136.8	146.9	149.4
	Middle Course	187	273.8	254.0	252.6	60.2	93.6	97.8
	Upper Course	25	433.5	444.6	449.8	0.0	0.0	0.0
Rapeseed	Lower Course	1871	125.3	126.6	124.8	79.2	83.1	77.4
	Middle Course	1223	237.3	224.0	232.5	56.2	65.3	65.4
Vegetables	Lower Course	917	20.2	19.3	18.8	38.0	37.5	37.1
	Middle Course	187	143.6	136.0	132.9	66.5	82.6	86.3
	Upper Course	69	253.9	272.6	280.8	2.9	0.9	1.6
Rye	Lower Course	57	238.4	235.8	239.5	197.5	211.1	202.6
	Middle Course	154	372.1	354.9	346.2	127.3	142.6	136.7
	Upper Course	514	293.9	282.3	272.1	2.6	1.1	0.2

Table 34. Actual Evapotranspiration (ETa) and Net Irrigation Requirements in other major crops in the three segments of Segre basin during the reference period (2002-2011) and in Short (2021-2030) and Long Term (2041-2050).

			ET_C (mm)		
Basin	Crop	Basin Segment	Reference Period (2002-2011)	Short term (2021-2030)	Long term (2041-2050)
Muga	Maize	Lower Course	473.0	473.7	469.8
		Middle Course	470.9	472.1	467.3
	Alfalfa	Lower Course	684.4	695.8	702.2
		Middle Course	663.7	676.7	683.3
		Upper Course	637.5	649.0	655.1
	Blat	Lower Course	393.8	395.8	389.5
		Middle Course	382.6	382.5	378.3
	Olive	Lower Course	567.0	576.9	582.2
		Middle Course	559.5	570.2	576.4
		Upper Course	534.8	547.3	555.8
	Grapevine	Middle Course	271.0	275.9	276.5
	Grassland	Middle Course	852.0	869.0	878.2
		Upper Course	816.4	830.5	837.4
Ter	Maize	Lower Course	501.6	496.5	495.3
		Middle Course	546.3	546.3	545.3
		Upper Course	208.1	271.8	304.2
	Alfalfa	Lower Course	693.7	701.7	712.7
		Middle Course	750.1	758.9	771.5
		Upper Course	632.6	647.8	658.4
	Wheat	Lower Course	427.7	424.6	420.4
		Middle Course	462.8	454.9	450.3
		Upper Course	476.8	465.8	459.1
	Apple	Lower Course	528.1	532.5	536.7
		Middle Course	575.1	579.8	585.6
Segre	Maize	Lower Course	649.1	655.1	648.2
		Middle Course	346.8	361.9	364.7
		Upper Course	114.8	137.4	151.4
	Alfalfa	Lower Course	752.3	779.1	786.7
		Middle Course	673.4	693.8	701.0
		Upper Course	308.6	313.7	316.1
	Wheat	Lower Course	442.3	449.7	444.1
		Middle Course	478.5	479.4	466.1
		Upper Course	285.5	275.4	264.9
	Barley	Lower Course	377.6	377.2	368.7
		Middle Course	411.9	409.1	396.9
		Upper Course	274.3	261.3	269.3
	Olive	Lower Course	625.2	647.2	654.1
		Middle Course	550.2	569.9	575.3
		Upper Course	254.1	259.8	262.5
	Grapevine	Lower Course	274.3	280.9	281.7
		Middle Course	237.4	251.1	253.8
	Almond	Lower Course	647.2	663.4	665.6
		Middle Course	530.1	558.3	568.8
	Peach	Lower Course	613.4	612.3	611.6
		Middle Course	523.94	520.92	518.13

Table 35. Crop specific Evapotranspiration (ETC) of some major crops analysed in the three basins by basin segment and during the reference period (2002-2011) and in both future period under RCP4.5 climate change scenario: Short (2021-2030) and Long Term (2041-2050).

Basin	Basin Segment	ET_0 Penman-Montheith mm year^{-1} Reference period	% changes Short term (2021-2030)	Long term (2041-2050)	Effective Precipitation mm year^{-1} Reference period	% changes Short term (2021-2030)	Long term (2041-2050)
Muga	Lower Course	873.3	1.7	2.8	537.4	-3.1	-7.7
	Middle Course	856.1	1.9	3.0	622.6	-2.9	-8.2
	Upper Course	819.6	2.0	3.2	750.8	-1.1	-6.3
Ter	Lower Course	921.1	0.9	2.4	620.7	-4.4	-8.6
	Middle Course	905.9	1.4	3.2	689.5	-5.8	-8.7
	Upper Course	779.5	2.4	4.1	783.1	-4.5	-5.8
Segre	Lower Course	981	3.1	4.1	364.5	-8.9	-8.0
	Middle Course	911	3.2	4.3	633.8	-10.7	-10.9
	Upper Course	421	2.0	2.9	719.5	4.3	4.8

Table 36. Annual Potencial Evapotranspiration calculated by Penman-Montheith methodology and Effective Precipitation averaged for the three basin segment established in each basin for the reference period (2002-2011; mm year -1) and % of change for the both future periods under RCP4.5 climate change scenario: short and long term.