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Future precipitation in Sardinia and streamflow changes for a small basin using EURO-CORDEX regional climate simulations and the SWAT model

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Highlights:

- EURO-CORDEX climate models and SWAT can be coupled to analyze future hydrology
- Climate Change projections show a general decrease of mean precipitation in Sardinia
- Climate change projections reflect on hydrologic cycle with a decrease of mean discharge in South-West Sardinia
- Future surface runoff in South-West Sardinia can augment in winter due to the increase of the extreme events predicted by the Climate Models.

Abstract

The effects of climate change on hydrologic cycle are essential for the assessment of water management strategies. Climate models can provide projections of precipitation changes in the future, also considering greenhouse gas emissions. In this study the EURO-CORDEX (European COordinated Regional Downscaling EXperiment; Jacob et al. 2020) climate models were first analyzed for the island of Sardinia , against observed precipitation for the historical period of 1976-2005. A Multi-Model Ensemble (ENS) was built, weighting different models based on their performance against observed precipitations. Future projections (2071-2100), were analyzed using the 8.5 RCP emissions scenario to evaluate changes in precipitations. Climate models were then used as climate forcing for the SWAT model (Soil and Water Assessment Tool, Arnold et al.,1998), aiming to evaluate the effects of such changes on streamflow and runoff of two small catchments located in the South-West Sardinia. A general decrease of mean precipitation values, up to -25 % at yearly scale in the South-West Sardinia, is expected for the future, along with an increase of extreme events. Especially in the eastern and southern areas, extreme events are projected to increase by +30%. Such changes reflect on the hydrologic cycle with a decrease of mean streamflow and runoff, except in spring, when runoff is given to increase by 20-30%.

Keywords: EURO-CORDEX, Climate Change, Hydrology, SWAT model, Sardinia, Multi-Model Ensemble

1 Introduction

In the Mediterranean basin, the future reduction of mean precipitation, cumulatively with the increased temperatures in a global warming context, may further exacerbate droughts, heat waves and water shortages as well as more frequent floods, and may be critical for many human activities (Soares et al. 2017; Zappa et al. 2015;Giorgi & Lionello 2008). In the last decades, the potential impact of climatic change on hydrology has gained considerable attention in hydrologic research community (Abbaspour et al., 2009; Akhtar et al., 2008; Amadou et al., 2014; Gardner, 2009). Nowadays, the evaluation of such impacts cannot be disregarded in watershed management plans. Watershed-scale models can provide a primary support for the assessment of environmental issues (Yan et al., 2018; Zhou et al., 2020; Giang et al., 2017), helping decision makers in watershed management and water resources protection.

For well-planned adaptation measures, which can include the use of impact models driven by Regional Climate Models (RCM), decision makers demand more precise projections of how the future might look like (Von Trentini et al., 2019).

A state-of-the-art ensemble of regional climate models for Europe was developed within the CORDEX consortium (EURO-CORDEX European COordinated Regional Downscaling EXperiment; Jacob et al. 2020). EURO-CORDEX models represent the largest ensemble of regional climate models ever produced focused on a common European domain. This ensemble was used for projecting the European future climate (Jacob et al. 2014), was extensively evaluated for a wide range of surface variables (e.g. Katragkou et al. 2015; Kotlarski et al. 2014; Knist et al. 2017) and enabled more detailed studies on the consequences of climate change in specific regions, in particular related to precipitation, temperature and wind (Soares et al. 2017; Cardoso et al. 2018; Nogueira et al. 2019; Frei et al., 2018; Rulfova et al., 2017).

For the southern Europe, General Circulation Models (GCM) and RCM simulations, project a future decrease of mean precipitation with an intensification of extreme values (Sillmann et al. 2013b; Casanueva et al. 2015; Alpert et al. 2002; Sánchez et al. 2004; Gao et al. 2006; Rajczak et al. 2013; Soares et al. 2015). Moreover, climate projections have confirmed a tendency for drier and warmer Mediterranean climate in the next century (Piras et al., 2014; Mariotti et al. 2015). Giorgi (2006) identified the Mediterranean Sea region as one of the most prominent ''hot spots" in the world due to its vulnerability to climate change. Sardinia is an island located in the West Mediterranean Sea and it is particularly exposed to such future scenarios. Thus, assessing the effect of these projected changes at the local scale becomes a main concern to better plan adaptation strategies. Evaluating the effects of climate change on the hydrologic balance is the crucial step to understand environmental evolution and conceive water plan management. Previous studies were conducted in Sardinia testing EURO-CORDEX performances considering only historical simulations (Mascaro et al. 2018) or including Sardinia as part of a wider study area, hence with lower resolution (Aristeidis et al, 2018).

SWAT (Soil and Water Assessment Tool) is a hydrological model physically based and parametric, in which all the processes are simulated using specific equations that users can modify through several physical parameters. It was used for evaluating the impact of climate change and anthropogenic factors on stream flow, agricultural chemical and sediment yields in large river basins (Arnold et al., 1998; Arnold et al., 2000; Jha et al., 2006). SWAT is commonly used offline or coupled with climate models to assess climate change impacts on future water resources and watershed management (Nerantzaki et al., 2016; Perra et al., 2018; Carvalho-Santos et al., 2017). In recent studies focused on Sardinia, SWAT was combined with ENSEMBLES project climate models, providing future climate forcing for water resources assessment and drought risk evaluation (Perra et al., 2018; Piras et al., 2015). Findings of these investigations project a future decrease of mean precipitations and, among them, the reduction of streamflow discharge, with an increase of the extreme events.

The current study aims at building a multi-model ensemble, using the EURO-CORDEX simulations, to characterize the future precipitation changes in Sardinia, and investigate their impact on the hydrologic cycle of two small Sardinian catchments using the SWAT model.

2 Data and Methods

2.1 Area of study

The study area is the Sardinia Island (Figure 1), which has a surface of around 24,000 km^2 and is in the West Mediterranean Sea. Sardinia has a topography mainly characterized by mountains, interrupted by valleys and planes, such as Campidano plain, due to structural horst-graben features.

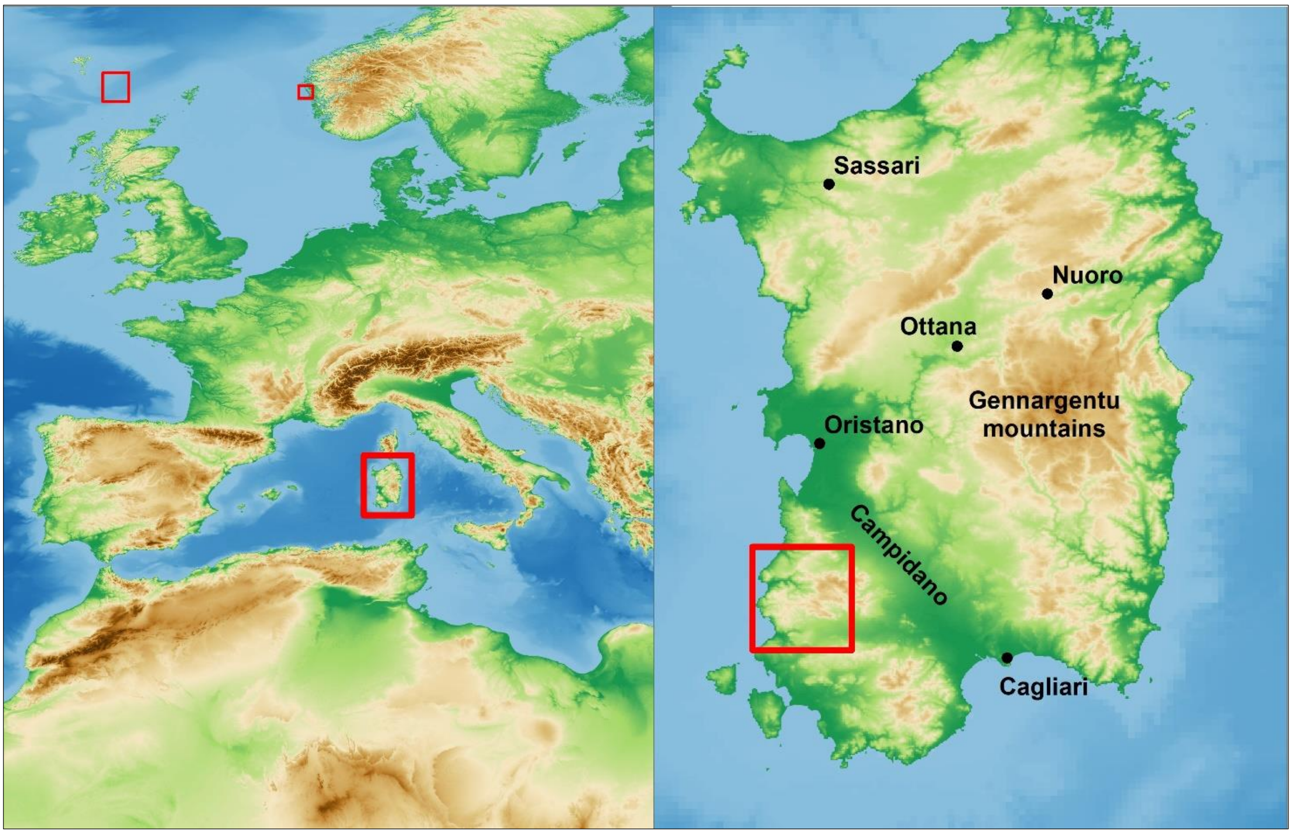


Figure 1 - Study area: location of Sardinia Island in the Mediterranean Sea (left) and domain of the SWAT model for the hydrological modelling (right)

The highest elevation is given by the Gennargentu mountains (1834 m a.s.l.), located in the Center-East of the island. The Gennargentu influences the local circulation and precipitation distribution. Minor mountain ranges characterize the South-West region. Climate in Sardinia is typically Mediterranean, with the occurrence of a wet period from September to May and very dry summer from June to August (Mascaro et al. 2018). In Sardinia, almost the 90% of the rivers are non-perennial (Mulas et al, 2009). Major rivers, such as Tirso, Flumendosa and Coghinas, are barred by several dams in order to regulate water resources. The predominant contribution to the flow of such rivers is the surface runoff (Montaldo and Sarigu, 2017) that mainly occurs in autumn and winter, during the wet season. As in most of the Mediterranean regions, runoff in Sardinia decreased over the past three decades, due to the decrease of precipitations (Montaldo and Sarigu, 2017).

Two watersheds located in the South-West region, namely Rio San Giorgio and Rio Mannu di Fluminimaggiore, were modeled using SWAT. Rio San Giorgio (RSG from now on) is a small river that origins nearby the town of Iglesias and drains an area of around 3082 hectares. In natural conditions, Rio San Giorgio has an intermittent regime, with flow strictly related to the occurrence of precipitations. Wastewaters from the urban area of Iglesias are discharged in the watershed, allowing a small continuous flow during the dry periods. Rio Mannu di Fluminimaggiore (RMF from now on), located few kilometers norther than Rio San Giorgio, is a perennial river that drains an area of around 12500 hectares. Due to the presence of a streamflow measurement gauge, this river was modeled along with Rio San Giorgio for the calibration of the SWAT model.

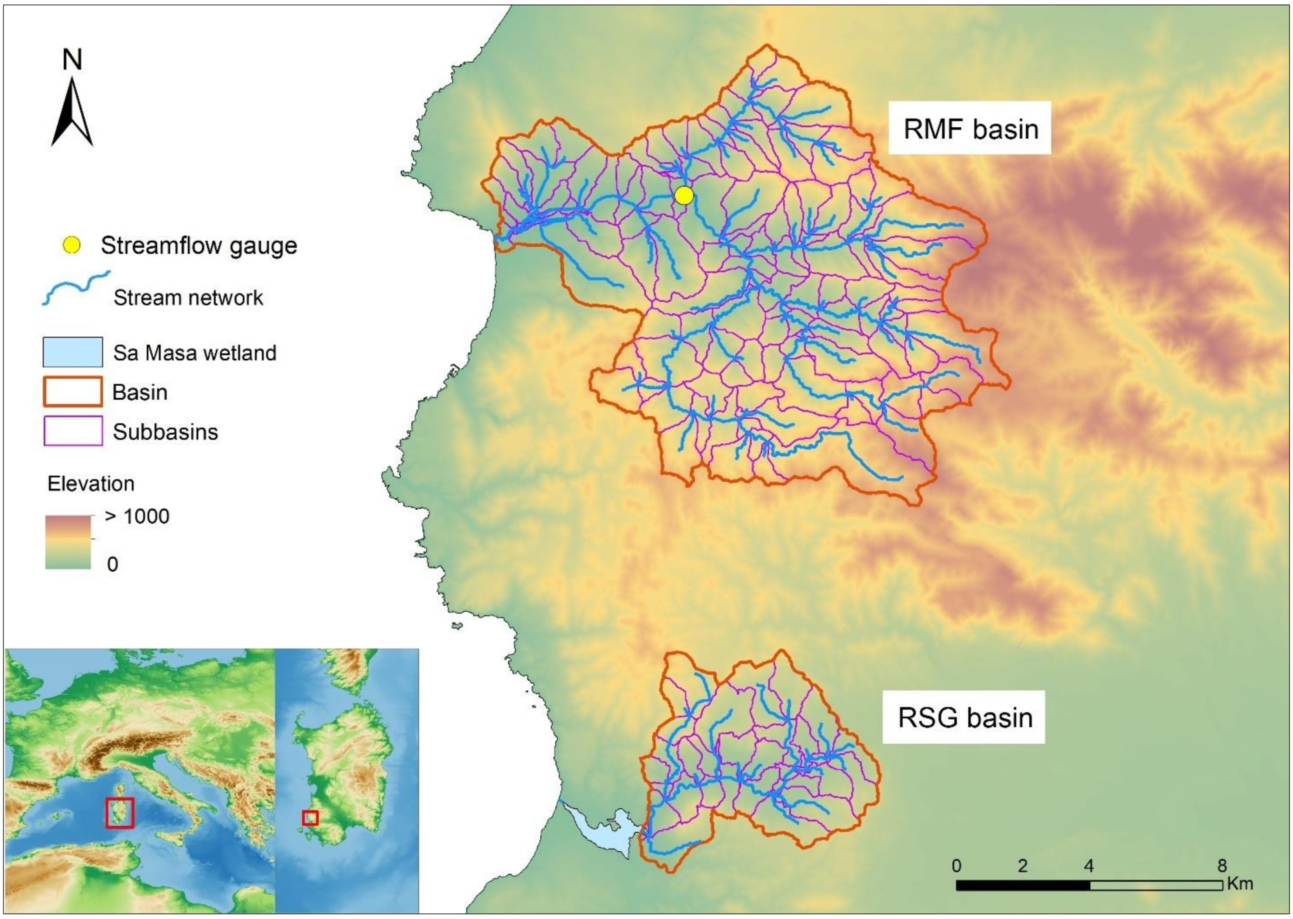


Figure 2 - SWAT model sub-domain within the island of Sardinia. Rio San Giorgio basin (southern basin) is the area of interest, while Rio Mannu di Fluminimaggiore (northern basin) was modeled due to the presence of a streamflow measurement gauge.

2.2 Observational data

Observed data used in this study includes daily precipitation measured by 242 of the 441 rain gauges of the Sardinian Hydrological Survey for the period 1979-2008. The 242 stations were chosen among the 441 after analyzing the missing values for the historical period. As shown in Figure 3, the stations (red dots) are evenly distributed throughout the island, with approximately one station each 100 km^2 covering a wide range of elevations up to 1467 m a.s.l.

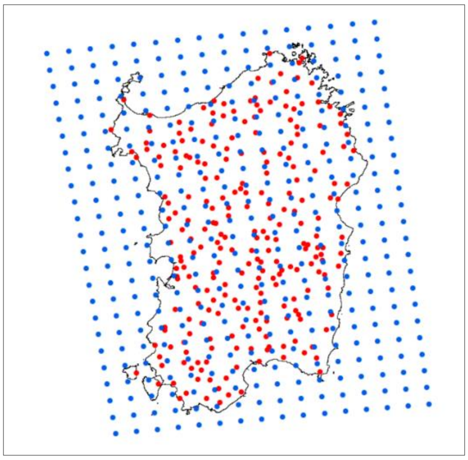


Figure 3 – Euro-CORDEX precipitation regular grid (blue dots) and rain gauges network (red dots)

2.3 EURO-CORDEX Simulations

The Coordinated Regional Climate Downscaling experiment (CORDEX) project (Giorgi et al. 2009) provides a set of RCM simulations driven by different GCM over Europe, as part of the EURO-CORDEX initiative (Kotlarski et al. 2014; Katragkou et al. 2015). The EURO-CORDEX simulations used in this study cover the period 1976–2005 for the historical climate and 2071–2100 for the future projections, in agreement with the RCP8.5 scenario (Riahi et al. 2011) for future greenhouse gas emissions. The model results daily precipitation at 0.11° resolution were retrieved from ESGF portal (Earth System Grid Federation). As shown in Table 1, 13 different model datasets at 0.11° resolution were available in the portal and were analyzed in this study. The model acronyms will be kept in this text to simplify figures and tables (see last column of Table 1).

Table 1. EURO-CORDEX regional climate models considered in the present study, along with the responsible institution, the forcing global climate model, the acronym for each model combination (RCM-GCM).

Institution	**Reference**	**Model**	**Forcing Model**	**Acronym**
Climate Limited-area Modelling Community	Rockel et al. (2008)	CCLM4-8-17	ICHEC-EC-EARTH	CLM1
			MOHC-HadGEM2-ES	CLM2
			CNRM-CERFACS-CNRM-CM5	CLM3
			MPI-M-MPI-ESM-LR	CLM4
Danish Meteorological Institute	Christensen et al. (2006)	HIRHAM5	ICHEC-EC-EARTH	DMI
Koninklijk Nederlands	van Meijgaard et al. (2008)	RACMO22E	ICHEC-EC-EARTH	KNMI1

Meteorologisch Instituut			MOHC-HadGEM2-ES	KNMI2
Helmholtz-Zentrum Geesthacht, Climate Service Center, Max Planck Institute for Meteorology	Jacob et al. (2001)	REMO2009	MPI-M-MPI-ESM-LR	MPI
Swedish Meteorological and Hydrological Institute	Samuelsson et al. (2011)	RCA4	ICHEC-EC-EARTH	SMHI1
			MOHC-HadGEM2-ES	SMHI2
			CNRM-CERFACS-CNRM-CM5	SMHI3
			MPI-M-MPI-ESM-LR	SMHI4
			IPSL-IPSL-CM5A-MR	SMHI5

2.4 Models evaluation

In this study similar error metrics to Soares et al. (2017) were used to evaluate the precipitation model's results. The assessment of each precipitation model results is based on the comparison against observations measured by the 242 stations over Sardinia, for a historical reference period (1979-2008), relying on the nearest neighbor grid point. With this purpose, standard statistical errors are computed, for the monthly, seasonal and yearly scales. The following statistics are calculated by pooling together time and space: bias (1), percentual bias (2), mean absolute error (3), mean absolute percentage error (4), root mean square error (5), normalized standard deviation (6), spatial correlation (7) and Willmott-D score (8) (Willmott et al. 2012). The grid points of the EURO-CORDEX RCMs correspond to the nearest neighbors to the Sardinia's station.

$$Bias = \frac{1}{N}\sum_{k=1}^{N}(p_k - o_k), \qquad (1)$$

$$Bias\% = \frac{\sum_{k=1}^{N}(p_k - o_k),}{\sum_{k=1}^{N} o_k} \times 100, \quad (2)$$

$$MAE = \frac{1}{N}\sum_{k=1}^{N}|p_k - o_k|, \quad (3)$$

$$MAPE = \frac{\sum_{k=1}^{N}|p_k - o_k|}{\sum_{k=1}^{N} o_k} \times 100, \quad (4)$$

$$RMSE = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(p_k - o_k)^2} \;, (5)$$

$$\sigma_n = \frac{\sigma_p}{\sigma_o} = \frac{\sqrt{\frac{1}{N}\sum_{k=1}^{N}(p_k - \bar{p})^2}}{\sqrt{\frac{1}{N}\sum_{k=1}^{N}(o - \bar{o})^2}}, (6)$$

$$r = \frac{\sum_{k=1}^{N}(o_k-\bar{o})-(p_k-\bar{p})}{\sqrt{\sum_{k=1}^{N}(o_k-\bar{o})^2 \sum_{k=1}^{N}(p_k-\bar{p})^2}}, \quad (7)$$

$$D = \begin{cases} 1 - \frac{\sum_{k=1}^{N}|p_k-o_k|}{2\sum_{k=1}^{N}|o_k-\overline{o}|}, \; if \; \sum_{k=1}^{N}|p_k - o_k| \quad \leq \; 2\sum_{k=1}^{N}|o_k - \overline{o}| \\ \frac{2\sum_{k=1}^{N}|o_k-\overline{o}|}{\sum_{k=1}^{N}|p_k-o_k|} - 1 \, , \; if \; 2\sum_{k=1}^{N}|o_k - \overline{o}| \quad > \sum_{k=1}^{N}|p_k - o_k| \end{cases}, \quad (8)$$

$$YK = \left[\frac{(P_{95}-P_{50})-(P_{50}-P_5)}{(P_{95}-P_5)}\right]_{model} - \left[\frac{(P_{95}-P_{50})-(P_{50}-P_5)}{(P_{95}-P_5)}\right]_{obs} \quad (9)$$

where N is the number of observed/modelled days, o_k and p_k represents the observed/modelled values and, $\overline{o}$ and $\bar{p}$ the mean of observed/modelled values. For the Willmott-D score, a perfect skill is obtained when $D = 1$ and no skill when $D = -1$. The analysis around the mean values is done with the metrics in Eq. 1 to 9, and to measure the differences between distributions, the S (Eq. 10) and Yule-Kendall (Eq. 11) skill scores are used. In agreement with Perkins et al. (2007), the probability density functions (PDF) matching scores are computed, as well as the Yule-Kendall skewness measure (Ferro et al. 2005). The PDFs of each dataset are calculated using the daily data.

$$S = \int \min(E_M, E_O), \quad (10)$$

$$YK = \left[\frac{(P_{95}-P_{50})-(P_{50}-P_5)}{(P_{95}-P_5)}\right]_{model} - \left[\frac{(P_{95}-P_{50})-(P_{50}-P_5)}{(P_{95}-P_5)}\right]_{obs}, \quad (11)$$

The P represents the percentiles, E_M and E_O represents the empirical distribution function of the model and observed pooled sample, respectively. The S score measures the overlap between observed and modelled PDFs, whilst the Yule-Kendall measure the difference between the two PDFs skewness.

2.5 Ensemble building

To perform a robust characterization of the precipitation response to global warming in Sardinia, a EURO-CORDEX multi-model ensemble was built taking into account the relative performance of each RCM (Christensen et al. 2010) for describing the Sardinian rainfall. All above metrics were included in the ranking process. Since the optimal result of bias, MAE and RMSE is zero, the inverse of its absolute value was calculated. For normalised standard deviation, since the best result is 1, this metric was transformed as:

$$\vartheta_n = \begin{cases} \sigma_n \ \ if\ \sigma_n < 1 \\ \frac{1}{\sigma_n} \ \ if\ \sigma_n > 1 \end{cases}.$$

At the same way, the Yule-Kendall score became:

$$YK_{new} = \begin{cases} YK + 1 \ \ if\ YK < 0 \\ \frac{1}{YK+1} \ \ if\ YK > 0 \end{cases}.$$

For each metric, the individual model ranks were obtained by dividing each value by the sum of all model values, resulting in a sum of the ranks equal to 1. The ranks of all the metrics were firstly multiplied and then divided by the sum of the weights, resulting in a weight for each model. The precipitation's multi-model weighted ensemble was obtained by multiplying the respective EURO-CORDEX RCM weight as:

$$\overline{pr} = \frac{\sum_{i=1}^{N} pr_i w_i}{\sum_{i=1}^{N} w_i}.$$

2.6 SWAT model

SWAT is a physically based semi-distributed model that calculates daily and monthly hydrological balance parameters in a watershed (Arnold et al. 1998; Neitsch et al. 2011). It is based on physical parameters that the user can modify to better represent the real conditions of the modeled watershed. In the current study, firstly, SWAT was run using real precipitation time series and calibrated against streamflow data measured at the RMF gauge. Secondly, SWAT was forced with the EURO-CORDEX climate model both for historical and future runs. This allowed to quantify the effect of projected precipitation changes on the streamflow of Rio San Giorgio watershed.

Input data for the model setup was retrieved from local government offices and is listed in Table 2. SWAT divides the watershed in sub-basins and calculates the water balance based on the Hydrologic Response Units, namely unique combinations of land use, soils and slope class. 160 sub-basins and 2773 HRUs were delineated. Slope was split into 3 classes: 0–5%; 5–10%; > 10% to reproduce the spatial variability of this feature in the watershed. Constant daily flow from 2 point-sources of urban wastewater were modeled, with an annual discharge of 90000 m^3/year and 110000 m^3/year.

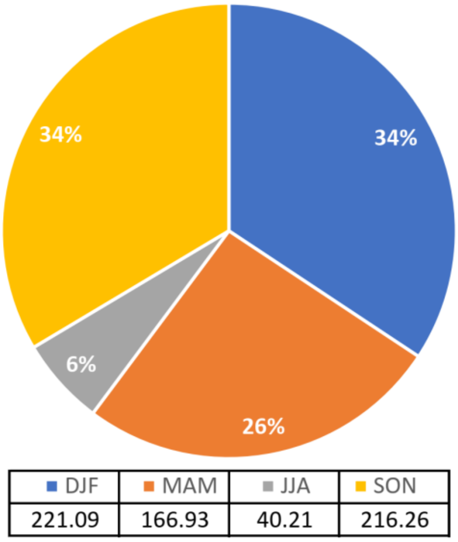
Table 2 - Input data for the implementation of the SWAT model

Input data	Resolution	Source
Digital Elevation Model	10m	Regione Autonoma della Sardegna
Stream Network	-	Regione Autonoma della Sardegna
Soil map and custom database	02:40.0	CRS4 Research Center
Land use map	01:25.0	Regione Autonoma della Sardegna
Point Sources discharge	Annual amount	IGEA s.p.a.
Observed precipitation and measurement network	Daily	Regione Autonoma della Sardegna
Temperature statistics	Monthly	Regione Autonoma della Sardegna
Observed streamflow (for calibration)	Monthly/daily	Regione Autonoma della Sardegna

3 Results and discussion

3.1 Observed precipitation

The mean yearly observed precipitation for the historical period (1976-2005) is 645 mm, considerably lower than the 710 mm reported by Mascaro (2018) for a wider period (1950-2005), with the lowest value of 365 mm and a maximum of 1040 mm in the Gennargentu mountainous area. Seasonal mean precipitations are distributed as follows:



■ DJF	■ MAM	■ JJA	■ SON
221.09	166.93	40.21	216.26

Figure 4 – Precipitation seasonal distribution.

Almost 70% of the total rainfall is distributed between September and February, around 25% in the spring months and only 6% of the precipitation falls in summer, revealing a strong seasonality. The spatial variability of the precipitations is very high (Figure 5), especially in winter due to the orographic precipitation. Different seasonal spatial patterns can be highlighted: in summer (JJA) a decreasing rainfall pattern from North-East to South-West, ranging from 75-100 mm in the North East to 0-10 mm of the South-West area, and in winter (DJF) with a clear precipitation gradient from 350-400 mm in the East to 100-150 mm in the West, with the exception of the mountain range of the South-West area that shows higher precipitation values if compared with the surrounding stations.

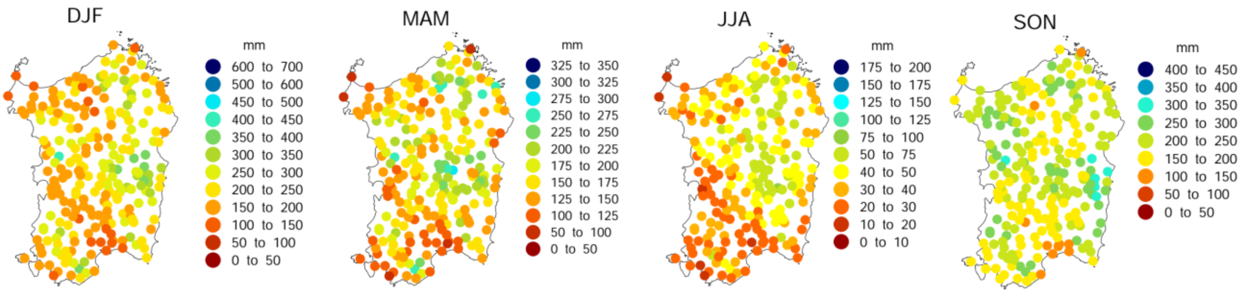


Figure 5 - Seasonal mean cumulated rainfall calculated on the observational network

3.2 Evaluation of Euro-CORDEX simulations and the weighted multi-model ensemble

The performance of the models in the historical period is crucial to evaluate their reliability and determine their weights to build the multi-model ensemble for climate change assessment. Figure 6 shows the bias and the mean average percentage error of the models against the observed precipitation. RCMs show percentual biases in the range of +40 % and -25 %, and MAPEs between 15 % and 55 %. CLM3, DMI, KNMI2 and MPI display rather low biases and MAPEs. KNMI2 shows a good representation of the seasonal and monthly scale rainfall, while CLM3, DMI and MPI are less reliable at these time scales. KNMI2 shows the lowest MAPE, followed by the KNMI1 and CLM4 models. CLM3 and CLM1 show good performance at yearly scale, with a large detachment at monthly and seasonal scales.

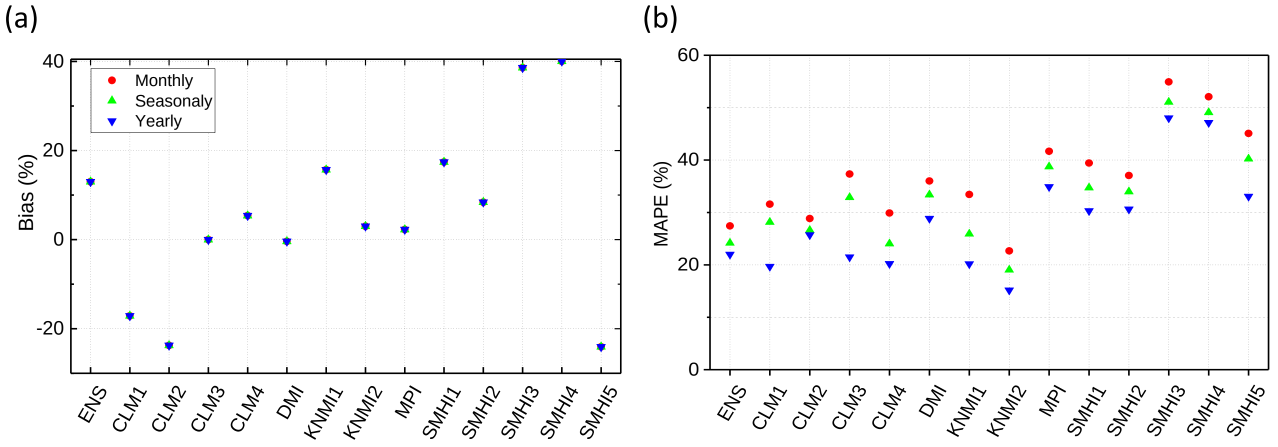


Figure 6. Statistical errors of EURO-CORDEX RCMs and ENS precipitation against the observational stations data for the Sardinia: (a) percentual bias and (b) mean absolute percentage error. The errors are computed for monthly (red), seasonally (green) and yearly (blue) accumulation periods of precipitation pooling all data together.

The statistical errors and skill scores, calculated for each model are summarized in Table 3. The aim of this ranking process is not to individuate the which model is the best performing model, but to evaluate the weight of the different models and use them to build the ENS.

The best three models, that represent over 50% of the ENS, are KNMI2, KNMI1 and CLM4. KNMI2 shows the lowest MAPE (19.05) and the highest Wilmott-D score overall with a low Bias (3 %),. KNMI1 has the best spatial correlation (0.61) reproducing quite well the spatial distribution of the precipitation, further highlighted in Figure 7, with a bias of 15.68 % thus a tendence to overestimate precipitations. CLM4 has a low bias (5.39 %), but, within the best performing models, is the one with the lowest spatial correlation (0.39) and must be carefully considered when looking at spatial distribution of rainfall. Based on the RCM scores, the weighted model ensemble was built and are shown in Table 3, as the ENS correspondent error measures. ENS has a bias of 12% and a relatively low MAPE that attains at 24,18 for seasonal resolution, while at yearly and monthly scale the MAPE has a small (respectively lower and higher) variation around the seasonal value.

Table 3 - Statistical errors and skill scores for EURO-CORDEX RCMs and ENS against observational stations data. The errors are the seasonal percentual bias, MAPE, normalized standard deviation and Willmott-D score, the yearly spatial correlation

RCMs	**Bias%**	**MAPE**	**Normalized Standard Deviation**	**Wilmott-D**	**Spatial Correlation**	**S**	**Yule-Kendall**	**Weight**
KNMI2	3	19.05	1.01	0.78	0.59	83.13	0.06	27.43%
KNMI1	15.68	25.91	0.95	0.7	0.61	82.34	0.027	15.80%
CLM4	5.39	24.04	0.98	0.72	0.39	88.78	0.019	12.27%
CLM1	-17.12	28.16	0.68	0.67	0.56	85.88	0.036	8.53%
CLM2	-23.75	26.62	0.77	0.69	0.45	85.37	0.04	8.52%
DMI	-0.4	33.39	1.27	0.61	0.5	90.4	0.072	5.24%
SMHI2	8.39	33.98	1.26	0.6	0.5	86.86	0.043	5.19%
SMHI1	17.42	34.73	1.39	0.59	0.51	88.16	0.04	4.51%
SMHI5	-24.06	40.23	0.93	0.53	0.44	81.61	0.036	4.04%
CLM3	-0.005	32.87	0.69	0.61	0.34	84.62	0.009	3.96%
SMHI3	38.59	51.06	1.42	0.4	0.46	89.67	0.025	1.87%
SMHI4	40.03	49.09	1.63	0.42	0.45	91.32	0.032	1.69%
MPI	2.26	38.75	1.2	0.54	-0.12	88.01	0.074	0.96%
ENS	12.99	24.18	1.12	0.72	0.57	87.48	0.041	

The Figure 7a shows the yearly mean accumulated precipitation for each model and for the ENS. KNMI1, KNMI2 and CLM4 reproduce rather well the spatial patterns, which is also confirmed by Figure 7b that shows the relative differences between the observed annual precipitation and the simulated by the RCMs. SMHI5 underestimates precipitation in the East coast up to -80/ -90% of relative error and in the southern Campidano area, ranging from -60% to -70% of relative error.

SMHI3 and SMHI4 hugely overestimate values in the western stations with peaks of +100% of relative errors. MPI and DMI models do not reproduce the spatial distribution of the annual precipitation, particularly the MPI model overestimates rainfall in most of the stations, reaching relative errors > +100% and underestimates it in all the eastern coast with ~ -50% error.

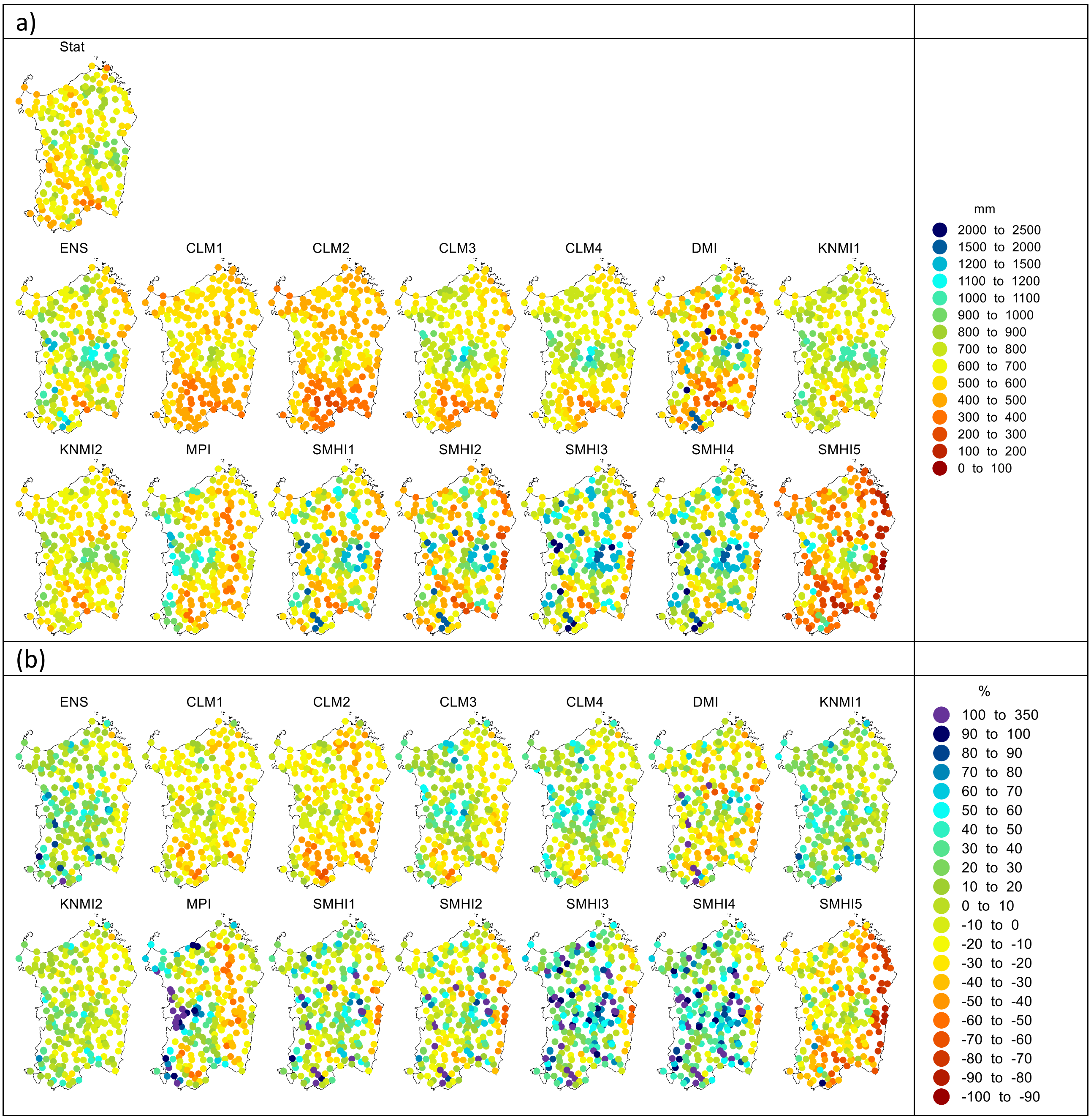


Figure 7. (a) Yearly mean precipitation from observations (1979-2008), from 13 EURO-CORDEX RCMs and from EURO-CORDEX weighted multi-model ensemble (1976-2005); and (b) relative differences between historical EURO-CORDEX individual RCMs runs and the weighted multi-model ensemble against the observations.

The seasonal precipitation (Figure 8) highlights the complexity of the orography and its influence on the spatial distribution of the rainfall. The seasonal precipitation ranges from values always above 200 mm in the Gennargentu mountains to values below 100 mm in the southern area around the city of Cagliari, which is the driest zone, even in winter.

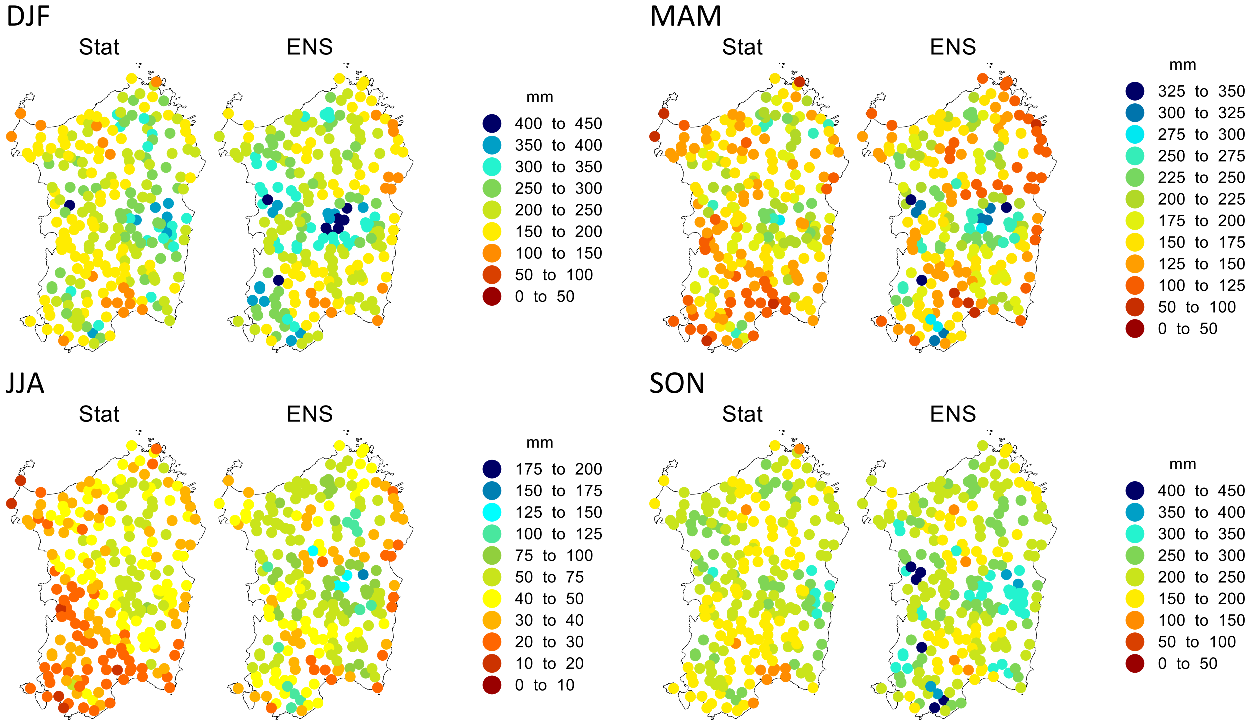


Figure 8. Seasonal mean precipitation from observations (1979-2008) and from the weighted multi-model ensemble (ENS) (1976-2005).

Despite a general overestimation of the precipitation, the weighted multi-model ensemble (ENS) reproduces well the spatial patterns of the seasonal cumulates (Figure 8), except in summer (JJA) were there is a notable spatial and quantitative disagreement. Precipitation in South-West area is overestimated in all the seasons, while there is a good reproduction of the patterns in the South Campidano region that is, as mentioned above, one of the driest areas. Generally, precipitations in the mountain ranges all over the island are overestimated by ENS, by around 40-50 % on average at yearly scale with peaks of 100 % in the South-West region, suggesting that EURO-CORDEX RCMs still not capture well the local conditions in mountainous areas.

3.3 Precipitation future projections

The precipitation projections are analyzed following the future RCP8.5 emissions scenario. The relative changes for precipitation in the period 2071 – 2100, when compared with the historical period 1976-2005 of ENS (Figure 9), show a general rainfall decrease at the yearly scale, which is rather significant in the South-West area (-20 to -25 %) with a negative gradient from North-East to South-West. The projected seasonal relative changes highlight different patterns: DJF is characterized by a general decrease of precipitation, larger in the East and South-West regions of Sardinia, amounting to values between -15% and -25%. In MAM, a more considerable change is displayed, especially in the south of the island with a reduction of precipitation ranging from -25% to -30%. In JJA a positive steep gradient has a South-East to North-West orientation, going from positive small changes above 5% to a larger decrease up to -35% in the North-West area. Another gradient of relative change is predicted for SON from North-East to South-West, with positive changes up to 5% in the North-East, down to -25% in the South-West cape.

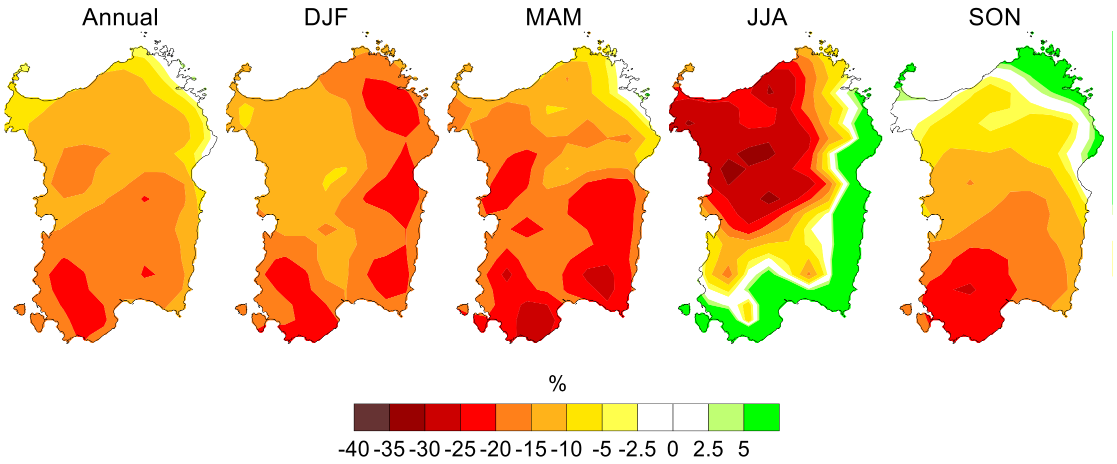


Figure 9. Yearly and seasonal mean precipitation relative changes in %, (2071-2100 minus 1976-2005)/1976-2005, for the ENS.

The ENS reveals a striking future relative change in the number of wet days (daily precipitation above 1 mm; Figure 10) that reaches values around -25%. The decrease in percentage of wet days, projected by the ENS all over the island (Figure 10), has a North-East to South-West gradient, with larger decreases in the Campidano area (South-West), in the Gennargentu mountains (Center-East) and in the Ottana plain (Center-West). These changes agree with others climate change analysis that were performed in the Mediterranean region (Dubrovsky et al., 2013; Ducic et al., 2012;).

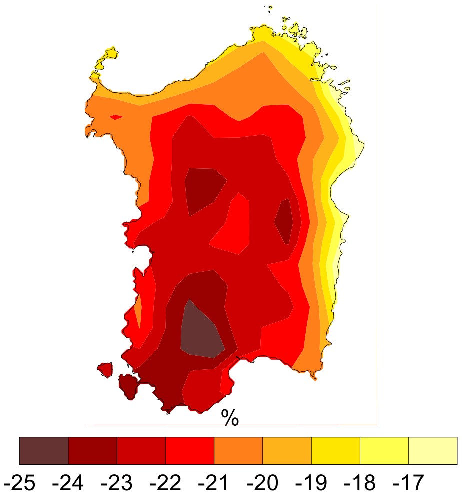


Figure 10. Relative change of the number of yearly wet days (daily precipitation above 1 mm).

3.4 Changes in extremes

The projected relative change in wet days above 10 mm of precipitations shows a different pattern, but adds to a wide-distributed rainfall decrease, with the South-West area that still shows a decrease that could amount up to -25 %. Although, an increase of precipitations above 20 mm in some regions is projected, such as in Campidano and Sassari' province. This points to the increase of intense rainfall events in those areas. Rainfall events above 20 mm are also expected to decrease large extensions of the eastern regions, with higher negative values in the mountainous areas of Gennargentu, and in the South-West range.

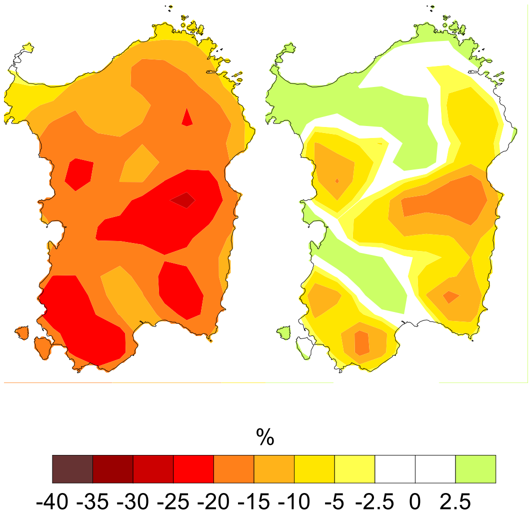


Figure 11. Relative change of number of yearly wet days when precipitation is above a) 10 mm and b) 20 mm.

The future projections for the relative changes of high rank precipitation percentiles (95th and 99.9th percentiles) are depicted in Figure 12, showing an overall increase of both percentiles, which have similar spatial patterns. The higher percentages of change are projected for the East side with maxima increases above +30 % in mountainous areas and southern island capes, for the 99th percentile. Extremes in the southern and eastern areas are in some way in agreement with the zones historically impacted by extreme rainfalls.

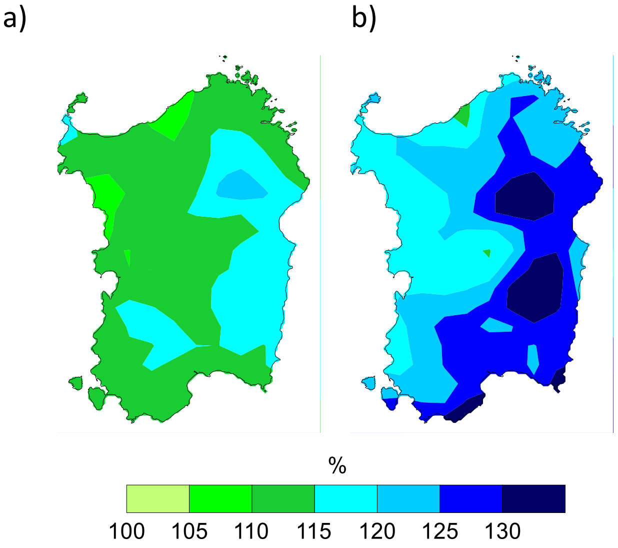


Figure 12 - Relative changes of precipitation 95th and 99th percentiles after adjusting for scale, comparing future (2071–2100) and present (1976–2005)

3.4 Hydrological SWAT simulations and the impact of Climate Change in two basins

The SWAT model was calibrated and validated against daily streamflow observations (1985-1994) measured at the RMF station, split in two independent series: 1985-1992 for calibration (Figure 13) and 1992-1994 for validation, using the SUFI-2 procedure (Abbaspour et al., 2007). In SUFI-2 the goodness of the model is evaluated accounting and measuring uncertainty, while the fitting of the modeled and observed discharge is measured with Nash-Sutcliffe index that is calculated as follows:

$$NS = 1 - \frac{\sum_i (Q_m - Q_s)_i^2}{\sum_i (Q_{m,i} - \overline{Q}_m)^2}$$

where Q is a variable (e.g., discharge), and m and s stand for measured and simulated, respectively, and the bar stands for average. A perfect model would have a NS index of 1, while a NS below 0 corresponds to an unreliable model. Suggested values of NS are > 0.5. Daily calibration scored a NS index of 0.66 and 0.60 for validation period.

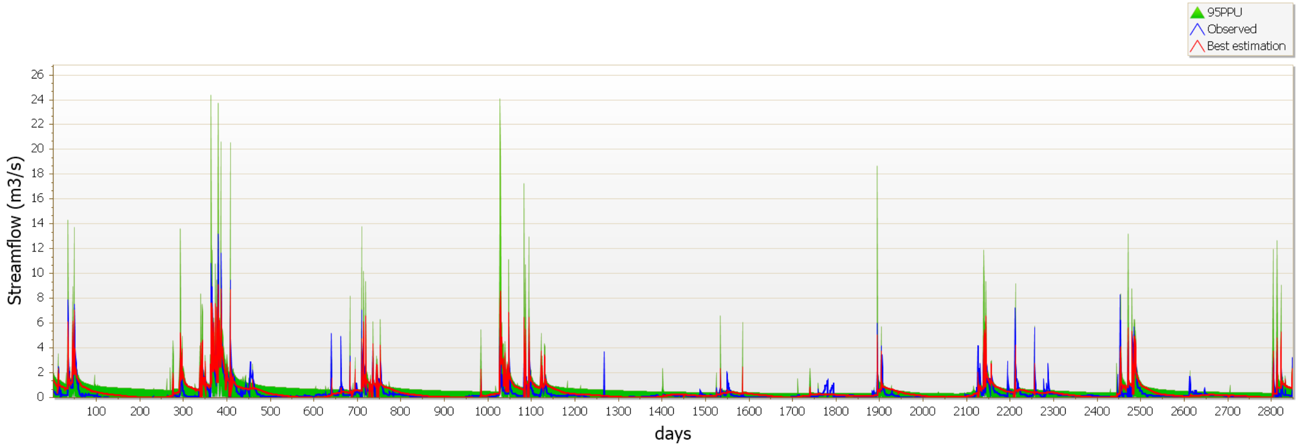


Figure 13 - Calibration of the daily streamflow (m³/s February 1985- December 1992) at the RMF measurement station scoring a (NS) index of 0.66.

The validation at monthly scale (Figure 14) was also performed for the period 1985-1992, obtaining a NS of 0.88. The model seems to better reproduce the monthly mean streamflow, in agreement with the chosen scale for long-term future simulations.

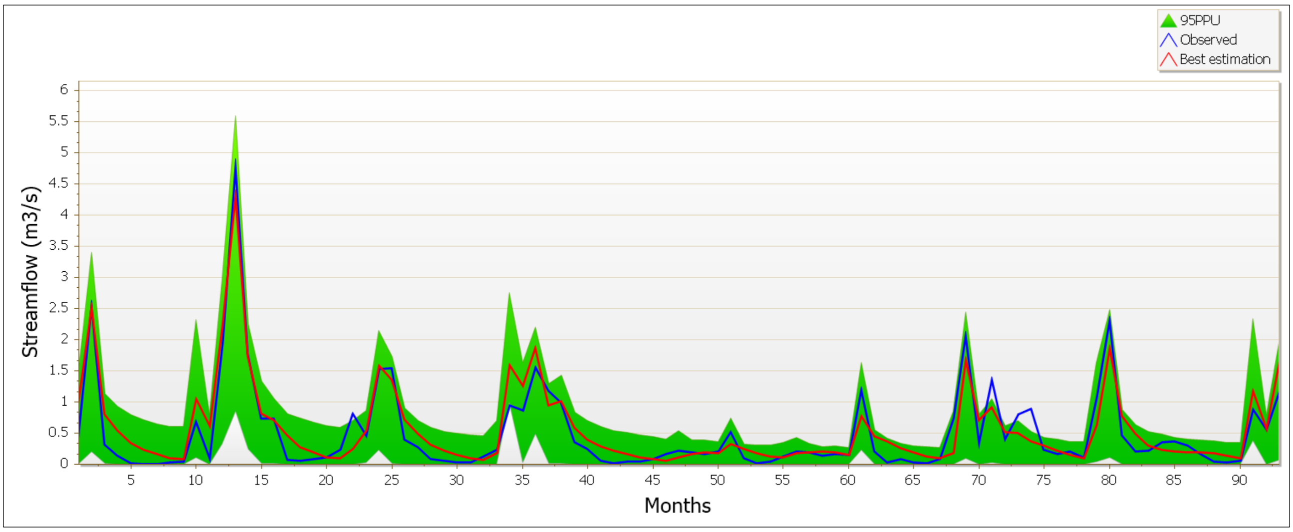


Figure 14 - Monthly streamflow validation ((m³/s) February 1985- December 1992) at the Flumineddu measurement station

The SWAT model was firstly forced with EURO-CORDEX historical simulations (1976-2005) in order to compare the model’s output with the observed streamflow. Future SWAT simulations were run from 2071 to 2100 according with the climate change analysis. All the hydrological simulations were preceded by two years of warm-up, both for historical (1976-1978) and future period (2071-2073). SWAT model's weather generator needs continuous daily rainfall time series, with standard Gregorian calendar. Due to the use of 360 calendar days in the MOHC-HadGEM2-ES GCM simulations, 3 RCMS forced by this GCM have been excluded from the hydrological simulations. Based in the weights assigned to the climate models to build the ENS, the different SWAT model's outputs have been weighted normalizing the weights to 100% (Table 4).

Table 4 - Multi model ensemble (ENS) weights normalized after excluding MOHC-HadGEM2-ES GCM from the hydro-climate simulations

	CLM1	**CLM3**	**CLM4**	**DMI**	**KNMI1**	**MPI**	**SMHI1**	**SMHI3**	**SMHI4**
Original ENS weight	8.53%	3.96%	12.27%	5.24%	15.80%	0.96%	4.51%	1.87%	1.69%
Norm. ENS weight	15.56%	7.22%	22.38%	9.56%	28.82%	1.75%	8.23%	3.41%	3.08%

In the following analysis, for practical reasons, each SWAT output resulting from a different forcing model will be mentioned as SWAT-name of the model (e.g. SW-CLM1, SW-MPI), while SWAT weighted output based on multi-model ensemble weights will be named SW-ENS.

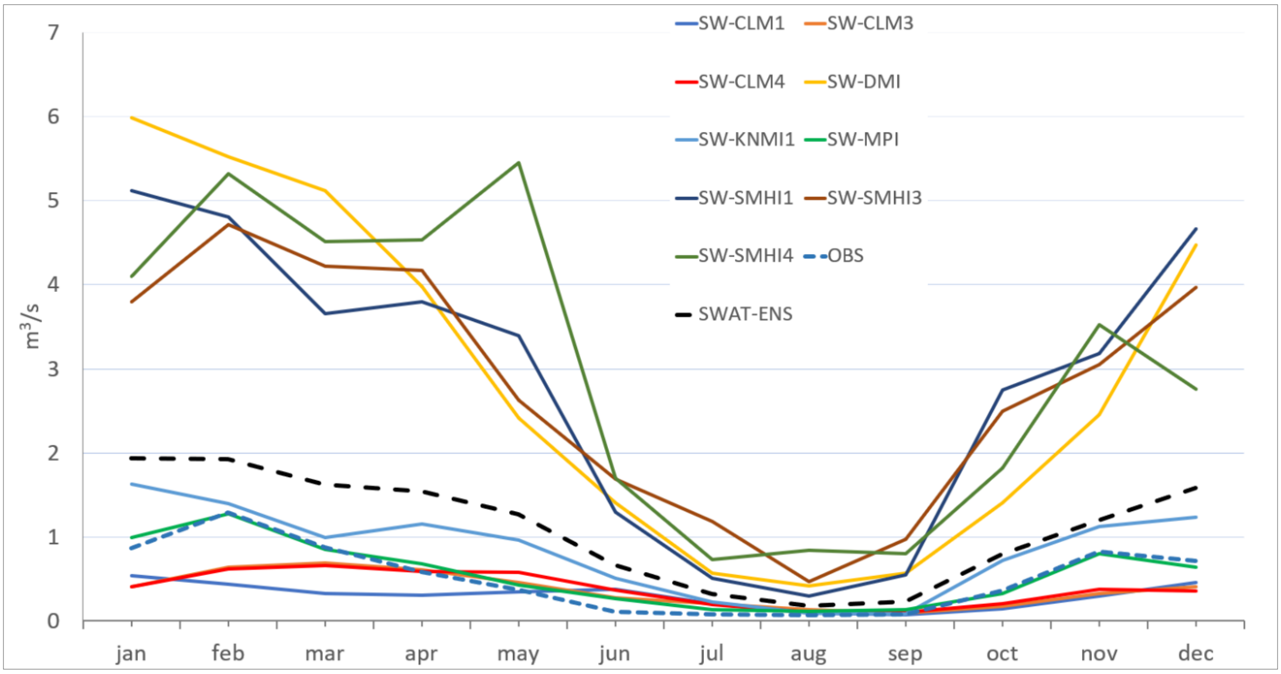


Figure 15 - SWAT monthly mean outflow (1985-1992) under different GCM-RCM forcing at the RMF gauge. ENS flow refers to the weighted outflow, calculated using the same weights of the relative forcing climate model .

A first comparison of the RMF outflows was analyzed for the period of observation 1985-1992 in order to compare the annual cycle of the different SWAT models against the observed streamflow at the measurement gauge.

SWAT Models' outputs show huge biases in some cases (SW-SMHI4, SW-SMHI3, SW-SMHI1 and SW-DMI), while SW-MPI shows the best agreement, followed by SW-CLM1, SW-CLM3, SW-CLM4 and SW-KNM1. As the KNM1 model has the highest weight in the ENS (15.8%, normalized to 28.8%), the SW-ENS outflow has a similar monthly cycle as the SW-KNMI1 outflow, with an overestimation of the discharge that in winter can reach large values (above 200%). The Nash-Sutcliffe (NS) index was also calculated for the different SWAT - RCMs combinations (Table 5).

Table 5 – NS scores of SWAT model forced by the climate models

	SW-CLM3	SW-CLM1	SW-CLM4	SW-MPI	SW-KNMI1	SW-SMHI3	SW-DMI	SW-SMHI1	SW-SMHI4	SW-ENS
NS	0.04	0.03	0.01	-0.3	-0.58	-15.8	-19.37	-19.61	-20.76	-0.28

The NS score of the best performing SW-RCMs (SW-CLM1, SW-CLM3 and SW-CLM4) is around 0, meaning that models are performing only as well as the mean target value used for prediction, according to literature (Abbasspour et al., 2007; Moussa, 2010). A disagreement between best performing RCMs for precipitations and the best performing SW-RCMs combinations. For example, the less performing RCM used within the Ensemble, MPI (normalized weight 1.75%), is one of the best performing RCMs when coupled with SWAT (SW-MPI NS=--0.3). The NS score of the SW-ENS model is -0.28, indicating a limited reliability for future hydrological projections, due to the high number of uncertainty sources.

Figure 16 shows the comparison between historical (1976-2005) and future (2071-2100) model's monthly mean outflow at the control point of RMF, for the SW-ENS model. A general decrease of the monthly mean discharge is expected, according with the future projections, attaining to an average of around -25%. The main loss is projected for spring months, in particular for May in which the flow is reduced of around -40% (1.02 m^3/s for reference period against 0.62 m^3/s in the future).

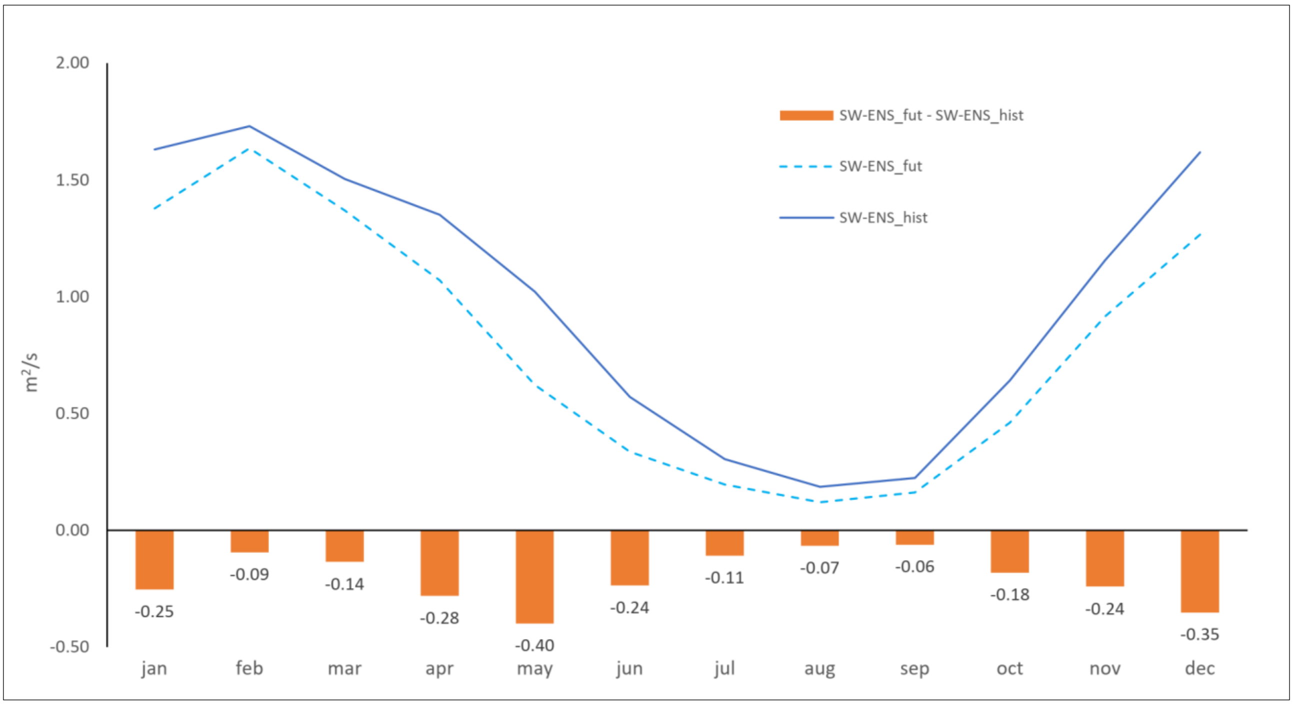


Figure 16 - SW-ENS outflow of RMF: historical (1978-2005) against future (2071-2100) annual cycle and differences between SW-ENS_hist and SW-ENS_fut (orange bars)

Analyzing the RSG catchment (Figure 17), the comparison between historical (SW-ENS_hist) and future (SW-ENS_fut) periods shows that outflow decreases of around -18% on average in the future run, in particular from January to May, ranging from -0.10 m^3/s to -0.13 m^3/s loss. A future scenario (SW-ENS_fut_NOPS) that simulates the outflow after removing the two point sources from the catchment is also shown (Figure 17): the contribution the point sources is around 0.05 m^3/s and in very dry periods it represents the only inflow in RSG.

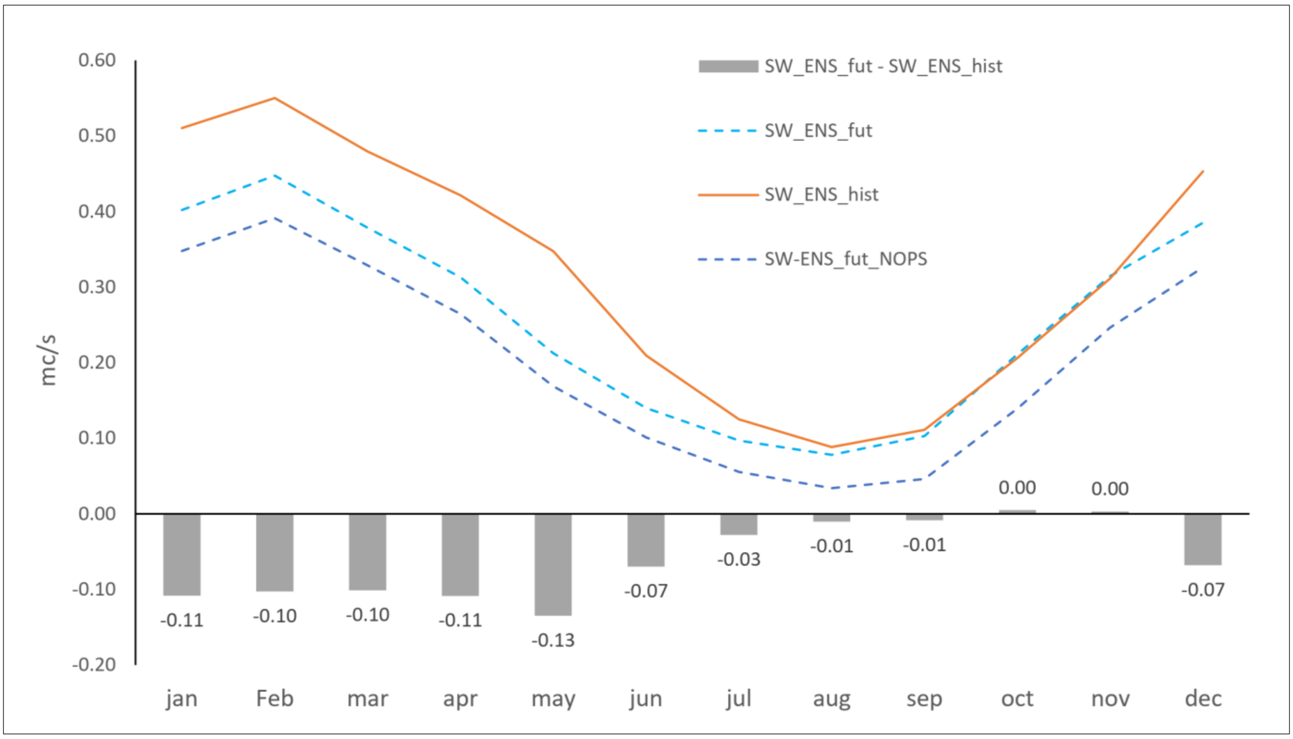


Figure 17 - Comparison between annual streamflow cycle at the RSG outlet for past (SW-ENS_hist), future (SW-ENS_fut) and future removing point sources discharge (SW-ENS_fut_NOPS). The grey bars represent the relative difference between SW-ENS_fut and SW-ENS_hist.

Analyzing the models which, within the ENS signal, scored the best NS index (SW-MPI, SW-CLM1, SW-CLM3, SW-CLM4 and SW-KNM1) is notable that all the models predict a significant decrease for winter and spring seasons (Figure 18), except SW-CLM1 that predicts a sensible increase for January and February.

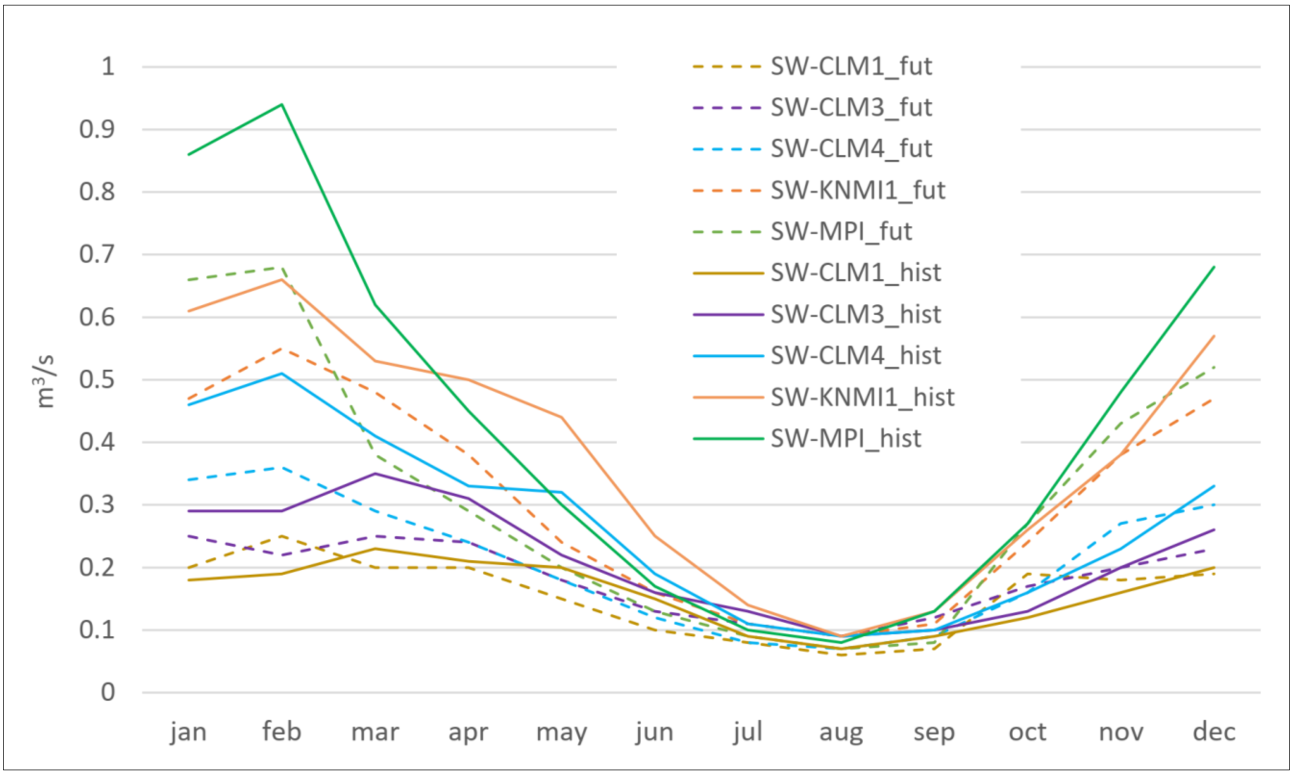


Figure 18 - Monthly mean outflow comparison between SWAT simulations, forced by the best performing SWAT/Euro-CORDEX coupled models, for historical period (1976-2005, continuous lines) and future (2071-2100, dashed lines)

Summer and autumn are expected to be dryer, except for SW-MPI that projects an increase of the precipitation for October, probably related to extreme events. Nevertheless, it should be taken in account that MPI climate model was the less performing model within the ENS, while it showed a very good agreement in resulting outflow when coupled with SWAT model. Hence, this model has to be carefully considered for future projections, taking into account its tendence to overestimating the precipitation in the south west of the island, as highlighted in Figure 7.

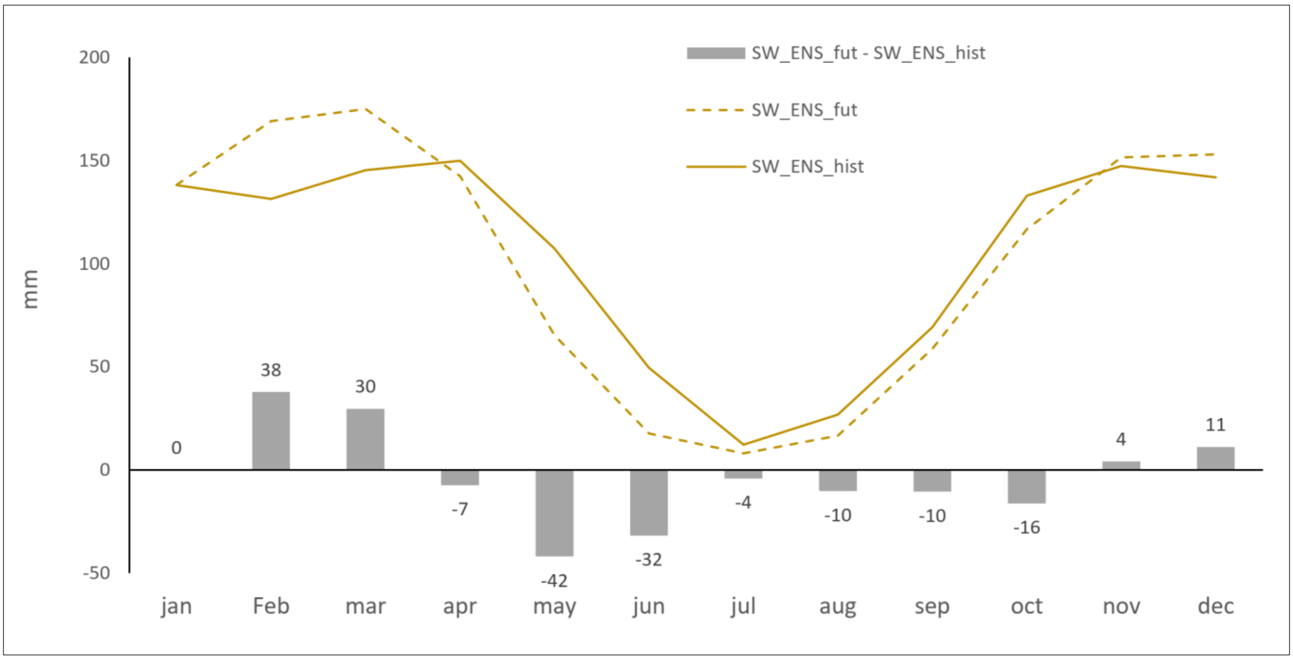


Figure 19 - Comparison between monthly mean surface runoff calculated over RMF basin for past (SW-ENS_hist) and future (SW-ENS_fut) and relative differences (grey bars)

Runoff was calculated by SWAT over the RMF basin (Figure 19) and RSG basin (Figure 20) as mm of water generated in each subbasin averaged on a monthly basis. Runoff in the RMF basin decreases in the future projections from April to October, with the highest absolute loss of -42 mm in May (-39 %) and the highest percent loss of -64 % in June (-32 mm). A significant rise of +38 mm (+29%) is predicted for February and +30 mm (+20 %) for March. The increase of the mean runoff in February/March together with a decrease of the mean outflow could be related to the extreme precipitation events, analyzed at daily resolution in previous section 3.4 Changes in extremes, that cause a very rapid response of the basin that cannot be highlighted at monthly timestep.

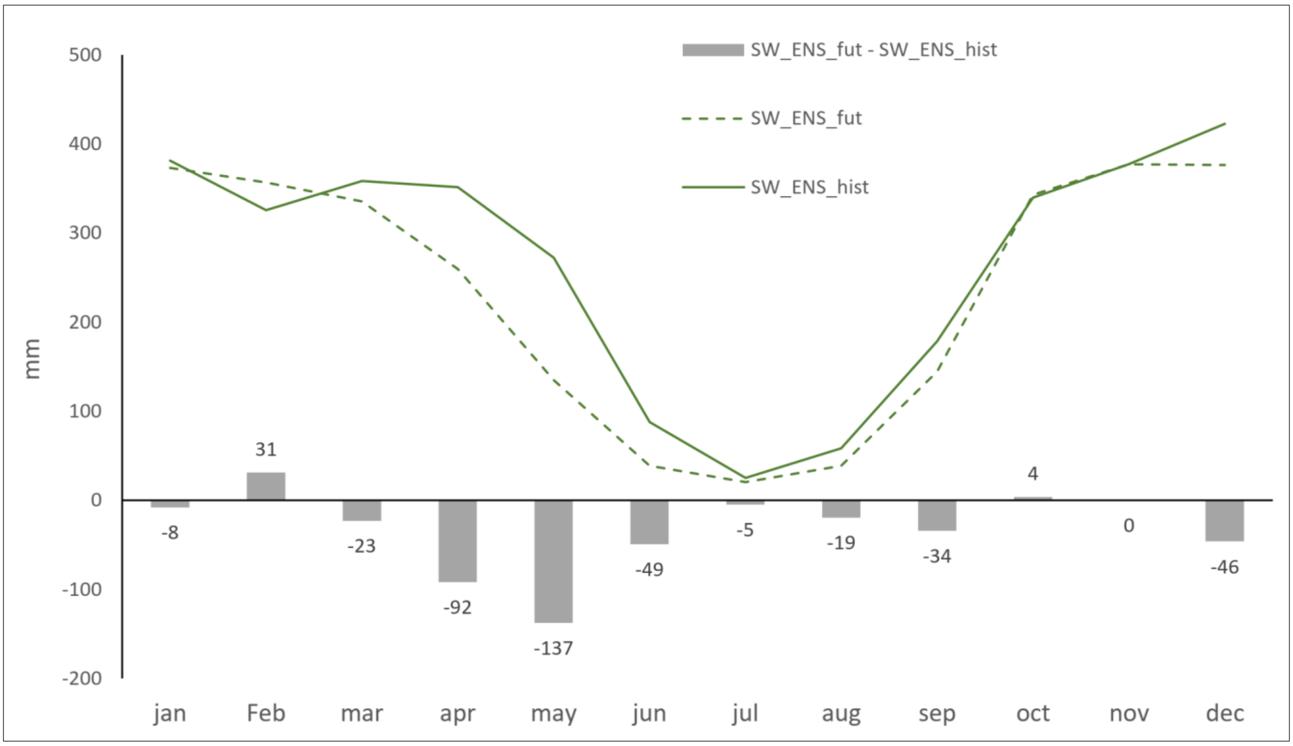


Figure 20 - Comparison between monthly mean surface runoff calculated over RSG basin for past (SW-ENS_hist) and future (SW-ENS_fut) and relative differences (grey bars)

In RSG basin, projections of runoff budget highlight a mean decrease of -18%, with the highest absolute loss of -137 mm (-50%) in May and the highest percentage loss of -56 % in June (39 mm against the historical mean of 88 mm). Despite the small spatial difference between the two basins, the increase of runoff that is predicted for RMF basin is not so pronounced in RSG basin where only a rise of 31 mm (+10%) is noticeable in February.

4 Conclusions

In this study, a weighted multi-model ensemble, composed of different climate models of the EURO-CORDEX experiment (RCP 8.5 emissions severe scenario) was built and used as climate forcing for the SWAT hydrological model. First, a climate model analysis was performed through the comparison between modeled and observed rainfall for a historical reference period (1979-2008), using several statistical indexes (Bias%, MAPE, Normalized Standard Deviation, Wilmott-D Score, Spatial Correlation, S score and Yule-Kendall index). This analysis allowed to build a weighted multi-model ensemble (ENS) through model ranking based on their performances against observed rainfall. The analysis of historical simulations revealed that the ability of RCM models to reproduce local precipitation, such as the precipitation at small scales in regions with uneven orography, is still a bit limited, as reported also by Mascaro et al. (2018). Future climate-change-signals project a general decrease of mean precipitation up to -20 to -25 %, in particular in the South-West area, while in summer and autumn a small increase of precipitation (5%-10%) is projected for the East and South-East regions.

An increase of precipitation events above 20 mm is projected, with different patterns: events above 20 mm regard mainly the North-West and the Campidano plain, while extreme events increase is more pronounced in the East side and in the southern capes, with rises of +30 %.

The SWAT model was implemented in a sub-domain of the Sardinian Island, specifically in two catchments located in the South-West region. Firstly, SWAT was run using observed rainfall, thus it was calibrated and validated against observed streamflow; subsequently SWAT was forced by the EURO-CORDEX models for the analysis of future outflow and runoff. A general disagreement between the performances of RCMs and SWAT-RCMs couples was noticed: best performing RCM, when coupled with SWAT, do not simulate properly the observed outflow. Moreover, some of the RCMs, such as SW-MPI and SW-CLM3, despite having bad skills in reproducing precipitation, show best NS indexes when coupled with SWAT for the simulation of the outflow. This reflects well the uncertainty caused by low-quality observations, SWAT model implementation/calibration and in EURO-CORDEX models' performances in the complex orography of Sardinia.

Future projections predict a general decrease of -20% of mean outflow in both RMF and RSG catchments. In RSG catchment the planned stop of wastewater (around 0,05 m^3/s on average) would further affect the streamflow regime, as simulated in Figure 17.

The surface runoff, which is the main contribution to the natural flow of the studied streams, is predicted to decrease up to -60 % in spring months according to the future projections. In RMF, a rise in runoff in February and March and December is predicted, while a diminution is projected for the rest of the year (-12% on average). In RSG basin runoff mean decrease is -31%, with a small increase for February. This could drastically affect the RSG streamflow when, in the future, wastewaters will be addressed to a different basin.

However, the reliability of these projections is limited, and more accurate projections can be performed only reducing the incoming uncertainties in the hydro-climate model chain. Model capabilities could be improved with the collection of more accurate data, such as precipitation and more streamflow measurements. Furthermore, also the different domains of the climate model analysis, that was carried out for the whole island, and the SWAT model simulations, limited to 2 small catchments, must be taken into account when evaluating the performances. The described model chain could hence become a very powerful tool for water and basin management decision-making.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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