Water resources management in the Medjerda basin (Tunisia):

assessment of hydrological impacts of climatic change in the Siliana and Béja catchments

Haykel Sellami[1], Marnik Vanclooster[1*], Slaheddine Khlifi[2],

Ahlem Gara[2], Raouf Mahjoub[2]

1 : Université catholique de Louvain (UCL), Earth and Life Institute/Environmental Sciences (ELIE), Louvain-la-Neuve, Belgique.
2 : Ecole Supérieur d'Ingénieurs en Equipement Rural (ESIER), Mjaz El Bab, Tunisie.

*Contact : marnik.vanclooster@uclouvain.be

1. Introduction

Under the current conditions, water resources in Tunisia are intensively exploited and mobilized to meet the increasing demands of all water users. While these resources are limited, approximately estimated to 4,5 Milliards of m^3, more than 50% of the total volume of renewable water is withdrawn and mainly used for agricultural purposes (80%). With almost 11 Million of inhabitants, the average of the annual available water volume per person is about 470 m^3 which is clearly below the threshold of water scarcity sets to 500 m^3/inh/year. Furthermore, water resources are unevenly distributed within the country. About 56% of available waters are surface waters against 44% of groundwater including deep and shallow aquifers. In addition, more than 80% of surface water is mainly from the North, 12% from the center and 8% from the south. One of the most important watercourses in Tunisia is the Medjerda. This river basin covers an area about 23,700 km^2 and extends from across the border in Algeria up to the Gulf of Utica (Fig. 1). About 32% of the basin falls within Algeria and 68% in Tunisia (16,100 km^2).

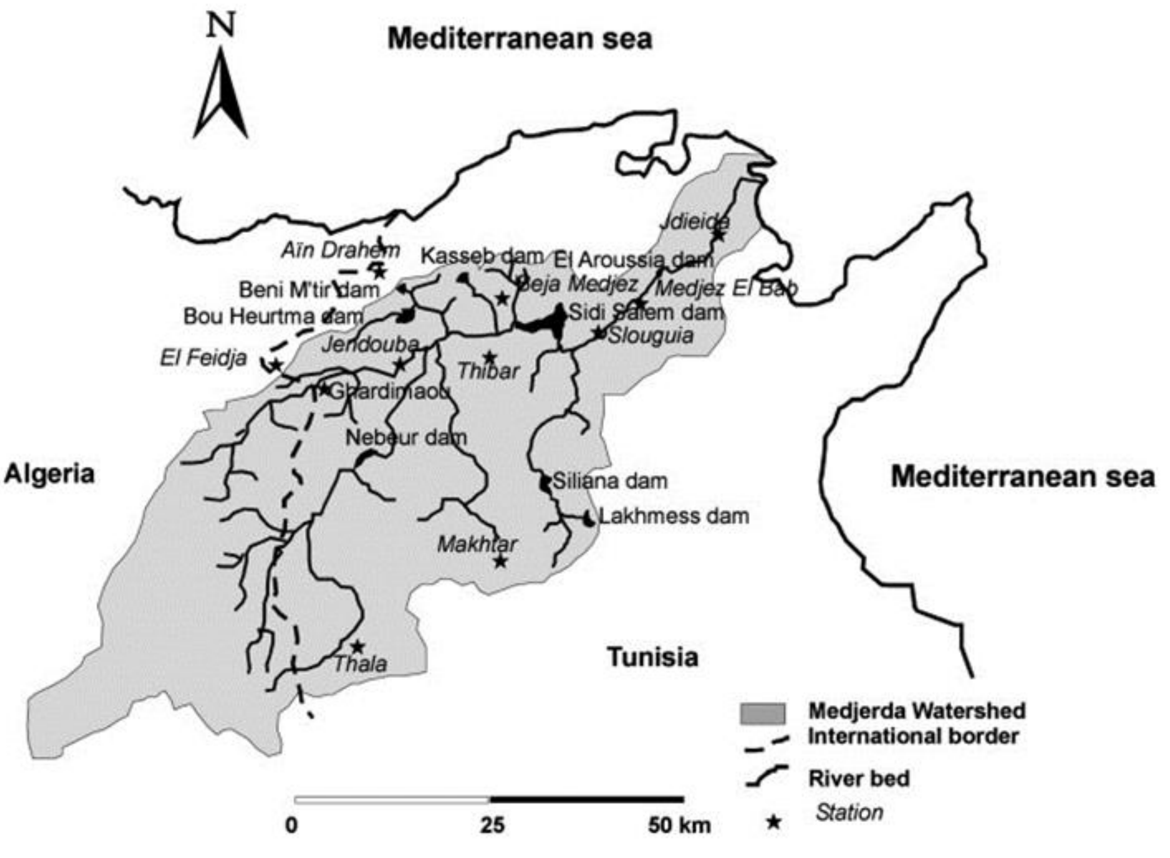

Fig.1. Map of the Medjerda basin (adopted from Zahar et al., 2008)

The waters of the Medjerda represent nearly 37% of Tunisia's surface waters and supply water to more than half of the Tunisian population (5.5 million inhabitants out of 10 millions). The food security of the entire country relies on it. More than 13% of the Tunisian population lives along the river and its tributaries. Agriculture is the primary economic activity in the basin, providing the bulk of production and employment (35%) and occupying an essential place in the national strategy for food security. Within the basin itself, 90,000 ha are irrigated with water from the Medjerda (Zahar et al., 2008). Therefore, the management of the water resources in the Medjerda basin has been a real issue and one of the priorities for the Tunisian local, regional and national authorities. It has been fully integrated within the national water strategy which has been based on a maximum mobilization and control of renewable waters through an extensive construction of reservoirs. Within this perspective, eight dams controlling a total water volume of 1 billion m3 have been construed within the Medjerda basin. Additional reservoirs are also projected. These dams are interconnected by a network of channels to transfer water in between dams and regions, regulate the quantity and quality of water stocked in each reservoir and ensure a supply of water during dry years. Besides these dams, many others small superficial and temporary hydraulic structures (e.g. artificial lakes) are built in the Medjerda basin and its tributaries to store water for drinking and irrigation purposes. In addition, soil erosion has been the challenge to overcome for many centuries. Several soil conservation techniques and runoff water-harvesting systems (e.g. locally called *jessour and tabias*) have been developed to capture surface water for crop production and attenuate floods and their soil erosive power. Evidences for the impact of such human disturbances on streamflow have been widely demonstrated (Zahar et al., 2008; Oussar et al., 2009). While this is controlled insofar as possible in the Medjerda, the diversity and their heterogeneity in scale (from large dams to small *jessours*) of those human influences cannot be ruled out in the management of the water resources.

Besides human influences, climatic change is expected to be an additional threat to water resources. At the Mediterranean scale, changes in climate are expected to manifest through drier and warmer conditions leading to a reduction in fresh water availability, more exacerbating forms of water pollution and modification of the magnitude, timing and seasonal distribution of river flows (Ludwig et al., 2010, 2011; Schneider et al., 2013). So, it is normal to assume that the Medjerda river flows will be prone to similar changes. The study elaborated by the Tunisian Ministry of Agriculture and Hydraulic Resources in 2007 was based on the projection of the HadCM3 regional model underpinned with the A2 and B2 emission scenarios (IPCC, 2007) for 2020s (2011-2040) and 2050s (2041-2070) for the entire country. This study indicated that temperature will increase by 0.8°C while annual precipitation will drop by -5% for 2020s with respect to the reference period of 1961-1990, in the North of Tunisia and the region of the Medjerda basin. However, these changes will further amplify in 2070s leading to a reduction of -11% for precipitation and an increase in temperature of 1.7°C in the Medjerda region. Despite climate model projections are recognized to be the largest source of uncertainty in modelling the hydrological impacts of climatic change (Arnell, 2011; Teng et al., 2011; Kwon et al., 2012), these predictions are not associated with their degree of uncertainty as they rely on a single climate model projections. Therefore, there is a little knowledge and much debate as to how climate change will manifest itself and what the effects will be on the water availability in the Medjerda basin. The need to consider more than on climate models downscaled and bias corrected using local observation is apparent for assessing hydrological impacts of climatic change in the Medjerda basin to provide more robust predictions.

This report focuses on quantifying the impacts of climatic change on the flow regime of two main rivers, Siliana and Béja, of the Medjerda basin.

2. Approach for modelling the hydrological impacts of climatic change in the Medjerda

The following flowchart summarizes the general modelling approach followed for assessing the hydrological implications of climatic change in the Medjerda. It consists of four steps which are developed in details in the next sections.

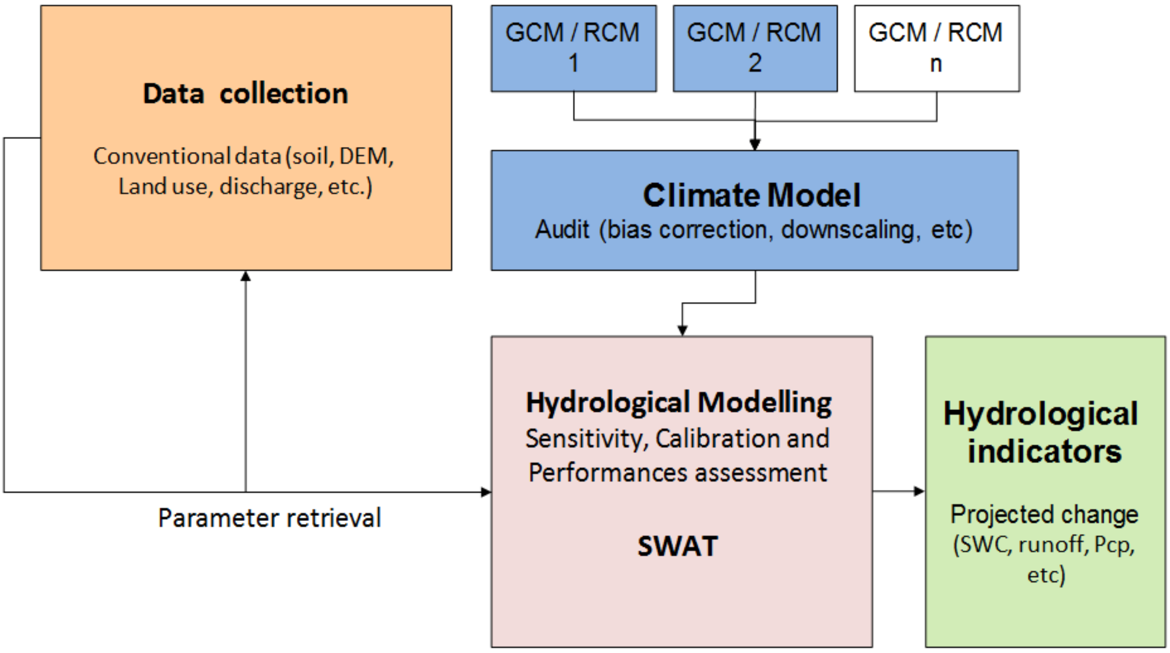

Fig. 2. Conceptual framework for assessing the hydrological impacts of climatic change in the Medjerda

2.1. Step I: data collection

During this step necessarily data including hydrometeorological data, image data, land use and soil maps, etc. for implementing physically based hydrologic model in the Medjerda have been collected. As these data are not always 'standard' available from literature or government organizations, description files including data origin, resolution, provider, quality, etc., were created and associated with each data. A harmonization work was necessary to mitigate gaps and deficiencies in the collected data. A Medjerda data repository was created and stored on DROPBOX server. It provides an access to the reference data that should be used in the project to reduce uncertainty when driving hydrological models. In addition, a literature survey has been conducted and the collected publications (scientific publications, technical reports, etc.) have been added to the reference repository. However, this early data availability assessment revealed serious informational, temporal and spatial hydrometeorological data gaps which may hinder the understanding of the hydrological processes in the Medjerda. More efforts on developing specific field monitoring programs coupled with novel techniques (e.g. remote sensing) are needed to consolidate this database.

2.2. Step 2: hydrological modelling

2.2.1. Selection of the hydrological model

Hydrologic models are essential tools to carry out climate change impact studies. To date, several models have been used to predict hydrological impacts of climate change all over the world under different climatic conditions. However, in Mediterranean catchments a broad set of requirements is imposed on the selection of the hydrological model. These requirements include the applicability of the model for large and small spatial scales, like river basins, and for long time scales, in view of climate change impact assessment. Furthermore, it should be flexible to deal with poor quantity and quality of data. When the aim of the study is to deliver the modelling results to assist practical implementation of water resources management in the catchment, the hydrological model needs to be able to deal with the spatial heterogeneity of the catchment physiography, represent the physical processes and provide results in a distributed way. The computational cost is also an important factor in the selection of the hydrological model in particular when long-term impact of climate change is to be assessed. The latter requirements call for a physically based and spatially distributed hydrological model. Among the wide existing panoply of physically based and spatially distributed models, the Soil and Water Assessment Tool (SWAT) was selected for this study for the following reasons.

SWAT is embedded within a GIS environment thus physically based inputs both spatially and temporally can be easily incorporated within the model to simulate a set of comprehensive processes such as surface runoff, infiltration, soil percolation, evapotranspiration, groundwater flow, etc. Although SWAT requires large amount of input data, the model has demonstrated good performances in predicting hydrological variables (e.g., discharge) and processes in Mediterranean catchments (Sellami et al., 2013, 2014) including the Medjerda (Bouraoui et al., 2005).In addition, many SWAT parameters can be retrieved automatically using the GIS interface and meteorological information combined with rich soil and land use parameters internal databases. These parameters are assumed to have physical meaning and, thus, reflect the physical processes occurring within the catchment. These are the motivations, among others, for selecting the SWAT model in this study.

2.2.2. Description of the SWAT model

SWAT is a continuous-time and physically based hydrological model. developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex catchments with different soil, land use and management conditions over long periods of time (Eckhardt et al., 2005). The hydrological model operates by dividing the catchment into subbasins. Each subbasin is further discretized into a series of hydrologic response units (HRUs), which are unique soil-land use combinations. Soil water content, surface runoff, nutrient cycles, sediment yield, crop growth and management practices are simulated for each HRU and then aggregated for the subbasin by a weighted average.

Water in each HRU in SWAT is stored in four storage volumes: snow, soil profile, shallow aquifer, and deep aquifer. Surface runoff from daily rainfall is estimated using the Soil Conservation Service curve number (CN) method (SCS, 1972) which estimates the amount of runoff based on local land use, soil type, and antecedent moisture condition. Calculated flow, sediment yield, and nutrient loading obtained for each subbasin are then routed through the river channel using the variable storage or Muskingum method. The catchment concentration time is estimated using Manning's Kinematic Equation, considering both overland and channel flow. The soil profile is subdivided into multiple layers that support soil water processes including infiltration, evaporation, plant uptake, lateral flow, and percolation to lower layers. The soil percolation component of SWAT uses a water storage capacity technique to predict flow through each soil layer in the root zone. Downward flow occurs when field capacity of a soil layer is exceeded and the layer below is not saturated. Percolation from the bottom of the soil profile recharges the shallow aquifer. The amount of water entering the shallow aquifer is a function of the total water volume exiting the soil profile and an exponential decay function to account for the recharge time delay. The latter is depending on the overlying geologic formations. If the depth of the shallow aquifer increases above the user defined threshold value, it is assumed that groundwater discharge is occurring and contributing to the reach. Upward flow movement to the overlaying unsaturated soil layers is simulated by routing water from the shallow aquifer storage component to the soil by capillary pressure or by direct absorption by the plant roots. The model computes evaporation from soils and plants separately. Potential evapotranspiration can be modelled with three options available in SWAT, that is, Penman-Monteith, Priestley–Taylor and Hargreaves methods (Neitsch et al., 2005), depending on data availability. Potential soil water evaporation is estimated as a function of potential ET and leaf area index. Actual soil evaporation is estimated by using exponential functions of soil depth and water content. Plant water evaporation is simulated as a linear function of potential evapotranspiration, leaf area index, and root depth, and can be limited by soil water content. More detailed descriptions of the SWAT model can be found in Neitsch et al., (2005).

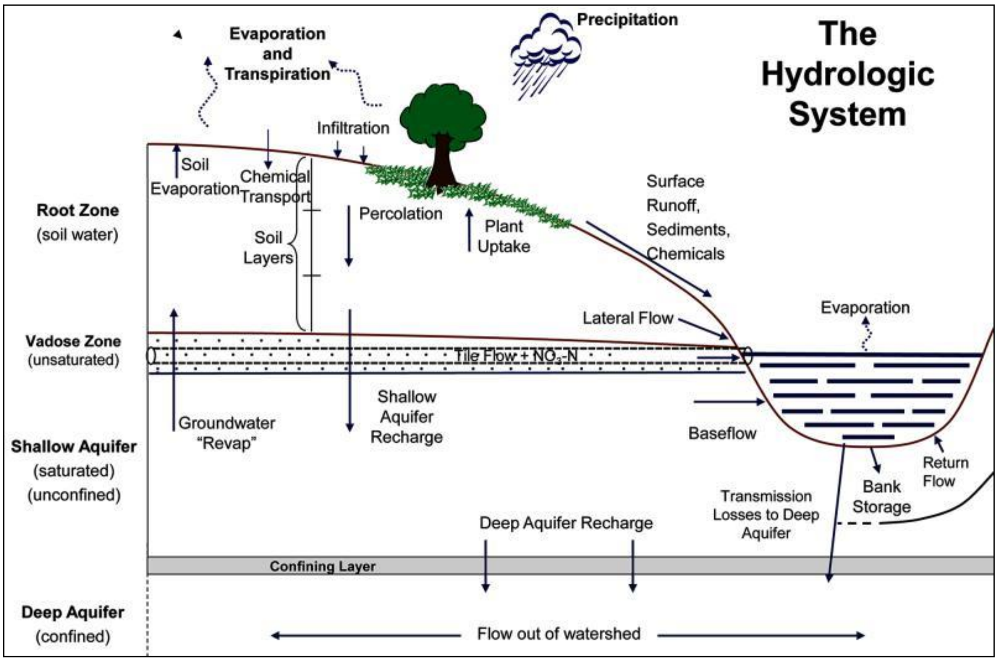

Fig. 3. Conceptualization of the hydrological cycle in the SWAT model (Source: Soil and Water Assessment Tool, Theoretical documentation, Version 2009. http://twri.tamu.edu/reports/2011/tr406.pdf)

2.2.3. Implementation of SWAT model on the Medjerda

SWAT was implemented on two important catchments of the Medjerda basin, namely the Siliana and Béja. Table 1 reports some physical characteristics of both catchments.

Table 1. Some characteristics of the Silaian and Béja catchments

Characteristics	Siliana	Béja
Area (ha)	205248.9516	20670.9675
Elevation (m) [min-mean-max]	[83-511.45-1296]	[134-328.91-710]
Dominant land use	Pine and garrigue	Whinter wheat and garrigue
Dominant soil	calcareous brown soil	Vertisol
Dam capacity (billion m^3)	Initial =70, actual=53	N.a
Average rainfall (mm/year)	430	
Average temperature (°C/year)		

Two types of data are required for the implementation of the SWAT model; time series climatic data and spatial data. Climatic time series data including precipitation, maximum and minimum temperatures, solar radiation, air relative humidity, and wind speed, are generally required on a daily time step. Air relative humidity is required if the Penman-Monteith or the Priestly- Taylor evapotranspiration routines are selected. Wind speed is only necessary if the Penman-Monteith method is used. Measured or generated sub-daily precipitation inputs are required if the Green and Ampt infiltration method is selected. The maximum and minimum temperatures are used to calculate daily soil and water temperatures. Generated weather inputs are calculated from tables consisting of 13 monthly climatic variables, which are derived from statistics of long-term measured weather records. Table 1 gives an example of the required data as well as their resolution, provider, etc. for the Siliana catchment.

Table 2. Data for implementing SWAT on the Siliana catchment

Data	Resolution	Provider
Precipitation	Daily(1979-2009)	**7** Stations (Bargou, Bousalem, Bouarada, Bargou, Makthar, touboursouk, Siliana) Source: **DGRE* (Tunisia)**
Temperature	Daily(1979-2009)	**9** climatic stations (SWAT generated 22 Km grid). Source: **http://swat.tamu.edu/**
Wind, Solar radiation, Humidity	Daily(1979-2009)	**9** climatic stations (SWAT generated 22 Km grid). Source: **http://swat.tamu.edu/**
D.E.M	30 m	SRTM
Soil	1:50000	Soill map (**Ministry of Agriculture, Tunisia**); Soil parameters (**Sellami, 2014**)
Land use	1:50000	Land use map (**Ministry of Agriculture, Tunisia**); Land use class parameters (**SWAT model crop database**)
Discharge	(9/1999 to 8/2008)	**DGRE (Tunisia)**

* DGRE: Division Générale des Ressources en Eau

Note that for both catchments, measured weather data related to daily temperature, solar radiation, wind and air relative humidity were not available. Therefore, they have been extracted for both catchments from the generated climate data of the National Centers for Environmental Prediction’s Climate Forecast System Reanalysis (CFSR). The CFSR weather is produced using cutting-edge data-assimilation techniques (both conventional meteorological gauge observations and satellite irradiances) as well as highly advanced (and coupled) atmospheric, oceanic, and surface-modeling components at ~38 km resolution (Saha et al., 2010). This indicates that the production of CFSR data involves various spatial and temporal interpolations. Therefore, it is uncertain whether these data would yield similar climatic results to the conventional weather data at the extracted locations. In order to check the accuracy of the CFSR generated data, the latter are compared to the measured precipitation of the Rarey catchment which is also in the Medjerda basin. The results indicated that observed precipitation are satisfactorily reproduced by the generated CFSR data especially for daily precipitation with probability of exceedance lower or equaled than 10% (Fig. 4). However, the discrepancy between the CFSR and measured precipitations starts to increase for exceedance probability higher than 50%. As flows in the Medjerda rivers are mainly generated by heavy rainfall events, CFSR data can be used whenever observation data are lacking in the Medjerda.

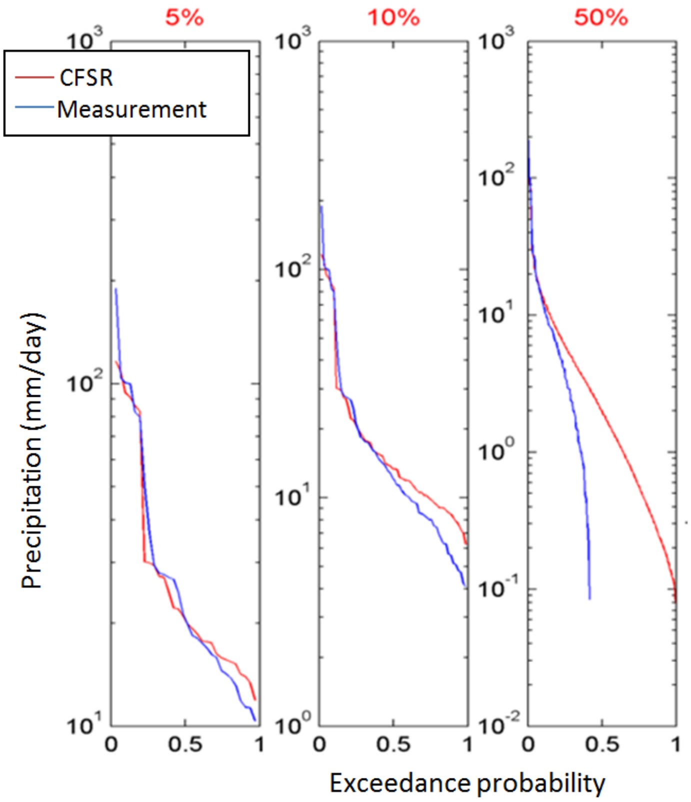

Fig. 4. Comparison between CFSR and measured precipitation at the Rarey catchment

For the Siliana and Béja catchments, the modified SCS curve number method is chosen for surface runoff volume computing. The variable storage coefficient method is selected for the flow routing through the channel and potential evapotranspiration is estimated by the Penman-Monteith method. For the Siliana catchment, discharge simulations were conducted for 11 years starting from 1998 while for the Béja catchment the simulation time period extents from 2006 to 2011. The model simulation time period for each catchment was selected since it covers the time period of the available measured discharge. To minimize the effects of the initial state of the SWAT variables on the river flow, a warming-up period of two years was considered in both catchments.

2.2.4. SWAT model calibration

Model calibration is the process of adjusting the values of model parameters such that the hydrological behaviour of the catchment can be closely simulated by the model. However, due to the large number of free parameters in the SWAT model the calibration process becomes tedious and challenging. A way to deal with such high-dimensional hydrological model is to conduct sensitivity analysis (SA) to select only sensitive parameters.

Sensitivity analysis (SA)

SA is conducted using the Latin Hypercube (LH) sampling technique, combined with the one at a time (OAT) method. This method is called the LH-OAT and is implemented in the SWAT model (van Griensven et al., 2006). The LH is a stratified sampling without replacement technique which divides the parameter range into *p* (*p*= 10) equal probability intervals. Only one input parameter is modified between two successive runs of the model. Therefore, the change in model output can be attributed to such a parameter modification. The SA will rank the parameters according to their sensitivity importance and thus. Table 3 gives the SWAT parameters selected for SA in the Siliana and Béja catchment.

Table 3: SWAT parameters selected for SA

Parameter	Range of variation	Parameter description [Unit]
ALPHA_BF	V [0 – 1]	Base-flow alpha factor [days]
GW_DELAY	R [-25% – 25%]	Groundwater delay [days]
GW_REVAP	A [-0.036 – 0.036]	Groundwater "revap" coefficient [none]
GWQMN	V [0 – 2000]	Threshold water depth in the shallow aquifer for flow [mm]
CN2*	R [-25% – 25%]	SCS CN II value [none]
ESCO	V [0– 1]	Soil evaporation compensation factor [none]
EPCO	V [0 -1]	Plant uptake compensation factor [none]
SURLAG	V [1 – 24]	Surface runoff lag time [days]
CH_N2	V [0.1 – 0.3]	Manning's n value for main channel [none]
CH_K2	R [-25% – 25%]	Channel effective hydraulic conductivity [mm/hr]
SOL_AWC	R [-25% – 25%]	Available water capacity [mm/mm soil]
SOL_K	R [-25% – 25%]	Soil hydraulic conductivity [mm/hr]
SOL_Z	R [-25% – 25%]	Soil depth [mm]
SOL_ALB	R [-25% – 25%]	Moist soil albedo [none]
SLOPE*	R [-25% – 25%]	Average slope steepness [m/m]
SLSUBBSN	R [-25% – 25%]	Average slope length [m]
REVAPMN	V [0 – 500]	Threshold depth of water in the shallow aquifer for ‘‘revap’’ to occur [mm]

The initial parameter is: V = replaced by the sampled value, R= multiplied by the relative percentage; A= added a value.

Parameter calibration

Initially, SWAT parameter calibration was conducted by changing manually the parameter values and comparing model simulation to observation using the Nash and Sutcliffe (NS) criteria (Eq.1).

$$NS = 1 - \frac{\sum_{i=1}^{n} \left(P_i - O_i\right)^2}{\sum_{i=1}^{n} \left(O_i - \overline{O}\right)^2} \tag{1}$$

with O_i is the observed discharge, $\overline{O}$ mean observed discharge values and P_i is the predicted discharge value. The range of NS lies between 1 and −∞ with NS=1 being a perfect fit between model simulation and observation. NS value lower than zero indicates that the mean value of the observed time series would have been a better predictor than the model.

Subsequently, new narrower parameter ranges were identified and introduced for an automatic calibration procedure to locate the “best” parameter set and assess parameter uncertainty. The Sequential Uncertainty Fitting (SUFI-2) (Abbaspour *et al.* 2004) was used for this purpose. This calibration and uncertainty analysis method is an inverse optimization approach that uses the Latin Hypercube sampling procedure along with a global search algorithm to examine the behavior of objective functions. Parameterization is applied to a parameter set rather than to an individual parameter. The initial parameter ranges are updated each iteration, and a narrower parameter uncertainty is obtained. SUFI-2 is iterated (1000 iterations for each catchment) until some statistical criteria expressing the model performances are satisfied. In this case the NS coefficient was selected as objective function in SUFI-2.

2.3. Step 3: climate model auditing

An auditing scheme and bias correction procedures have been developed to reduce uncertainties and provide reliable information at the catchment scale relevant for subsequent hydrological modelling. The selection and subsequent post-processing procedures in this project followed the following routine.

2.3.1. Selection of climate models

The future climatic impact is studied with the help of simulated climate time series, generated by global circulation models (GCM) and regionalized or downscaled by regional climate models (RCM). Two climate models the DMI-HIRHAM5_A1B_ECHAM5 (Danish Meteorological Institute) and the MPI-M-REMO_SCN_ECHAM5 (Max Planck Institute for Meteorology) from the ENSEMBLES project were selected. These climate models are forced with the greenhouse gas emissions scenario (SRES) A1B and provide daily climate projections for the period 1951-2100 on 0.223° resolution as spatial grid. The data of these climate models are stored in NetCdf files and can extracted for each latitude-longitude grid. Within each catchment, three latitude-longitudes coordinate corresponding to high, medium and low altitude have been selected and their corresponding simulated climatic variables (precipitation, maximum and minimum temperature, wind speed, humidity and solar radiation) were automatically extracted via series of developed Matlab programs.

2.3.2. Bias correction

Climate model simulations are subject to systematic bias when are compared to local observation data. This bias was corrected by applying the CDF matching technique for monthly precipitation and temperature. In this technique the empirical Cumulative Distribution Functions (CDFs) of both simulated and observed precipitation for a reference period are constructed for each extracted grid and for each month. The CDFs are then fitted to gamma distributions (Fm and Fo for model and observation, respectively).For each simulated event (M^i) the corresponding cumulative probability (CP_m^i) is found in Fm. In the function used to fit observations (Fo), that cumulative probability (CP_m^i) corresponds to an intensity O^i (Fig. 5).

The simulated intensity M^i is replaced with O^i. Then, this transfer function is applied to the model simulations for the future period.

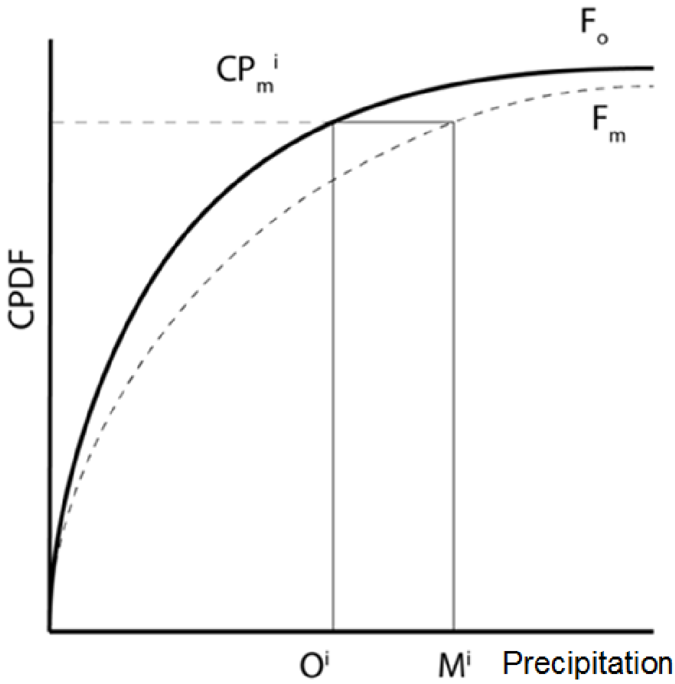

Fig. 5. Schematic representation of the CDF matching technique for climate model bias correction

The examples of monthly original biased and bias corrected precipitation for the Béja catchment provided in figure 6 illustrate that the bias-correction process removes both bias in the precipitation predictions and the tendency of the climate model to over-predict precipitation during the wet months (September-April). The corrected CDFs of the simulated monthly precipitation for the reference period fits better the reference data (observed) in the Béja catchment. Similar results were obtained for monthly precipitation in the Siliana catchment using both climate models (results not shown).

Using the CDF bias correction technique with local observation data allow not only to correct the systematic bias but also to provide climate model simulations at the local scale which are ready to drive the hydrological model for climate change impact assessment. Hence the chain of information for climate impact is: Scenario - emission - GCM - RCM - (bias correction) - impact model.

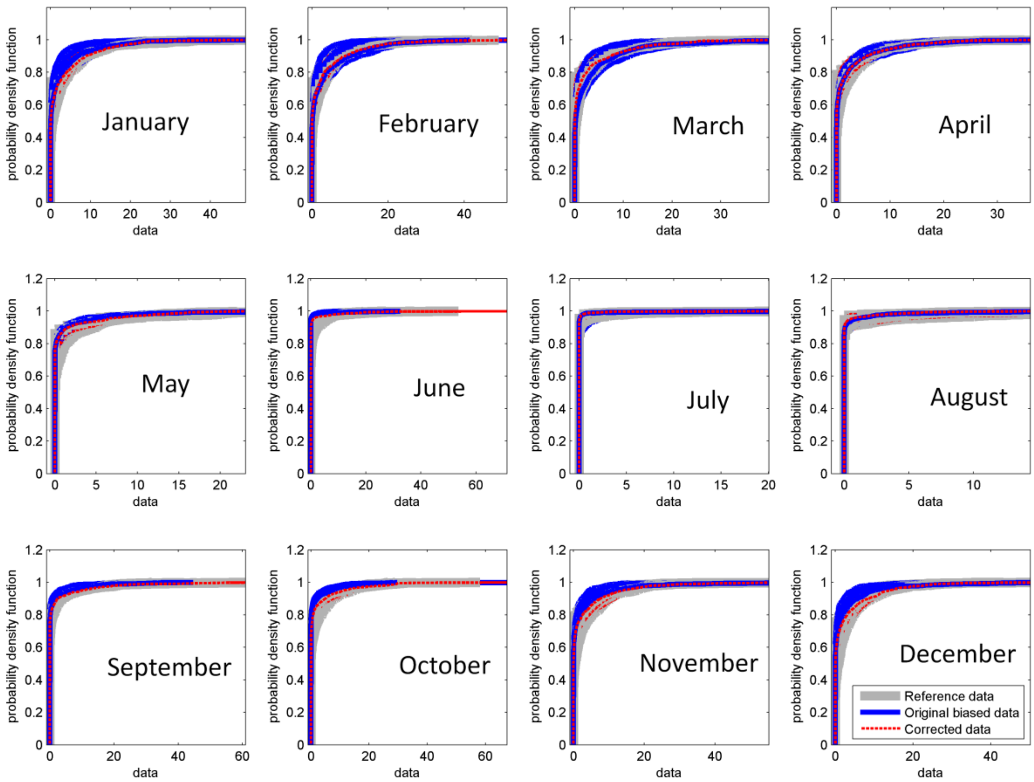

Fig. 6. Comparison of CDFs of original biased, bias corrected as simulated by the DMI-HIRHAM5_A1B_ECHAM5 model, and reference (observation) monthly precipitation for the Béja catchment

2.4. Step 4: hydrologic indicators

Once the meteorological climate models outputs were available they were used to drive the hydrological SWAT model on a daily basis for a reference (1971-2000) and future (2041-2070) periods. Changes in catchment flow regime between these two time periods can be assessed using a broad range of existing hydrologic indicators. A suite of 7 hydrological indicators deemed relevant for the Siliana and the Béja catchments were selected (Table 4). These metrics are able to reflect the projected changes in: (i) climate and meteorological conditions through changes in monthly precipitation and temperature, (ii) changes in catchment hydrological processes by investigating changes in monthly runoff, potential and actual evapotranspiration (PET and ETr, respectively) and soil water content (SWC), and (iii) changes related to flow frequency by analyzing flows magnitude and frequency of 30-years daily flow duration curves, low flow days and high flow days.

Table 4: Selected hydrologic indicators for climatic change impact assessment

Process group	Hydrologic indicator
Climate conditions	- Cumulative monthly precipitation - Monthly temperature
Water balance	- Potential and actual evapotranspiration (ETP, ETr) - Monthly runoff - Soil water content (SWC)
Flow magnitude and frequency	- Number of low flow days per month - Number of high flow days per month - FDC (30 years daily discharge)

For each climate model the projected deviation (Δv, either relative change or absolute difference between the reference and the future period) in the hydrologic indicator (*v*) is calculated and the values are averaged to consider multi-climate models ensemble mean ($\overline{\Delta v}$):

$$\Delta v = \begin{cases} \dfrac{v_{Fut} - v_{\mathrm{Re}f}}{v_{\mathrm{Re}f}} \times 100, & \text{relative change (\%)} \\ v_{Fut} - v_{\mathrm{Re}f}, & \text{absolute change (indicator unit)} \end{cases} \tag{2}$$

$$\overline{\Delta v} = \frac{1}{N}\sum_{i=1}^{N} \Delta v_i \tag{3}$$

with *N* is the total number of climate model members (*N*=2), $\overline{\Delta v}$ is the multi-model mean of the relative change for the indicator *v.* The calculated multi-model mean of long-term climate change projections is used here as the best guess projection. The use of multi-climate model makes model structural uncertainty calculation in the projected magnitude of change possible as follows:

$$\delta_{\Delta v} = \left[\frac{1}{N}\sum_{i=1}^{N}(\Delta v_i - \overline{\Delta v})^2\right]^{1/2} \tag{4}$$

where $\delta_{\Delta v}$ corresponds to the root-mean-square difference of the change in the indicator *v*, and the uncertainty interval around the mean projected magnitude of change is then given by $\overline{\Delta v} \pm \delta_{\Delta v}$ and centered around $\overline{\Delta v}$.

3. ResultsSWAT model calibration and performances

3.1.1. Sensitivity analysis (SA)

The results of the SA of the SWAT model parameters for the Siliana and the Béja catchments are displayed in Table 5. The most sensitive parameter is ranked 1 and the less sensitive parameter is given a rank equals to the total number of parameters.

Table 5. SA parameter ranking for the Siliana and the Béja catchments

Parameter	SA rank for Siliana	SA rank for Béja
ALPHA_BF	6	7
GW_DELAY	10	12
GW_REVAP	8	10
GWQMN	7	3
CN2	1	1
ESCO	4	2
EPCO	12	4
SURLAG	11	11
CH_N2	15	14
CH_K2	2	13
SOL_AWC	5	6
SOL_K	3	9
SOL_Z	9	5
SOL_ALB	13	15
SLOPE	14	8
SLSUBBSN	16	16
REVAPMN	17	17

Parameter ranking with grey shaded area is selected for model calibration

The first ten ranked parameters in each catchment were selected for SWAT calibration. The most sensitive parameter in both catchments was the CN2 which is used to compute runoff depth from total rainfall depth. It is a function of catchment properties that include soil type, land use and antecedent soil moisture condition. ESCO is the soil evaporation compensation factor which directly influences the evapotranspiration losses from the catchment. The importance of this parameter in both catchments is due to the long dry period. Soil parameters related to available water capacity (SOL_AWC), hydraulic conductivity (SOL_K) and depth (SOL_Z) were sensitive in both catchments. These highlight the importance of the soil parametrization for the discharge simulation in the Siliana and Béja catchments. It should be noted here that these soil parameters were derived by Sellami (2014) from literature review and pedo-transfer functions. Hence, they are subject to inherent uncertainty. The CH_K2 parameter was found very sensitive in the Siliana catchment. This parameter expresses the amount of water lost through channel transmission. Many catchments especially in semiarid areas have alluvial channels that abstract large volume of water when the flood wave is traveling downstream. For instance, in a river bed that has been dry for long period, the transmission losses following an event of rainfall is expected to be initially high and decreases progressively. These losses in SWAT are function of the geometry and geomorphologic characteristics of the channel (width, length, CH_K2, Manning's coefficient, etc.). For example, for catchments where the groundwater level is beyond the river bed, there shouldn't be a waste of water via channel transmission and, thus, the value of the CH_K2 should be equal to zero. EPCO is the plant uptake compensation factor and expresses the amount of water needed to meet the plant uptake demand. While this parameter was sensitive in the Béja catchment it was not selected for the Siliana catchment. It is difficult to relate the difference in the parameter rank between two catchments to their physical properties. Among the groundwater parameters, ALPHA_BF which expresses the rate at which the groundwater is returned to the flow was relatively sensitive in both catchments since it shapes the recession flow.

3.1.2. SWAT performances

Although, pprevious studies (e.g. Sellami et al., 2013) showed that SUFI-2 is an efficient parameter optimization and uncertainty analysis procedure with low computational cost, in this work, the automatic procedure did not improved the manual calibration despite the large iteration number of 1000 for each catchments. Therefore, the results of calibration were only restricted to those obtained manually. Figure 7 shows the best SWAT model simulation against the observed discharge of the Siliana (a) and the Béja (b) catchments.

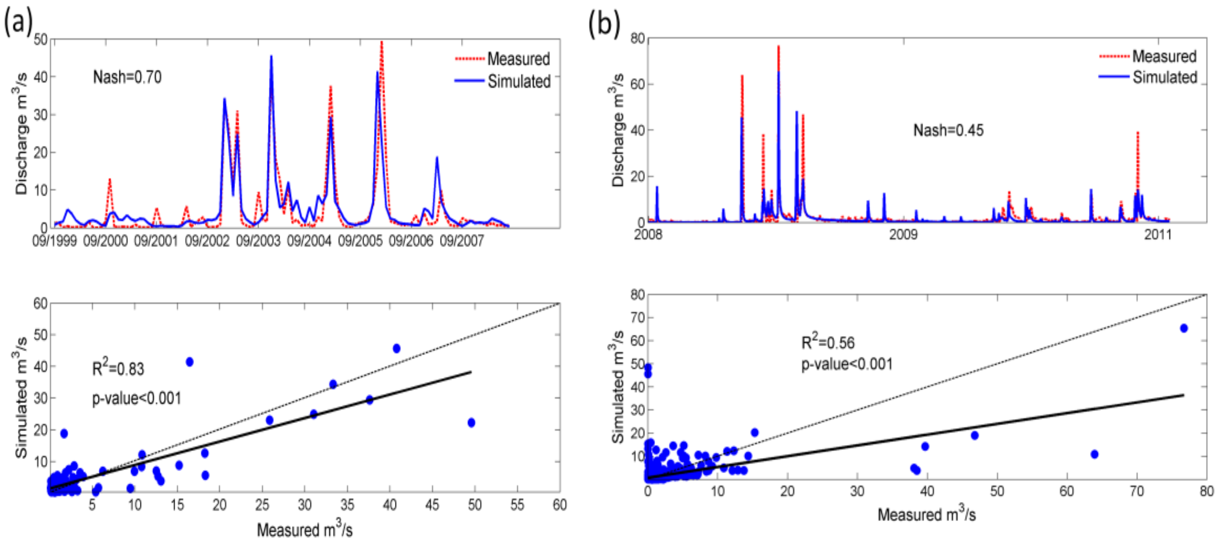

Fig. 7. Measured (red) versus best simulated (blue) discharge for the Siliana (a) and Béja (b) catchments

Although SWAT was able to follow the temporal dynamic of the observed discharge in both catchments, the highest Nash (NS) value between simulation and observation obtained during the calibration process was 0.70 and 0.45 for the Siliana and the Béja catchments, respectively. It should be noted here that SWAT performances in the Siliana catchment were assessed on a monthly basis while for the Béja catchment they were based on daily results. This is because the length of the available discharge time series for the Béja catchment was not enough to conduct monthly analyses.

There is a big difference in the SWAT performances between the Siliana and the Béja catchments. In the former catchment, the largest errors between modelled and observed discharge are in the recession flow (Fig. 7a) while in the Béja catchment, SWAT under-predicts the peak flows. In both catchments, the quality of the measured discharge data could be the reason behind these discrepancies. For instance, Fig. 8 shows the processing steps applied to the observed discharge data of the Béja catchment to derive the daily discharge time series used for SWAT calibration.

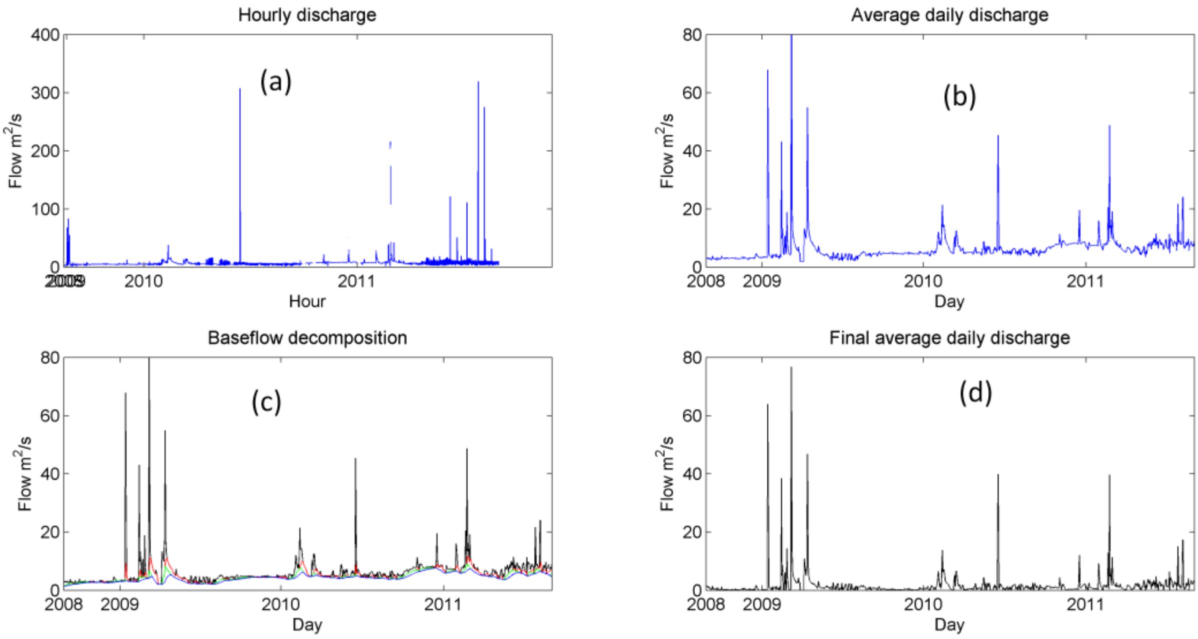

Fig. 8. Observed discharge data processing to derive daily discharge time series for the Béja catchment.

The original discharge data of the Béja catchment were at hourly time step (Fig. 8a). Then, they were averaged to derive daily values (Fig. 8b). This process led to non-zero discharge value time series. The analysis of the discharge data obtained at this stage suggests that there is a sustainable baseflow contribution to the Béja river flow even during summer season (June to August). This was confusing since, according to our knowledge, no groundwater measurements or aquifer characteristics in the Béja catchment were available to check this statement. Therefore, a base flow separation technique based on automated digital filter (Arnold et al., 1995) was applied to the average daily discharge data (Fig. 8c). Subsequently, the baseflow contribution was removed from the data leading to the discharge time series plotted in Fig. 8d which is used for SWAT calibration and performances assessment. So, the calibration and the performances of the SWAT model could be affected by the quality of the discharge data. Indeed, Sellami et al. (2013) showed that quality and uncertainty in the discharge data affect the model performances.

Given the quality of the available input and discharge data, the performances of the SWAT model in both catchments can be considered as satisfactory. Of course other errors in input data (e.g. precipitation) and uncertainty in model parameters can affect the model performances. Therefore, discharge measurement and field data collection and analyses coupled with enhanced methodologies and tools (e.g. remote sensing) are recommended to reduce data uncertainty and, thus, improve hydrological model performances in the Siliana and the Béja catchments.

3.2. Climate model performances

Before assessing the impacts of climatic change it is important to assess the performances of the climate models in reproducing current or past climatic conditions. This was done by comparing climate model bias corrected simulations for monthly precipitation and temperature to the measured ones in the Siliana and Béja catchments (Fig. 9).

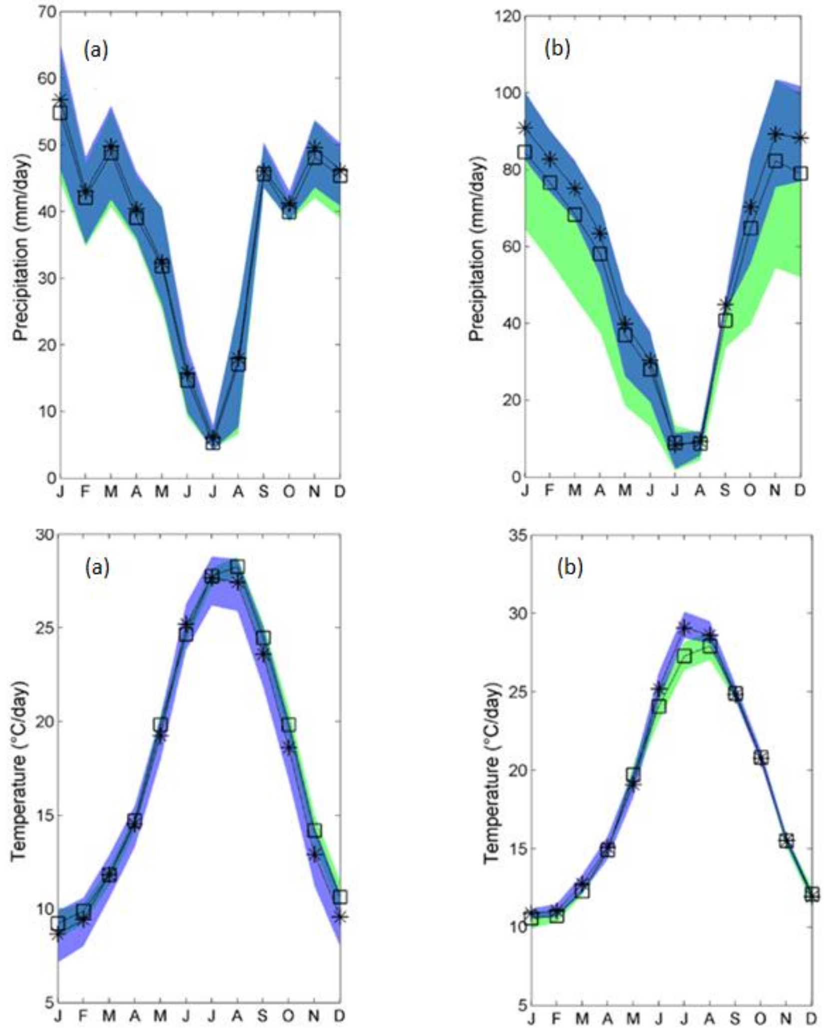

Fig. 9. Climate models bias corrected simulations versus measurements for monthly precipitation and temperature for the Siliana (a) and Béja (b) catchments. The shaded area refers to the variability interval of values extracted at the three spatial locations with green colour for measurement and blue for simulations. The black line with stars refers to the ensemble mean while black line with squares refers to the measurement mean.

The climate models are able to reproduce not only the magnitudes of precipitation and temperature for the reference period (1971-2000) but also the seasonality and monthly variability of the climate over the Siliana and the Béja catchments. The difference between the interval widths of the measured and simulated precipitation in the Béja catchment (Fig. 9b) in comparison to these in the Siliana catchment (Fig. 9a) indicates that climate models are able to better simulate the spatial variability of precipitation in bigger catchment. In addition, as the so-called measured precipitations of the Béja catchment were extracted from the CFSR data they are subject to uncertainty. Nevertheless, climate models have good performances in both catchments, thus, they could be used to drive the SWAT model.

3.3. Projected changes in catchment hydrology

3.3.1. Changes in climatic conditions

Projected changes in climatic conditions for the future period (2041-2070) are assessed by calculating the climate models average relative deviation in monthly cumulative precipitation and absolute changes in monthly temperature with respect to the baseline period (1971-2000) for both catchments (Fig. 10).

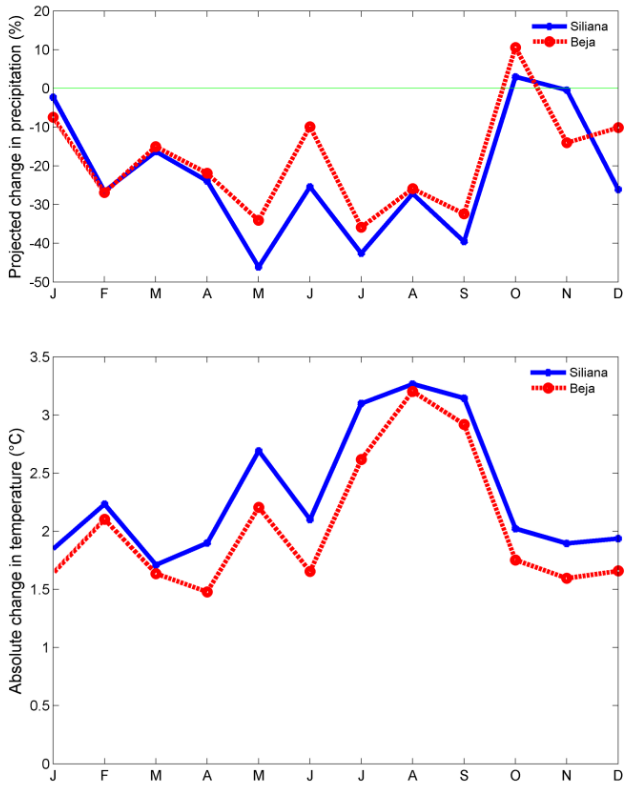

Fig. 10. Climate models average changes in monthly cumulative precipitation (upper panel) and monthly temperature between the reference and the future periods over the Siliana and the Béja catchments

The Siliana and Béja catchments are likely to experience similar climactic patterns towards drier and warmer conditions in the 2050s. In both catchments, climate models project a general decrease in precipitation which is very likely to be more pronounced during the dry season (May to September) the wet season (October to April). Summer precipitation is expected to drop by a range of -25 to -45% in the Siliana catchment while it is expected to decline by -10 to -35% in the Béja catchment, with respect to the reference period. Less reduction in winter precipitation is expected in both catchments. Projected magnitudes of relative changes range between -2 and -27% for Siliana against -8 to -27% in the Béja catchment. In the meanwhile, temperature is likely to increase across all the months with the highest rise for summer months. In this season, average reference temperature will increase in the future by a range of +2.5 to 3.2°C in both catchments. Winter temperature is also projected to increase by +1.6 to 2.2 °C in both catchments. Therefore, the already hot and dry conditions in the Siliana and Béja catchments are expected to amplify in the 2050s based on the climate model projections. These results are consistent with these reported in several studies conducted at the Mediterranean basin (e.g. IPCC, 2007; Schneider et al., 2013).

3.3.2. Changes in water balance indicators

Changes in water balance indicators were assessed through changes in catchment runoff, actual and potential evapotranspiration (ETr and PET, respectively), soil water content (SWC) and available water which consists of the difference between precipitation and ETr.

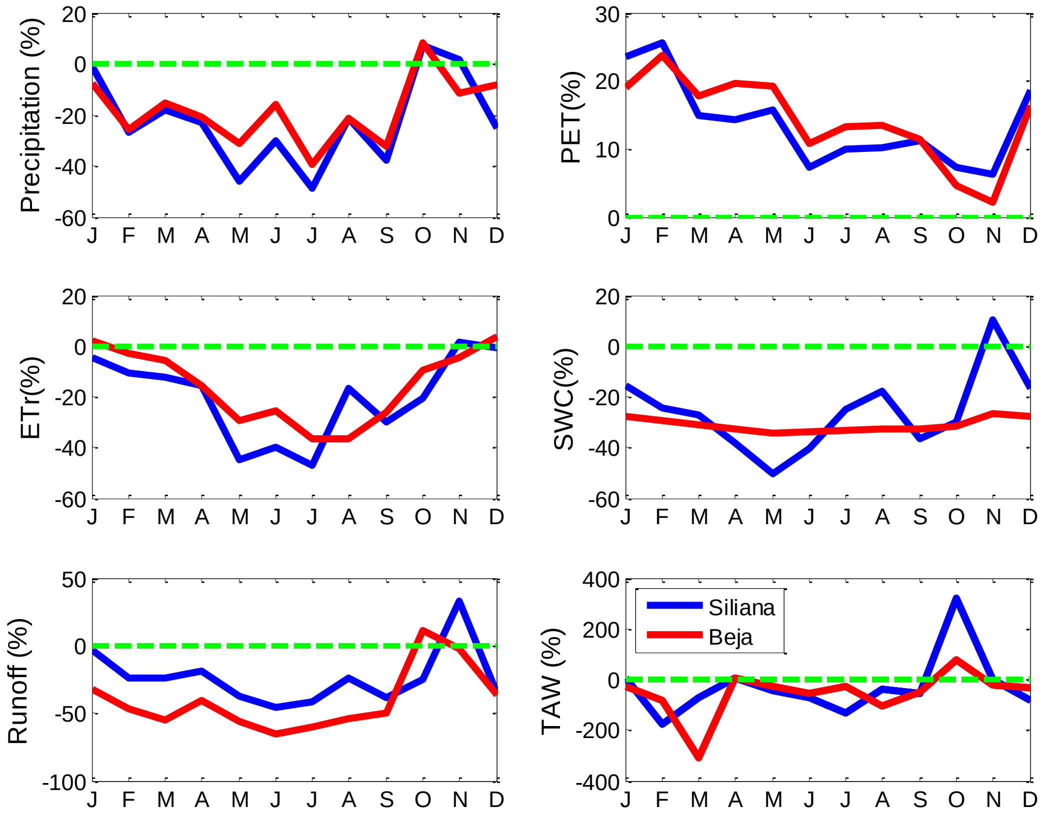

Fig. 11. Relative change in water balance indicators in the Siliana and Béja catchments

In both catchments, climate models project general decrease in the water balance indicators except for PET which is expected to increase as consequence to the combine decrease in precipitation and increase in temperature. The projected changes in ETr indicator in winter season are not significant in both catchments while during the summer season, their projected magnitude of changes vary between -18 and -45 % in the Siliana catchment and between -22 and -40% in the Béja catchment, with respect to the reference period. Changes in Etr follow closely the projected trend of precipitation in both catchments. Runoff is projected to decrease across all the months except in October and November for the Béja and the Siliana catchment, respectively. This is due to the slight increase in precipitation projected for these two months. While runoff changes exhibit similar trends in both catchments, higher reduction during the dry season in comparison to the wet season, the magnitudes of changes between the two catchments are different. Runoff in the Siliana catchment is likely to drop by a range of -3 to -36% during the winter and -24 to -45% during the summer. In the Béja catchment, the reduction in runoff is likely to vary between -32 and -47% in the winter against -53 and -65% in the summer. SWC is also projected to decrease in both catchments. This could be caused by increased PET under a warmer climate. However, there is a large difference in the projected trend of SWC between the two catchments. While the magnitudes of changes in the SWC for the Siliana catchment vary across the months with higher reduction in the dry season (-17 to -56%) in comparison to the wet period (+10 to -28%), they are less variable for the Béja catchments (-27 and -34%). This may highlight the role that catchment properties (e.g soil characteristics and land use) can play in climate change impacts assessment. For instance, Vertisols which are clay- and organic matter- rich soils are able to store large amounts of soil water, and are the most abundant soil type in the Béja catchment. Therefore, they may have an important buffer function under the projected climate change and will sustain soil moisture in the future. In addition, due to their spatial abundance they may induce less spatial variability in SWC changes over the Béja catchment.

Changes in the water balance indicators will clearly reduce the total available water (TAW) calculated as the difference between precipitation and Etr in both catchments (Fig. 11). All the months feature a decline in the TAW except for October where a slight increase in precipitation and runoff are projected. In average, the reduction in TAW during the dry period will range between +5 to -100% with an average of -43% while in the wet period it will range between +75 to -310% with an average of -67% in the Béja catchment. For the Siliana catchment, these ranges are +4 to -130% with an average of -55.68% for the dry period against +322 to -175% with an average of -0.17% for the wet period. These statistics suggest that the annual available water will reduce by an average of -28 and -55% in the Siliana and Béja catchment, respectively. However, the wide range in the projected magnitudes of change in the TAW indicator reflects the large monthly variability which could be related to uncertainty in projected precipitation and Etr, especially during the wet period. One way to address this uncertainty is to adopt the ensemble modelling approach but with larger climate model members.

3.3.3. Changes in flow magnitude and frequency

Changes in magnitudes and frequency of the flow can be assessed in various ways. In this study these changes are assessed by comparing 30-years daily flow duration curves as simulated by the climate model ensemble between the reference and the future period (Fig. 12). Results show clear tendency towards a decrease in daily discharge magnitude in the future over the Siliana and the Béja catchments. For a given frequency or exceeded probability (P) flow magnitude in the future scenario is lower than that in the base scenario in both catchments, in particular for medium (flows with $0.1<P<0.7$) and low flows (flows with $P \geq 0.7$).

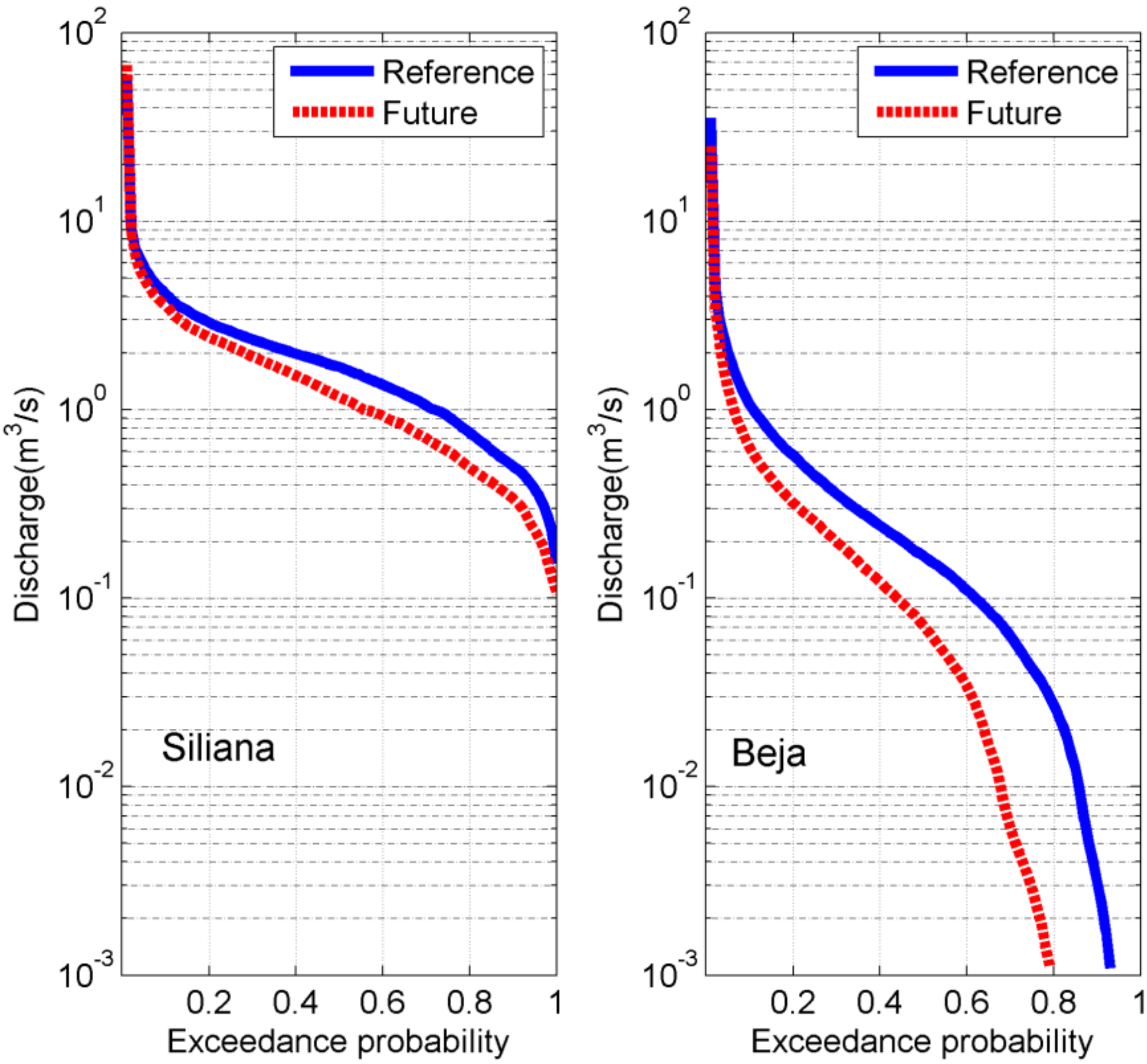

Fig. 12. Simulated FDCs for the reference and future period in the study catchments

Although changes in high flows (flows with P≤0.1) between the reference and the future periods are not straightforward to detect in the Siliana catchment as high flows encompass extreme simulated values, the general tendency is to decrease. In average floods magnitudes are projected to decrease by -10% with respect to the reference period. In the Béja catchment, floods magnitudes are expected to decrease by an average of -35% in comparison to the reference values. Reduction in high flows may occur as consequence to projected decrease in precipitation particularly during the winter season.

There is a consistent decreasing trend in low flow magnitudes in both catchments. However, the Béja catchment is likely to experience more amplified decrease in low flow magnitudes than the Siliana catchment leading to more intermittent flow regime in the former(Fig. 12). In Fig. 13 are plotted the distributions of the low flow magnitudes for the reference and future periods in the Siliana and the Béja catchments. The figure clearly shows that the entire low flow percentiles (e.g. extremes and median) will decrease lading to an extended zero-flow magnitudes in the future in comparison the reference values.

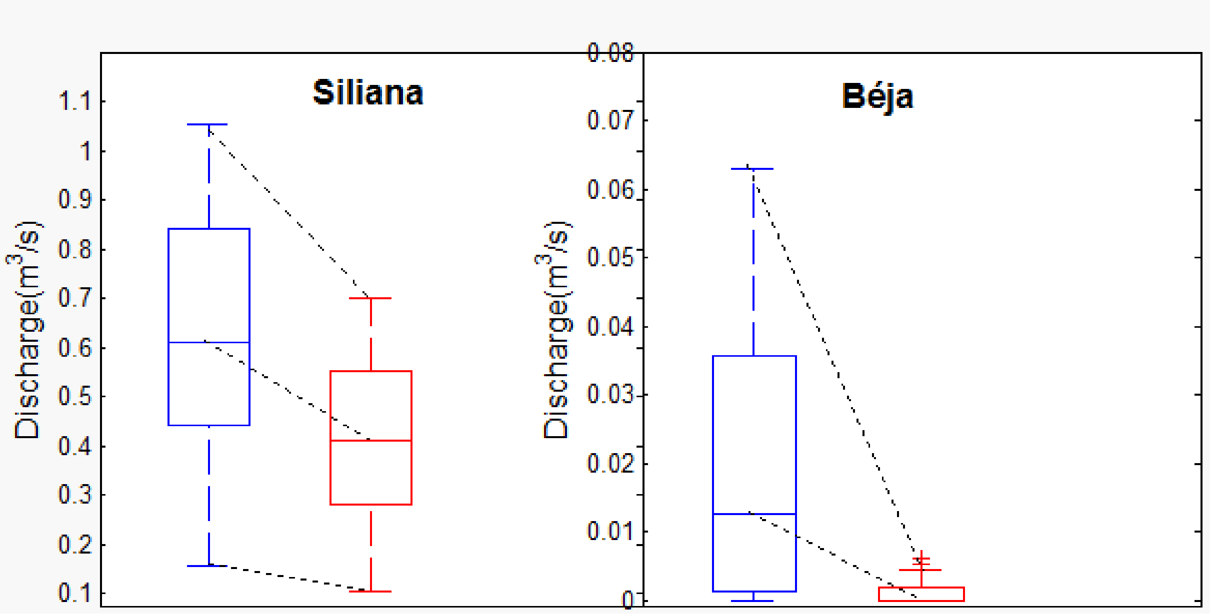

Fig. 13. Boxplots of low flow magnitudes for the reference (blue) and future period (red) in the Siliana and Béja catchments. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points not considered outliers, and outliers are plotted individually.

These extreme low flow conditions will generally have a negative impact on aquatic ecosystems, agriculture and domestic and industrial sectors. The reduction in low flow could be related to reduced rainfall, elevated potential evapotranspiration and reduced soil water content.

To assess changes in high flow and low flow frequency, the number of days with flow magnitude higher than the threshold value of high flows and lower than the low flows threshold discharge, respectively, for the reference period was calculated for each month (Fig. 14). While the largest frequencies in high flow days for the future scenario will likely remain restricted to the wet period, similarly to the reference period, monthly high flow frequency is projected to decrease in both catchments. The highest decrease is projected for the winter months with magnitude of relative change ranging between -2 and -48% for Siliana and -35 and -52% for the Béja catchment suggesting a decreasing trend in floods frequency. These results are in line with the projected change in high flow magnitude and precipitation. The highest low flow frequency in the reference period over both catchments is recorded during the dry period, in particular in summer season. This statement is likely to be true in the 2050s indicating that no changes in the low flow events timing are projected. However, it is clear on Fig. 14 that the frequency of low flow will undergo an increase in the next mid-century in comparison to the reference period in both catchments. Thus, more low flow days will occur in the Siliana as well as in the Béja catchment. In the Siliana catchment, the monthly percentage of low flow days in the future will increase by half and three times the number of low flow days per month in the reference period in the summer season. In addition, low flow frequency in the winter season will also increase by a range of +16 to +58%, with respect to the reference values. In the Béja catchment, the projected increase in low flow days ranges between +16 and +67% during the summer and +3 to +350% in the winter.

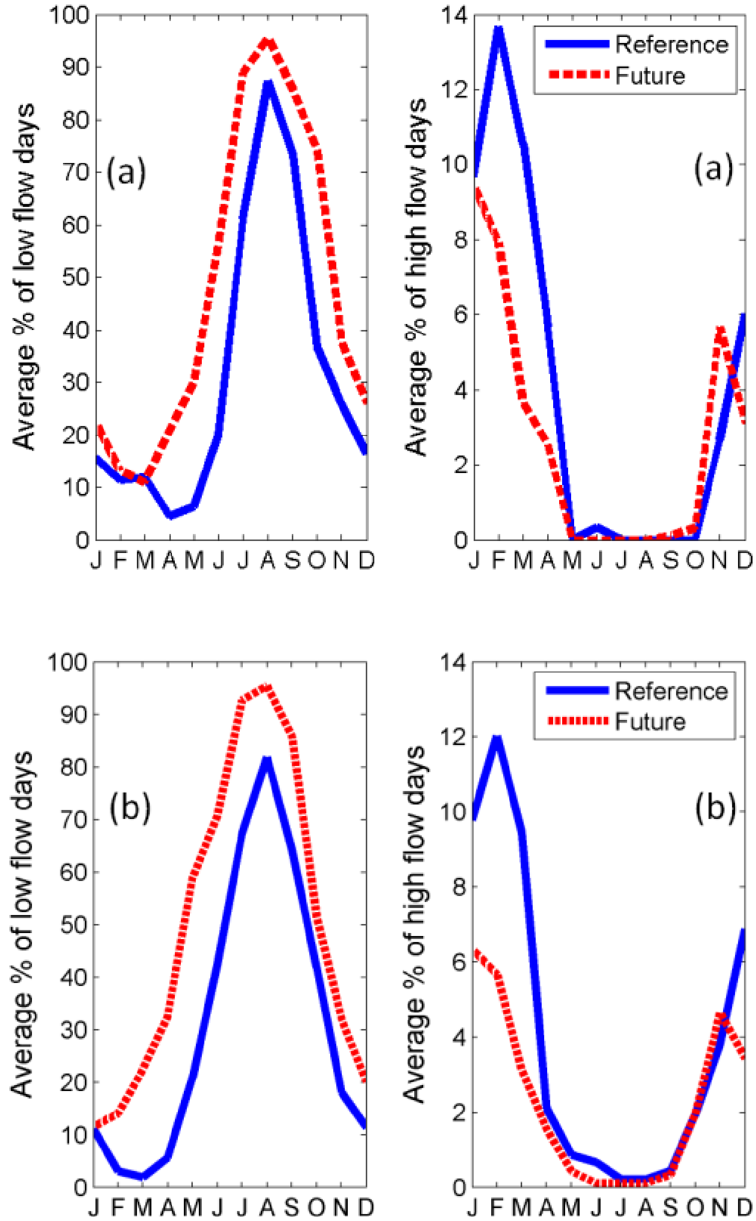

Fig. 14. Changes in high flow and low flow days for the Siliana (a) and the Béja (b) catchments

Therefore, less flooding events but higher low flow conditions are expected for the Siliana and the Béja catchment as consequence to climatic change. This may increase the risk of hydrological droughts and water pollution as water volume is expected to drop.

4. Conclusions

Based on projections of two downscaled and bias corrected climate models for a baseline (1971-2000) and future (2041-2070) scenarios, an assessment of hydrological impacts of climatic change has been conducted at two catchments the Siliana and the Béja in the Medjerda basin in Tunisia. This study showed that the hydrologic regime of both catchments is vulnerable to changes in climatic conditions. As drier and warmer climate is expected for

2050s over these catchments, a decrease in the available fresh water is projected. In addition, low flow conditions, thus droughts, are likely to increase in the future which may induce several negative impacts on drinking water and water system operational management (e.g dams) in a region where the water strategy has been based on maximum mobilization of surface water through interconnected reservoirs.

The need for further assessment of these impacts in this region and their associated uncertainty is apparent to improve our knowledge about the way that climatic change can impact hydrologic regime and to assist water manager's decisional process. The following actions are to consider in assessing hydrological impacts of climatic change in the Medjerda.

- Improve, extend and integrate methods for better climate model auditing. Climate models are subject to uncertainty and their associated projections can be contradictory. Therefore, to reduce this uncertainty and improve climate model projections the multi-model ensemble approach can be adopted with as larger climate model members as possible. The multi-model ensemble approach can be used in either un-weighted or weighted way. In the latter, models with better performances in reproducing the historical climate can be given higher weight than the others.

- Assess and enhance methodologies and tools for data collection and analyses to come up with consolidated database through collection and correction of existing data with the appropriate resolution and high degree of accuracy to reduce their inherent uncertainty when driving hydrological models. Integration of novel techniques such as remote sensing will help to improve data quality and provide additional useful information and knowledge. Hydrogeological data is also important to better understand the surface-groundwater system and, hence, improve hydrological model predictions in the Medjerda basin.

- Consider hydrological and climate models uncertainty as well as all possible uncertainty sources (e.g. input data) in an integrated schema to provide better reliable model prediction under climatic change conditions.

- Foster the synergy between researchers and local and regional water stakeholders through dissemination of the project outputs which will assist identification of appropriate adaptation strategies to include in the management plans of the Medjerda water resources under climate change.

References

Abbaspour, K.C., Johnson, C.A., van Genuchten, M.T., 2004. Estimating Uncertain Flow and Transport Parameters Using a Sequential Uncertainty Fitting Procedure. Vadose Zone Journal, 3(4): 1340-1352.

Arnell, N.W., 2011. Uncertainty in the relationship between climate forcing and hydrological response in UK catchments. Hydrology and Earth System Sciences. 15(3), 897-912. doi:10.5194/hess-15-897-2011

conditions of rivers: Aggradation and reduction of the Medjerda channel capacity downstream of the Sidi Salem dam (Tunisia). J. Hydrol. 326, 318 _330.

Eckhardt, K., Fohrer, N., Frede, H.-G., 2005. Automatic model calibration. Hydrological Processes, 19(3): 651-658.

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA,:996.

Kwon, H.-H., de Assis de Souza Filho, F., Block, P., Sun, L., Lall, U., Reis, D.S., 2012. Uncertainty assessment of hydrologic and climate forecast models in Northeastern Brazil. Hydrological Processes, 26(25): 3875-3885

Ludwig, R., Roson, R., Zografos, C., Kallis, G., 2011. Towards an inter-disciplinary research agenda on climate change, water and security in Southern Europe and neighboring countries. Environmental Science & Policy, 14(7): 794-803.

Ludwig, R., Soddu, A., Duttmann, R., Baghdadi, N. S. B., Deidda, R., Marrocu, M., Strunz, G., Wendland, F., Engin, G., Paniconi, C., Prettenthaler, F., Lajeunesse, I., Afifi, S., Cassiani, G., Bellin, A., Mabrouk, B., Bach, H., and Ammerl, T. 2010. Climate-induced changes on the hydrology of Mediterranean

Neitsh, S.L., Arnold, J.G., Kiniry, J.R., Srinivasan, R., Williams, J.R., 2005. Soil and Water Assessment Tool input/output file documentation, version 2005. Temple, Texas: Grassland, Soil and Water Research Laboratory, Agricultural Research Service.

Ouessar, M., Bruggeman, A., Abdelli, F., Mohtar, R. H., Gabriels, D. and Cornelis, W. M. (2009). Modelling water-harvesting systems in the arid south of Tunisia using SWAT. Hydrol. Earth Syst. Sci., 13, 2003-2021, 2009.

République Tunisienne, Ministère de l'agriculture et des ressources hydrauliques, 2007. Stratégie nationale d'adaptation de l'agriculture tunisienne et des écosystèmes aux changements climatiques.

Saha, S., S. Moorthi, H.-L. Pan, X. Wu, J. Wang, S. Nadiga, P. Tripp, R. Kistler, J. Woollen, D. Behringer, H. Liu, D. Stokes, R. Grumbine, G. Gayno, J. Wang, Y.-T. Hou, H.-Y. Chuang, H.- M.H. Juang, J. Sela, M. Iredell, R. Treadon, D. Kleist, P. Van Delst, D. Keyser, J. Derber, M. Ek, J. Meng, H. Wei, R. Yang, S. Lord, H. Van Den Dool, A.

Kumar, W. Wang, C. Long, M. Chelliah, Y. Xue, B. Huang, J.-K. Schemm, W. Ebisuzaki, R. Lin, P. Xie, M. Chen, S. Zhou, W. Higgins, C.-Z. Zou, Q. Liu, Y. Chen, Y. Han, L. Cucurull, R.W. Reynolds, G. Rutledge, and M. Goldberg, 2010. The NCEP Climate Forecast System Reanalysis. Bulletin American Meteorological Society 91:1015-1057.

Schneider, C., Laizé, C.L.R., Acreman, M.C., Flörke, M., 2013. How will climate change modify river flow regimes in Europe? Hydrology and Earth System Sciences, 17(1): 325-339.

SCS, 1972. SCS National Engineering Handbook. Section 4. Hydrology, Soil Conservation Service, US Department of Agriculture:Washington, DC.

Sellami, H., La Jeunesse, I., Benabdallah, S., Baghdadi, N., Vanclooster, M., 2014. Uncertainty analysis in model parameters regionalization: a case study involving the SWAT model in Mediterranean catchments (Southern France). Hydrology and Earth System Sciences, 10(4): 4951-5011

Sellami, H., La Jeunesse, I., Benabdallah, S., Vanclooster, M., 2013. Parameter and rating curve uncertainty propagation analysis of the SWAT model for two small Mediterranean catchments. Hydrological Sciences Journal, 58(8): 1635-1657.

Teng, J., Vaze, J., Chiew, F.H.S., Wang, B., Perraud, J.-M., 2011. Estimating the Relative Uncertainties Sourced from GCMs and Hydrological Models in Modelling Climate Change Impact on Runoff. Journal of Hydrometeorology, 13(1): 122-139.

van Griensven, A., Meixner, T., Grunwald, S., Bishop, T., Diluzio, M., Srinivasan, R., 2006. A global sensitivity analysis tool for the parameters of multi-variable catchment models. Journal of Hydrology, 324(1-4): 10-23.

Zahar, Y., Ghorbel, A., and Albergel, J. (2008). Impact of large dams on downstream flow

Websites

http://swat.tamu.edu/

https://www.giz.de/de/html/index.html

http://www.ensembles-eu.org/