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ABSTRACT

The objective of this study was to examine the impacts of climate and land use changes on water availability and sediment loads for a water supply reservoir in northern Morocco using data-intensive simulation models in a data-scarce region. Impacts were assessed by comparing the simulated water and sediment entering the reservoir between the future period 2031–2050 and the 1983–2010 reference period. Three scenarios of land use change and two scenarios of climate change were developed in the Tleta watershed. Simulations under current and future conditions were performed using the Soil and Water Assessment Tool (SWAT) model. The simulations showed that climate change will lead to a significant decrease in the annual water supply to the reservoir (−16.9% and −27.5%) and in the annual volume of sediment entering the reservoir (−7.4% and −12.6%), depending on the climate change scenarios tested. The three scenarios of land use change will lead to a moderate change in annual water inflow into the reservoir (between −6.7% and +6.2%), while causing a significant decrease in sediment entering the reservoir (−37% to −24%). The combined impacts of climate and land use changes will cause a reduction in annual water availability (−9.9% to −33.3%) and sediment supplies (−28.7% to −45.8%). As a result, the lifetime of the reservoir will be extended, but at the same time, the risk of water shortages will increase, especially from July to March. Therefore, alternative water resources must be considered.

1. Introduction

Soil erosion is a serious threat to the environment (Lal, 2003). It causes on-site damage, such as the deterioration of the physico-chemical and biological properties of soils, the loss of nutrients, the reduction in agricultural productivity and the loss of arable land. Off-site damage, such as river sediment deposition, reservoir sedimentation, and channel silting, results in significant economic loss (Pimentel et al., 1995). Soil water erosion is a widespread phenomenon in Mediterranean countries (De Franchis & Ibanez, 2003; Kosmas et al., 1997) because of the combination of climatic and anthropogenic erosion-prone factors (García-Ruiz, Nadal-Romero, Lana-Renault, & Beguería, 2013; Raclot, Le Bissonnais, Annabi, Sabir, & Smetanova, 2018). As a result, reservoir siltation represents a major issue for many Mediterranean countries, especially in North Africa (Ayadi, Abida, Djebbar, & Mahjoub, 2010;

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Lahlou, 2000), where water availability is mainly based on the surface water mobilization capacities. Because the Mediterranean region is considered a global "hot spot" in terms of climate variability and change, as well as the rate of land transformation processes (García-Ruiz, López-Moreno, Vicente-Serrano, Lasanta-Martínez, & Beguería, 2011; Giorgi & Lionello, 2008), it is crucial to anticipate the futures of reservoir in terms of water availability and lifetime.

There is a growing consensus in Earth systems science that global temperatures are increasing and will continue to do so over the next century, leading to changes in global climate regimes (IPCC, 2014; Nunes & Nearing, 2010). The projections of greenhouse gas increases are expected not only to increase the global average temperature but also to influence precipitation patterns (IPCC, 2014). Although variable from region to region, these trends tend to increase the frequency of extreme events such as heat waves and high-intensity storms (Nunes & Nearing, 2010). Li and Fang (2016) recently reviewed the direct and indirect impacts of climate change on water erosion. Direct impacts are mainly caused by changes in precipitation (quantity, intensity, spatial and temporal distribution), and indirect impacts are related to temperature increase: a warm climate will affect soil erosion mainly through changes in vegetation cover and soil moisture. Other indirect impacts are associated with anthropogenic or socioeconomic factors; the combination of precipitation and temperature changes is likely to be accompanied by changes in crop management, agricultural planning, crop types and prices. Variations in rainfall patterns (i.e., the amount of rainfall per event, intensity, frequency and the seasonality of precipitation) could have a significant impact on the hydrological regime and soil erosion (Bangash et al., 2013; Li & Fang, 2016; Nearing et al., 2005; Pruski & Nearing, 2002; Zhang, Nearing, & Liu, 2005, 2010). Lu et al. (2013) reported that a 1% change in precipitation resulted in a 2% change in sediment loads and a 1.3% change in water inflows. Other studies have shown that a simple change in rainfall seasonality can have significant effects on soil losses (Choukri et al., 2016).

Unfortunately, the complex interactions between land use and climate make it difficult to predict the impacts of global change on runoff and erosion because of possible antagonist or synergistic effects (Tomer & Schilling, 2009). For instance, a decline in precipitation can cause less erosion, but at the same time, it can also reduce vegetation cover that will favour erosion. This antagonist phenomenon is discussed extensively in Nunes and Nearing (2010). The consequence of a decline in precipitation on runoff can also be very complex, as highlighted by the "Sahel paradox", i.e., the fact that the Sahel has witnessed a paradoxical increase in surface water despite a general precipitation decline in recent decades (Descroix et al., 2013, chap. 10; Gal, Grippa, Hiernaux, Pons, & Kergoat, 2017). The impacts are even more unexpected when considering land use change induced by socioeconomic conditions in addition to climate change (Nunes, Jacinto, & Keizer, 2017).

A modelling approach is a common and useful way to project runoff and soil erosion under global change, as shown by the review of Li and Fang (2016). Climate scenarios may be based on outputs of general circulation models (GCMs) or regional climate models (RCMs). GCMs are unable to assess site-specific climate impacts in a reliable way because of their coarse spatial resolution (Hulme et al., 1993; Zhang, 2005). RCMs dynamically simulate climate characteristics at resolutions of 10–50 km, taking into account time-varying atmospheric conditions at the boundary of a specified domain (Wilby, 2007; Zhang et al., 2019a). Downscaling methods are used to fill spatial and temporal resolution gaps between climate modelling and modeller needs (Wilby, Dawson, & Barrow, 2002; Zhang et al., 2019b). Land use scenarios at the regional scale are generally based on narrative storylines such as those associated with the shared socioeconomic pathways (SSPs) established at the global scale, as shown in O'Neill et al. (2017). As with any prospective work, the assumptions behind modelling approaches lead to uncertainties (Ludwig & Roson, 2016), such as those related to climate projections, socioeconomic scenarios, data availability and quality, and knowledge deficiency on both the biophysical processes involved and the models used for the simulations (Ghaffari, Keesstra, Ghodousi, & Ahmadi, 2010; Nunes et al., 2017).

In this study, the Soil and Water Assessment Tool (SWAT model, Neitsch, Arnold, Kiniry, Williams, & King, 2005) was applied to the Tleta watershed to examine for the first time the impact of global change on the surface water mobilization capacities of a reservoir in northern Morocco. The model was applied for current conditions using observed data and for future conditions using climate inputs resulting from a bias-corrected RCM and map inputs resulting from a separate land use scenario building exercise. The impacts of climate or land use changes on runoff and erosion have been evaluated separately to differentiate the distinct impacts of climate change from the distinct impacts of land use change and jointly to identify the combined impacts of climate and land use changes on the studied watershed. SWAT was selected as it has been previously used for similar studies in Mediterranean environments (Bucak et al., 2017; Nunes et al., 2017; Serpa et al., 2015), and it has been shown to be adapted to the northern Morocco context without adjustments other than parameterization to fit the local conditions, e.g., for simulating the impact of climate change on the vulnerability of water resources and crop performance (Brouziyne et al., 2018) or the impact of management practices on runoff and erosion (Briak, Moussadek, Aboumaria, & Mrabet, 2016, 2019).

The main objectives of this study are (1) the evaluation of the performance of the SWAT model in terms of runoff and sediments for a semi-arid Mediterranean watershed in the northern region of Morocco; (2) the quantification of the impacts of global change on water availability and sediment loads to the Ibn Batouta reservoir by 2040; and 3) the assessment of the implications for the water mobilization capacities of the reservoir and surrounding agricultural activities.

2. Material and methods

2.1. Site description

Located between Tangier and Tétouan (North Morocco), the Tleta watershed covers an area of 180 km^2 (Fig. 1a) upstream of the Ibn Batouta reservoir built in 1977 with an initial storage capacity of 43.5 Mm^3 to provide drinking water for the city of Tangier. The reservoir is located in the foothills of the Rif Mountains, which is an intensive water erosion-prone area. Although it covers only 6% of Morocco's area, the Rif Mountains and its foothills provide more than 60% of the sediment mobilized each year throughout the country (Issa, Lech-Hab, Raissouni, & El Arrim, 2016). Land degradation in the Tleta watershed has been described as alarming in the absence of soil conservation efforts (Merzouk, Fenjiro, & Laouina, 1996). Thus, the storage capacity of the Ibn Batouta reservoir is constantly decreasing (43.6 Mm^3 in 1978 to 29.1 Mm^3 in 2013), which represents an annual siltation of approximately 0.4 Mm^3/year and a loss of 33% of its initial capacity.

The watershed elevations range from 23 to 672 m at the highest point with terrain slopes ranging from 0 to 30% (Fig. 1c). With a subhumid to humid Mediterranean climate and wet winters and dry summers (Briak et al., 2016), the watershed is located in one of the most humid areas in the country. At the Ibn Batouta dam, the average annual precipitation was 692 mm over the period 1980–2010, and the potential evapotranspiration (PET) derived

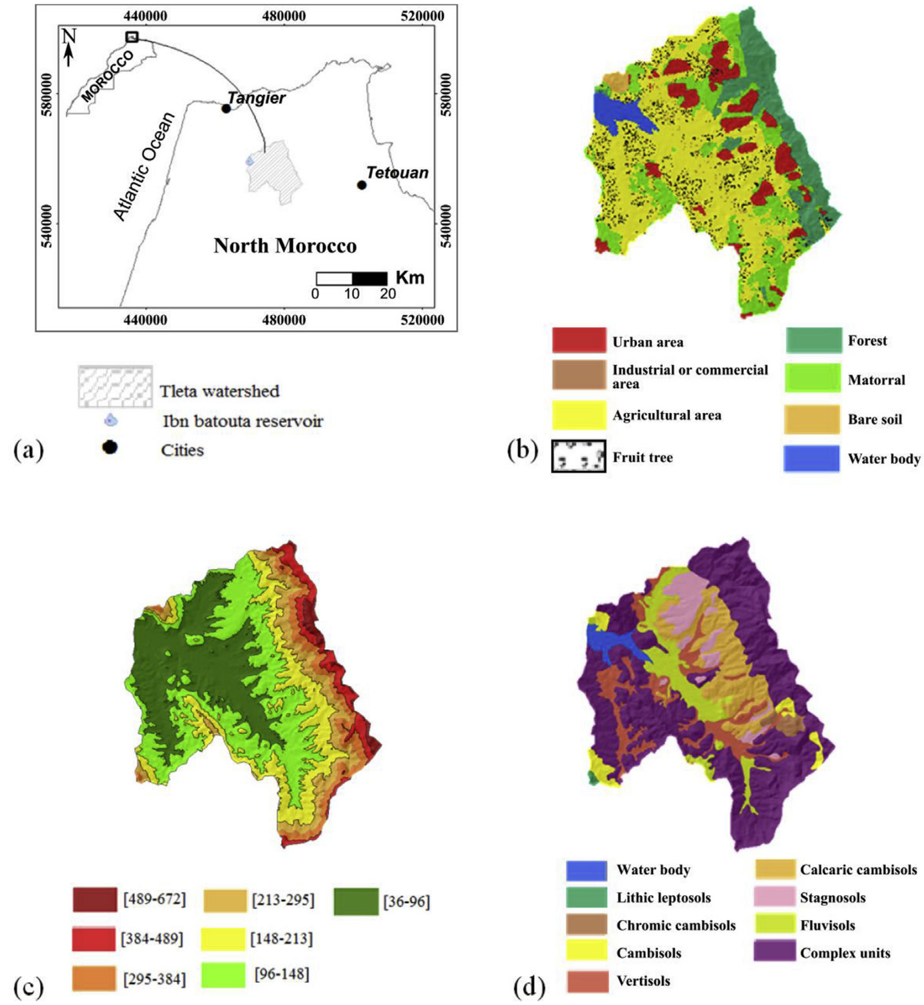

Fig. 1. (a) Geographic location of the Tleta watershed (Lambert conformal conical projection, Clarke 1880), (b) land use/cover map (LU 2010), (c) altitude map and (d) soil map (WRB, 2006).

from a Colorado evaporation pan and a correction factor of 0.7 was approximately 1190 mm over the period 1983–2010. The average minimum and maximum daily temperatures over the same period were 14–23 °C at the closest station (Tangier airport). The watershed is characterized by a dominance of marly substrate, indicating the low permeability of the subsoil. The main lithostratigraphic features of the Rif Mountain ridge are well represented in the watershed, namely, the overlay of several bedrock layers (flysch) forming the ridge line above the native Tangier unit (Meloussa) forming the hills (Michard, 1976). This lithological variety has allowed the development of a rather important soil mosaic (Fig. 1d) composed of Cambisols, Vertisols, Fluvisols, Stagnosols, and Leptosols. The land use/cover (Fig. 1b) was quite stable between 1980 and 2010. It was partially conditioned by the morpho-pedological disposition. The sandstone and flysch facies constitute the substrate of forested and matorral lands that are sometimes very degraded, while the marly facies is mostly cultivated. The forest and the dense and clear matorral occupy the highest parts of the hills, i.e., the upstream part of the watershed (Merzouk et al., 1996). Agricultural lands are dominant in the lower parts of the watershed, while bedrock outcrops are limited to an area near the reservoir. Cereals (e.g., wheat, barley and oats) are the dominant crops and are sometimes cultivated in rotation with leguminous crops (e.g., chickpeas and faba beans) or in association with olive trees or other fruit trees. Water and sediment inputs into the reservoir have been monitored at the watershed outlet since the installation of the Ibn Batouta dam, and a network of rain gauges was installed to capture the spatial variability of rainfall. As in many Mediterranean watersheds, direct runoff processes are predominant, and the watershed time response is typically less than one day.

2.2. Dataset used for SWAT implementation

Relief and land use maps were produced from remote sensing images and field surveys (see Table 1 for description and Fig. 1 for illustration). A detailed soil description of the study area made for agricultural purposes was composed of a soil map with a complete description of the representative profile for each soil type, including the maximum rooting depth of the soil profile and standard soil parameters for each soil layer (e.g., texture, total and organic carbon content, soil bulk density, and available soil water content). Additional soil descriptions and analyses were performed between 2010 and 2017 to cross validate the existing source of data and quantify hydrological soil properties such as water infiltration rates.

Considering climatic data (see Table 1 for description and Fig. 3 for location), time series were available at eight stations for daily

Table 1
Dataset used as input for SWAT implementation.

Type	Source	Period	Description
Relief	SPOT images (20 m resolution)	2014	20 m digital elevation model (see Fig. 1c)
Land use/cover	Classification of a 2010 Landsat image (30 m resolution), field surveys and interpretation of aerial photographs (Hérivaux, Vinatier, Sabir, Guillot, & Rinaudo, 2018)	2010	See Fig. 1b for land use/cover classes (these data are called LU2010 in this paper)
Soil map and description	LCGS/Inypsa (1/50,000)	1989	See Fig. 1d for soil classes. Also includes a complete description of a representative profile by soil type with standard soil parameters for each soil layer.
Soil characteristics	Soil sampling and analyses	2010–2017	Additional standard soil properties (texture, carbon content, water retention …) and infiltration rates (derived from single-ring, double rings measurements or rainfall simulations)
Rainfall	ABHL - Loukkos Hydraulic Basin Agency	1980–2010	Daily rainfall in 8 locations (see Fig. 3 for locations)
Temperatures	Direction of National Meteorology and ABHL	1980–2010	Daily temperatures (min., max., average) at four gauge stations (including a complete climatic station at Tangier airport)
Runoff	ABHL	1980–2010	Daily runoff (Ibn Batouta station at catchment outlet) calculated by a reservoir hydrological balance
Erosion	ABHL + post-treatment	1980–2010	Daily sediment yield (Ibn Batouta station at catchment outlet) calculated by a reservoir sediment balance

rainfall and at four gauge stations for daily temperatures and relative humidity. Existing gaps in the daily rainfall and temperature time series for a given station were filled using multiple linear correlations between stations to obtain continuous series from 1980 to 2010. The daily temperatures (minimum and maximum) and precipitation amounts at the different gauge locations were finally interpolated using an inverse distance weighting method (IDW), which allows the production of synthetic daily time series on a regular grid with a resolution of 1 km. Datasets from all the climatic stations were considered in the interpolation process because they can be captured by the IDW interpolation function and improve interpolation at the edge of the watershed. Because relative humidity, solar radiation and wind were only available at the Tangier station, these three climatic datasets were assumed to be uniform over the whole watershed.

Daily streamflow was derived from the hydrological budget of the reservoir, as explained in Raclot and Albergel (2006). This assessment is based on the knowledge of the height-surface and height-volume curves established by bathymetric surveys. A differentiation between direct and delayed runoff was determined using the graphic method on some individual events and automatic filtering methods (local minimum method, one parameter digital filter and recursive digital filter included in the Web-based Hydrograph Analysis Tool available at https://engineering.purdue.edu/mapserve/WHAT/) on the whole daily runoff dataset. Sediment volumes entering the reservoir between two bathymetries were estimated by differences between the bathymetric surveys and a correction using a trapping efficiency coefficient of 93% evaluated from Heinemann's formula (Heinemann, 1981). The volume of sediment arriving at the dam between two measures was then deconvoluted at a daily time step, assuming that the daily solid flows (Sed) are proportional to the maximum flow (Qmax) and the daily total runoff volume (Vtot) according to Equation (1) proposed by Williams (1975):

$$Sed \sim (Vtot \times Qmax)^{0.56} \times K \times LS \times C \times P \tag{1}$$

The main datasets used as input for SWAT implementation are summarized in Table 1.

2.3. Implementation of the SWAT model under current conditions

The SWAT model was implemented over a 31-year period (1980–2010) using the Hargreaves method for PET estimation and the dataset listed in Table 1, knowing that temperature and rainfall time series were interpolated on the 1 km resolution grid before being used as input data. Thus, each subbasin in SWAT was assigned with the closest bias-corrected climatic time series from the regular grid. For each land use type, the most similar land use type from the SWAT land use database was selected, and only minor adjustments for some plant growth/management parameters were made.

In a very traditional split-sample approach (Klemeš, 1986; Refsgaard, Henriksen, Harrar, Scholten, & Kassahun, 2005), this period was divided into an initialization or warm-up phase (1980–1982), a calibration phase (1983–1996) and a model validation phase (1997–2010). The calibration was carried out manually in two successive steps. The first step consisted of adjusting parameters related to the surface runoff routing (SURLAG) and to the interaction among the underground compartment, unsaturated zone and flow in the stream (GW_REVAP, GWQMN and ALPHA_BF) to reproduce as closely as possible the daily runoff at the outlet of the watershed for the calibration period, ensuring that the respective contributions of direct and delayed runoff were properly simulated. Once runoff was correctly replicated during the calibration period, the second step consisted of adjusting parameters related to channel sediment detachment and routing (SPCON, SPEXP, CH_COV1 and CH_COV2) to minimize the differences between measured and simulated daily sediment flows. The performance of model prediction was assessed for the calibration and validation periods using the following standard statistical indicators (Arnold et al., 2012): the determination coefficient (R^2), the Nash-Sutcliffe coefficient (NSE) and the bias indicator (PBIAS). According to Moriasi et al. (2007), a monthly model simulation can be judged as "satisfactory" if NSE > 0.50 and if PBIAS < ±25% for streamflow and PBIAS < ±55% for sediment. In the present study, the recommended statistics proposed by Moriasi et al. (2007) have been used to analyse SWAT simulation performance for both monthly and daily time steps. For the daily time steps, these statistical indicators were also calculated after smoothing the observed and simulated daily values using a moving average over 3 days to explore issues related to daily discretization when running

SWAT at the daily time step in the Mediterranean context.

2.4. Implementation of the SWAT model under future conditions

2.4.1. Land use change scenarios

Three land use/cover scenarios have been elaborated by Hérivaux et al. (2018) for 2040 and described by Fig. 2. These scenarios are the outcomes of a prospective study conducted by a multidisciplinary team on the studied watershed. Only the main lines of each scenario are reproduced here:

- Scenario **S1**, entitled **"Urbanization and industrial development"**, assumes strong economic development in northern Morocco, associated with a high entry of labour from other regions. Urbanization is very important near the recently created city of Chrafat and along roads with the construction of houses, second homes, factories and logistic platforms. This urbanization is mainly at the expense of agricultural lands, with the exception of the very difficult-to-access western zone.
- Scenario **S2**, entitled **"Tleta fruit basket"**, assumes moderate development of Chrafat and its surroundings and very low industrial development. In this context, the state considers the development of agriculture as a priority and supports the implementation of agricultural development projects oriented towards rainfed arboriculture and agroforestry (olive, fig and walnut), beekeeping, goat farming and market gardening (irrigation in the vicinity of Ibn Batouta dam), as well as the creation of agricultural cooperatives.
- Scenario **S3**, entitled **"One foot in the city, one foot in the countryside"**, is based on the development of the city of Chrafat combined with an ambitious rural development programme for very small neighbouring villages called douars, enabling the population to remain in the douars and derive livings from both agriculture and activities in urban areas (Chrafat, Tangier and the industrial area). Cooperatives have been set up to develop the local products sector, such as honey, goat cheese, prickly pears and aromatic plants.

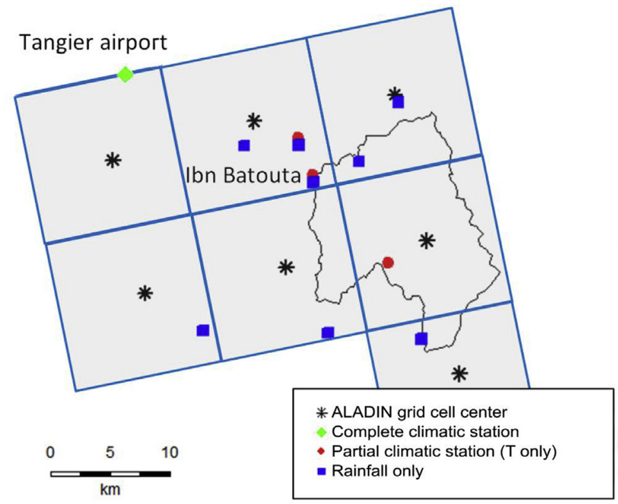

Fig. 3. Geographic location of the climatic dataset.

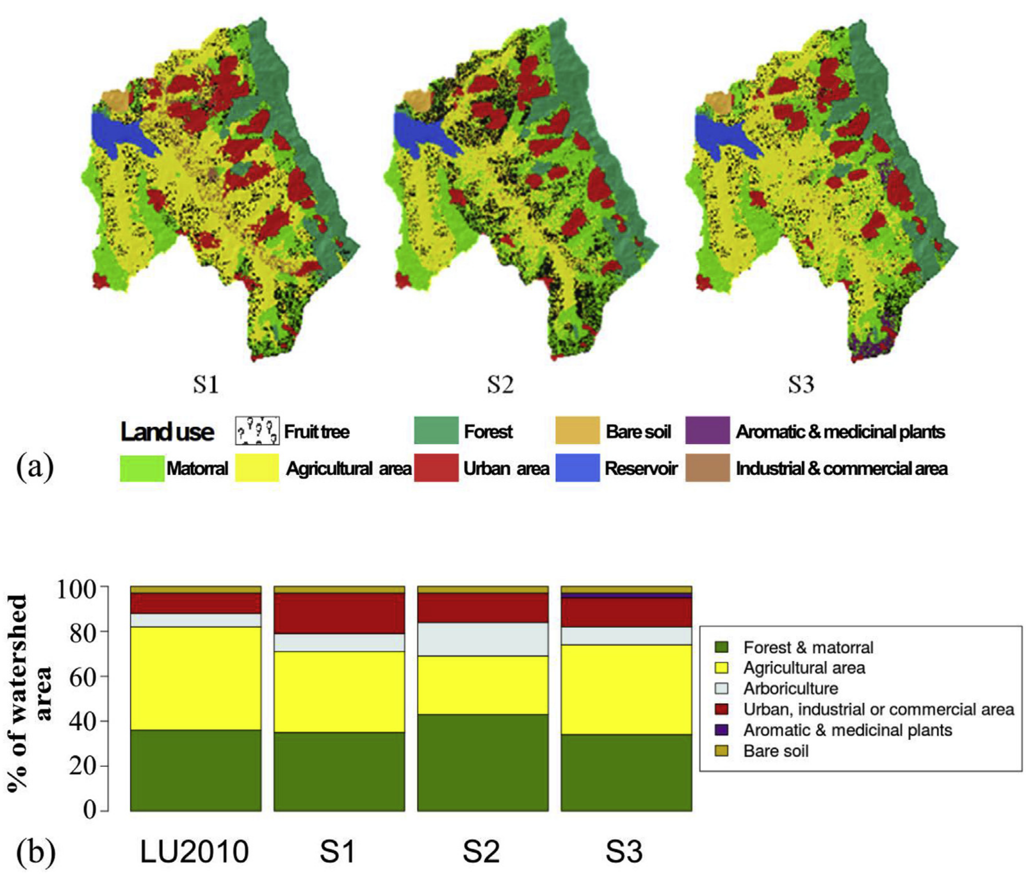

Fig. 2. (a) Map of the three land use scenarios (S1 to S3) by 2040 (from Hérivaux et al., 2018) and (b) land use distribution for the LU2010 and S1 to S3 scenarios.

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2.4.2. Climate change scenarios

Two climate scenarios based on weather forecast projections from France's ALADIN-Climat (Aire Limitée Adaptation dynamique Développement InterNational) regional model have been tested. They correspond to projections based on RCPs (Representative Concentration Pathways) 8.5 and 4.5, i.e., to radiative forcings of 8.5 and 4.5 W m^{-2} by 2100. The time series provided by ALADIN-Climat are at daily time steps and refer to minimum and maximum temperatures (T), relative humidity (Hr), rainfall (R), global radiation (Rg) and wind speed (W) 2 m above the ground. Considering the location of the watershed, the different climatic stations used and the native resolution of 12 km of ALADIN-Climat, the data provided by ALADIN-Climat on 7 grid cells were selected (Fig. 3).

For each grid cell, simulated historical time series from 1950 to 2005 and time series associated with the two RCP scenarios over the period 2006 to 2100 were considered. A common statistical downscaling technique, described in detail in Huard et al. (2019), was used to correct biases in climatic time series between the outputs of the ALADIN regional climate model and the local in situ climatic observations available within or near the Tleta watershed. The bias correction was based on a quantile mapping with breakpoints, i.e., a method very similar to the ARRM (Asynchronous Regional Regression Model) approach proposed by Stoner, Hayhoe, Yang, and Wuebbles (2013). Table 2 provides an example of standard statistics on the daily bias-corrected rainfall time series at the Ibn Batouta climatic station (see Fig. 3 for location), which enables a global comparison between current and future daily rainfall conditions that have been used as input data in SWAT.

The bias-corrected daily temperatures (minimum and maximum) and precipitation in the future climate at the different sites were finally interpolated to produce, for each climate scenario, future daily time series on the same regular grid with a resolution of 1 km and with the same interpolation process as that for current climatic conditions.

2.4.3. Implementation of SWAT under global change scenarios

The impact of global change scenarios was evaluated by running SWAT over the period 2021 to 2050 with parameters calibrated over the current period. Compared to the reference scenario, the only changes in SWAT implementation consisted of considering i) climate and/or land use change scenarios and ii) a warm-up period of 10-years (2021–2030). The land use scenario consisted of a change in land use type only, and no change in agricultural practice for a given land use type has been implemented between current and future conditions (i.e., the SWAT management file was unchanged for a given land use between the current and future simulations). Finally, water and sediment entering the reservoir by 2040 were quantified by averaging the simulation outputs between 2031 and 2050.

2.5. Evaluation of the global change impacts

Several combinations between the current and future land use and climate conditions (Table 3) were simulated using SWAT. The simulated runoff and sediment yield entering the reservoir for each combination was compared to the reference combination to quantify the distinct and combined impacts of changes in land use and climate. For example, the distinct impact of land use change was analysed by comparing SWAT outputs based on the combination between the three land use scenarios and the 1983–2010 climatic conditions (combination name 'S1' to 'S3' in Table 3) with SWAT output under current conditions (combination name 'Baseline' in Table 3).

3. Results and discussion

3.1. Model performance under current conditions

Visually, a good correspondence between monthly simulated and observed runoff and erosion fluxes can be observed for both the calibration and the validation periods (Fig. 4).

The statistical indicators (Table 4) confirm the good performance of runoff and sediment yield simulations at the monthly time step. The results obtained therefore show that SWAT is able to correctly reproduce the monthly inputs of water and sediment into the outlet reservoir of the studied watershed. When considering simulation results at daily time steps, the performance of SWAT to reproduce daily runoff and sediment yield was not as good as that at monthly time steps. This highlights the difficulties in getting the timing right in SWAT, especially in a poor data context. The discrepancy between daily observed and simulated values may result from problems in the water transfer module but it may also be induced by the daily splitting in the observed time series. Indeed, performance indicators are highly impacted by daily data splitting when watershed time response and hydrograph diffusivity are both very low. Because the mean response time is only approximately 6 h in the studied watershed, the simulated runoff of a rainfall pulse that occurs at the beginning of the day will be registered in the same day, whereas the simulated runoff of the same rainfall slot that occurs at the end of the day will be registered in the next day. There is therefore a non-systematic delay of 1 day between rainfall and runoff that cannot be taken into account in daily time step modelling. The interpretation of the indicators of performance on the 3-day smoothed observed and simulated timeseries provided interesting information on the likely reason for the discrepancy. Indeed the performance indicators obtained after smoothing over 3 days (Table 4) were significantly higher than those obtained without smoothing, which indicates that daily splitting partially explained the difficulties in getting the timing right in SWAT in the Mediterranean context. For sediment yield, however, a poor performance at the daily time step was obtained for the validation period, even after smoothing of the data, which indicates that problems in the sediment transport module remained. A similar situation has been observed in other studies (Nunes et al., 2018), which proposed as a likely explanation that the model performed well in the erosion simulation, but problems in the sediment transport module led to imprecisions in the daily discretization of sediment yield, which were averaged out at the monthly time step.

SWAT simulation between 1983 and 2010 showed that, for an annual average precipitation of 791 mm over the entire Tleta watershed, 59% (466 mm) was returned to the atmosphere by

Table 2
Standard statistics on the bias-corrected daily rainfall time series on the period 1983–2010 (REF) and the period 2031–2050 (RCP4.5 and RCP8.5) at the Ibn Batouta climatic station. Note that only daily rainfall values over 2 mm were considered.

	Minimum	First quartile	Median	Mean	Third quartile	Maximum
REF (1983–2010)	2.00	4.52	9.10	13.38	17.80	103.00
RCP4.5 (2041–2060)	2.09	4.42	8.99	12.91	16.99	81.41
RCP8.5 (2041–2060)	2.10	4.40	8.48	12.04	15.96	72.93

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Table 3
The tested combination of climate and land use changes.

	Combination name	Land use	Climate
REFERENCE	Baseline	LU2010	1983–2010
Land use change only	S1	S1	1983–2010
	S2	S2	
	S3	S3	
Climate change only	RCP4.5	LU2010	RCP4.5
	RCP8.5		RCP8.5
Combined change in land use and climate	S1_RCP4.5	S1	RCP4.5
	S1_RCP8.5		RCP8.5
	S2_RCP4.5	S2	RCP4.5
	S2_RCP8.5		RCP8.5
	S3_RCP4.5	S3	RCP4.5
	S3_RCP8.5		RCP8.5

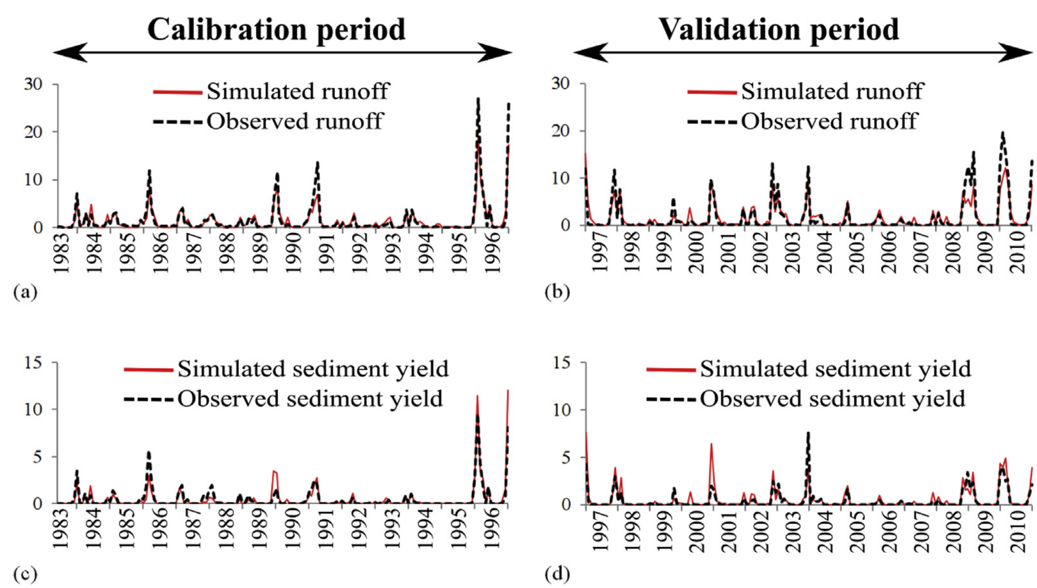

Fig. 4. Comparison between observed and SWAT simulated monthly runoff (m^3/s) and sediment yield (10^5 tons) for (a and c) the calibration period and (b and d) the validation period.

Table 4
Performance of SWAT in reproducing measured runoff and erosion fluxes for daily and monthly time steps and for the calibration and validation periods (values in italics and in brackets for the daily time step correspond to the performance indicators obtained after smoothing over 3 days, as explained in the Methods section).

	Time step	R^2		NSE		PBIAS (%)	
		Calibration	Validation	Calibration	Validation	Calibration	Validation
Runoff	**Daily**	0.55 *(0.76)*	0.47 *(0.69)*	0.52 *(0.71)*	0.43 *(0.62)*	−2 *(-2)*	−2 *(-2)*
	Monthly	0.92	0.84	0.89	0.81	−3	−3
Erosion	**Daily**	0.56 *(0.67)*	0.40 *(0.55)*	0.40 *(0.59)*	−0.01 *(0.25)*	−10 *(-10)*	−37 *(-37)*
	Monthly	0.84	0.70	0.74	0.52	−10	−37

evapotranspiration, and 8% (62.14 mm) percolated into the deep aquifer (i.e., the part of the aquifer not contributing to stream flow) and 33% (262.86 mm) contributed to stream flow. The annual stream flow rate was divided into direct runoff (192.93 mm), lateral flow contribution (22.46 mm) and shallow aquifer contribution (47.47 mm). This means that SWAT estimated a 74% contribution to total annual runoff for direct flow and a 26% contribution for indirect flow. These values were consistent with the distribution of stream flow between direct runoff and delayed runoff estimated using the graphic method (between 20 and 25% of indirect flow) or different automatic filtering methods (between 15 and 25% of indirect flow). SWAT was therefore able to reproduce the hydrological processes in a semi-arid watershed such as the Tleta watershed, as already shown by Briak et al. (2016) in the very close Kalaya watershed.

3.2. Distinct and combined impacts of global change on runoff and sediment yield

Table 5 summarizes the main annual average terms of the water and sediment budget at the reservoir outlet under the baseline situation and the different combinations of land use and climate change scenarios by 2040.

3.2.1. Impact of land use change

Simulation results showed that the change in land use in

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Table 5
Interannual average precipitation, evapotranspiration, runoff, sediment yield and sediment concentration for the reference situation (baseline) and for the different combinations of land use change (LUC) and climate change (CC).

Combination name	Precipitation		Evapo-transpiration		**Groundwater losses**		Runoff		Sediment yield		Sediment concentration	
	mm	Δ (%)	mm	Δ (%)	mm	Δ (%)	mm	Δ (%)	t/ha	Δ (%)	g/l	Δ (%)
Baseline	791.0		466.0		62.1		Δ (%)		26.9		1,02	
S1	791.0	0	470.1	+0.9	41.6	−33.0	279.3	+6.2	20.4	−24.4	0,73	−28.6
S2	791.0	0	491.1	+5.4	54.7	−11.9	245.2	- 6.7	16.9	−36.9	0,69	−32.6
S3	791.0	0	483.6	+3.8	52.8	−15.0	254.6	- 3.2	19.6	−27.3	0,77	−24.8
RCP4.5	741.6	−6.2	470.2	+0.9	53	−14.7	218.4	−16.9	24.9	−7.4	1,14	+11.4
RCP8.5	699.2	−11.6	467.1	+0.2	41.6	−33.0	190.5	−27.5	23.5	−12.6	1,23	+20.6
S1_RCP4.5	741.6	−6.2	470.5	+1.0	34.3	−44.8	236.8	−9.9	19.2	−28.7	0,81	−20.8
S1_RCP8.5	699.2	−11.6	469.5	+0.8	21.3	−65.7	208.4	−20.7	18.2	−32.4	0,87	−14.6
S2_RCP4.5	741.6	−6.2	492.8	+5.8	45.9	−26.1	202.9	−22.8	15.7	−41.5	0,77	−24.4
S2_RCP8.5	699.2	−11.6	490.2	+5.2	33.7	−45.7	175.3	−33.3	14.6	−45.8	0,83	−18.6
S3_RCP4.5	741.6	−6.2	485.6	+4.2	43.9	−29.3	212.1	−19.3	18.3	−32.3	0,86	−15.7
S3_RCP8.5	699.2	−11.6	483.0	+3.6	31.6	−49.1	184.6	−29.8	17.2	−36.3	0,93	−8.9

scenario S1 will provide a +6.2% increase of annual water inflow into the reservoir. This annual increase in water supply is consistent with the significant development of urbanized areas (from 9% currently to 18% of the watershed surface area in S1) and a moderate increase in evapotranspiration (+4 mm), which results from a slight increase in the fruit tree area (2%). Note that the increase in both runoff and evapotranspiration was compensated by a significant decrease in the amount of water that percolated into the deep aquifer (i.e., groundwater losses in Table 5), partially due to the development of urbanization that prevents percolation. In the two other land use scenarios, the annual water supply to the reservoir will decrease by −6.7% for S2 and by −3.2% for S3. This decrease in runoff is mainly explained by the weak development of urbanized areas (from 9% to 13% and 14% of the watershed surface area in S2 and S3), which would not compensate for the increase in evapotranspiration due to vegetation changes. For example, both forested (+7%) and fruit tree (+7%) areas increased at the expense of agriculture (−20%) in the S2 scenario, and it is known that an increase in canopy (more plant biomass and high leaf area index) favours interception and evapotranspiration (Wang & Kalin, 2011). The changes in vegetation in scenarios S2 and S3 will also generate a decrease in water percolation to the deep aquifer.

Regarding erosion, SWAT predicted a significant decrease in sediment yield (from −25 to −37%) and sediment concentration (from −25 to −33%) for the 3 tested land use scenarios. The greater decrease recorded for scenario S2 can be explained by a decrease in erosion-prone land use (crops decrease from 46% to 26% of the total area of the watershed), combined with an increase in more soil-protective land use (fruit tree activity increases from 6% to 15% and forest/matorral from 36% to 43%). The decrease in erosion in S3 is due to a decrease in croplands (from 46 to 40%) and an increase in matorral area, whereas the decrease in erosion for S1 is linked to the decrease in agricultural area and an increase in non-erodible areas related to an increase in urban and industrial activities.

In summary, the three land use change scenarios will impact the water supply to the reservoir in a minor way, whereas they will significantly decrease the rate of sediment input into the reservoir. These results are in line with the results of Carvalho-Santos et al. (2016) and Nunes et al. (2017), who reported a low impact of land use change scenario on runoff rates in several watersheds of Portugal. The results are also in line with studies reporting a higher impact of land use or crop management changes on erosion rather than on runoff (Serpa et al., 2015).

3.2.2. *Impact of climate change*

For the studied watershed, the climate change conditions will result in an increase in average temperatures (+1.3 °C to +2 °C) and a decrease in mean interannual precipitation (−6.2% to −11.6%) for RCP4.5 and RCP8.5, respectively (Table 5, combination name 'RCP4.5' and 'RCP8.5'). SWAT simulations showed that evapotranspiration will be impacted by less than 1%, whereas the annual water supply to the reservoir will significantly decrease by 16.9% and 27.5% for RCP4.5 and RCP8.5, respectively. The decrease in water supplies will be logically more significant under RCP8.5 than under RCP4.5. SWAT also simulated a decrease in the amount of water percolation to the deep aquifer because of less soil saturation induced by less rainfall. The results on erosion flows are less expected. Indeed, the annual volume of sediment entering the reservoir will also decrease, but to a much lesser extent than that of runoff, with reductions of 7.4% and 12.6%, respectively. This result is surprising because greater changes in sediment yields than in water flows are generally reported in the literature (Lu et al., 2013). The increase in the average annual sediment concentration in the stream flow of 11.4% and 20.6% for RCP4.5 and RCP8.5, respectively (Table 5), partially offsets the annual decrease in runoff. The reason for the increase in sediment concentration is discussed below.

The monthly evolution of SWAT outputs (Fig. 5) provides more precise insight into the climate change impact on water and sediment entering the Ibn Batouta reservoir. First, the seasonal rainfall pattern is expected to be greatly modified, with more precipitation in spring and summer and significantly less precipitation in autumn and winter.

Fig. 5 also shows that future precipitation amounts can be very different for some months between RCP4.5 and RCP8.5. For example, the projected rainfall by RCP8.5 is 50 mm higher than the projected rainfall by RCP4.5 in December. However, a seasonal comparison of the occurrence of rainfall greater than 20 mm between the reference period and the two RCPs (Fig. 6) does not show a significant change in the occurrence of major rainfalls.

The future monthly runoff patterns will also be greatly modified, with an increase in runoff amounts in spring and a significant reduction during autumn and winter regardless of the RCP considered. The change in monthly runoff patterns is globally similar to the change in rainfall patterns. However, the runoff response to rainfall change is more complex since it appeared to be nonlinear. For example, the slight decrease in precipitation in January for the two RCPs (i.e., −7% for RCP4.5 and −14% for RCP8.5) will lead to a large decrease in runoff (i.e., −21% for RCP4.5 and −32% for RCP8.5). In March, a significant increase in rainfall will only generate a slight runoff increase.

The monthly sediment yield patterns under the future climate will also be greatly modified, with a significant increase in

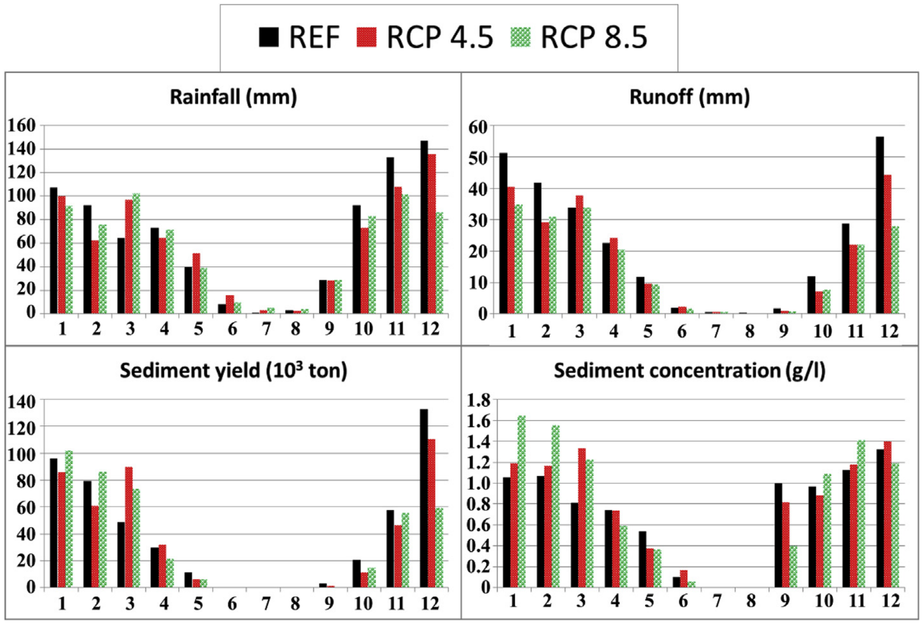

Fig. 5. Monthly SWAT simulated values of rainfall, runoff, sediment yield and sediment concentration at the Tleta watershed outlet during the period 1983–2010 (REF) and the period 2031–2050 (RCP4.5 and RCP8.5).

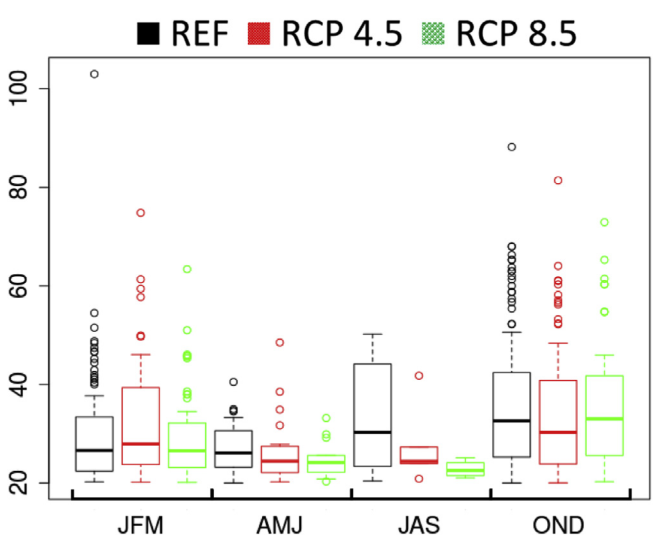

Fig. 6. Seasonal occurrence of major rainfall events using boxplots based on rainfall events greater than 20 mm during the period 1983–2010 (REF) and the period 2031–2050 (RCP4.5 and RCP8.5).

sediment yield amounts in March for both RCPs and a significant reduction during autumn, while a reduction in sediment yield will be observed from May to December. During January and February, sediment yield will increase for RCP8.5 and decrease for RCP4.5. The increase in sediment yield for RCP8.5 in January combined with a decrease in rainfall highlights the complex and nonlinear response of sediment yield to rainfall change. This result is in line with previous studies that have already shown that erosion in the Mediterranean context was highly nonlinear (González-Hidalgo, Pẽna-Monné, & de Luis, 2007).

Analysing the monthly average sediment concentration under current and future climates (Fig. 5) highlights a significant increase in sediment concentration in the streamflow, especially from January to March. Since no significant change in the seasonal occurrence of major events has been detected, it is more likely that the large increase in sediment concentration from January to March is the result of a reduction in soil protection by vegetation. Indeed, the sharp drop in rainfall from October to January will result in both a decrease and delay in vegetation development, which will favour soil detachment by rainfall during the same months and the following months (February and March). The decrease in vegetation development is confirmed by the decrease in biomass simulated by SWAT, especially for croplands, orchards, forests and matorrals.

Most existing studies that have analysed the impact of climate change on runoff and erosion are generally based on the 2000 Special Report on Emission Scenarios (SRES) named by family (A1, A2, B1 and B2). To relate the results of these existing studies to those of our studies based on the RCPs defined in 2010, we can consider that A2 is quite similar to RCP8.5, B1 is quite similar to RCP4.5, and A1B and B2 are intermediate scenarios between RCP4.5 and RCP8.5. More details on the comparison between SRES and RCP can be found at https://www.globalchange.gov/browse/multimedia/emissions-concentrations-and-temperature-projections. Most of these studies have indicated that slight variations in the amount of precipitation can have significant effects on annual average runoff and that climate change is therefore a main factor determining total runoff in a watershed (Yang, 2013). For example, Bussi, Francés, Horel, López-Tarazón, and Batalla (2014) assessed the impact of climate change on the hydrological and sedimentological cycles of the Ésera River catchment (Spain) under A2 and B2 scenarios (2070–2100). They found that the total water yield is expected to decrease by 40 and 35% under the A2 and B2 scenarios, respectively, while the total precipitation is expected to decrease by only 13 and 12%. Nunes et al. (2017) simulated a decrease in runoff of approximately 25% in a Mediterranean watershed of Vale do Gaio, south of Portugal, under the two climate scenarios A1B and B1 over the period 2071–2100, while the amount of precipitation decreased by only 9%. The impact of climate change on sediment yield described in other Mediterranean studies often showed an increase in erosion rates in response to a decrease in rainfall. For example, Paroissien et al. (2015)

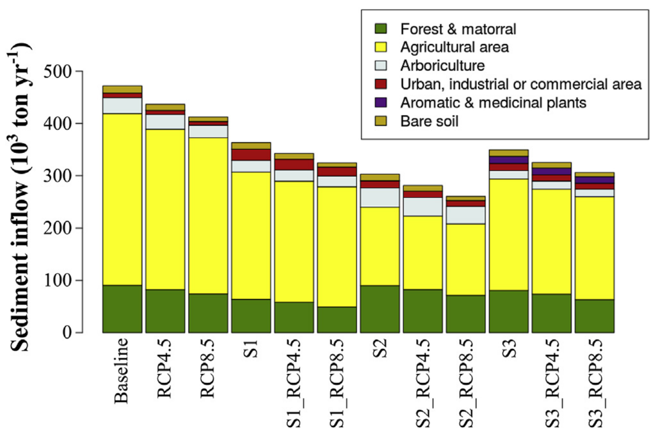

Fig. 7. Average inflow rates of sediments into the Ibn Batouta reservoir for each land use under the different combinations of land use and climate change scenarios.

simulated a 20% increase in the median soil erosion rate in response to a 7% decrease in projected annual precipitation, and Simonneaux et al. (2015) showed that a decrease in rainfall by 10–15% may increase sediment yield by 5–10%. However, more contrasting results were also reported. For example, Bussi et al. (2014) showed a strong decrease (−50%) in sediment yield for the A2 scenario and a small increase (+10%) for the B2 scenario, while Nunes et al. (2017) found limited change for both the A1B and the B1 scenarios (+4.3 and −5%, respectively), indicating that local topography and land use can influence the response to climate change (as already proposed by Nunes & Nearing, 2010, and shown by Serpa et al., 2015).

3.2.3. Combined versus distinct impacts of climate and land use changes

Finally, the combined impact of climate and land use changes (Table 5, combination name 'S1_RCP4.5' to 'S3_RCP8.5') will always generate a reduction in annual water supplies from 9.9% to 33.3% and a reduction in annual sediment supplies from 28.7% to 45.8%, respectively, in the Tleta watershed. The results also highlight that the combined impact of land use and climate change will generate a greater reduction in sediment inputs to the reservoir than water inputs to the reservoir, whereas this was not the case when considering the distinct impact of climate change (combination 'RCP4.5' and 'RCP8.5'). Globally, the results showed that the combined impact of climate change and land use change consisted of the addition of the distinct impact of climate change or land use change. Since both of the distinct impacts generally indicate a reduction in runoff and sediment yield, the combined changes in land use/cover and climate on water and sediment entering the reservoir are expected to generate larger changes than those when the effects of land use and climate are analysed separately. For example, the reduction in runoff and sediment yield for the combination "S2_RCP4.5" is larger than the reduction for the combination "S2" or the reduction for the combination "RCP4.5". In addition, the combined impact of climate and land use change will always generate a reduction in sediment concentration from 8.9% to 24.4%. This result was more difficult to predict, as the distinct impacts of land use change and climate change were opposite since land use change will lead to a decrease in sediment concentration, while climate change will lead to an increase in sediment concentration.

The analysis of the distinct impacts of climate and land use changes showed that the reduction in annual sediment delivery to the Ibn Batouta reservoir is mainly due to land use change, whereas the reduction of annual water volume to the reservoir is mainly due to climate change. While a cluster of previous works has shown that the impacts of land use and crop management changes can be more considerable than the direct impact of climate change (Mullan, Favis-Mortlock, & Fealy, 2012; Paroissien et al., 2015; Rodriguez-Lloveras et al., 2016; Serpa et al., 2015; Simonneaux et al., 2015), runoff results for the Tleta watershed highlight that this is not always the case. In southern Portugal, the combined effect of climate and land use change is expected to generate a decrease of approximately 20% in runoff (Nunes et al., 2017), a value quite similar to the present results. However, the authors predicted an increase in sediment yield of approximately 90%, a value significantly higher than that obtained in the Tleta watershed. This comparison highlights that the expected impact of global change may be very different from one site to another, even if the two sites are quite close, as mentioned by Serpa et al. (2015) for two sites in Portugal. These differences support the need to conduct global change studies on a case-by-case basis (Raclot et al., 2018) to take into account the large diversity of site-specific conditions existing in the Mediterranean environment (Lagacherie et al., 2018; Smetanová et al., 2018).

3.3. Implications for reservoir water mobilization capacities and agricultural activities

Of the various land uses implemented in the Tleta watershed, agriculture is the most important contributor to the sediment entering the reservoir, regardless of the scenario tested (Fig. 7). Reducing the area under winter cereal crops in favour of fruit trees, forest or matorral appeared to be a very effective way of reducing sediment inflow into the reservoir. This is especially the case for the combination including the S2 LUC scenario.

The analysis of rainfall, runoff and erosion changes at the monthly time step (Fig. 5) provided very useful seasonal information for managing agricultural activities and water storage in the reservoir of the Tleta watershed. First, the analysis reveals that the seasonal rainfall pattern is expected to be greatly modified, with the expected reduction in annual precipitation by 2040 (−50 mm/year with RCP4.5 and −100 mm/year with RCP8.5) occurring mainly from October to February. The monthly decrease could even reach −60 mm for December with RCP8.5. At the same time, a significant increase would be recorded during the month of March, with more than 40 mm (+50%) expected according to the two climate scenarios, whereas a slight rainfall increase is expected during the summer months, especially in June and July (approximately +4 to +8 mm cumulated for these two months). The expected change in annual rainfall and seasonality by 2040 will lead to a significant decrease and delay in the water supply to the Ibn Batouta reservoir just after the hot and dry summer season. The decrease will be in the range of −29% to −28% for autumn and −24% to −37% for winter for RCP4.5 and RCP8.5, respectively. Therefore the risk of the reservoir drying out will significantly increase, as shown in other Mediterranean countries (López-Moreno et al., 2014; Nunes et al., 2017), and alternative water resources must be considered to meet water needs for consumption or irrigation especially between July and March. Such a change in rainfall patterns will also deeply impact rainfed agricultural activities by delaying ploughing and seeding as well as vegetation growth. As a result, winter cereal crops will become a risky option, whereas they currently represent 60% of the cultivated land. For farmers, measures to adapt to the observed negative hydrological impacts of global change may include reducing winter cereal cropping in favour of spring cereals and pulses that have a shorter and more spring-centred cycle. Another beneficial change would be to further develop fruit trees, such as olive, at the expense of winter cereals since permanent vegetation will protect the soil against erosion and

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Table 6
Impact of the different scenarios on reservoir volume capacity by 2040 and the year the storage capacity of the reservoir would fall below 1 Mm^3.

Combination name	Remaining reservoir volume in 2040 (10^6 m^3)	Year when reservoir storage capacity would fall below 1.10^6 m^3
Baseline	19.01	2093
S1	20.19	2114
S2	20.80	2131
S3	20.32	2117
RCP4.5	19.35	2097
RCP8.5	19.59	2100
S1_RCP4.5	20.38	2118
S1_RCP8.5	20.55	2122
S2_RCP4.5	21.00	2137
S2_RCP8.5	21.19	2144
S3_RCP4.5	20.54	2122
S3_RCP8.5	20.72	2127

therefore participate in the expansion of the reservoir lifetime.

An overall decrease in sediment input to the reservoir is expected to be distributed almost year-round (Fig. 5), except during some months at the beginning of the year depending on the RCP considered. Higher precipitation and runoff amounts can explain the sediment yield increase in March, but only a change in vegetation development could explain the increase for the other months. The benefit on erosion rates of a clear decrease in rainfall during the fall season when cereal cropped lands are bare is therefore very significant. By reducing the siltation rate of the reservoir, global change is likely to expand the lifetime of the reservoir. Table 6 shows the remaining water volume capacity of the reservoir in 2040. It also provides the year when the water storage capacity of the reservoir will fall below 1 Mm^3, assuming a constant annual erosion rate beyond 2040 and a trapping efficiency updated each year using Heinemann's formula.

An increase in internal deposition in the watershed, particularly in the stream, can also be expected due to higher concentrations of sediment in the stream flow associated with a decrease in stream frequency and flow that will result in a decrease in hydro-sedimentological connectivity.

4. Conclusions

The Soil and Water Assessment Tool was applied to the Tleta watershed to determine for the first time the distinct and combined impacts of global change (climate and land use changes) on the runoff and erosion responses in northern Morocco. All combinations of three climate and four land use scenarios (one being the reference conditions) were simulated by the SWAT model over the period 2031–2050 with calibrated parameters over the reference period 1983–2010. The SWAT model successfully reproduced water and sediment entering the reservoir located downstream of the studied watershed over the reference period 1983–2010. Climate change resulted in an increase in average temperatures (+1.3 °C to +2 °C) and a decrease in mean interannual precipitation (−6.2% to −11.6%) for RCP4.5 and RCP8.5, respectively, with the highest reduction in the fall and winter seasons. The combined impact of climate and land use changes is expected to generate a reduction in water availability for consumption and irrigation (9.9%–33.3%) and a large reduction in annual sediment entering the downstream reservoir of the Tleta watershed (28.7%–45.8%). The combined changes in land use/cover and climate on water balance and sediment outputs will generate larger changes compared to those of the effects of land use/cover change alone. The analysis of the distinct impacts of climate and land use changes suggests that the reduction in annual sediment delivery to the reservoir is mainly due to land use change, whereas the reduction in annual water volume to the reservoir is chiefly due to climate change. A seasonal analysis of the change highlights the need for the adaptation of agricultural activities and of water supply from the reservoir because of the higher risk of reservoir depletion between July and March. Finally, consideration should be given to the use of alternative water resources to meet the region's water needs. Comparison with the results obtained for other Mediterranean regions shows that the expected impact of global change can be very different from one site to another, even if the two sites are very close to each other. This supports the need to conduct global change studies on a case-by-case basis to be able to take into account site-specific conditions. Future developments will require testing a wider range of scenarios and quantifying uncertainties associated with the results provided on the expected changes.

Declaration of competing interest

I declare no conflict of interest.

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