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Assessment of soil salinity in Cebala-BorjTouil irrigated area under different climate change scenarios (Northeastern Tunisia): application of SaltMod tool

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Abstract - The delta areas throughout the world are highly vulnerable to climate change. In arid regions, the delta landscapes and hydrologic balance have greatly changed. The irrigated areas from these regions will be more affected by runoff changes, and anthropogenic impacts. In the present study, the irrigated and drained area of Cebala-Borj Touil (Cebala) from the Low Valley of the Medjerda delta was selected to investigate the impact of climate change on soil salinization using the SaltMod model. A plot from the Cebala area with an area of 0.243 ha was simulated in order to predict the impact of climate change on soil salinity. Four climatic scenarios were run involving precipitation decrease, drought condition, evapotranspiration increase and a decline in the quality of irrigation water. The simulations showed a significant influence of precipitation and evaporation on the root zone salinity. Indeed, the application of irrigation water of 8 $dS.m^{-1}$ would cause a rise of around 1.0 and 1.5 $dS.m^{-1}$ in soil salinity during the wet and the dry season, respectively. The combination of the climatic change scenarios contributes to an acceleration of the soil salinization process: the projected mean salinities in 2050 will almost double. The present results indicate that the perimeter is highly vulnerable to soil degradation under climate change scenarios.

Key words: Soil Salinization, Irrigation, Drainage, Climate change, SaltMod, Tunisia.

1. Introduction

During the last centuries, the quality of soil and water resources has been a big challenge in arid and semi-arid countries which are the most vulnerable areas to climate change (Jabbar and Chen, 2008; Garcia-Franco et al., 2018; Ziadat et al., 2022). Soils are already affected by erosion, salinity, and degradation due to human activities (Gitz et al., 2016). The situation is worsened by increasing temperatures and extreme rainfall events (Sivakumaran, 2015; Ljungqvist et al., 2016; Pendergrass et al., 2017). Sea levels are also expected to rise, thus threatening the coastal zones. Predictions of global mean rise in the sea level are between 0.1 and 0.2 m during the 21th century (IPCC, 2001). Recent studies have found a rise in global mean sea level of 0.21 to 0.24 m since 1880 (IPCC, 2019). The main damages caused by the sea level rise include the expansion of flooded areas, the degradation of coastal wetlands, and the increase in the soil and aquifer salinity (Nicholls and Tol, 2006; Hinkel et al., 2012; Hallegatte et al., 2013). In Tunisia, the effects of climatic changes have been observed: an increase in mean annual temperatures by about 1.4°C in the 20th century and a decrease in annual rainfall by 5% per decade since 1950 (IPCC, 2013). The threat of soil salinization in coastal irrigation plains would therefore become a major agricultural problem, especially in the Lower Medjerda Valley (Northern Tunisia), which is the largest irrigation area in Tunisia (Riahi et al., 2018). It is a coastal deltaic plain characterized by saline shallow groundwater and poor natural drainage. The process of soil salinization in the Low Valley of Medjerda (LVM) is still controversial because of the complexity of the involved factors. Thus, the aim of this study was to contribute to the understanding of soil salinization state and to study its future development using a numerical model. The study area is a plot command from the Cebala irrigation area belonging to the LVM. The SaltMod model was chosen for its easy application and its requirement for seasonal input data, which are more available (Srinivasulu et al., 2004). In the current study, the SaltMod was applied for the first time to investigate soil salinity variation under different climate change scenarios.

The outcomes of the study led to a better characterization of soil salinity evolution in the selected area which could help decision-makers opt for the appropriate management. Moreover, these findings could be applied at a larger scale, in similar cases of coastal irrigation areas (Azuz-Adeath and Yañez-Arancibia, 2019; Rokonuzzaman and Hattori, 2021).

2. Materials and methods

2.1 Study area

The Cebala-Borj Touil irrigated area, located in the North of Tunisia, is a large flat plain with an area of 3200 ha belonging to the Low Valley of Medjerda River. It is equipped with a drainage network composed mainly of open ditches. The drainage network efficiency has progressively deteriorated over the last three decades. The natural drainage system of the study area is composed of the Khelidj and the El Maleh Wadis.

The study area is characterized by a semi-arid climate with a wet season extending from September to May and a dry season from June to August. The average annual rainfall is 450 mm and the potential evapotranspiration is about 1300 mm.year-1. As part of the Low Valley of the Medjerda River, the Cebala area lies on Quaternary alluvial deposits. The soil texture is loamy-clay with high salinity varying between 2.0 and 3.5 dS.m-1 at the soil surface layer. The soil salinity was determined using the saturation extract method (USSL, 1954). The groundwater table in this area is shallow and it ranges from 0.2 to 1.8 m above sea level (ASL) and the water table depth ranged from less than 0.5 m from the ground surface to more than 8 m. The groundwater salinity is varying between 10 and 20 dS.m^{-1}.

The present study focused on a plot of 0.243 ha, drained by a secondary ditch D2 (Figure1). The selection of this area is mainly based by the existence of the needed data for the simulation: irrigated areas, irrigation doses and salinities, piezometric level, the root zone depth, etc. The drain depth is 1.5 m. The main selection criteria were the availability of field data and the presence of an efficient drainage network. The plot was previously studied by Dahmouni et al. (2019).

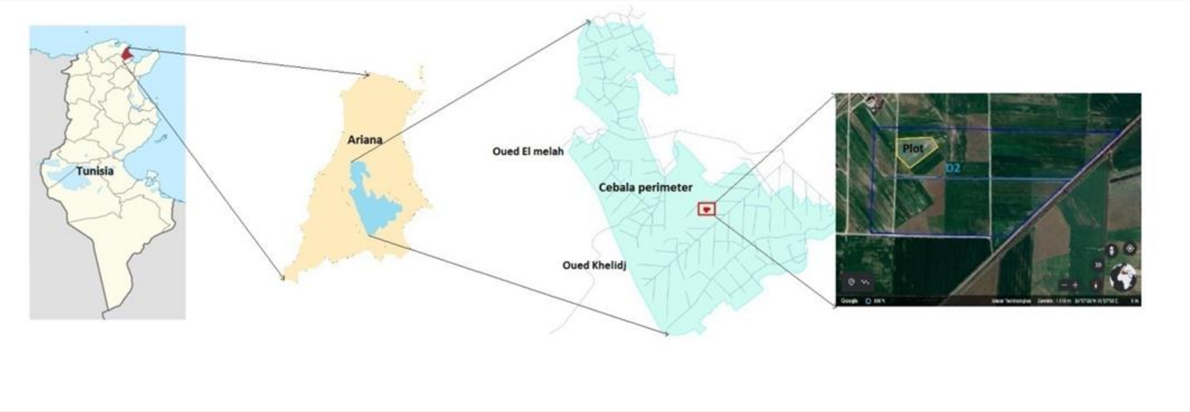


Figure 1. The location of the study area:(A) Region location (B) Ariana gouvernate; (C) Localization of the command area from the irrigation area of the Cebala-Borj Touil (D) Boundaries of the command area (Google earth image).

2.2 Model Setup

2.2.1 Model description

SaltMod is an agro-hydro-salinity model developed by Oosterbaan and Pedrose (1989). It consists of three principal components, namely the agronomic aspects, especially the kinds of agricultural practices (agro), the water balance model (hydro), and the salt balance model (salinity). The model uses a seasonal time step in the calculation of salt and water balances. The largest seasons' number is set to four with duration of a given number of months varying from 0 to 12. SaltMod was first tested and validated in the pilot areas in Egypt, India, and Portugal (Oosterbaan, 1997). It was then applied to many case studies all over the world (Isidoro and Grattan, 2011; Saidi et al., 2015; Chamaki et al., 2019). It considers four reservoirs, namely the surface reservoir, the root zone, the transition zone, and the aquifer. The water flows are all vertical except the subsurface drain flow located in the transition zone. The program is designed to separately estimate salt and water balance for each reservoir using a mass conservation equation for boundaries defined in space and time (Oosterbaan, 2001):

Inflow = Outflow + Storage (1)

The water content increases if the storage is positive and inversely. The required input data for the model are the hydro-meteorological data, the soil characteristics, and the agricultural aspects. The principal model outputs are the soil salinity, water table depth, and drain discharge in irrigated agricultural lands.

2.2.2 Data acquisition

Data were obtained from several studies, organizations, and administrations. The main climatic data components are rainfall, air temperature, and evaporation rates. Daily climatic data were taken from Tunis-Carthage meteorological station, close to the study area, operated by the National Institute of Meteorology (NIM). Based on climatic data, the evapotranspiration rates were estimated using the SIMPEL Model (Hörmann, 2014), a one-dimensional soil water model (bucket model) used for the calculation of water balance on light and medium soils. In the current study, the FAO Penman-Monteith method (Zotarelli et al., 2010) was applied to estimate the PET rates at a daily time step. The input parameters required by SaltMod are summarized in table 1.

Table 1: Input parameters required by SaltMod

Input parameter	Value
1. Duration of season	
Season 1 (month)	5
Season 2 (month)	7
Fraction of irrigated area in season 1	0.1
Fraction of irrigated area in season 2	0.9
2. Soil properties	
Total porosity of the root zone (m/m)	0.15
Total porosity of the transition soil (m/m)	0.3
Total porosity of the aquifer (m/m)	0.5
Drainable porosity (m/m)	0.14
3. Water balance components	
Irrigation in season 1 (m)	0.249
Irrigation in season 2 (m)	0
Precipitation (m)	(Time series)
Potential evapotranspiration (m)	(Time series)
Storage effeciency (fraction)	0.2
Surface runoff i ($m^3.season^{-1}.m^{-2}$)	0.1
4. Drainage criteria and system parameters	
Root zone thikness (m)	0.75
Drain depth (m)	1.5
Transition zone thikness (m)	1
Aquifer thikness	3
5. Initial boundary conditions	
Depth to water table at the beginning of season 1 (m)	0.5
Initial salinity in the root zone($dS.m^{-1}$)	3.5
Average salt concentration of irrigation water ($dS.m^{-1}$)	5

2.3 Climate Change scenarios

1- The Representative Concentration Pathways (RCP):

In order to predict changes in climate parameters, the Intergovernmental Panel on Climate Change (IPCC) uses scenarios based on the rate of CO_2 emissions while taking into account the impact of human intervention (IPCC 2014). In AR5 (5th IPCC Assessment Report) four-way approach were maintained for climate change modeling. These pathways differ in the range of radiative forcing values in the year 2100. In fact, the RCPS: RCP4.6, RCP4.5, RCP6 and RCP8.5 correspond to radiative forcing values of 2.6, 4.5, 6 and 8.5 W/m2, respectively. RCP8.5, which corresponds to a maximum radiative forcing and a warming of 4 to 5°C by 2100, is considered the most pessimistic scenario.

2- Climate scenarios based on the RCP 8.5

In the current work, the climate change scenarios used refer to the RCP8.5 from the Fifth Assessment Report (AR5) of the United Nations Intergovernmental Panel on Climate Change (IPCC, 2013). The AR5 prediction scenarios are run with near and long-term projections covering the periods up to 2050 and 2100, respectively (Terink et al., 2013). In the current study, only near term projections (2050) are considered since the goal of the study is to help decision-makers opt for the adequate adaptation strategies by understanding the near-future impacts of the climate change on soil salinization. The scenarios simulation was compared to those of the calculations under standard conditions. Descriptions of different climate change scenarios are provided in table 2.

Table 2: Description of simulated scenarios.

Scenarios	Description
Standard Condition	A standard condition simulation consists on using the seasonal averages of precipitations and evapotranspiration calculated for the period 1970-2019 as input data for each year from the simulated period (2020-2050). Thus for the standard condition simulation, the input precipitation averages for each year are constant and equal to 100 mm and 360 mm respectively for the dry and the wet season. Similarly, the evapotranspiration input values are 740 mm and 470 mm for the dry and the wet season respectively. For the impact scenarios the climatic input data for the period 2020-2050 are set similarly to the used data from 1990-2019.
Rainfall decrease (scenario 1)	This scenario is based on the AR5 report. It estimates an annual precipitation decrease of -20% by 2050 in Tunisia, correspondingly to the RCP 8.5 scenarios.
Drought (scenario 2)	This scenario aim to test the impact of the occurrence of the drought events. That represents the other side of the precipitation changes. To simulate the impact of drought on the soil salinity, the precipitation input data were set respectively to 77 mm and 306 mm for the dry and the wet seasons of the successive drought events happening each 5 years. The considered minimal rainfall values correspond to the results of a frequency analysis of exceedance probability for a return period of 100 years.
PET increase (scenario 3)	The potential evapotranspiration rates increase is also considered as a promising scenario. According the IPCC (2014), the evapotranspiration is expected to continue to increase as long as water is available. This rise is estimated to be between +0.37 mm.year^{-1} to +0.51 mm.year^{-1} in the MENA region (Ajjur and Al-Ghamdi, 2021). Thus, for the present simulations, we adopted the maximum possible increase with +0.51 mm.year^{-1}.
Water irrigation salinity increase (scenario 4)	This scenario is in relation with the irrigation water quality degradation due the climate change. In this case, the irrigation water salinity was estimated using results from a similarly study in Tunisia were it is supposed to raise from 3 to about 6 dS.m^{-1} (Haj-Amor et al., 2020). Subsequently, a mean increase of 3 dS.m^{-1} in the irrigation water salinity is adopted. The irrigation salinity rises from 5.0 dS.m^{-1} to 8.0 dS.m^{-1}.

2.4 Model parameterization

In this study, the SaltMod simulation was processed in two seasons per year. The duration is 5 months (May-September) for the dry season and 7 months (October- April) for the wet season. Soil and groundwater data were implemented in the model during the calibration and the simulation processes. The total simulation period is 60 years, starting from 1990 to 2050 and divided in two steps. The first simulation started on January 1st, 1990 and ended on December 31st, 2019. During this period, all the calculations were based on the cumulated precipitation values for each season calculated for the period extending from 1990 to 2019. The input evapotranspiration amounts input from 1990 to 2019 were given by the total daily values calculated for the dry and the wet seasons using the SIMPEL model (Hörmann, 2014). It is a one-dimensional soil water model (bucket model) used for the calculation of the water balance on light and medium soils. (Figure 2). During the period 2012 to 2014, the total PET is lower than the mean. This is maybe due to the successive low precipitation during this period and the reduction of the irrigated areas. Thus, the reduction of the water recharge might be the origin of the evapotranspiration decrease. A second simulation for the period 2020 to 2050 was run to forecast the salinities in the root zone.

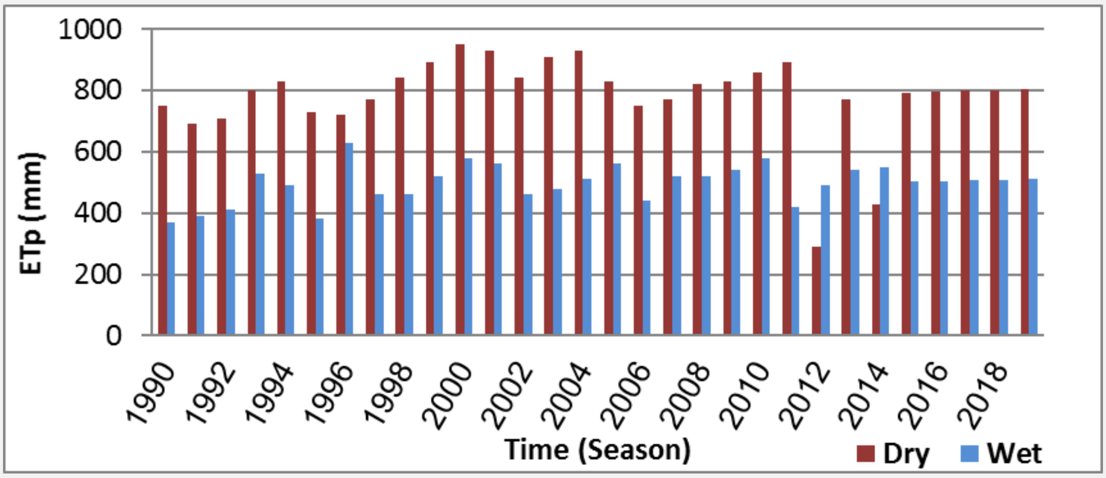


Figure 2. Calculated evapotranspiration (mm) from 1990 until 2019 using SIMPEL mode

2.5 Model calibration and validation

In the SaltMod model, the calibration process consists of a trial and error numerical method in order to reach appropriate salt and water balances. Calibration was therefore performed by running trial simulations with different values of leaching efficiency and natural drainage until the simulated values of soil salinities and depths to water table (Dw) agree with the field observations. The validation processes were carried out over a 30-year period, from 1990 to 2019. The input data for each year were given as average values over two seasons: wet and dry. The Nash-Sutcliffe efficiency (NSE) was calculated both for the calibration and the validation processes. It is a normalized statistic determining the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe, 1970). Based on the validated model, scenarios of the climate change effects were simulated.

2.5.1 Calibration process of leaching efficiency

The leaching efficiency of the root zone (Flr) is the ratio of salt concentration of the water percolating from the root zone to the average concentration of soil water at saturation. It measures the proportion of the water supposedly able to leaching salts from the root zone, and that efficiently removes salt. Therefore, the leaching efficiency varies between 0 and 1 (Oosterbaan, 2001). The leaching efficiency parameter is variable and its particularity depends on the soil. The Flr parameter is estimated at 0.8 in the heavy alluvial clay soils of the Nile Delta of Egypt (Oosterbaan and Abu Senna, 1990). However, for the Tagus Delta of Portugal, characterized by a clay-loam texture with high lime content, a lower Flr value of 0.15 was adopted for the simulation (Vanegas Chacon, 1993). In the current study, the adopted initial value of Flr was 0.8 according the previous study of (Morri, 2013), which investigated a similar area from the low valley of Medjerda (Northern Tunisia). The calibration process consists in varying the leaching efficiency values arbitrarily using a trial-and-error procedure.

2.5.2 Calibration process of natural drainage

The natural subsurface drainage is defined as subsurface lateral drainage (Gn (m/season)). It is defined as the subtracting of the excess of the horizontally outgoing water (G0) minus the horizontally incoming groundwater (Gi). This parameter was determined by arbitrarily varying the range of Gn values, in pairs, and proportionally to the season duration. Then, the value giving a good coordination between the simulated and the field observed depth to water table was adopted for the next calculations. The Gn value was determined by setting the Gi at zero and arbitrarily changing the Go.

3. Results

3.1. Model calibration

3.1.1. The leaching efficiency

The tested values of the leaching efficiency of the root zone (Flr) are 0.2, 0.5, and 0.9. The salinity results of each simulation were compared with the measured values (Figure 3).

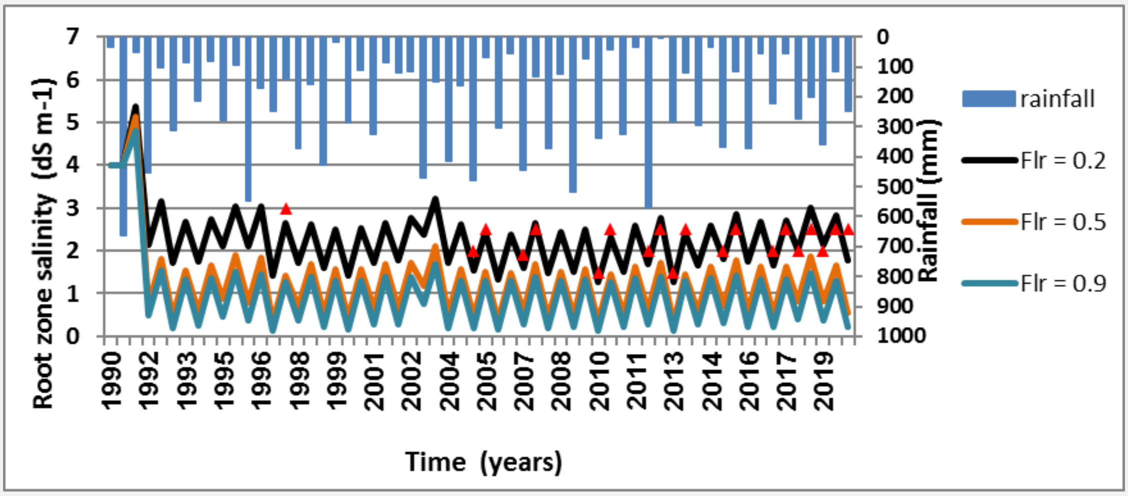


Figure 3. Calculated and observed root zone salinities during the calibration period

A leaching efficiency of 0.2 for the root zone gives the best match to the observed values. The calculated Nash-Sutcliffe coefficient of efficiency of 0.746 shows a good correlation between the measured and the observed values. For all the simulations, the general curves appear to be analogous. Seasonal variation shows a peak during the dry season and it reaches the minimum during the wet season. The different Flr values cause a parallel shift of the curves. The difference between maximum and minimum decreases when the Flr values are reduced. The leaching efficiency in the root zone depends on the salinity of the water percolating while the concentration of the soil water at saturation is maintained.

3.1.2 The natural drainage

Taking into account the two simulation periods (1st season (5 months, Go1), 2nd season (7 months, Go2)), arbitrary Go1 and Go2 values were tested. Since the first season is shorter than the second one, the seasonal range of Go values for the first and second seasons respectively, are in pairs 0 (0–0), 0,03 (0.01–0.02), 0.1 (0.04–0.06), and 0.09 (0.03–0.06).

These results (Figure 3) shows a good match to the observed depth of water for a Gn value at 0.003, corresponding to a Go1 = 0.01 and Go2 = 0.02. The corresponding calculated Nash-Sutcliffe, is 0.874. Therefore, a Go of 0.03 m/year (0.01-0.02) was maintained for the model simulation (Figure 4).

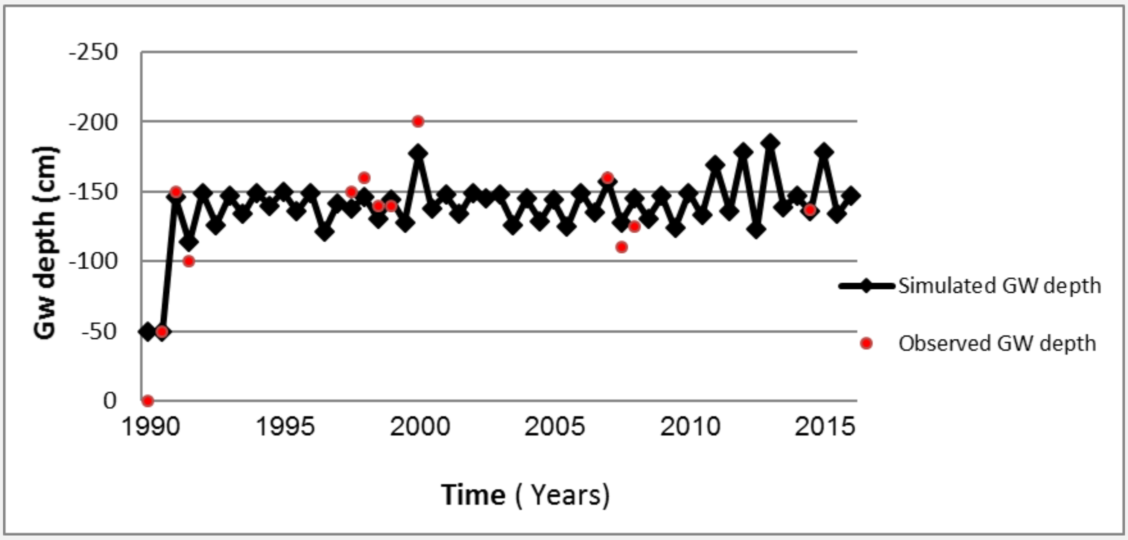


Figure 1. Calculated and observed groundwater depth during the calibration period

3.2Effects of climate change on soil salinity

3.2.1 Effect of rainfall decrease (scenario 1)

The initial input precipitation of the year 2020 was set to rainfall values for the dry and the wet seasons from the year 1990. During the simulation, the values series 1990-2019 were decreased progressively for the dry and the wet seasons with a total percent of 20% reached by the year 2019. The given soil salinity remains close to that of actual conditions until early 2030.The results reveal an increase of soil salinity of respectively 9% and 25% by the end of the wet and the dry seasons, in 2050 (Figure 5 (a)). Thus, the effect of decreasing rainfall will be noticeable especially during the dry season. The Cebala soil is non-saline in the wet season and it is slightly saline in the dry season. Comparison of the mean annual salinity evolution in the 1st scenario and the standard condition clearly shows a mean salinity rise from 2.16 to 2.54 dS.m^{-1} by the end of 2050.

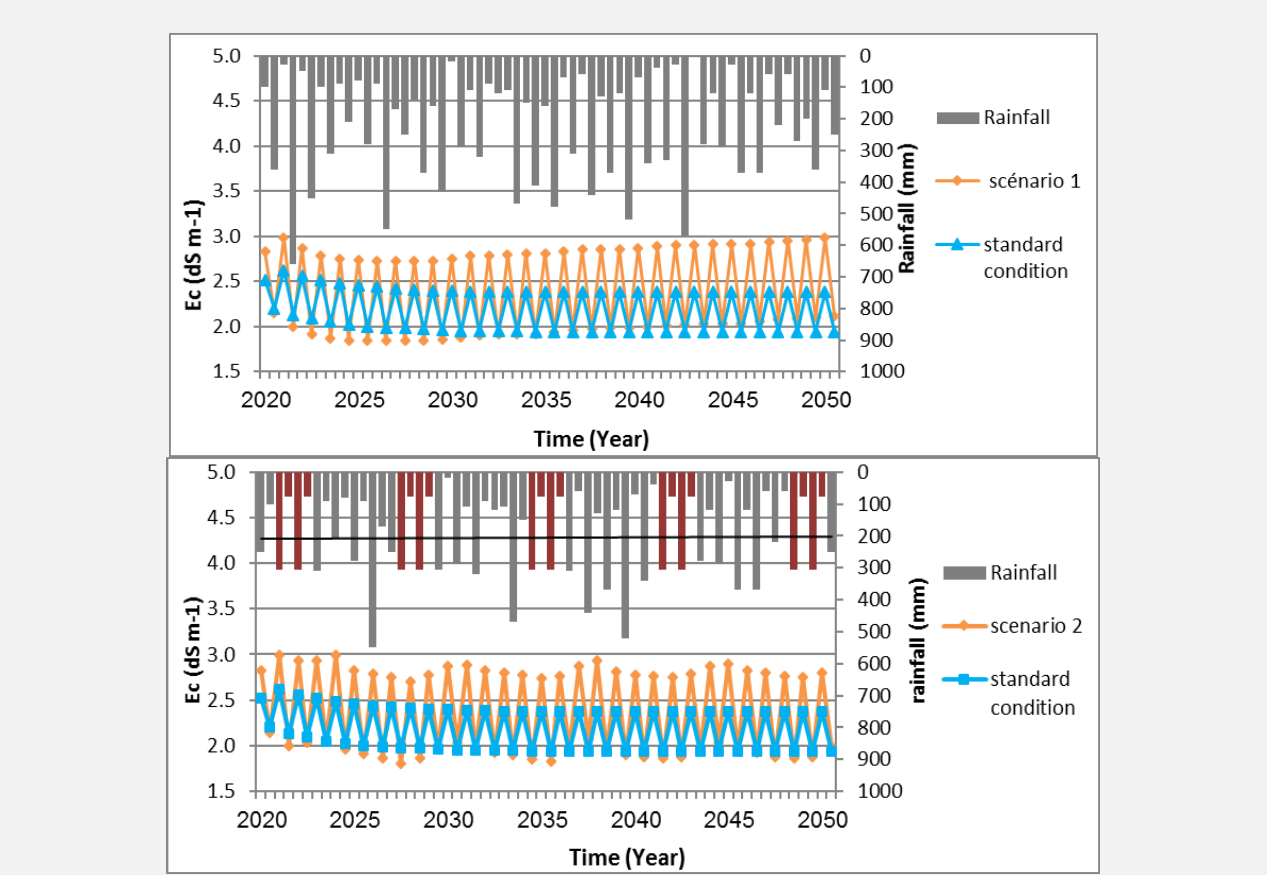
3.2.2 Effect of drought event (scenario 2)

The results of the recurring drought condition simulation show a shifted increase in soil salinity with a maximum in the second season of the year 2024, where the observed electrical conductivity will rise from 2.75 to 2.99 dS.m^{-1} (Figure 5 (b)). The minimum observed is about 1.81 dS.m^{-1} two years after the first drought period. Precipitation during the wet season would not be enough to leach the salt into the groundwater and to contribute to salt accumulation. In the current scenario, the effect of rainfall changes is not immediately observed. Compared to rainfall decrease, intermittent drought will cause much more accelerated salinity rise. However, salt balance is quickly coming back in equilibrium after its perturbation.

3.2.3 Effect of change in the PET (scenario 3)

The initial PET during the dry and the wet seasons at the beginning of simulation for the year 2020 was also assigned to the corresponding values from 1990. During the simulation the PET series from 2020 to 2050 are similar to the period 1990-2019 with an increase of 0.51 mm.year^{-1} .

As shown in figure 5 (c), at a seasonal time step, the impact of PET increase is higher during the dry season. The maximum salinity rise will be about 3.77 mm on 2049 and a minimum of 2.14 in 2021. The salinity variability would be very important for this scenario. The loss caused by evapotranspiration in the water balance during the dry season cannot be totally compensated by the irrigation amount. The estimated ECe in the root zone would increase with an important slope, presenting an alarming progress.



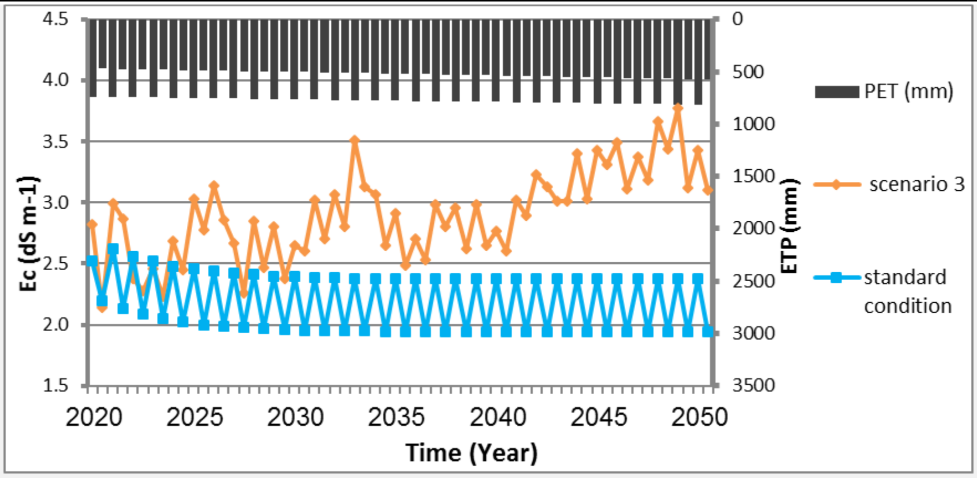


Figure 5. Effect of the precipitation increase (a) extreme rainfall (b) and PET rise (c) on the root zone salinity

3.2.4 Effect of the degradation of irrigation water quality (scenario 4)

The results of the simulation are presented in figure 6. Salts in irrigation water would contribute to a significant increase in the root zone salinity from 2.38 to 5.15 dS.m^{-1} and from 1.95 to 3.93 dS.m^{-1} during the dry and the wet seasons, respectively. The average mean salinity rise will be around the double in both seasons. Salt accumulation would be more marked during the dry season since the irrigation amount is higher and the evaporation process is more important. The predicted salinity has a similar trend during the simulation since the corresponding scenario is defined only by the initial conditions. However, this scenario reveals the high sensitivity of the study area to irrigation water quality. In addition, the predicted maximum salinity of 5.15 dS.m^{-1} would widely exceed the crop tolerance and might reduce their growth.

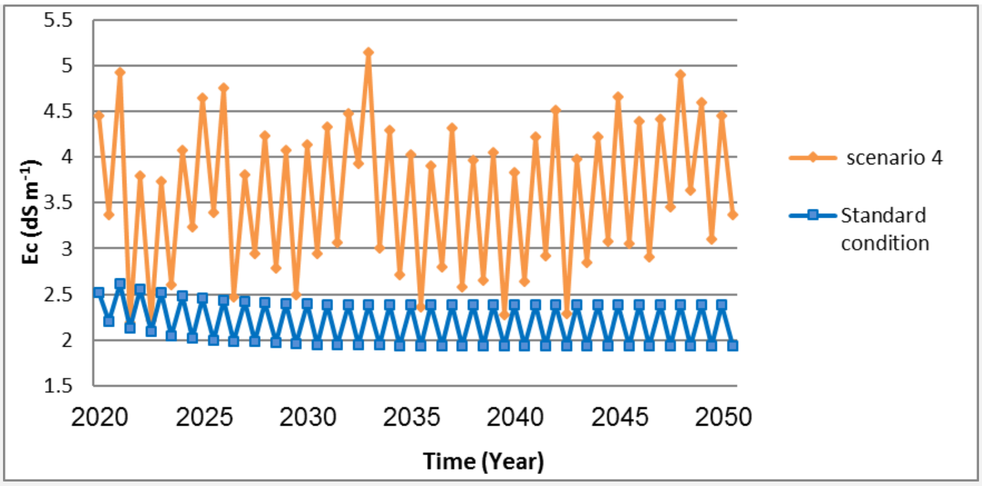


Figure 6. Effect of water quality degradation (scenario 4) on the root zone salinity.

4. Discussion

The current research focuses on the model application to simulate the soil salinization risks under climate change in a coastal area affected by shallow saline groundwater and irrigated by brackish treated wastewaters. Such irrigated areas exist in several deltaic regions in many semiarid and arid countries. The risks of soil salinization result from residual primary salinization and secondary salinization caused by irrigation water, capillary rise from shallow groundwater, and climate factors. The climate change will be the origin of the decrease of water balance at a local scale (increase of temperature and decrease of rain. The case study of Cebala exemplifies this complex situation.

The present study confirms that the Cebala area is highly vulnerable to salinization and that the climate change scenarios are worsening the situation. These results indicate an increasing salinization process under all the simulated scenarios. The effect of the decreasing rainfall will be noticeable. The Cebala soil would be non-saline in the wet season to slightly saline in the dry season. The comparison of the mean annual salinity evolution of the 1st scenario compared to the standard condition shows clearly a future salinity rise. However the occurrence of periodic extreme events in scenario 2 would be much more influential. But in both simulations the soil EC would not exceed 3 dS.m^{-1}. On the other hand, the impact of the ETp increase will be clearly higher especially during the dry season because the losses by evapotranspiration in the water balance during the dry season could not be totally compensated by the irrigation amount. According the scenario 3, a maximal Ec of 3.77 would be observed on 2049. Nevertheless, the scenario 4 considering a degradation of the water irrigation quality reveal a very important potential impact on the salt accumulation in the Cebala soil: This finding presents an alarmist situation with a mean salinity of about 3.6 dS.m^{-1} and a maximum of 5.54 dS.m^{-1}.

The present research outcome is still valuable compared to similar studies. Studies conducted in the coastal regions of Bangladesh (Dasgupta et al., 2015; Rahman et al., 2018). They showed an annual median projected change in soil salinity of 39 % by 2050 with a maximum monthly salinity of 13.1 dS.m^{-1} in the dry season. The study of many catchments from Australia reported a large increase, exceeding 18%, in soil salinity under climate change conditions by 2070 (Austin et al., 2010). The latter findings are consistent with those of Cebala case study, where salinity rise varies between 11% to 59%. These results also reveal the potential impact of water irrigation quality on salt accumulation in the Cebala soil. The particularity of the region and the selected model may lead to specific outcomes. Hence, the results of this study are essentially helpful for the implementation of an adequate adaptation management to soil salinization in the Cebala irrigation area.

Conclusion

This study is based on a simulation procedure using SaltMod to investigate soil salinity variation in the Cebala irrigation area. The study region is already affected by the problem of soil salinization. The results of the simulated ECe in the root zone indicate a high salinity of around 2.7 dS.m^{-1}. The results of the RCP8.5 simulations of climate change scenarios for the coming thirty years reveal a serious threat of the soil degradation in the Cebala area. The irrigation water quality degradation is the major factors of the substantial increase in the root zone salinity. The predicted soil salt content exceeds the crops salt tolerance and consequently it might limit agricultural production.

The obtained results seem to be realistic and they illustrate the SaltMod ability to predict the soil salinity variation under different climate change scenarios. Despite the model limitation in the representation of salt chemistry in soils, it is still an efficient tool in the presence of data scarcity.

Future research on the simulation of management scenarios simultaneous to climate change projections could be helpful in evaluating the area aptitude to rehabilitation. Overall, this research provides a solid base for the decisions-makers to plan a strategy for the prevention of climate change impact on soil salinization.

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