Environmental Science and Pollution Research (2020) 27:32157–32178
https://doi.org/10.1007/s11356-019-06105-x

RENEWABLE ENERGY AND WATER SUSTAINABILITY

Assessment of climate change impacts on water quality parameters of Lake Burullus, Egypt

Ahmed Shalby[1] · Mohamed Elshemy[1,2] · Bakenaz A. Zeidan[1]

Received: 16 April 2019 / Accepted: 29 July 2019 / Published online: 7 August 2019

Abstract

Egyptian Mediterranean coast hosts five shallow lagoons which play a vital role in the national economy. Lake Burullus is the second largest one that is located in the Nile Delta and is connected to the Mediterranean by a narrow outlet. This lagoon faces various anthropogenic-induced implications that threat its ecosystem and biodiversity. The prime objective of this study is investigating the impacts of future climate change (CC) on its characteristics. A 2-D hydro-ecological modeling for the lagoon was implemented, using MIKE21FM. The proposed model was calibrated and validated against the collected water quality records, for two successive years (2011–2013), at twelve monitoring stations throughout the lagoon. The simulations were executed for various parameters, including water depth, salinity, DO, BOD, and nutrient components. Six simulations from different regional climate models (RCMs) were obtained and examined to extract the most accurate climatic projections for the lagoon coordinates. These climatic estimates cover three Representative Concentration Pathways (RCPs) scenarios according to the IPCC's Fifth Assessment Report (AR5). A moderate sea level rise (SLR), locally projected offshore from the Nile Delta coast, was obtained. The validated model was forced with the climatic and SLR projections of 2 years representing the mid and long-term future of the twenty-first century. The model results showed that the developed model is an efficient tool to simulate the lagoon characteristics. The results of the modified model showed that CC has the potential to radically alter the physical and chemical structure of Lake Burullus. The results emphasized that the lagoon is expected to be warmer and more saline. The risk of oxygen depletion is firmly predictable with significant spatial differences of DO decreasing. A prolonged residence time is expected, accompanied by an increasing trend of phosphate and chlorophyll-a and a decreasing trend of nitrate. CC impacts on Lake Burullus should be considered in its urgently required management plan.

Keywords Climate change · Coastal lagoon · IPCC–AR5 · Lake Burullus · MIKE 21 · RCM · SLR · Water quality model

Introduction

Anthropogenic disturbance–induced implications on the water resources ecology have increased, apparently on the coastal ecosystems such as estuaries, bays, and lagoons (Rabalais et al. 2009). Globally, coastal zones are intensively populated and exhibit higher rates of urbanization combined with land-use changes and expanded human activities (Neumann et al. 2015). Consequently, they have exposed to excessive amounts of nutrients and heavy metals from industrial, agricultural, and domestic waste discharges. The anthropogenic acceleration of greenhouse gas (GHG) emissions is altering the planet's climate. Climate change (CC) is being an ominous and serious threat which strongly affected aquatic environments. Being located at the land-sea interface, coastal ecosystems will be

Responsible editor: Philippe Garrigues

✉ Ahmed Shalby
ahmed.shalby@f-eng.tanta.edu.eg

Mohamed Elshemy
m.elshemy@f-eng.tanta.edu.eg

Bakenaz A. Zeidan
b.zeidan@f-eng.tanta.edu.eg

[1] Department of Irrigation and Hydraulics Engineering, Faculty of Engineering, Tanta University, Tanta 31511, Egypt

[2] Faculty of Engineering, Al-Baha University, Al-Baha, Kingdom of Saudi Arabia

subjected to the combined effects of climatic changes and resulting modifications in the adjacent sea, and over the surrounding land surface (Pesce et al. 2018). Moreover, the effect of the sea level rise (SLR) accompanies climatic changes making the sequences and consequences more dramatically.

Indeed, coastal lagoons are fragile ecosystems in the face of CC, affected by their high sensitivity for any climatic changes (McLusky and Elliott 2007). Many risks can commonly be attributed to being related to temperature increases and hydrological cycle alterations. Increasing water temperature is an essential attribute of water quality degradation which consequently impacts the health of aquatic ecosystems (Stefan et al. 2001), as the increased temperature will reduce DO levels and increase the risk of oxygen depletion (Vigil 2003). Lagoons are particularly vulnerable to changes in precipitation relative to evaporation (the P/E ratio) because of their shallow depths and large surface to volume ratio (Vincent 2009). The nature and magnitude of the climatic impacts are diversifying felted by the characteristics of each lagoon. Moreover, the warming of the sea surface is resulting in increasing intensity and duration of storms, and hence, certain coastal lagoons may, therefore, be exposed to increased circulation and storm-induced mixing. Accelerated SLR, due to glacial melting and thermal expansion, has further consequences for species evolutionary, pattern, and distribution (Carrasco et al. 2016). SLR forces more water to flow into lagoons tending to alter the water budget and necessarily causes a general loss of variability of their physical properties. Additionally, SLR is likely to be responsible for weaker light attenuation in the water column due to the expected increase in their water depth (Lloret et al. 2008). SLR may cause changes either in the strength of the ebb relative to the flood tidal flow or in tidal prism at the lagoon mouth(s), affecting the mechanism of transport through the inlet(s), and thus to the lagoon basin (Smith 2001). SLR typically causes movement of the lagoon's bed load and, consequently, causes bathymetric changes according to the inlet geometry. The extent of the SLR impacts will vary from lagoon to another depending on the rate of the SLR, on the connectors with the adjacent sea, and on the basin morphology and human adaptation (Lopes et al. 2011). In lagoons, salinity is a fundamental driver of ecological processes and functional characteristics of aquatic biota (Telesh and Khlebovich 2010), mostly depending on the balance between marine and freshwater inputs, a balance that will be significantly altered by climatic changes and SLR. The changes appear to have already begun, and the evidence of changes in the ecology of lagoons can be noticed (Fichez et al. 2017). The threats were observed as an increase in salinity, decline in lagoon fisheries, and losses in biotic diversity (El-Shabrawy and Bek 2018). Large climatic shifts are expected by the mid and end of this century. Undoubtedly, those will limit the coastal ecosystem's economic and social functions reflected with far-reaching impacts on human health and welfare.

Better recognition of the likely hydrodynamic, water quality, and ecological impacts is essential for projecting the links between CC-related forcings and the lagoon ecosystems and biodiversity. In order to quantify such water quality impacts, the integrated approach is indispensable, where CC scenarios drive process-based models of aquatic systems. For the future climatic projection, a new set of scenarios called the Representative Concentration Pathways (RCPs) were addressed in the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). The advances that have been made for the computer resources were employed to get the future changes in a finer resolution than the general circulation model (GCM) outputs. This involves using regional climate models (RCMs) within GCMs to get the projected features of climate onto a regional scale. Numerical models have been adopted as a powerful tool, able to reliably predict the ecosystem under changing conditions. They are commonly applied to assess the impacts of CC on hydrodynamic and ecological characteristics of different aquatic systems. Weinberger and Vetter (2012) used the one-dimensional hydrodynamic model of DYRESM to identify the potential drawbacks of CC on Lake Ammersee, Germany. The DYRESM model was also employed to assess the impacts of global warming on two Italian south alpine lakes, namely Lake Como and Pusiano (Copetti et al. 2013). The CC impacts on the southern part of the Aswan High Dam Reservoir, Egypt, were investigated using two-dimensional hydrodynamic, and water quality model of CE-QUAL-W2 (Elshemy 2013). This model was also applied on the small deep reservoir of Hsinshan, Taiwan, to deduce the effect of climatic changes (Chang et al. 2015). The 3D hydrodynamic model of Delft3D Flow was applied to investigate the implications of CC on the hydro-physical behavior of Lake Constance, Germany (Wahl and Peeters 2013, 2014). However, several complications challenge the application of CC modeling in lagoons. The complex bathymetry with scattered islands and the connections with the sea are combined together to make them complex and unique in their hydrodynamics. The associated physical transport and dispersal processes of either the coastal flow or received pollutants are equally complex. Nevertheless, various aspects of impacts due to climatic changes and/or SLR on coastal lagoons have been estimated soundly using numerical models. The hydrological response of the Curonian lagoon, Lithuania, to global climatic changes and SLR was investigated in terms of water balance modeling by Hydrologiska Byrans Vattenbalansavdelning (HBV) software (Jakimavičius and Kriaučiūnienė 2013). Lopes et al. (2011) applied the morphodynamic model of MORSYS2D to represent the morphology impacts due to SLR projections by the period 2091–2100 under B1 and A2 SRES scenarios on the Ria de Aveiro lagoon, Portugal. Primo et al. (2018) used Delft3D Flow to investigate CC impacts on Songkhla lagoon, Thailand, using the downscaling results of two GCMs under SRES A2 scenario by 2100. Two different scenarios of the river flow into the lagoon were considered while the SLR effect was represented as deepening of the entire region. The results suggested an increase in the water velocities and a decrease of flushing time accompanied by complex changes in salinity. The eco-hydrodynamic impacts often reported in terms of salinity and thermal stratification. Using a calibrated 3D flow model, Nobuoka and Mimura (2008) investigated SLR impacts on Hinuma lake, Japan, expecting critical salinity concentration higher than the density for the clam to survive. The coastal lagoon of Mar Menor, Spain, had been chosen to investigate its transitional environment response to "A2" SRES scenario using a hydrodynamic model of SHYFEM (De Pascalis et al. 2012). After the model calibration, it was forced with the predicted air temperature and the precipitation of the year 2100 extracted from a selected RCM. The results showed an increase of the annual mean water temperature by an average of 3.28 °C and a decrease in the salinity value by an average of 1.53 PSU with a significant spatial variation. Ferrarin et al. (2014) investigated the response of ten Mediterranean lagoons to CC using SHYFEM, a 2D hydrodynamic model, in terms of water temperature, salinity, sea-lagoon water exchange, and water renewal times. The lagoons' responses to future CC were not equal because of significant differences in their geomorphology. The results indicated that salinity is likely to increase in most of the considered systems, significantly in brackish systems with a limited exchange with the sea, while the rise in water temperature was more pronounced in shallow lagoons with low flushing rates. The lagoons will have higher flushing efficiency. Numerous studies modeled the CC impacts on the lagoon ecosystem. Lloret et al. (2008) used a photosynthesis model to evaluate the effects of CC on the functioning of the *Caulerpa prolifera* bed in the Mar Menor lagoon, Spain. The results showed the lagoon is likely to collapse, since future conditions could make the *Caulerpa prolifera* unable to reach values of net photosynthesis greater than zero, and eutrophication processes are expected to appear. Brito et al. (2012) used "dCSTT-MPB" model (a new version of the dynamic Comprehensive Studies Task Team (dCSTT) model) to investigate the potential alterations due to SLR and global warming of about 2 °C on the Ria Formosa lagoon, Portugal. The impact modeling was conducted in terms of biochemical processes showing an increase of the lagoon vulnerability to eutrophication. Pesce et al. (2018) forced the ecological model of AQUATOX with the medium- and long-term projections of climate change, freshwater inputs, and nutrient loadings to deduce their effects on the phytoplankton community of Venice lagoon, Italy. The results reported an increase of eutrophication event frequency, and changes in the phytoplankton composition and also indicated that species adaption is inevitable.

Egyptian coastal lagoons, together with their ecological and socioeconomic services, could be among those most affected by the ongoing CC and SLR. They are five shallow lagoons laying along the Egyptian Mediterranean coast. Four brackish lagoons (Northern Delta Lakes) and one hypersaline lagoon (non-deltaic lagoon named Lake Bardawil) jointly constitute 25% of the northern wetlands, (Fig. 1). They have a significant role in the local economy, mainly as valuable sources of fish yield. In 1998, the annual catch from them had amounted the equivalent of LE 1.05 billion, or roughly 35% of the country's total fish income (Donia 2016). Several man-made wetlands have been found around their border where considerable areas have been allocated to aquaculture and commercial salt production owing to the availability of highly concentrated brine. They also provide inhabitants with various activities: bird hunting, reed harvesting, and livestock breeding. Moreover, the four delta lagoons receive an incremental quantity of agricultural runoffs and discharges of domestic and industrial sewage. During the last decades, they exposed to excessive nutrient and pollutant loads due to population growth and overuse of inorganic fertilizers and pesticides, in addition to manure.

Under their features of low flushing rates and restricted water exchange with the Mediterranean, they become potentially high pollutant concentrations and high primary productivity. The results include the following: degradation of water quality and losses of habitats leading to shifts in community compositions (Younis 2017). Being habitats on a CC hotspot (Giorgi 2006), they are considered an ecoregion strongly vulnerable to CC, which is expected to be an influential additional threat making serious stress on their ecosystem. The predictable effects generated by the projected climatic changes include increasing of the frequency and abundance of eutrophication events and related symptoms such as hypoxia, harmful algal blooms, and loss of habitat. Moreover, regional SLR has addressed as a critical variable which may impact their social and economic benefits (Frihy and El-Sayed 2013). The future CC impacts on the ecology of Egyptian coastal lagoons were not previously investigated. Few studies have attempted to address the impacts on their hydrodynamic characteristics. Using a calibrated hydrodynamic model of MIKE21FM, Elshemy and Khadr (2015) have expected significant changes in the Lake Manzalaa characteristics: water depth, temperature, and salinity with great spatial differences in its portion's response. The climatic changes were extracted from a selected RCM under two RCP scenarios, RCP 26 and RCP 85, while the corresponding global mean SLR was considered. In 2013, Soliman and Ushijima forced a calibrated mass transport model of Lake Burullus with the future precipitation and evaporation generated using four GCMs by 2100 and the corresponding mean global SLR. The

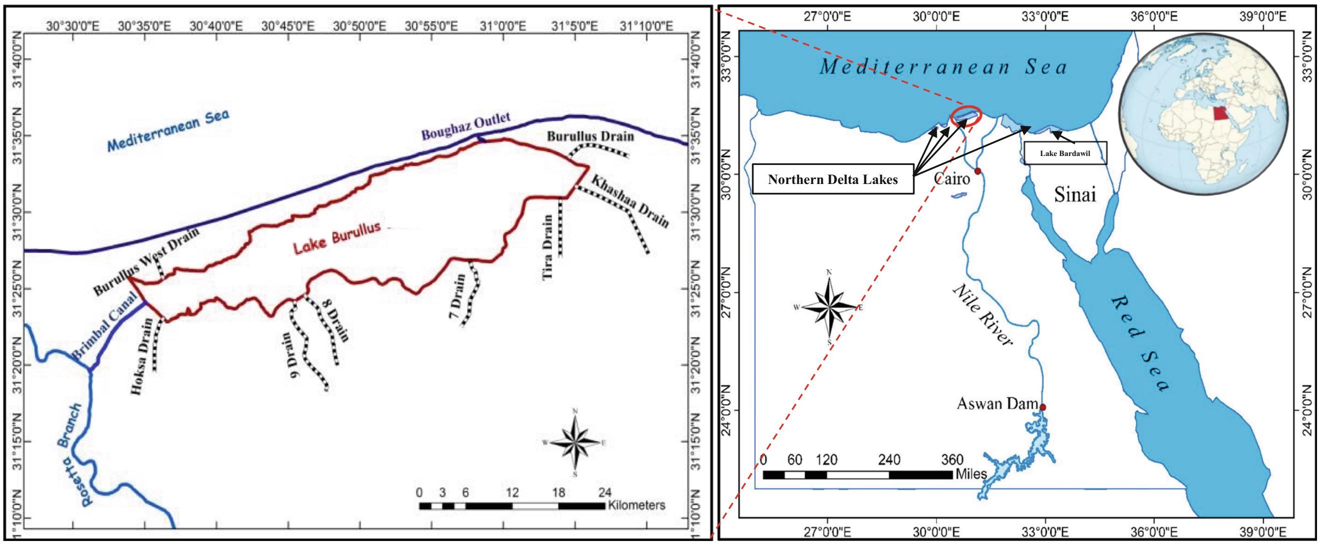


Fig. 1 The study area location and layout, Lake Burullus

results clearly showed that the salinity values would be almost doubled under the two considered scenarios: SRES B1 and SRES A2. El-Adawy et al. (2013) presented a modeling study of Lake Burullus based on Delft 3D model to investigate the impacts of global warming and local SLR, projected by the Coastal Research Institute (CoRI), for the years 2025, 2050, 2075, and 2100 under two emission scenarios of A1F1 and B1. The results revealed a significant increase in evaporation rates and salinity.

The three mentioned studies were focused on assessing the CC impacts on salinity and temperature. Some defects of using the global projection can be addressed. It is essential to investigate the consequences on water quality characteristics and nutrient components. Thus, this research was initiated for assessing of the ecological impacts of CC, considering regional and local divergences in future conditions' estimation, on Egyptian northern lagoons; Lake Burullus was selected as a case study. The first stage of this research project included creating a hydrodynamic model, which was validated with available data sets. The model was used to examine the lagoon sensitivity to future projected climate conditions under RCP 85 and the corresponding SLR, separately in terms of water depths, water temperature, and salinity (Shalby et al. 2018). This study represents the second stage where a coupling hydro-ecological model of the lagoon is employed to assess the combined impacts of CC and resulting SLR on its physical, hydrodynamic, and water quality characteristics. Three RCP scenarios, RCP 26, RCP 45, and RCP 85, are considered. In this article, the study area and modeling configuration are described. Then, the regional climatic change estimates implying the bias correction, and local SLR obtaining are addressed. The final progress forecasts the lagoon boundary alterations by CC and examines the behavior of the lagoon basin.

Study area

Lake Burullus is amidst the five Egyptian lagoons, locating totally inside the Nile Delta (Fig. 1). It is a shallow coastal lagoon where its water depth ranges from 0.5 to 2.0 m. Since 1998, it has been declared as a national protected area and was added to RAMSAR sites. Lake Burullus extends in an elongated elliptical shape with an area of 42,000 ha, ranked as the second largest lagoon in Egypt. It occurs between the two Nile River branches (Damietta and Rosetta) and connects to Rosetta Branch by Brimbal canal at the west. It extends in aligning with the Mediterranean where sand bars and dunes cover the land on its seaward side. Lake Burullus is considered a chocked lagoon since it is connected with the Mediterranean by a single narrow channel of 250 m long and 44 m wide at its northeastern side. This outlet represents the exclusive chance for the water renewal by exchange with the adjacent sea. The lagoon surface is above the mean sea level by 25 to 60 cm, and therefore, its water is in continuous movement toward the sea. Lake Burullus is used mainly as a receiving pool for large quantities of agricultural drainage waters from 1,300,000 feddans (546,000 ha) represent about 74.3% of the total area of the Nile Delta region (El-Shinnawy et al. 2002). The drainage discharge reaches the lagoon through eight agriculture drains which effluents into the lagoon through groups of pumping stations at the drains tails. The annual collected drainage water reaches about 3900 Mm^3/year, corresponding to roughly 97% of its water balance components. So, they are the main features influencing the hydrology and nutrient loads of the lagoon. The lagoon facilitates nutrient removal from the agricultural runoff before drawing it out to the Mediterranean through its single outlet. The accumulation of nitrogen and phosphorus loads led to a notable increase in biomass and productivity of primary producers. The average of salinity in Lake Burullus is 4.16 PSU as monitored during the period (2011–2013) with high spatial variability; it decreases going away from the lagoon mouth. The gradient between the brackish part of the lagoon and marine waters provides a unique zone where many marine and freshwater organisms flourish (Khalil 2010). In 2015, the fish productions from the lagoon were about 63,000 tons with a noticeable shift from marine species to freshwater fishes (Younis 2017). The lagoon area features, as a semi-arid Mediterranean climate, are highly impacted by the dominating continental climate over Egypt: warm low rainy winters and hot dry summers. Lake Burullus shows a strong correlation relationship between water and air temperatures, its water temperature follows the seasonal fluctuations of air temperature. The highest values happen in the summer reaching about 25–29 °C, while wintertime represents the lowest values, typically around 15–17 °C, as indicated by the recorded data of the period 2011–2013. The dissolved oxygen (DO) concentration varies spatially, and also, it fluctuates seasonally in a correlation with the water temperature. Averages for the 2011–2013 period reach 10 mg/l in winter, while it registered about 6 mg/l in summer. The trophic state of Lake Burullus is mainly due to the nutrient loads from large catchment which act in synergy with freshwater discharge from Brimbal canal, exchanged flow with the sea and climate conditions. The nitrogen to phosphorus ratio (N:P ratio) in Lake Burulus depicts that nitrogen is the limiting nutrient that controlled the plant biomass. As can be seen in Fig. 2, the dominating ratio was less than 2.50 except the northwestern parts, which show relatively higher values but less than 5.0.

Methodology

The proposed modeling approach, to quantify the impact of CC and resulting SLR on Lake Burullus, consists of three major phases: (1) numerical modeling of the lagoon's hydrodynamic and water quality characteristics, (2) regional CC estimating to modify the validated model, and (3) setting a statistical regression model to predict the future responses of the lagoon catchment (boundary conditions) to the future air temperature change. These three major phases can be further broken down into some more stages as shown in Fig. 3. The last part of the diagram shows the process of evaluating alterations within the lagoon basin; it involves various activities and tools to interpret the obtained results in a qualitative way.

Lake Burullus' hydro-ecological modeling

The hydrodynamic conditions of Lake Burullus suggest that two-dimensional (depth-averaged) models can fully address its characteristics and do capture the climatic and SLR effects. Among available numerical tools, MIkE21 Flow Model (MIKE21FM, developed by DHI Community n.d.) is a powerful coupled hydrodynamic and water quality model. It is distinguished with its capacities for simulating different eco-hydrodynamic and water quality parameters in such shallow lagoon with complex topographic and various inflow components. Additionally, its great advantage of having strong technical support that is provided by the DHI community. It has been extensively used in managing and modeling lagoon characteristics: e.g., Vistula Lagoon, Baltic Sea (Chubarenko and Tchepikova 2001); Ria de Aveiro lagoon, Portugal (Pelicano et al. 2001; Lopes et al. 2005); the Chilika Lagoon, India (Panda and Mohanty 2008; Panda et al. 2015); Drana lagoon, Greece (Zacharias and Gianni 2008); Baiyangdian Lake, China (Zhao et al. 2014). And it was utilized to simulate Egyptian lagoons: Lake Manzala (Rasmussen et al. 2009; Elshemy et al. 2016) and Lake Burullus (Assar et al. 2016; Elshemy et al. 2018).

The principal applicability of the modeling framework for Lake Burullus, based on MIKE21FM, was demonstrated (Shalby et al. 2019). The basic inputs for the developed model

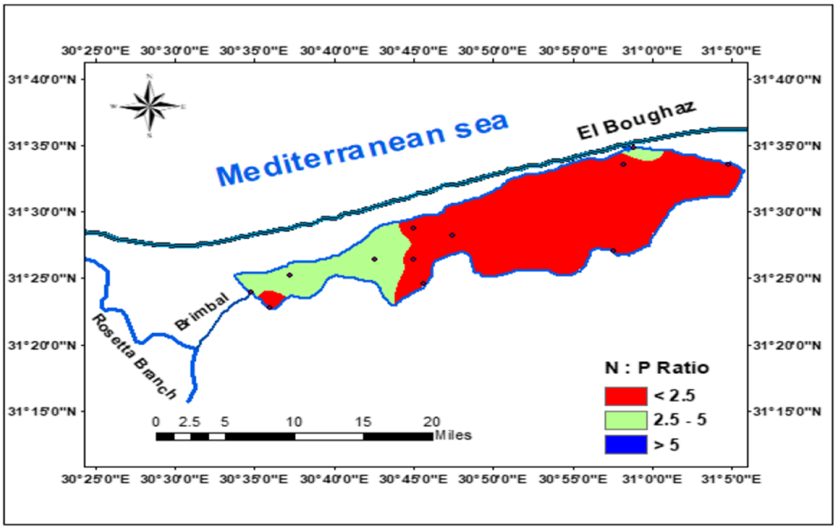


Fig. 2 Spatial distribution of N:P ratio for Lake Burullus during (2011–2013)

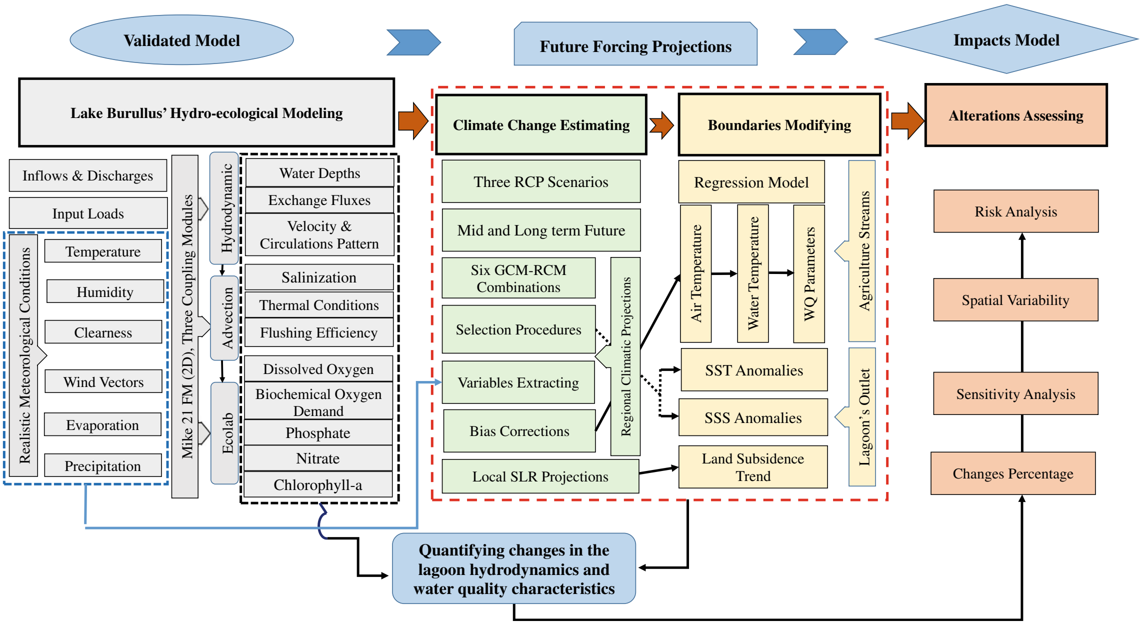


Fig. 3 Flowchart showing the adopted algorithm for modeling CC impacts on Lake Burullus

included lagoon topography (bathymetry), and stream flow and the outlet water levels as well as the related water quality records. The lagoon's bathymetric map was set up as 14,400 finite difference squared grids, each 300-m width, as shown in Fig. 4. The outlet was expressed as a boundary to represent the sea-lagoon exchange while nine-point sources were spatially assigned to represent the isolated streams effluents. Observations of monthly means for streams water discharge ($m^3\ s^{-1}$), semi-diurnal water level fluctuation at the outlet, and seasonal water quality records such as salinity (PSU), DO, BOD, nutrient loads (mg l^{-1}) as well as temperature (°C) were obtained for the period May 2011–August 2013. The streams' water quality records were measured at the ending pump station of each drain while the sea water quality measurements were obtained from the nearby coastal water quality monitoring station of El-Burg (Me-33). These observations were compiled, using the boundary editor of MIKE Zero, in a time series and grid series format to provide the lagoon model with separate boundaries and initial conditions files, respectively. The simulations were executed for 1 year (1 July to 30 June) in which the related conditions: time steps, time interval, warm-up period, and dry-flood depths were determined to satisfy the system to bring in a steady state.

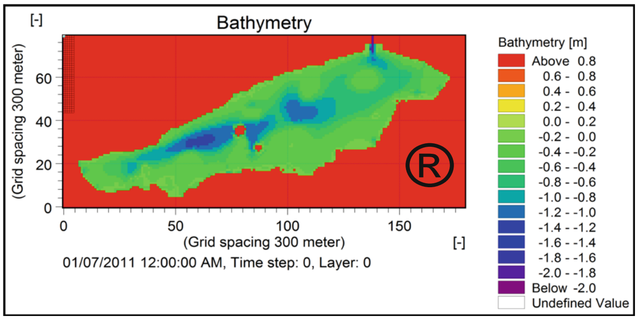


Fig. 4 Lake Burullus bathymetric map

Three coupling modules were employed to depict different conditions and major processes for the lagoon under the daily climatic conditions measured at the nearby local meteorological station, obtained through internet (Info-Space n.d.). Each module was calibrated where the associated coefficients were iteratively adjusted to optimize simulations based on the measurements. Then, the developed model was evaluated against observation in two phases: calibration phase (2011–2012) and validation phase (2012–2013).

The hydrodynamic module (HD) was used to compute water surface elevation, flow velocities, and circulation patterns throughout the lagoon basin as well as the exchange discharge with the Mediterranean within the outlet. The HD module was calibrated where the simulations of water levels were compared with the daily measurements at five-stage border stations (Fig. 5) showing good agreements. The absolute mean error (AME) was averagely estimated as 0.10 m for all stations. Figure 6 shows the profile of water level calibration at a specific station called "Shakhlobaa", while Fig. 7 presents the model estimation of net flow through the lake outlet in comparison with that estimated by El-Shinnawy (2003) based on the water balance model of the lagoon.

The advection (AD) module was developed to simulate temperature and salinity of the lagoon. Salinity diffusion was described as a conservative substance with no decay over the lagoon. It was successfully validated against the measurements at twelve monitoring stations, labelled St.1 to St. 12 in Fig. 5. The average AME were 0.42 PSU and 0.40 PSU, for the calibration and validation simulations, respectively. Figure 8 shows an example for the verification of salinity

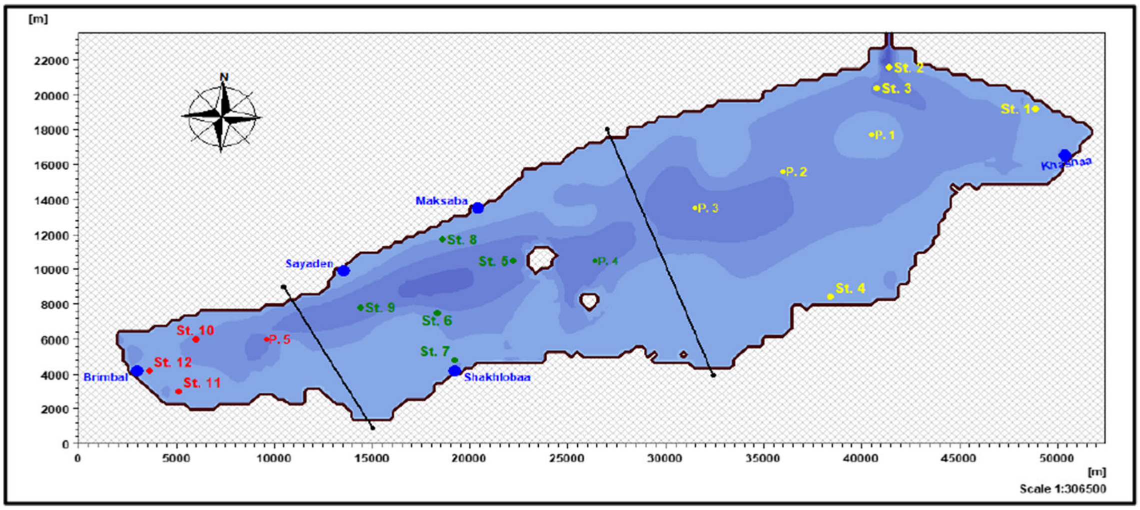
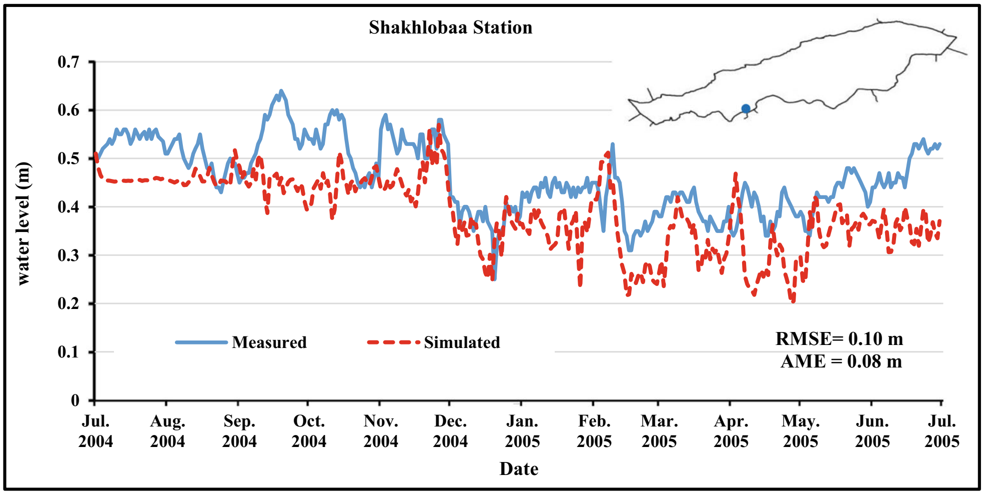


Fig. 5 Monitoring stations (St. 1 to St. 12) and observation points (P. 1 to P. 5) throughout Lake Burullus, adapted from EEAA and CoRI

simulations with the measurements at two different stations, namely St. 8 and St. 10. The heat exchange was applied to model the seasonal fluctuations of the lagoon temperature. It was efficiently simulated with average AME of about 0.29 °C and 0.40 °C at the twelve stations for the calibration and the validation periods, respectively. Figure 9 presents the temperature series, at station St. 5 and St. 11, respectively, for the calibration and verification periods, as examples. The modeled tracer method has been utilized to estimate the residence time within Lake Burullus, as a proxy for its flushing and cleaning efficiency (Monsen et al. 2002). It was defined as the time required to reduce the concentration of the seeded tracer, characterized by exponential decay, in the modeled basin to 37% (the multiplicative inverse of Euler number, e^{-1}) of its initial value (Cucco et al. 2006). This technique has been adopted to study the hydrodynamic and physical characteristics in numerous lagoons: e.g., Venice Lagoon, Italy (Cucco and Umgiesser 2006); Palm Jumeirah Lagoon, United Arab Emirates (Cavalcante et al. 2012); Chilika lagoon, India (Mahanty et al. 2016). Regarding Lake Burullus, the model indicated that there were substantial differences in simulated water residence time. The mean residence time for the lagoon was estimated as about 40 days.

The ecology (Ecolab) module has qualified to simulate water quality state variables, including DO, BOD, NO_3, PO_4, and Chl-a, where a predefined water quality template was mathematically described the related ecosystem process. The calibrated parameters included sediment oxygen demand, 0.5/day/m^2; BOD decay rate, 0.1/day; nitrification rate, 2.0/day; denitrification rate, 0.1/day; death rate of chlorophyll-a, 0.01/day; and half-saturation concentration of phosphorus-uptake, 1 mg/l. The model performance was evaluated by comparing observed and modeled series distribution in the two mentioned periods. It is possible to evidence that the majority of simulated variables were in good agreement with the observed data, as acceptable values of the errors can be noticed in Figs. 10 and 11. Moreover, the seasonal fluctuations were preserved. The discrepancies between the modeled and

Fig. 6 Measured and simulated water levels at Shakhlobaa station



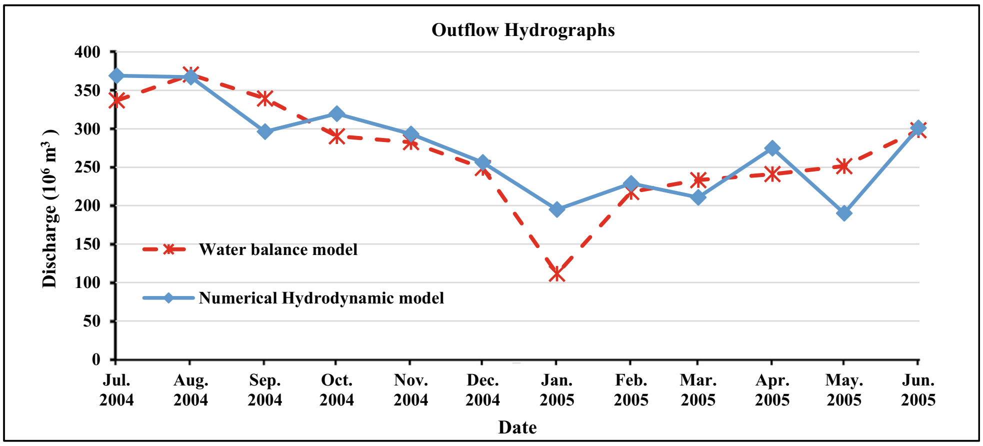


Fig. 7 Outflow hydrographs through the lake outlet

observed values were attributed to the lack of continuous measurements. For all stations, the average AME values were as follows: 0.85 and 0.70 mg/l for DO, 1.06 and 0.89 mg/l for BOD, 0.10 and 0.05 mg/l for NO_3, 0.04 and 0.05 mg/l for PO_4, and 0.015 and 0.02 mg/l for Chl-a, respectively, for the calibration and the validation periods.

Regional climate change estimates

A vast number of future climatic projections, obtainable from GCM-RCM combinations, are available for CC impact assessment studies. Thus, selection methodology has to be applied to get the accurate simulations and to narrow uncertainty in future projections. Such criteria often depend on ranking the climate models' skills to represent some relevant climate variables in historical and recent periods (e.g., Jacob et al. 2007; Perkins et al. 2007; Anagnostopoulos et al. 2010; Deidda et al. 2013).

In this perspective, Shalby et al. (2017) examined six RCM simulations covering two domains (Africa and MENA) over the extent of the lagoon with a high spatial resolution of 0.44° (approx. 50 km.). Table 1 shows their details including RCM and GCM names, and institutions that provided model output. These simulations provide daily climatic conditions for two experiments. (1) The "historical" is for much of the industrial period (from 1850 to 2005) where the models were forced with observed conditions. (2) The "future" starting with the year of 2006 simulates the future time horizons under different Representative Concentration Pathways (RCPs). For the selection of the most accurate simulation, the model outputs

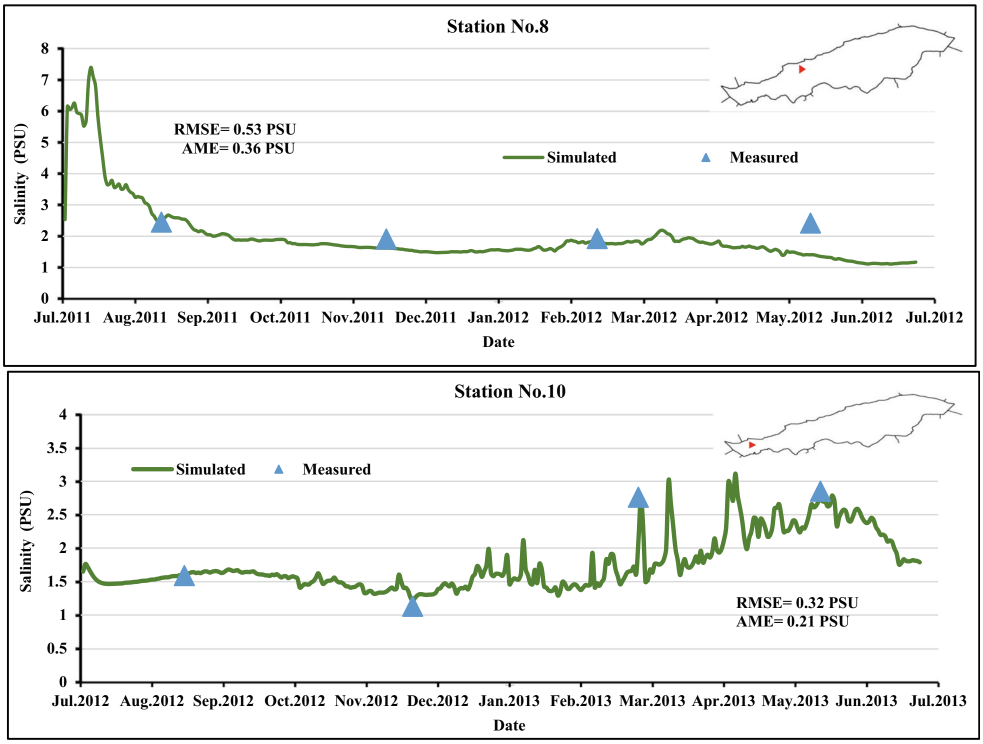


Fig. 8 Measured and simulated salinity concentrations at St. 8 (up) and St. 10 (down)

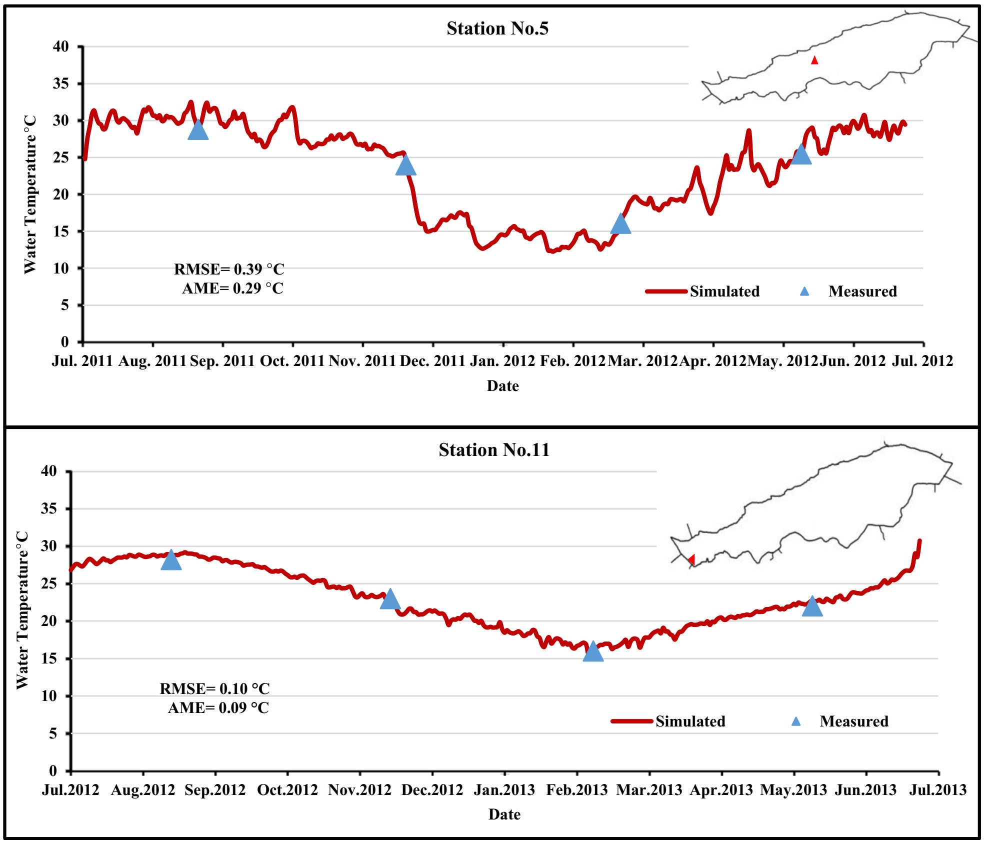


Fig. 9 Measured and simulated temperature at St. 5 (up) and St. 11 (down)

were compared with corresponding observation, at the nearby metrological station, of daily air temperature components: maximum, mean, and minimum. The comparison was implemented in two periods: under the "historical" experiment (1994 to 2005) and also for two RCP scenarios (i.e., RCP 26 and RCP 85) from 2005 to 2015. Six statistical metrics were used for the comparison procedure. Three measures were employed to compute the inter-errors:root mean square error (RMSE), percent of bias (PBIAS), and AME, while the coefficient of efficiency (*E*), index of agreement (*D*), and the correlation coefficient (C_r) were utilized to represent the conformity between the simulated and observed temperature. The results showed the outputs of "MPI-ESM-LR/RCA4, GCM/RCM nested simulations (labelled as S5), available through CORDEX project (CORDEX n.d.), were the well fit with the day-climate at the lagoon area in the two studied periods. This was generated by the coupling of the RCM, named RCA4, developed by SMHI (Swedish Meteorological and Hydrological Institute), with the variable resolution version of the GCM, ESM-LR, developed by the MPI-M (Max Planck Institute for Meteorology), over Africa domain. Nevertheless, it underestimates the observed air temperature. Hence, the linear scaling, a widespread bias correction method, was used to adjust the simulated values, by estimating the monthly offset or deviation with the observation within the control period (1994–2005). Table 2 summarizes the obtained correction factors which were added to the daily series of projected air temperature, providing a bias-corrected mean air temperature under three RCP scenarios: RCP 26, RCP 45, and RCP 85. The selected RCM was utilized to extract other relevant climatic variables such as precipitation, evaporation, relative humidity, clearness, and wind conditions. Noticeably, the bias correction was applied for temperature only due to the lack of continuous observation of precipitation and the absence of well-assessed bias correction approaches for some climatic conditions like relative humidity and wind conditions. In fact, the majority of climate impacts on shallow lakes is expected to be associated with changes in temperature and related process. Air temperature is the essential climatic variable on aquatic ecology (Kanoshina et al. 2003), significantly on such warm and semi-dry regions. And in the meantime, the model that well represents temperature, as a basic variable, often also performs well in other variables (Gleckler et al. 2008).

The climatic conditions were extracted for 2 years; I (2049–2050) and II (2084–2085)—averages of 10 years' projections around each—represent the mid and long-term future of the twenty-first century. Large climatic shifts including air temperature increase, and changes in rainfall and evaporation patterns were concluded. Table 3 summarizes the projected changes in some climatic conditions. Climate projections pointed out a significant increase in temperature accompanied

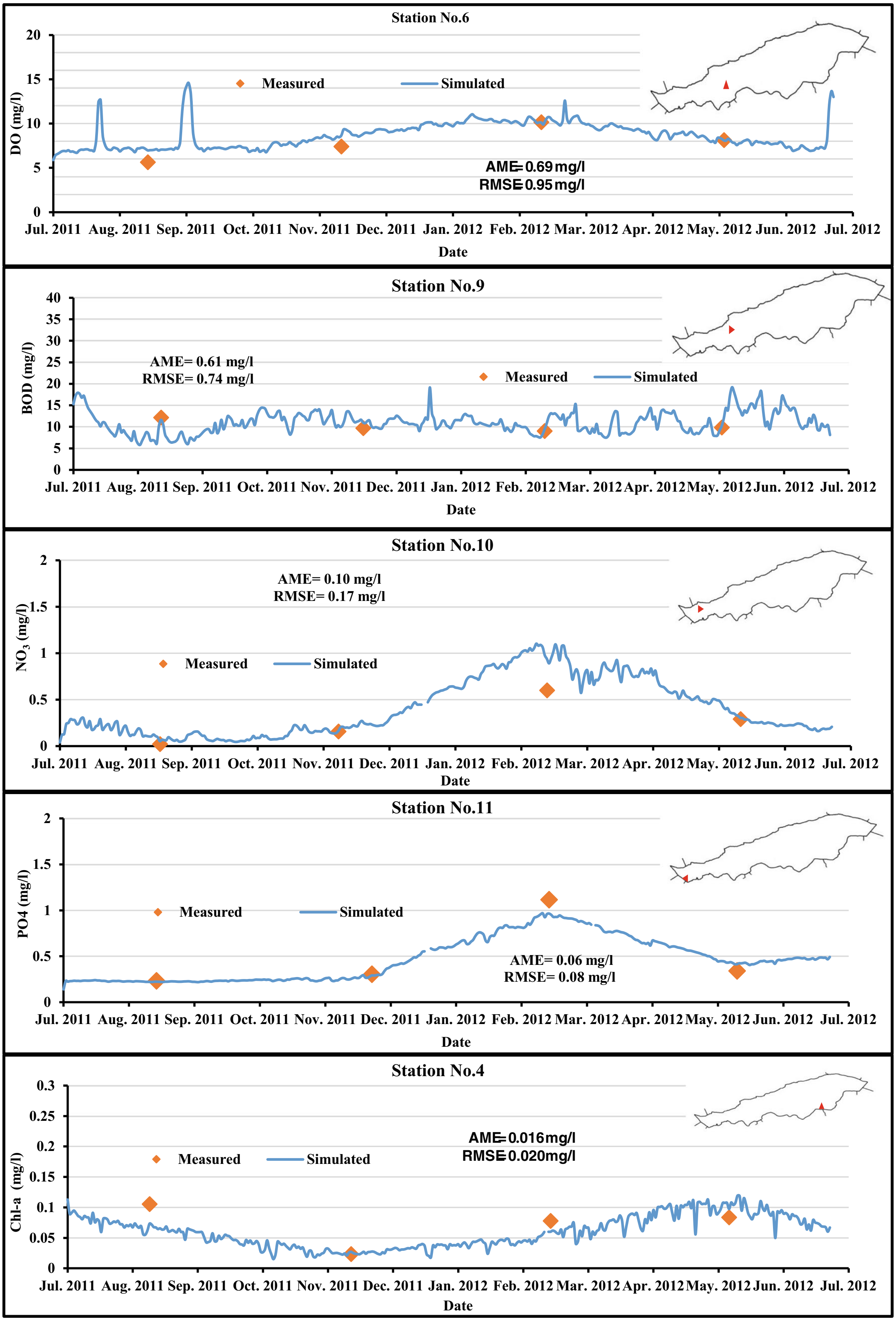


Fig. 10 Lake Burullus water quality model calibration results at different stations (2011–2012)

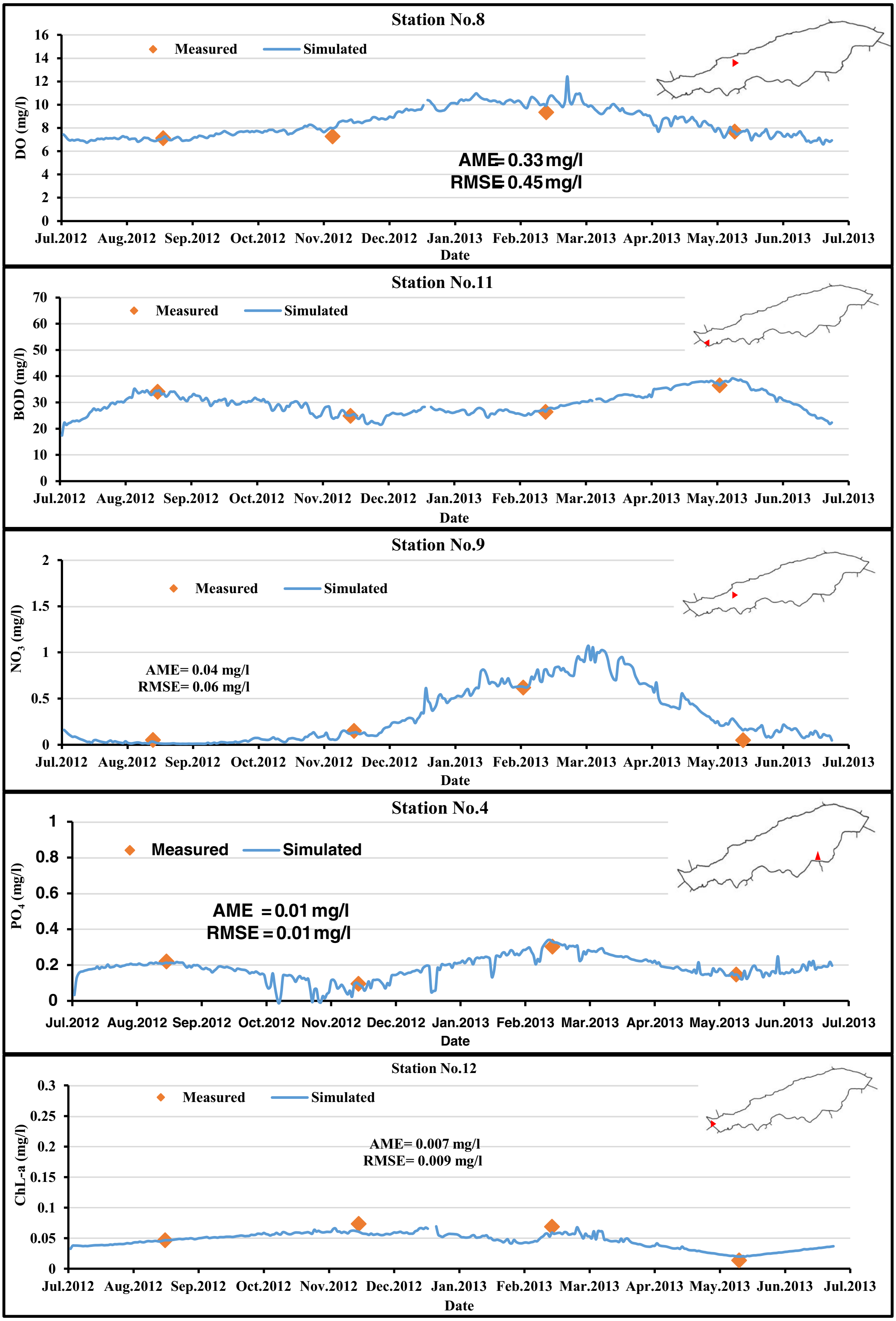


Fig. 11 Lake Burullus water quality model validation results at different stations (2012–2013)

Table 1 GCM-RCM combinations of the selected simulations

Label	GCM	RCM
S1	ICHEC-EC-EARTH	SMHI-RCA4
S2	ICHEC-EC-EARTH	MPI CSC-REMO2009
S3	MPI-M-MPI-ESM-LR	MPI CSC-REMO2009
S4	MOHC-HadGEM2-ES	SMHI-RCA4
S5	MPI-M-MPI-ESM-LR	SMHI-RCA4
S6	CanESM2	CCCMA-CanRCCM4

by an upward trend in accumulative evaporation losses. Great changes in the precipitation pattern were projected under the considered scenarios, as can be noticed for RCP 46 in Fig. 12. The projected wind conditions showed variations in both speed and frequency. For instance, Fig. 13 presents the projected wind conditions near the end of this century under RCP 85. The mean wind speed would be about 4.7 m/s compared with the observation of 3.2 m/s in the base case, whereas the maximum value would increase by 3.5 m/s.

Regarding anticipated SLR, it is confirmed that it will be accelerated in the future. Likewise the climatic conditions, there are significant uncertainties in the future projection. A global SLR of 53–98 cm has been predicted by 2100 under RCP 85 (Gregory 2014). While the projection of Vermeer and Rahmstorf (2009) is substantially higher, they expected a global SLR of 75–190 cm. Moreover, many causes, including gravitational effects due to land ice mass changes, thermal expansion, and ocean dynamics, work on regional SLR variation. The characteristics of the Mediterranean, as a semi-enclosed sea, increase the inter-variations between mean global and its local rising. Indeed, the exchange of water between the ocean and the reservoir is responsible for about 30% of their level equilibrium (Lopes et al. 2011). Hence, instead of using any projected global average sea level, the local sea level change was obtained. It was dynamically calculated using two examined Fluid Dynamics Laboratory (GFDL) models that best describe recent sea-level trends offshore from the Nile Delta region (Shaltout et al. 2015). Five atmospheric/oceanic components were considered: (1) barotropic response, (2) ocean mass exchange through the Gibraltar Strait, (3) sea-level variations west of the Gibraltar Strait, (4) steric sea-level variations due to changes in water salinity, and (5) thermal expansion. The results depicted future mean SLR for different emission scenarios over the 2020 year. There was a strong seasonal variation in the projected sea levels. The projections indicated a moderate SLR along the Egyptian Mediterranean coast, less than either the average global SLR (Kopp et al. 2014) or that calculated for the whole Mediterranean Sea (Tsimplis et al. 2008). Table 4 summarizes the expected SLR for two future years under three RCP scenarios relative to the 2020 year. The observed tide gauge trend near the Lake Burullus' mouth indicates 1.2 mm/year SLR and 1.1 mm/year land subsidence (tidal trends equal to about 2.3 mm/year) (El-Adawy et al. 2013). These rates were included to cover the differences of the time datum and to address the process of vertical tectonic motion of the Egyptian Mediterranean coast.

Table 2 Correction coefficients estimated for mean air temperature

Month	Correction (°C)
January	0.13
February	0.10
March	0.17
April	0.10
May	0.50
June	0.83
July	0.84
August	0.53
September	0.77
October	0.10
November	0.57
December	0.99

Table 3 Average changes (%) due to climate change scenarios (relative to the base case 2011–2012)

Variable	Year	RCP 26	RCP 46	RCP 85
Temperature	I (2049–2050)	7.8%	8.1%	13.5%
	II (2084–2085)	14.5%	19.0%	19.7%
Evaporation	I (2049–2050)	66.6%	72.3%	81%
	II (2084–2085)	77%	86%	96.2%

Rationales and caveats for impact modeling

Simulations of the future conditions were performed using the model calibration setting. But, a number of procedures and assumptions have to be applied, that is modifying the climate forcing and sea level based on the regional projections. In addition, a plausible alteration of the lagoon boundaries is essential.

The future sea surface temperature (SST) and salinity (SSS) were extracted from a selected GCM available at CMIP5 (CMIP5 2008) "MPI-ESM-LR" to provide the projected boundary conditions for the lagoon inlet. Monthly anomalies were estimated as the difference between the two studied years under different RCP scenarios and the corresponding simulated for the baseline year (Table 5).

Regarding the future streams' discharge and the associated nutrient loads, they both depend on climatic conditions and on other anthropogenic factors (e.g., land-use and agricultural practices). It is extremely complicated to predict the role of development plans to shift drainage water discharges and nutrient availability from such large catchment. Moreover, the adaptation options, against the engagement of global

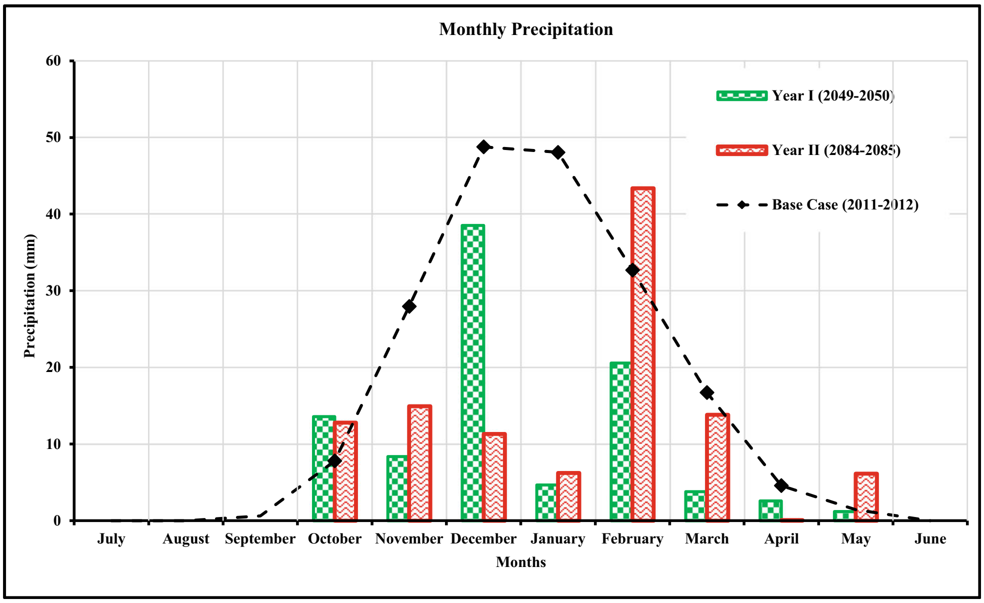


Fig. 12 Monthly precipitation for the calibration year and the two studied years under RCP 45 scenario

warming, local SLR, fresh water shortage, and populations growing, to change the land cover and crop patterns are still under consideration (Agrawala et al. 2004). In this study, the effect of land-use change on the drainage water to the lagoon was negligible. The modification of the drain boundaries was based on the expected temperature rising. A linear regression model was developed to predict the water temperature of each stream (*T*s) relative to the air temperature (*T*a). The results show that water temperature is well-correlated with monthly average air temperature. As an example, Fig. 14 depicts the developed relationship for "Hoksa" drain, where the coefficient of determination (R^2 values) was 0.96. It was found that, with 95% confidence, the true increase in "Hoksa" drain water temperature for a 1 °C increase in air temperature ranges between 0.90 °C and 1.30 °C.

The lagoon response to the projected regional climatic changes and local SLR was manifested and addressed in three main different aspects (e.g., physical, hydrodynamic, and ecological). The impacts were compared along the model cascade, where the alterations are discussed relative to the base case simulation (2011–2012). The changes were calculated as in Eq. (1). Additional observation points (Fig. 5) were assigned throughout the modeled basin to follow the spatial changes over the lagoon portions. The annual average changes were calculated at each station for each CC scenario and studied year.

$$\Delta = \left(\frac{P_{cc}-P_{ref.}}{P_{ref.}}\right)\times 100 \tag{1}$$

where:

Δ	The change in the studied parameter record (%)
P_{CC}	The parameter record due to the applied CC scenario
$P_{ref.}$	The parameter referenced record (the calibrated - base case simulation- record)

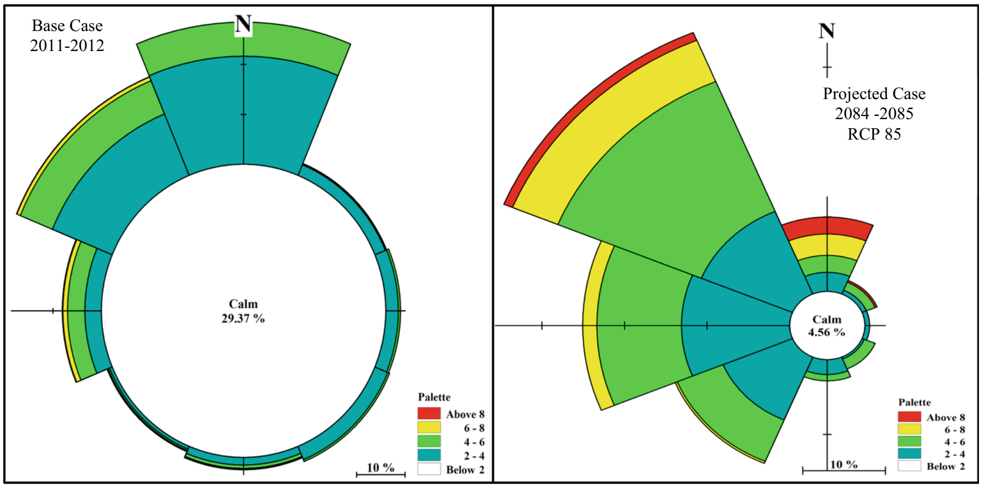


Fig. 13 The observed wind rose during the base case and the projected by 2084–2085 under RCP 85 scenario

Table 4 Expected SLR along the Egyptian Mediterranean coast (extracted from Shaltout et al. 2015)

Scenario	RCP 26	RCP 45	RCP 85
2050	2.5 cm	6.7 cm	7.8 cm
2085	8.0 cm	9.3 cm	16.6 cm

Results and discussions

Hydrological impacts

Water quality of coastal lagoons is affected by many hydrological and physical processes, including, water exchange with the adjacent sea, lagoon circulation, and turn over or flushing rates. The deficiency of water exchange between the Mediterranean Sea and Lake Burullus was addressed in some recent studies (e.g., El-Kolfat 2012; El-Adawy et al. 2014), resulting in dampened tidal oscillation and a long flushing time. Thereby, the combined effects of projected regional CC and local SLR on these features are critical and, therefore, were investigated near the end of the twenty-first century (2084–2085).

The water balance of Lake Burullus is governed by inputs—inflow from point sources, gained precipitation (P_g) on the lagoon surface, as well as subsurface and groundwater inflow—and by outputs, namely net exchange flow with the sea (Q_{net}) and evaporation losses (E_L). The direct alterations of the lagoon's water budget due to CC can be quantified, based on these three main water budget components (i.e., P_g, E_L, and Q_{net}). The net changes (Δ) by 2085 were estimated as 43, 50, and 67 Mm^3 for RCP 26, RCP 45, and RCP 85, respectively. These differences show an increase in the lake water volume, which is expected to increase its depth and areal extent (if allowed). Moreover, the prediction of increasing in seawater inflow into Lake Burullus will necessarily increase the lake salinity.

Lake Burullus is suffering from very poor circulation, which is responsible for degradation in its water quality and increasing spatial variation of its salinity. As a chocked lagoon, the wind-driven circulation dominates the tidal circulation throughout the basin. Wind-driven circulation almost causes direct water transport (Zacharias and Gianni 2008), downwind regardless of the wind direction. Earlier surveys in Lake Burullus revealed that vertical moving (i.e., from south to north, V) was the dominant most of the time (Abayazid and Al-Shinnawy 2012), affected by the overwhelming drainage discharges from the served watershed side. Regarding the projected wind condition, Lake Burullus will be exposed to an increased circulation and a storm-induced mixing. Moreover, the SLR will allow more saline water to enter the lagoon, and therefore, a higher density gradient might be resulted. This process alters the lagoon circulation and modifies its pattern by increasing the horizontal moving (i.e., from east to west, U) versus the vertical moving. The alterations of the circulation pattern can be easily noticed by comparing at the same time step, as shown in (Fig. 15). Moreover, the simulations depicted great changes of flow velocities throughout the lagoon and significantly near the outlet regardless of the flow direction. It is likely that the lagoon morphology will be affected by the expected high water velocity, in particular, the eastern portion.

Table 5 Annual mean anomalies of SST and SSS

Variable	Year	RCP 26	RCP 46	RCP 85
SST (°C)	I (2049–2050)	0.5	0.8	1.30
	II (2084–2085)	0.6	1.4	2.80
SSS (PSU)	I (2049–2050)	0.1	0.2	0.2
	II (2084–2085)	0.3	0.3	0.4

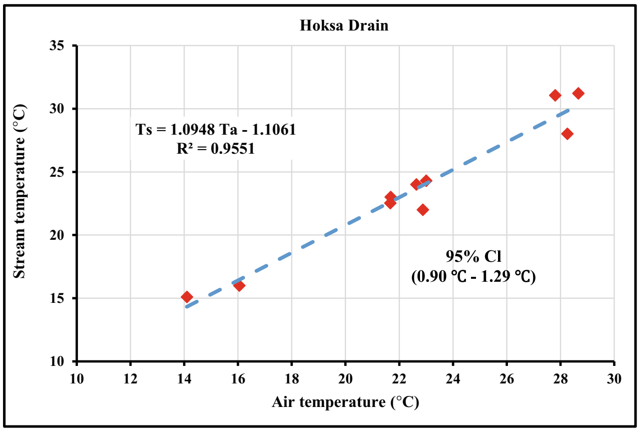


Fig. 14 Developed linear regression model of water temperature as a function of air temperature of Hoksa drain

Water exchange, evaporation, advection, and diffusion are reasonably considered among the main physical processes that influence the cleaning capacity of the lagoon ecosystem (Cucco and Umgiesser 2006). Under the projected increase of evaporation losses and seawater intrusion, a prolonged residence time would be resulted. The estimated residence time exceeds 52 days for RCP 26, 60 days for RCP 45, and 73 days for RCP 85, compared with a residence time of about 40 days during the base case simulations (Fig. 16). This would affect the chemical composition of the lagoon waters by controlling the time available for biochemical and photochemical processes to operate and the extent of accumulation and loss of dissolved and particulate materials. Moreover, in eutrophic lagoons such as Lake Burullus, nutrients that accumulated over several years will be recycled.

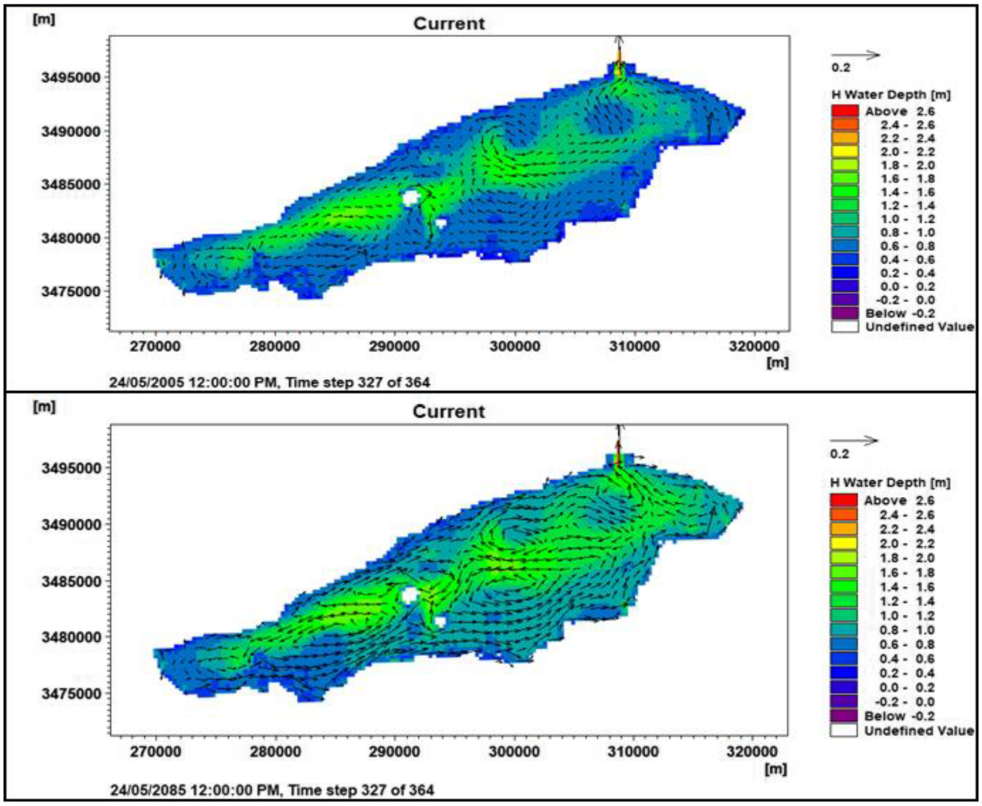


Fig. 15 Internal circulation pattern of Lake Burullus, base case simulation (up) and simulation of RCP 85 (down)

Hydrodynamic impacts

The hydrodynamic implications on Lake Burullus were investigated with respect to the CC in three characteristics: water depths, water temperature, and salinity. These parameters were simulated considering the combined effect of future meteorological conditions and SLR, for three RCP scenarios and two studied years; I (2049–2050) and II (2084–2085) represent the mid and long-term future, respectively. Table 6 summarizes the annual average changes in the lagoon's eco-hydrodynamic conditions.

CC will produce higher water depths than the referenced base case. The results are proportional to the predictions of SLR and evaporation. It is totally understood that the SLR is responsible for the positive change on the lagoon water depths, while the change in the meteorological conditions (evaporation) causes a negative effect. The results emphasized the stronger effect of the SLR than evaporation. Their differential effect under RCP 85 scenario was quantified (Shalby et al. 2018). The response to the sea water intrusion spatially varies, depending on the morphological characteristics and station positions away from the outlet. The average changes

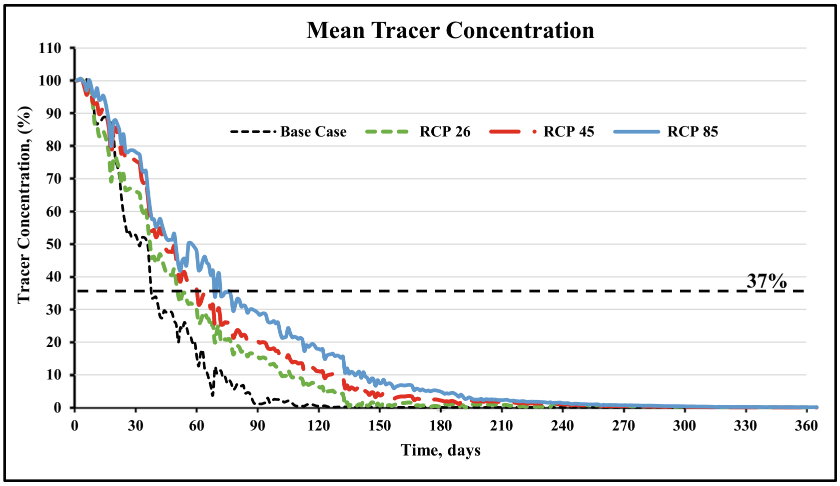


Fig. 16 Mean residence time for Lake Burullus for the base case and the future scenarios

Table 6 Average changes (%) of Lake Burullus' hydrodynamic conditions due to climate change scenarios

Year	Mid future (2049–2050)			Long future (2084–2085)		
Parameters	Depth	Temperature	Salinity	Depth	Temperature	Salinity
RCP 26	4.6%	6.1%	9.2%	12.6%	7.9%	18.6%
RCP 45	8.6%	8.2%	14.7%	16.3%	12.2%	23.4%
RCP 85	13.5%	10.4%	15.4%	22.5%	15.3%	27.3%

were estimated as 14 cm, 10 cm, and 8.1 cm, respectively for the three considered scenarios (i.e., RCP 26, RCP 45, and RCP 85) for the long-term future. While the changes were 8.6 cm, 5.2 cm, and 2.8 cm for the mid-future projections.

For water temperature, it will increase under the CC, proportionally to the annual average change of air temperature, as can be seen in Tables 3 and 6. It can be noticed that the response of the lagoon temperature will be lower than the projected increase in the air temperature, clearly in the study year II for the long-term future. That may return to the rising of sea level that is forcing more sea water to enter the lagoon with a weak positive upward of SST (Table 5). Under RCP 85 projections, the increase is expected to be about 4.15 °C and 2.83 °C, respectively, for the two study periods; 3.7 °C and 2.5 °C for RCP 45; and to 2.1 °C and 1.2 °C for RCP 26. The water temperature changes are slightly varied spatially throughout the lagoon, where the eastern portion represents the lowest influenced portion. The seasonal fluctuations are expected to diverge. Considering RCP 85 projections, the average summer water temperature will increase by about 4.8 °C and 3.1 °C, respectively, for long and mid future, while the winter temperature will increase by 3.9 °C and 2.5 °C. As a result of increasing water temperatures, water quality would be adversely affected. Most physical properties of water, and the rates of many chemical and biological processes in water are a function of temperature. In such an eutrophic lagoon where nutrient conditions are suitable, increase in water temperature is typically accompanied by major upshifts in the concentrations of algal.

The scenario simulations illustrated that high salinity increases are expected due to saline water intrusion and evaporation losses. The sensitivity analysis emphasized that SLR has a dominant effect over evaporation on the lagoon's salinity (Shalby et al. 2018). Near the end of this century, the lagoon's average salinity is expected to be increased by 0.8, 1.0, and 1.45 PSU respectively for the three considered scenarios (i.e., RCP 26, RCP 45, and RCP 85), while the average increase by 2050 will be 0.28, 0.53, and 0.90 PSU, respectively. The changes in the lagoon's salinity significantly vary from station to station depending on the station location. Figure 17 depicts the changes in the spatial distribution of salinity under the considered scenarios by 2085 and for the base case. The northeastern corner will experience maximum change in salinity with an average of 3.8 PSU under RCP 85 scenario, and decreases to 3 PSU for RCP 46 and to 2.4 PSU under RCP 26 assumptions. The eastern corner has a lower response estimated as 2 PSU, 1.5 PSU, and 1 PSU, respectively, that returns to the effect of drainage water from "Burullus," "Khashaa," and "Tira" drains (see Fig. 1). The lagoon's middle portion is expected to have a moderate increase by about 0.6 PSU, 0.47 PSU, and 0.32 PSU, but the border stations will increase by an average of 0.35 PSU, 0.24 PSU, and 0.15 PSU. The average changes in the western portion were 0.37 PSU, 0.27 PSU, and 0.18 PSU, respectively for the RCP scenarios.

The inter-lagoon variability by 2085, computed as the standard deviation of the simulated values throughout the lagoon, is predicted to increase from 2.16 PSU in the base case to 2.72 PSU, 3.16 PSU, and 3.43 PSU respectively for the three scenarios. All organisms and specifically fish are firmly affected by the salinity distribution.

Ecological impacts

The impacts on four water quality parameters of Lake Burullus were investigated with respect to the CC: e.g., dissolved oxygen (DO), nitrate (NO_3), phosphate (PO_4), and chlorophyll-a (Chl-a). The projected changes are summarized in Table 7. The changes were estimated using Eq. (1), showing a significant decreasing for DO and NO_3 and increasing for PO_4 and Chl-a, compared with the base case concentrations.

The DO concentration is expected to decrease, significantly in the long-term future (2084–2085) due to the strong increase of surface water temperature. There are significant spatial differences of DO decreasing. The eastern portion of the lake represents the least affected portion that may return to the effect of seawater intrusion with relatively high DO concentrations. For instance, the average changes by 2085 under RCP 85 scenario for the three portions (i.e., east, mid, and west) would be − 8.6%, − 9.8%, and − 15.8%, respectively, while the corresponding changes under RCP 26 would be − 6.0%, − 6.5%, and − 10%. The risk analysis was identified as the probability of being lower than a specific threshold value, based on the cumulative distribution function (CDF) as shown in (Fig. 18). The risk probability for DO to be less than a threshold of 6.0 mg/l is projected to increase by 10%, 17%, and 20% under the RCP scenarios (i.e., RCP 26, RCP 45, and RCP 85). In addition, the anoxia frequency in the western portion would be climbed affected by temperature increase

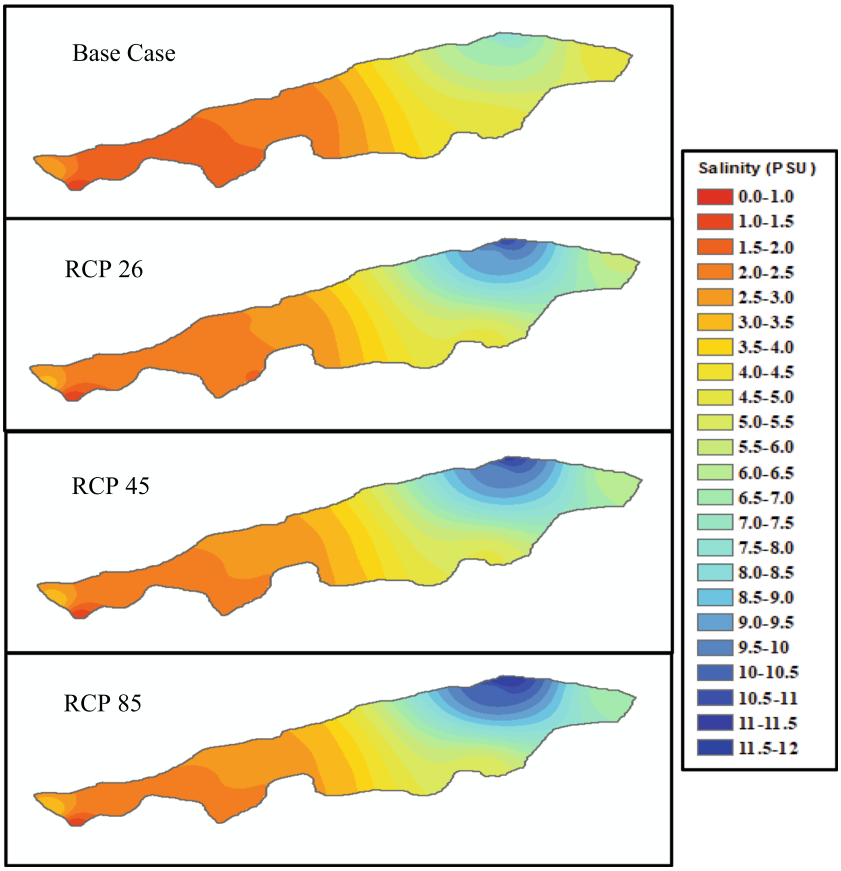


Fig. 17 Salinity spatial distribution of Lake Burullus for different climatic scenarios and the base case

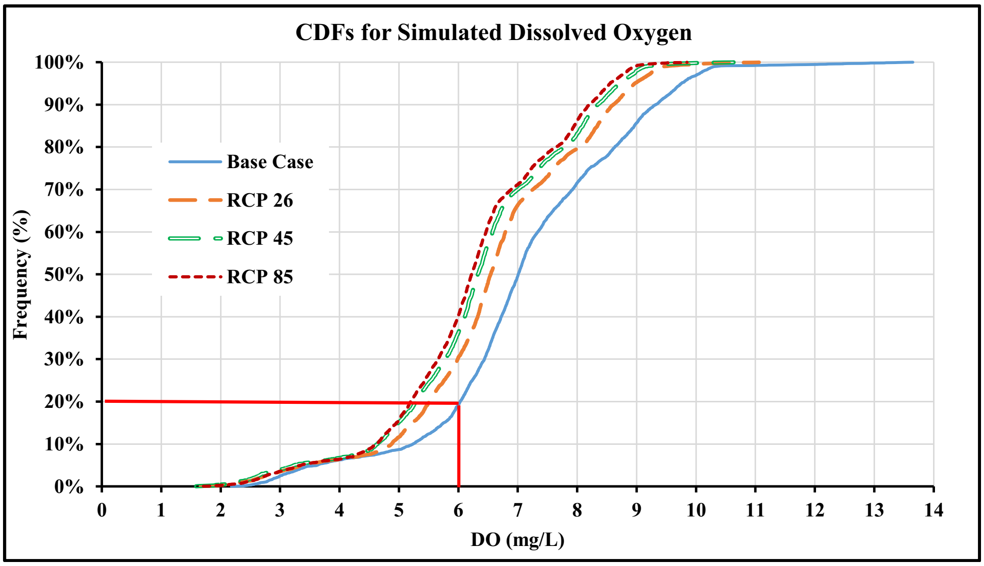
and will aggravate the release of nutrients from the sediment. The western portion would experience an increase by about 13%, 22%, and 27% of daily hypoxic condition probability (DO concentration less than 6 mg/l), respectively for the three scenarios by the current century end. This behavior is owed to the rise of its water temperature which is considered a fundamental factor of oxygen reduction in shallow lakes, since the solubility of oxygen decreases while temperature increases.

Additionally, the results show that CC will have an obvious impact on the nutrient components of Lake Burullus. Relative to the base case simulation, phosphate concentration is expected to increase by 13.4%, 21.5%, and 16.9% for the long-term future under the three RCP scenarios, respectively. This suggests that phosphate release from the sediments is favored by higher temperatures (Fulweiler and Nixon 2009). The upsurge in the phosphorus consumption, due to increasing rates of algal growth in warmer water, will be compensated and exceeded by the projected increase in phosphorus flux from sediment. However, the eastern portion of the lagoon shows a decreasing trend of PO_4 under RCP 85 scenario for the long-term future affected by SLR and the intrusion of Mediterranean water with low PO_4 concentration into the lagoon. The middle and western portions always show upward trends, and the latter is the most affected. The CC simulations show lower nitrate concentrations which is the limiting nutrient of algal growth in Lake Burullus. That is attributed to the increased rates of algal growth and bacteria denitrification as well as the extended growing period of aquatic plants under the warmer climate. Anoxia causes increasing in nitrogen losses from the ecosystem through bacterial denitrification process, where nitrate is converted to nitrogen gas. According to the decreasing trend of nitrate, it is evident that

Table 7 Average changes (%) of Lake Burullus' water quality parameters due to climate change scenarios

Year	Mid future (2049–2050)				Long-term future (2084–2085)			
Parameters	DO	NO_3	PO_4	Chl-a	DO	NO_3	PO_4	Chl-a
RCP 26	− 3.0%	− 4.5%	5.5%	0.9%	− 7.6%	− 9.6%	13.4%	2.3%
RCP 45	− 3.1%	− 3.0%	6.2%	1.5%	− 11.0%	− 14.7%	21.5%	4.7%
RCP 85	− 6.9%	− 9.2%	12.3%	2.1%	− 11.5%	− 18.3%	16.9%	3.7%

Fig. 18 CDF curves for simulated DO of the base case and under the projections by 2085



the supply of nitrate from different sources is less than the increased consumption due to the warmer climate, in particular the middle and the western portions. The eastern portion shows a decreasing trend of about − 6%, − 10.9%, and − 16.8% under long-term climate change projections, while the middle portion will be the most affected part through the lagoon. It reveals a decrease in nitrate concentration by about − 11.2%, − 17.3%, and − 23.8%, respectively, for the three scenarios by the current century end.

The simulated values of Chl-a during the model calibration indicate a hypertrophic state of the lagoon; CC will significantly increase the concentrations of Chl-a. The warmer water is supporting the growth of algae, albeit this is limited by the favorable nutrient concentrations. Increase in Chl-a concentration can be easily noticed at the three portions. The eastern portion shows a less severe positive trend revealing increases by 1.7% and 3.3%, respectively for the two studied years under RCP 85, and 1.2 % and 4.5% under RCP 45, while the western part would register an increase by 3.2% and 4.9% under RCP 85, and 1.8% and 5% under RCP 45. Scenario of RCP 45 would be the worst storyline of the lagoon eutrophication category by the end of this century; it reveals an average increase by 4.7% and 21.5% of the chlorophyll and phosphate concentrations within the lagoon, respectively.

Conclusions

This study promoted a coupled modeling approach, based on Mike 21FM, for assessing the potential effects of CC at a sub-regional scale of Lake Burullus. A suite of widely used GCM-RCM combinations were evaluated. The selected ensemble provides future surface meteorological forcings for the study region including precipitation, evaporation, air temperature, relative humidity, and wind. The regional projections of the influencing climatic conditions, as well as the local SLR projections, were used to feed the validated model to deduce the changes in the lagoon characteristics. The results indicated that CC and resulting SLR will likely alter current hydrological, hydrodynamic, and water quality characteristics of Lake Burullus, and accordingly have serious implications on its ecosystem health.

The impacts on the physical and hydrological characteristics were investigated, near the end of this century, in terms of water balance, circulation pattern, and residence time. The SLR will increase the inflow water from the Mediterranean. This flux increase combined with significant changes in precipitation to evaporation (P/E) ratio will lead to significant alterations of the lagoon water budget. The lagoon volume is expected to increase under the three RCP scenarios. An increase in the outlet water velocity accompanied by changes in the circulation pattern within the lagoon basin is expected. CC and SLR will lead to a prolonged residence time and would result in an elevated eutrophication level, which may trigger the shift from oxygenated to anoxic conditions.

Regarding the impacts on the hydrodynamic conditions, the medium (2049–2050) and long-term (2084–2085) projections were aggregated to assess the impacts on the lagoon water depths, temperature, and salinity. The changes in the lagoon water budget were deduced as an accretion in its water volume and subsequently caused an increase in the lagoon depths. The shallow waters of Lake Burullus showed a rapid temperature equilibrium in which its water temperature is following the expected upward trends of air temperature projections. The combined effect of the SLR and projected increase in the evaporation rates will lead to an increase in the lagoon's salinity. The findings of the effect on the lagoon's salinity are in agreement with the two studies that concerned with Lake

Burullus salinity. The differences are in the alterations magnitudes. The obtained changes were less than the results of El-Adawy et al. (2013) and Soliman and Ushijima (2013) who used the global SLR projections.

For the ecological impacts, future mid-term and long-term projections of water quality parameters (DO, NO_3, PO_4, Chl-a) are compared toward the control period (2011–2012). Lake Burullus revealed a distinct response to the regional changes in climates and local SLR projection. As water temperature rises, in the presence of an abundance of nutrients, the metabolic rates of the most water organisms as well as algae biomass increase. That was noticed through a significant increase in the concentrations of Chl-a, and necessarily increase the consumption of oxygen. Simulated results of DO indicate that concentrations would feature a decrease in both mid- and long-term periods for the three RCP scenarios. The risk of oxygen depletion will increase and consequently causes fish killing. The results of nutrient simulation show an increasing trend of PO_4 and a decreasing trend of NO_3 in the future. The occurrences of warmer water and high phosphorus concentrations are both predicted to increase, resulting in a higher risk of eutrophication events and algal bloom in Lake Burullus. Moreover, it can conclude that the presence of nitrate in Lake Burullus underperformed the level required by the algae. Future projections of N/P ratio exhibit the events of nitrogen going to be the limiting nutrient more frequent than in present times. This suggests relevant effects on the composition of phytoplankton in Lake Burullus that can modify the competitive advantage of phytoplankton species.

Model simulations revealed that the magnitude and direction of change would differ within the lagoon basin. Regarding the water quality parameters, the eastern portion of the lagoon is expected to be the least affected portion that may return to the effect of seawater intrusion. However, the combined effects of climatic changes and SLR do not change the substance of each storyline implications; RCP 85 exhibits a nightmare scenario on the lagoon characteristics.

Consequently, CC is going to alter its biological attributes affecting its ability to maintain the present-day communities of aquatic plants, animals, and microbes, and will contribute to reduce its capacity to provide ecosystem services for species composition, biota, and fishes.

Similar to any impacts assessing study on aquatic ecosystems, the obtained results involve many sources of uncertainty and it is ideally to be considered an indication of the effects of CC on hydro-ecological characteristics of Lake Burullus rather than be supposed as exact predictions. Following the adopted framework, the main limitation of the modeling stage is the lack of data for the lagoon. The model results closely mimic the monitoring values and preserve the measured annual profiles and the seasonal fluctuations, and do capture the spatial distribution pattern of the simulated parameters. However, for future modeling efforts, there is an urgent need for high-quality simultaneous measurements of different water quality parameters at several points spread across the lagoon with monitoring frequency not exceeding 30 days.

Moreover, the implemented modeling approach necessitated some assumptions and simplifications that added uncertainty to the study. This study focused on the effect of climatic changes and SLR; it succeeded to rather produce more accurate regional projections and decrease the within uncertainty. However, the effect of the land-use change and other non-climatic pressures (e.g., population dynamics, agronomic and aquaculture practices) may be important drivers and therefore, the integration of projections on land-use and other human influences could add further value to the impact modeling approach. Moreover, using of various bias correction methods for different influencing climatic conditions can be considered a potential area of improvement.

Urgent water quality management plans have to be commenced where the synergistic effects of local anthropogenic impact and ongoing CC should be involved in the feasibility studies. Coupling water quality and fish habitat models of the lagoon to investigate impacts of future CC should be further explored in following studies. Also, expanding this work, including suggested improvements, for other Egyptian lagoon could be part of future research activities.

Acknowledgments This research was originated as part of a completed M.Sc. work for the first author at Faculty of Engineering, Tanta University, Egypt. The authors extremely thank the Coastal Research Institute, Egypt (CoRI), and the Egyptian Environmental Affairs Agency (EEAA) for providing field records for Lake Burullus. The authors extend their sincere thanks to the World Climate Research Programme's Working Group on Regional Climate, and the Working Group on Coupled Modelling, former coordinating body of CORDEX and responsible panel for CMIP5 for making the simulations available through the ESGF web services. Sincere thanks must go to the reviewers as their comments and suggestions have improved the paper considerably.

References

Abayazid H, Al-Shinnawy I (2012) Coastal lake sustainability: threats and opportunities with climate change. IOSR J Mech Civ Eng 1(5):33–41 Available at: http://www.iosrjournals.org/iosr-jmce/papers/vol1-issue5/G0153341.pdf. Accessed Dec 2018

Agrawala S, Moehner A, ElRaey M, Conway D, Aalst MV, Hagenstad M, Smith J (2004) Development and climate change in egypt: focus on coastal resources and the nile. Technical Report Published by Organisation for Economic Co-Operation and Development, Egypt. Available at: http://www.oecd.org/env/cc/33330510.pdf. Accessed Dec 2018

Anagnostopoulos GG, Koutsoyiannis D, Christofides A, Efstratiadis A, Mamassis N (2010) A comparison of local and aggregated climate model outputs with observed data. Hydrol Sci J 55(7):1094–1110. https://doi.org/10.1080/02626667.2010.513518

Assar W, Elshemy M, Zeidan BA (2016) Water quality modeling for Lake Burullus, Egypt, part I: model calibration. Mansoura Eng J 40(2):53–60

Brito AC, Newton A, Tett P, Fernandes TF (2012) How will shallow coastal lagoons respond to climate change? A modelling investigation. Estuar Coast Shelf Sci 112:98–104. https://doi.org/10.1016/j.ecss.2011.09.002

Carrasco AR, Ferreira O, Roelvink D (2016) Coastal lagoons and rising sea level: a review. Earth-Science Reviews 154:356–368. https://doi.org/10.1016/j.earscirev.2015.11.007

Cavalcante GH, Kjerfve B, Feary DA (2012) Examination of residence time and its relevance to water quality within a coastal mega-structure: the Palm Jumeirah Lagoon. J Hydrol 468-469:111–119. https://doi.org/10.1016/j.jhydrol.2012.08.027

Chang CH, Cai LY, Lin TF, Chung CL, Van der linden L, Burch M (2015) Assessment of the impacts of climate change on the water quality of a small deep reservoir in a humid-subtropical climatic region. Water (Switzerland) 7(4):1687–1711. https://doi.org/10.3390/w7041687

Chubarenko I, Tchepikova I (2001) Modelling of man-made contribution to salinity increase into the Vistula Lagoon (Baltic Sea). Ecol Model 138(1–3):87–100. https://doi.org/10.1016/S0304-3800(00)00395-1

CMIP5 (2008) Coupled model intercomparison project phase 5. Available at: https://esgf-index1.ceda.ac.uk/projects/cmip5-ceda/. Accessed: 1 September 2018

Copetti D, Carniato L, Crise A, Guyenon N, Palmeri L, Pisacane G, Strugila MV, Tartari G (2013) Impacts of climate change on water quality. In: Navarra A, Tubiana L (eds) Regional assessment of climate change in the Mediterranean. Springer Science+Business Media, Dordrecht, pp 307–332. https://doi.org/10.1007/978-94-007-5781-3

CORDEX (n.d.) Coordinated regional climate downscaling experiment. Available at: https://esg-dn1.nsc.liu.se/projects/cordex/. Accessed: 1 September 2018

Cucco A, Umgiesser G (2006) Modeling the Venice Lagoon residence time. Ecol Model 193(1):34–51. https://doi.org/10.1016/j.ecolmodel.2005.07.043

Cucco A, Perilli A, De Falco G, Chezzo M, Umgiesser G (2006) Water circulation and transport timescales in the Gulf of Oristano. Chem Ecol 22(suppl. 1):307–332. https://doi.org/10.1080/02757540600670364

De Pascalis F, Perez-Ruzafa A, Gilabert J, Marcos C, Umgiesser G (2012) Climate change response of the Mar Menor Coastal Lagoon (Spain) using a hydrodynamic finite element model. Estuar Coast Shelf Sci 114:118–129. https://doi.org/10.1016/J.Ecss.2011.12.002

Deidda R, Marrocu M, Caroletti G, Pusceddu G, Langousis A, Lucarini V, Puliga M, Speranza A (2013) Regional climate models' performance in representing precipitation and temperature over selected mediterranean areas. Hydrol Earth Syst Sci 17(12):5041–5059. https://doi.org/10.5194/hess-17-5041-2013

DHI Community (n.d.) MIKE 21: 2D modelling of coast and sea. Available at: https://www.mikepoweredbydhi.com/products/mike-21. Accessed March 2019

Donia N (2016) Water quality modelling of Northern Lakes case study (Egyptian Northern Lakes). In: Rashed MN (ed) Lake science and climate change. World's Largest Science, Technology & Medicine, pp 174–190. https://doi.org/10.5772/63526

El-Adawy A, Negm AM, Saavedra VOC, Nadaoka K, ElShinawy IA (2013) Assessment of climate change impacts on El-Burullus Lake , Egypt , based on hydrodynamic modeling. Proceeding of Seventeenth International Water Technology Conference, IWTC17, 3(4), pp 207–216. Available at: http://iwtc.info/wp-content/uploads/2013/11/256.pdf. Accessed Dec 2018

El-Adawy A, Negm AM, Saavedra VOC, Nadaoka K, ElShinawy IA (2014) Coupled hydrodynamic-water quality model for pollution control scenarios in El-Burullus Lake (Nile Delta, Egypt). Am J Environ Sci 10(6):546–565. https://doi.org/10.3844/ajessp.2014.546.565

El-Kolfat AI (2012) Environmental problems of Burullus Lake, Proceeding of the First Regional Conference on Perspectives of Arab Water Cooperation. Cairo, Egypt

El-Shabrawy GM, Bek MA (2018) Responses of zooplankton to long-term environmental changes in the Egyptian coastal lakes. In: Negm AM et al (eds) Egyptian coastal lakes and wetlands: part II - climate change and biodiversity, Hdb Env Chem. Springer International Publishing AG. https://doi.org/10.1007/698_2018_262

Elshemy M (2013) Climate change impacts on water resources in semi-arid regions: case study of Aswan High Dam Reservoir. In Younos T, Grady CA (eds) Climate change and water resources, Hdb Env Chem, pp 69–98. https://doi.org/10.1007/698_2013_223

Elshemy M, Khadr M (2015) Hydrodynamic impacts of Egyptian coastal lakes due to climate change - example Manzala Lake. Int Water Technol J 5(3):235–247

Elshemy M, Khadr M, Atta Y, Ahmed A (2016) Hydrodynamic and water quality modeling of Lake Manzala (Egypt) under data scarcity. Environ Earth Sci 75(19):1–13. https://doi.org/10.1007/s12665-016-6136-x

Elshemy M, Zeidan BA, Assar W (2018) Water quality mitigation scenarios for Burullus Coastal Lake , Egypt. Proceeding of Sixth International Conference on Estuaries and Coasts (ICEC-2018), August 20-23, 2018, Caen, France

El-Shinnawy IA (2003) Reservoir hydrologic routing for water balance of Al-Burullus Wetland, Egypt, Proceeding of the Seventh International Water Technology Conference IWTC7 Egypt, 867: 877. Available at: http://www.iwtc.info/2003_pdf/13-5.pdf

El-Shinnawy IA, Zeidan BA, Abd EL Rahman H (2002) Water balance of Al-Burullus Lake, Proceeding of the 4th International Confernce on Role of Engineering Twords A Better Environement Alexandria, Egypt, pp 157–171

Ferrarin C, Bajo M, Bellofiore D, Cucco A, De pascalis F, Ghezzo M, Umgiesser G (2014) Toward homogenization of mediterranean lagoons and their loss of hydrodiversity. Geophys Res Lett 41(16): 5935–5941. https://doi.org/10.1002/2014GL060843

Fichez R, Archundia D, Grenz C, Douillet P, Mendieta FG, Moreno MO, Denis L, Esparza ACR, Zavala-Hidalgo J (2017) Global climate change and local watershed management as potential drivers of salinity variation in a tropical coastal lagoon (Laguna De Terminos, Mexico). Aquat Sci 79(2):219–230. https://doi.org/10.1007/S00027-016-0492-1

Frihy OE, El-Sayed MK (2013) Vulnerability risk assessment and adaptation to climate change induced sea level rise along the Mediterranean coast of Egypt. Mitig Adapt Strateg Glob Chang 18(8):1215–1237. https://doi.org/10.1007/s11027-012-9418-y

Fulweiler RW, Nixon SW (2009) Responses of Benthic-Pelagic coupling to climate change in a temperate estuary. Hydrobiologia 629(1): 147–156. https://doi.org/10.1007/s10750-009-9766-0

Giorgi F (2006) Climate change hot-spots. Geophys Res Lett 33(8):1–4. https://doi.org/10.1029/2006GL025734

Gleckler PJ, Taylor KE, Doutriaux C (2008) Performance metrics for climate models. J Geophys Res Atmos 113(6):1–20. https://doi.org/10.1029/2007JD008972

Gregory J (2014) Projections of sea level rise, Climate change 2013: the physical science basis. Contribution of Working Group I to The Fifth Assessment Report of The Intergovernmental Panel on Climate Change. Cambridge. Available at: http://www.ipcc.ch/pdf/unfccc/cop19/3_gregory13sbsta.pdf. Accessed Sept 2018

Info-Space (n.d.) Web Server 'Russia's Weather'. Available at: http://meteo.infospace.ru/main.htm. Accessed: 1 April 2016

Jacob D, Barring L, Christensen OB et al (2007) An inter-comparison of regional climate models for Europe: model performance in present-day climate. Clim Chang 81(suppl. 1):31–52. https://doi.org/10.1007/s10584-006-9213-4

Jakimavičius D, Kriaučiūnienė J (2013) The climate change impact on the water balance of the Curonian Lagoon. Water Res 40(2):120–132. https://doi.org/10.1134/s0097807813020097

Kanoshina I, Lips U, Leppänen JM (2003) The influence of weather conditions (temperature and wind) on cyanobacterial bloom development in the Gulf Of Finland (Baltic Sea). Harmful Algae 2(1):29–41. https://doi.org/10.1016/s1568-9883(02)00085-9

Khalil MT (2010) Fisheries of Egyptian delta coastal wetlands; Burullus Wetland case study. In: Negm AM et al (eds) Egyptian coastal lakes and wetlands: Part II – climate change and biodiversity, Hdb Env Chem. Springer International Publishing, pp 41–53. https://doi.org/10.1007/698_2017_204

Kopp RE, Horton RM, Little CM, Mitrovica JX, Oppenheimer M, Rasmussen DJ, Strauss BH, Tebaldi C (2014) Probabilistic 21st and 22nd Century sea-level projections at a global network of tide-gauge sites. Earth's Future 2(8):383–406. https://doi.org/10.1002/2014EF000239

Lloret J, Marín A, Marín-Guirao L (2008) Is coastal lagoon eutrophication likely to be aggravated by global climate change? Estuar Coast Shelf Sci 78(2):403–412. https://doi.org/10.1016/j.ecss.2008.01.003

Lopes JF, Dias JM, Cardoso AC, Silva CIV (2005) The water quality of the Ria De Aveiro Lagoon, Portugal: from the observations to the implementation of a numerical model. Mar Environ Res 60(5):594–628. https://doi.org/10.1016/j.marenvres.2005.05.001

Lopes CL, Silva PA, Dias JM, Racha JM, Racha A, Picado A, Plecha S, Fortunato AB (2011) Local sea level change scenarios for the end of the 21st century and potential physical impacts in the lower Ria De Aveiro (Portugal). Cont Shelf Res 31(14):1515–1526. https://doi.org/10.1016/j.csr.2011.06.015

Mahanty MM, Mohanty PK, Pattnaik AK, Panda US, Pradhan S, Samal RN (2016) Hydrodynamics, temperature/salinity variability and residence time in the Chilika Lagoon during dry and wet period: measurement and modeling. Cont Shelf Res 125:28–43. https://doi.org/10.1016/j.csr.2016.06.017

Mclusky DS, Elliott M (2007) Transitional waters: a new approach, semantics or just muddying the waters? Estuar Coast Shelf Sci 71(3–4):359–363. https://doi.org/10.1016/j.ecss.2006.08.025

Monsen NE, Cloern JE, Lucas LV, Monismith SG (2002) A comment on the use of flushing time, residence time and age as transport time scales. Limnol Oceanogr 47:1545–1553. https://doi.org/10.4319/lo.2002.47.5.1545

Neumann B, Vafeidis AT, Zimmermann J, Nicholls RJ (2015) Future coastal population growth and exposure to sea-level rise and coastal flooding - a global assessment. PLoS ONE 10(3). https://doi.org/10.1371/journal.pone.0118571

Nobuoka H, Mimura N (2008) Adaptation to salinity change induced by sea-level rise in Hinuma Lake, Japan. In: Mohanty PK (ed) Monitoring and modelling lakes and coastal environments. Springer, Dordrecht, pp 125–135. https://doi.org/10.1007/978-1-4020-6646-7_10.

Panda US, Mohanty PK (2008) Monitoring and modelling of Chilika environment using remote sensing data. Proceeding of Taal2007: The 12th World Lake Conference, pp. 617–638. Available at: http://www.moef.nic.in/sites/default/files/nlcp/D%20-%20Remote%20Security%20GIS%20Application/D-2.pdf. Accessed Sept 2018

Panda US, Mahanty MM, Ranga RV, Patra S, Mishra P (2015) Hydrodynamics and water quality in Chilika Lagoon-a modelling approach. Procedia Eng 116(1):639–646. https://doi.org/10.1016/J.Proeng.2015.08.337

Pelicano CM, Lopes JF, Dias JM, Dekeyser I (2001) Heavy metals transport in Ria De Aveiro Lagoon, Portugal. In: XXVI General Assembly of The European Geophysical Society, Nice, France

Perkins SE, Pitman AJ, Holbrook NJ, McAneney (2007) Evaluation of the AR4 climate models' simulated daily maximum temperature, minimum temperature, and precipitation over Australia using probability density functions. J Clim 20(17):4356–4376. https://doi.org/10.1175/JCLI4253.1

Pesce M, Critto A, Torresan S, Giubilato E, Santini M, Zirino A, Ouyang W, Marcomini A (2018) Modelling climate change impacts on nutrients and primary production in coastal waters. Sci Total Environ 628-629:919–937. https://doi.org/10.1016/J.Scitotenv.2018.02.131

Primo B, Achete F, Mahanama S, Thatcher M, Hemer M, Sutat W, Duong T (2018) Climate change impacts assessment in coastal lagoons using available modelling tools. Preprints 2018, 2018050007. https://doi.org/10.20944/preprints201805.0007.v1

Rabalais NN, Turner RE, Diaz RJ, Justic D (2009) Global Change and eutrophication of coastal waters. ICES J Mar Sci 66(7):1528–1537. https://doi.org/10.1093/icesjms/fsp047

Rasmussen EK, Svenstrup PO, Thompson JR, Flower RJ, Ahmed MH (2009) Hydrodynamic-ecological model analyses of the water quality of Lake Manzala Nile Delta, Northern Egypt. Hydrobiologia 622(1):195–220. https://doi.org/10.1007/s10750-008-9683-7

Shalby A, Elshemy M, Zeidan BA (2017) Selecting of regional climate model simulations for modeling climate change impacts on the water quality status of Lake Burullus, Egypt. Proceeding of the Twentieth International Water Technology Conference, IWTC20, Hurghada, Egypt, pp 120-132. Available at: http://iwtc.info/wp-content/uploads/2017/05/46.pdf. Accessed March 2019

Shalby A, Elshemy M, Zeidan BA (2018) Climate change impacts on the hydrodynamic characteristics of Lake Burullus, Coastal Lagoon (Egypt). Proceeding of the Sixth International Conference On Estuaries And Coasts (ICEC-2018). Caen, France

Shalby A, Elshemy M, Zeidan BA (2019) Combined hydrodynamic and ecological modeling for Lake Burullus, Coastal Lagoon (Egypt). (Article in Review)

Shaltout M, Tonbol K, Omstedt A (2015) Sea-level change and projected future flooding along the Egyptian Mediterranean coast. Oceanologia 57(4):293–307. https://doi.org/10.1016/j.oceano.2015.06.004

Smith NP (2001) Seasonal-scale transport patterns in a multi-inlet coastal lagoon. Estuar Coast Shelf Sci 52(1):15–28. https://doi.org/10.1006/ecss.2000.0717

Soliman MR, Ushijima S (2013) Climate change impact on El-Burullus Lake salinization process. J Jpn Soc Civ Eng Ser 69(4):I_253–I_258 Available at: https://www.jstage.jst.go.jp/article/jscejhe/69/4/69_43/_pdf/-char/ja

Stefan HG, Fang X, Eaton JG (2001) Simulated fish habitat changes in North American Lakes in response to projected climate warming. Trans Am Fish Soc 3(130):459–477. https://doi.org/10.1577/1548-8659(2001)130

Telesh IV, Khlebovich VV (2010) Principal processes within the estuarine salinity gradient: a review. Mar Pollut Bull 61(4–6):149–155. https://doi.org/10.1016/j.marpolbul.2010.02.008

Tsimplis MN, Marcos M, Somot S (2008) 21st century Mediterranean sea level rise: steric and atmospheric pressure contributions from a regional model. Glob Planet Chang 63(2–3):105–111. https://doi.org/10.1016/j.gloplacha.2007.09.006

Vermeer M, Rahmstorf S (2009) Global sea level linked to global temperature. Proc Natl Acad Sci U S A 106:21527–21532. https://doi.org/10.1073/pnas.0907765106

Vigil KM (2003) Clean water - an introduction to water quality and water pollution control. Oregon State University Press Corvallis

Vincent WF (2009) Effects of climate change on lakes. Pollut Remediat: 55–60. https://doi.org/10.1016/B978-012370626-3.00233-7

Wahl B, Peeters F (2013) Studying climate impacts on hydrophysical processes in Lake Constance by 3D hydrodynamic modelling. Proceeding of the EGU General Assembly Conference ..., 15(EGU2013–7295.2013). Available at: http://adsabs.harvard.edu/abs/2013EGUGA..15.7295W. Accessed March 2019

Wahl B, Peeters F (2014) Effect of climatic changes on stratification and deep-water renewal in Lake Constance assessed by sensitivity studies with a 3D hydrodynamic model. Limnol Oceanogr 59(3):1035–1052. https://doi.org/10.4319/lo.2014.59.3.1035

Weinberger S, Vetter M (2012) Using the hydrodynamic model DYRESM based on results of a regional cimate model to estimate water temperature changes at Lake Ammersee. Ecol Model 244:38–48. https://doi.org/10.1016/j.ecolmodel.2012.06.016

Younis AM (2017) Environmental impacts on Egyptian Delta Lakes' biodiversity: a case study on Lake Burullus. In Negm AM et al (eds) Egyptian coastal lakes and wetlands: part II – climate change and biodiversity, Hdb Env Chem. https://doi.org/10.1007/698_2017_120

Zacharias I, Gianni A (2008) Hydrodynamic and dispersion modeling as a tool for restoration of coastal ecosystems. Application to a re-flooded lagoon. Environ Model Softw 23(6):751–767. https://doi.org/10.1016/j.envsoft.2007.09.007

Zhao YW, Xu MJ, Xu F, Wu SR, Yin XA (2014) Development of a zoning-based environmental-ecological coupled model for lakes: a case study of Baiyangdian Lake in Northern China. Hydrol Earth Syst Sci 18(6):2113–2126. https://doi.org/10.5194/hess-18-2113-2014