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**Article**

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## Numerical modeling of hydrodynamic circulation in Ichkeul Lake-Tunisia

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### Abstract

The Ichkeul Lake ecosystem, Northern of Tunisia, has been registered as a biosphere reserve in 1977 (MAB-UNESCO Convention), a UNESCO World Heritage site in 1979, and a RAMSAR site in 1980. Damming and global warming drought drastically diminished the fresh water supply to this lake. This leads to water level and salinity fluctuation throughout the year. Consequently, the water clarity of this shallow wind-stressed lake was altered and if this siltation continues to increase, will seriously affects the hydromorphology and ecology of this wetland. Therefore, to study the hydrodynamic water circulation in the lake and the transport of the Total Suspend Matter (TSM), hydrodynamic and transport models were calibrated and applied to this environment. Numerical model predictions based on water level, temperature and salinity sensitivity to the bed roughness show that the Delft 3D-Flow model reproduced well the measured data with RMSE < 0.027 for water level.

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*Keywords:* Delft3D-FLOW; Hydrodynamic circulation; Ichkeul Lake; Sedimentary material; TSM; Water clarity

### 1. Introduction

Wetlands cover 6% of the world's land surface and play an important role in the global carbon cycle [1]. According to De Vente et al. [2], in half a century, the world's water storage in reservoirs, especially in arid and semi-arid environments, will be half of the current storage capacity, due to sedimentation processes, which will have large economic and environmental consequences. Indeed, Nick [3] affirmed that the world has lost 50% of its wetlands. Many wetlands are suffering from sediment accumulation as the contrasting lakes in the Carpathians (Romania), Lake Hårsvatten (Sweden), Blelham Tarn, Cumbria (UK), Apopka Lake (Florida, USA),

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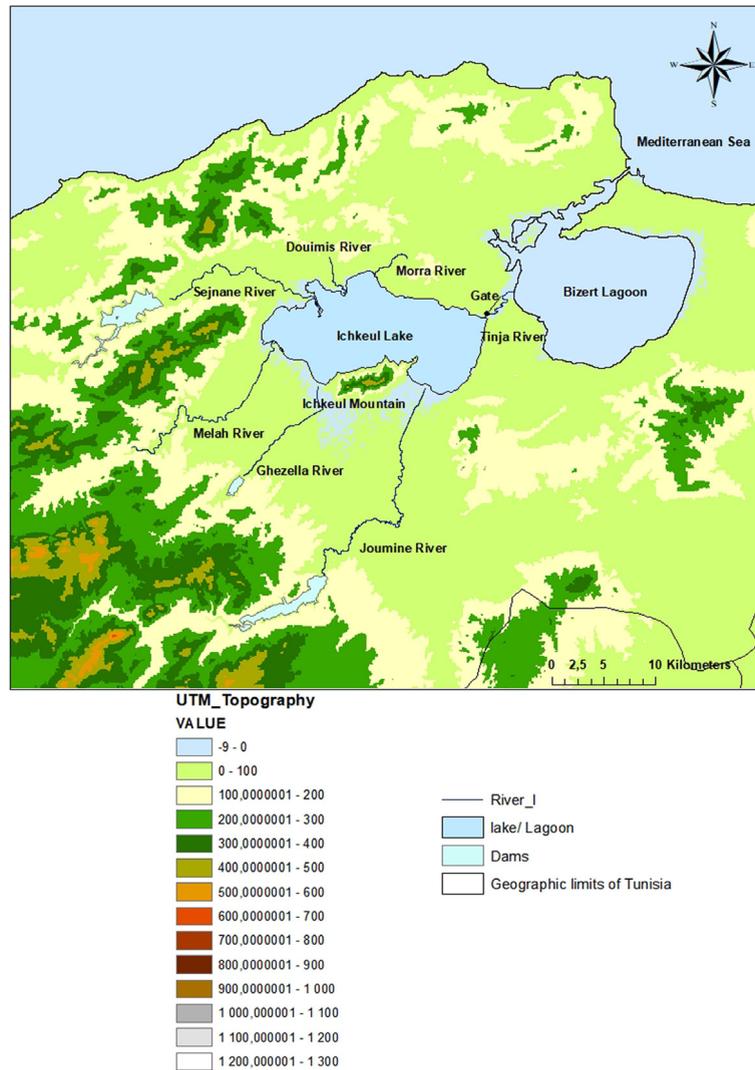


Fig. 1. Geographic location of Ichkeul lake.

Rushy Billabong (Australia), Esteros del Iberà (Argentina), Lake Taihu (China) ... etc. [4–10]. The magnitude and rate of climate change could alter the hydrology of the Great Lakes and affect wetland ecosystems [11]. In Tunisia, exist about 8 lakes, but the large Ichkeul Lake is endowed with exceptional importance, as a RAMSAR site. This shallow water lake covers over 87 km<sup>2</sup> at its summer minimum, and is located in North East of Tunisia (Fig. 1). The lake basin is very shallow with mean summer and winter depths of 1 and 2 m, respectively. In the hydrological context, six major rivers feed the lake. The water surface occupied 8700 ha with water capacity storage below 340 Mm<sup>3</sup>. The hydrodynamics of the lake was controlled by the Tinja Gate, which connects Ichkeul Lake to Bizerte Lagoon, and indirectly to the Mediterranean Sea. The Tinja River is exceptional because its flow is reversed in summer when the level of Ichkeul falls below that of the lagoon. This reversal is the result of flow cessation in the major rivers and of the high evaporation rate from the lake.

As highlighted by Trabelsi et al. [4], there is observational evidence that internal redistribution of sediments plays an important role in the sedimentary dynamics of this shallow wind-stressed lake. Besides, the spatial distribution within the lake body of sedimentary material supplied by the main inflows largely depends on the water circulation and the characteristic settling velocities of TSM with different grain sizes. Thus, the resuspension of sediments is one of the fundamental factors that govern the ecology of lakes. Therefore, this work aims to understand the

hydrodynamic circulation in Lake Ichkeul and its influence on the clarity of the water and find out the main sources of water surface suspended solids. The research approach included: (1) Delft-FLOW model implementation and calibration for Ichkeul lake and (2) Sensitivity analysis of water level, water temperature and salinity with bed roughness variation (3) The influence of discharge of the already mentioned physical parameters.

## 2. Methodology

### 2.1. Delft3D-Flow: the numerical model

Delft3D-Flow is a three-dimensional, finite difference hydrodynamic and transport model which simulates flow and transport resulting from tidal and meteorological forcing [12]. In this work, the hydrodynamic model solves the Reynolds-averaged Navier Stokes shallow water equations, including the linear momentum in horizontal and vertical directions with hydrostatic, Boussinesq and f-plane approximations, and the continuity (Eq. (1)) and transport equations (Eqs. (2) and (3)). This model uses a horizontal Arakawa-C grid. A spherical, curvilinear orthogonal grid with  $328 \times 145$  cell with 30 m resolution was designed to represent the main hydrodynamic features of the Lake. Three months simulation with initial condition of 0.4 m water level, 10 ppt salinity and 15 °C Temperature was enhanced.

$$\begin{aligned} \frac{\partial \zeta}{\partial t} + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial((d + \zeta) U \sqrt{G_{\eta\eta}})}{\partial \xi} \\ + \frac{1}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial((d + \zeta) V \sqrt{G_{\xi\xi}})}{\partial \eta} = (d + \zeta) Q \end{aligned} \quad (1)$$

While :

$$\begin{aligned} U &= \frac{1}{d + \zeta} \int_d^H u \, dz = \int_{-1}^0 u \, d\sigma \quad \text{and} \quad V = \frac{1}{d + \zeta} \int_d^\zeta v \, dz \\ &= \int_{-1}^0 v \, d\sigma \end{aligned}$$

Momentum equations in horizontal direction, respectively (ox) and (oy):

$$\begin{aligned} \frac{\partial u}{\partial t} + \frac{u}{\sqrt{G_{\xi\xi}}} \frac{\partial u}{\partial \xi} + \frac{v}{\sqrt{G_{\eta\eta}}} \frac{\partial u}{\partial \eta} + \frac{\omega}{d + \zeta} \frac{\partial u}{\partial \sigma} \\ - \frac{v^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial \sqrt{G_{\eta\eta}}}{\partial \xi} + \frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta} \\ - fv = -\frac{1}{\rho_0 \sqrt{G_{\xi\xi}}} P_\xi + F_\xi + \frac{1}{(d + \zeta)^2} \frac{\partial}{\partial \sigma} \left( \nu_v \frac{\partial u}{\partial \sigma} \right) + M_\xi \end{aligned} \quad (2)$$

$$\begin{aligned} \frac{\partial v}{\partial t} + \frac{u}{\sqrt{G_{\xi\xi}}} \frac{\partial v}{\partial \xi} + \frac{v}{\sqrt{G_{\eta\eta}}} \frac{\partial v}{\partial \eta} + \frac{\omega}{d + \zeta} \frac{\partial v}{\partial \sigma} \\ + \frac{uv}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial \sqrt{G_{\eta\eta}}}{\partial \xi} + \frac{u^2}{\sqrt{G_{\xi\xi}}\sqrt{G_{\eta\eta}}} \frac{\partial \sqrt{G_{\xi\xi}}}{\partial \eta} \\ + fv = -\frac{1}{\rho_0 \sqrt{G_{\eta\eta}}} P_\eta + F_\eta + \frac{1}{(d + \zeta)^2} \frac{\partial}{\partial \sigma} \left( \nu_v \frac{\partial v}{\partial \sigma} \right) + M_\eta \end{aligned} \quad (3)$$

With  $\zeta$  the water level (m);  $\sqrt{G_{\xi\xi}}$  and  $\sqrt{G_{\eta\eta}}$  coefficients used to transform curvilinear coordinates into rectangular coordinates (m); d: depth under a horizontal reference plane (datum) (m);  $v$  fluid velocity in the direction (oy) (m/s);  $\eta$ : relative availability of the sediment fraction in the mixing layer;  $Q$ : contributions per unit area of water intake/withdrawal, precipitation and evaporation (m/s);  $u$ : flow velocity in the direction (ox) (m/s);  $\omega$  flow velocity in the direction (oz) (m/s);  $\sigma$  vertical coordinate scaled;  $P_\xi$  hydrostatic pressure gradient in the direction  $\xi$  (kg/(m<sup>2</sup> s<sup>2</sup>));  $M_\xi$  moment in the direction (m/s<sup>2</sup>);  $F_\xi$  turbulent motion flow in the direction  $\xi$  (m/s<sup>2</sup>);  $f$  coriolis

parameter (inertial frequency) ( $1/s$ );  $F\eta$  turbulent motion flow in the direction  $\eta$  ( $m/s^2$ );  $P\eta$  hydrostatic pressure gradient in the direction  $\xi$  ( $kg/(m^2 s^2)$ );  $M\eta$  source or sink of momentum in the direction  $\eta$  ( $m/s^2$ ).

Boundary conditions for water temperature, water level and water salinity were considered at the open boundary (Tinja Gate) and a total of 7 control stations in the mouth of 6 connecting rivers and near the gate were assumed. A 100 m resolution bathymetry of March 2015 was used in the calculation of hydrodynamic quantities in this work. Since the samples have lower resolution compared to the grid cell, a triangular interpolation was used. The reference time chosen is the 1st September 2006. The meteorological forcing was assessed through the Heat flux model (relative humidity, Air Temperature and the Net radiation fluxes) and Wind speed and direction. Besides, the physical (Water level, salinity and water temperature) data added to the discharge from connecting rivers represent the input of this simulation.

## 2.2. Model calibration

The calibration of the bottom roughness through the Manning ( $n$ ) coefficient was performed using the truncated function of depth vs.  $n$  [12]. As highlighted by Liu [10], the lake circulation flow could generally be divided into wind driven current due to wind surface stress (wind influence), discharge driven current caused by surface pressure gradient due to surface elevation near the discharge point and density flow induced by the difference of salinity and temperature. The observed water level, water temperature and salinity data from Tinja Gate station were compared with model predictions for the hydrologic year 2006–2007. Then, the efficiency of the hydrodynamic prediction was discussed using the Root-Mean-Square Error (RMSE) (Eq. (4)). Delft3D-FLOW was used to find out the impact of water current on the clarity of shallow water. The meteorological forcing was also assessed. The physical data added to the discharge from the connecting rivers represent the input of this simulation.

$$RMSE = \sqrt{\frac{\sum_{i=1}^k (P_i - O_i)^2}{k}} \quad (4)$$

$k$  refers to the total number of samples;  $P$  represents the predicted data simulated by Delft3D-Flow and  $O$  for the observed data.

## 3. Sensitivity analysis and physical parameters

According to Liu [10], water level and depth average are the two indices used to determine the influence of changing parameters. In this work, the effect of the lake's bed roughness variation in water level and without discharge was discussed. After a set of simulations, the roughness varied following (Table 1) and a scenario without fresh water input to the lake was considered for  $n = 0.024$ . The predicted data for water level fit well with the observed one,  $RMSE < 0.027$ . Besides, the Root-Mean-Square Error of simulated Temperature (RMSE\_T) and Salinity (RMSE\_S) were presented too.

The influence of bed roughness on water level was not so significant and the RMSE\_WL was considered equal to the  $n$  values ( $RMSE\_WL = 0.022$  at  $n = 0.022$ ). On one hand, for the highest value of roughness used in this work, we observed a minimum value of RMSE\_T, but a maximum one for RMSE\_S. On the other hand, a high error in water temperature simulation was reached at minimum roughness contrary to water salinity. When neglecting the discharge, for  $n = 0.024$ , the error in water level simulation does not change. Contrariwise, the effect of discharge was detected on temperature and water salinity where the RMSE was decreased respectively with 2.87% and 25.43%.

However, Delft3D-Flow model took about 7 simulation days to reach an equilibrium state and get closer to observed data. Thus, a spin up time of a week is needed to decrease the error between measured and modeled

**Table 1.** Root-Mean-Square Error of water level, temperature and salinity with roughness variation, with and without discharge.

| Roughness | 0.026 | 0.024 | 0.022 | 0.018 | No discharge ( $n = 0.024$ ) |
|-----------|-------|-------|-------|-------|------------------------------|
| RMSE_WL   | 0.026 | 0.025 | 0.022 | 0.019 | 0.025                        |
| RMSE_T    | 1.887 | 1.988 | 1.975 | 1.932 | 1.931                        |
| RMSE_S    | 2.999 | 2.914 | 2.822 | 2.617 | 2.173                        |

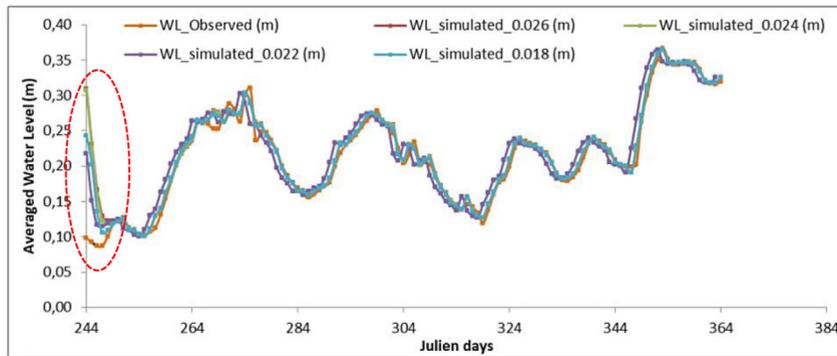


Fig. 2. Comparison between simulated and observed water level for different bed roughness.

water level (Fig. 2). After that, the same tendency of simulated and observed data was detected with small errors which can be due to the computer system or the quality of in situ data. To overcome this, one week was added to the simulation period in the next runs of the Ichkeul lake model.

#### 4. Discussion

Study on the influence of environmental and anthropogenic factors on hydrodynamic conditions in shallow lakes is a hot topic in recent years' study [6,10,12]. The Delft3D-Flow's first results for the physical parameters were satisfactory. In fact, the influence of bed roughness on water level simulation was not significant, as well as the discharge, which was matched with the findings of Liu [10]. Besides, water temperature and salinity were significantly affected by the bed roughness variation, as highlighted by Lencart e Silva et al. [12]. The model reproduces well the water level with  $RMSE_{WL} < 0.027$ . A spin-up time was used to decrease the simulation errors. However, as mentioned by Liu [10], the calibration of this hydrodynamic model with water level and depth average was used to detect the influence of discharge and wind factors. Furthermore, the water circulation in shallow wind-exposed lakes, as the case of Ichkeul Lake, was essentially influenced by wind forcing [13] and, according to Liu [10], the wind drag force, the surface flow generally follows the wind direction in most open areas. Further sensitivity tests were planned to improve the efficiency of the Delft model and help to better predict the hydrodynamic water circulation of Ichkeul Lake.

#### 5. Conclusion

The first results for the model calibration show that the model has succeeded in assessing water level, water temperature, and salinity of the Ichkeul Lake with respectively  $RMSE_{WL} < 0.027$ ,  $RMSE_T < 2$  and  $RMSE_S < 3$ . Besides, the influence of bed roughness on water temperature and salinity was well detected, contrary to water level. In addition, the effect of fresh water discharge on temperature and salinity was shown. However, a one-week addition to the simulation period was needed to reduce these errors, spin-up time. Further calibration tasks are crucial to better assess the hydrodynamic circulation of Ichkeul Lake and thus the spatial distribution of suspended material, water turbidity. Indeed, previous studies affirmed that the sedimentary material supplied by connecting rivers will be primarily deposited in a limited area of influence (around the mouth of rivers), and after that they may be subject to further resuspension and transport. Following the Sustainable Development Goals 13th and 14th, integrating climate change measures into national policies, strategies, and planning could preserve the natural resources.

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