TWO-DIMENSIONAL FLOW AND TRANSPORT SIMULATION OF THE NILE ESTUARY INVESTIGATING IMPACTS OF SEA LEVEL RISE

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Abstract

The possible changes in the flow and salinity balance in the Nile estuary due to the anticipated sea level rise were investigated in this research. For this purpose mathematical modeling was used to simulate two-dimensional flow and salinity transport processes.

The computational domain comprises the last reach of the Rosetta branch of the Nile River between the last barrage and the Mediterranean Sea. The TELEMAC2D modeling system which solves the two-dimensional (velocity-averaged) Saint-Venant equations has been chosen for the numerical simulation of the reach under study.

The results revealed that for average conditions the water level variations are very small and the flow velocities are very small, too, with a maximum of about 8cm/s. The sensitivity of the model to the turbulence viscosity and friction coefficient is very small. The intrusion of the salt water will increase from 4.8 km for an idealized storm under average conditions to be about 7.1km, 9.6km and 12.7km when the sea level increases by 0.25m, 0.5m and 1m respectively. To maintain the current balance an extra water flow has to be discharged from the last barrage.

Introduction

In the last few decades several observations and natural phenomena proved that the global climate changed in terms of temperature and rainfall, this change could have negative direct and indirect consequences on all the earth (IPCC, 2007; UNFCCC, 2007). One of the consequences that has taken great interest is the sea level rise which may affect the low lying areas close to the shores (Agrawala et. al., 2004; Ludwig & Vellinga, 2008; El Raey, 2010) and the fresh water at the mouths of the rivers, as the case of the Nile River.

The Nile River bifurcates at El-Qanater city (about 20 km north to Cairo) into two branches which are Rosetta branch (the western) and Damietta branch (the eastern), the two branches enclosing the Nile Delta and forming the Nile estuary. The two branches discharge the Nile water into the Mediterranean Sea. The discharge of the two branches is controlled through several water structures. The flow that is discharged into the sea (considered as waste from the water budget of the country) is the minimum flow that supports the navigational purposes, the natural processes in the river and to make balance with the sea water. Any changes in the sea level or in the Nile flow due to climate change could change the balance that currently exists between the fresh water and the saline water and hence it will affect the water management of the Nile estuary.

Mathematical modeling has emerged as a powerful tool in water resources management; it allows simulation of environmental water and prediction of the possible impacts due to the anticipated changes. Few works have been found where mathematical models for Nile River Estuary have been carried out using different modeling systems and tools; the focus of these trials was sedimentation processes. Mahmoud et. al. (2006) used SOBEK modeling system to make a one dimensional (1-D) model of Rosetta promontory to identify its actual capacity to pass the emergency and flood flows and the capacity in case of dredging. The research constructed a model to the last 30 km of Rosetta branch investigating the hydrodynamic behavior in different flow conditions. Moussa & Aziz (2007) used GSTARS 2.0 Model (developed by the U.S. Bureau of Reclamation) to calculate the amount of sediment discharge of Damietta branch of the Nile River and comparing several formulas used in this context.

Hence, mathematical modeling was used in this research to model the River Nile estuary to investigate the extension of saline water intrusion into the Nile River and its impact on the water management in Egypt regarding the sea level rise. Therefore following objectives were investigated:

a. Simulating the two-dimensional flow and salinity transport processes in the Nile estuary, that is considered as the baseline scenario
b. Comparing the baseline scenario to different scenarios of sea level rise
c. Pointing out the remarkable changes in the hydrodynamics and salinity transport
d. Examining the possible water management options for the different sea level rise scenarios and investigating the impact on the total water budget for the country

Study area

The last controlled reach of Rosetta branch of the Nile River (Figure 1) is chosen in this research to investigate the impacts of climate change. The reach under study is located between 31.32º and 31.45º north and 30.34º and 30.53º east with a total length of about 35 km. Edfina Barrage controls the flow in the reach under study at the upstream side (U.S.), and it ends with the Mediterranean Sea at the downstream side (D.S.).

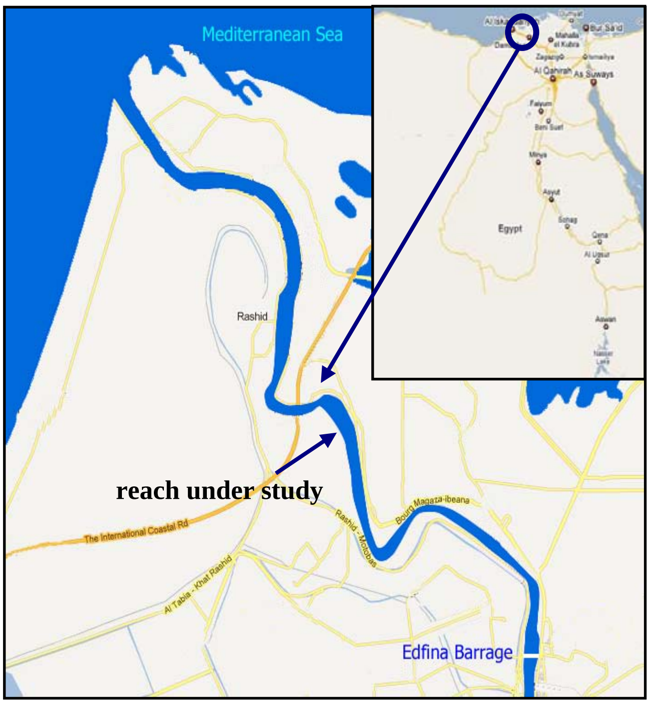

Figure 1: A map of the reach under study

In such a big domain, variations in the depths are expected. The water depth ranges from 2.30 m to about 26.5 m. The average width of the domain is about 500 m. The average discharge during the year is 83.6 m^3/s and the average water level at D.S. is 0.37 m mean sea level (msl). However, the discharge of the river and the sea level are changing during the year. The minimum discharge is 2.31 m^3/s, and the maximum discharge is 232.01 m^3/s. Also the sea level ranges from 0.0m msl as minimum level to about 0.89m msl in the maximum case.

Modeling system

TELEMAC-2D modeling system has been chosen to construct a two-dimensional (2-D) numerical model for the reach under study. TELEMAC-2D simulates open channel flow using finite element method (FEM) for solving the two-dimensional Saint-Venant equations. The main variables are the water depth and the velocity averaged over the vertical. Different turbulence models are available and in addition it considers the transport of a passive tracer (LNHE, 2010).

TELEMAC-2D allows the choice among several laws of friction, turbulence models, stabilization methods and solvers. In this research the Streamline Upstream Petrov-Galrkin method (SUPG) was used as the stabilization method for the FEM. Centered semi-implicit scheme was chosen for time discretization, but only in the hydrodynamic calculations and PSI (Positive Streamline Invariant) distributive scheme was used for the transport modeling. The solver applied in the research is the Generalized Minimum RESidual method (GMRES) for the non-symmetric matrices (Hinkelmann, 2005). TELEMAC-2D generally uses linear triangular finite elements, but it can also work with quadrilateral elements.
TELEMAC-2D has been applied for numerous studies in fluvial and maritime hydraulics (LNHE, 2010). The modeling process with TELEMAC-2D consists of pre-processing with MATISSE, processing and post-processing with RUBENS.

Model setup and parameters

A triangular grid is generated with MATISSE in the preprocessing stage. This stage is important for including the bathymetry of the river and for setting the boundary conditions. The discritezation length of the elements is 40m in most of the domain, and in specific parts where the bottom level has a sharp slope and in the parts of small width a finer grid with 20m discretization length is generated. The total number of nodes is 19448 and the total number of elements is 36669 (Figure 2).

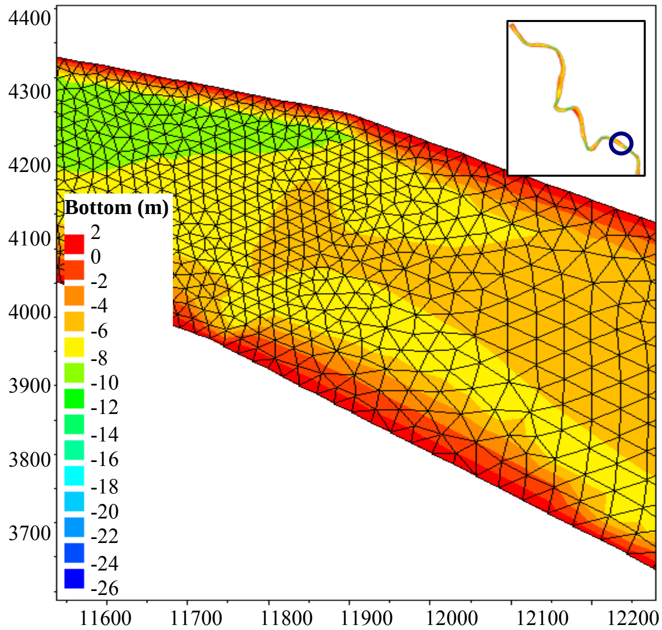

Figure 2: The grid at one position in the domain

The model is bounded from its U.S. side by Edfina Barrage where the discharge is known and from the D.S. side with the Mediterranean Sea where the water level is known, so those are considered the only two open boundaries in the domain and all the other boundaries, mainly the banks, are closed. Due to the fact that the flow of the river and the water levels of the sea are fluctuating during the year, the minimum, average, and maximum values have been used in the calculations for the boundary conditions.

The simulation was carried out with a time step of 5 seconds. A total simulation time of three days was carried out to reach a steady state condition assuming an initial condition of zero velocity and initial water level of 0.37 m msl. This steady state case was later chosen as initial condition for all the other calculations and scenarios.

In this research, Manning friction coefficient of 0.022 (Mahmoud et. al, 2006) and a simple turbulence model with constant viscosity (ν = 0.01 m^2/s) being equal to the turbulent viscosity were chosen in all the cases.

Results and discussion

Hydrodynamics of the Nile estuary at the average conditions

The average conditions (flow at U.S. boundary is 83.6 m^3/s and sea level is 0.37m) is the baseline scenario for all the other calculations. A simulation for three days showed that the steady state condition could be reached after about two and half days (Figure 3). The water level doesn't change much through the domain; it ranges from 0.37 at the D.S to 0.372 at the U.S.

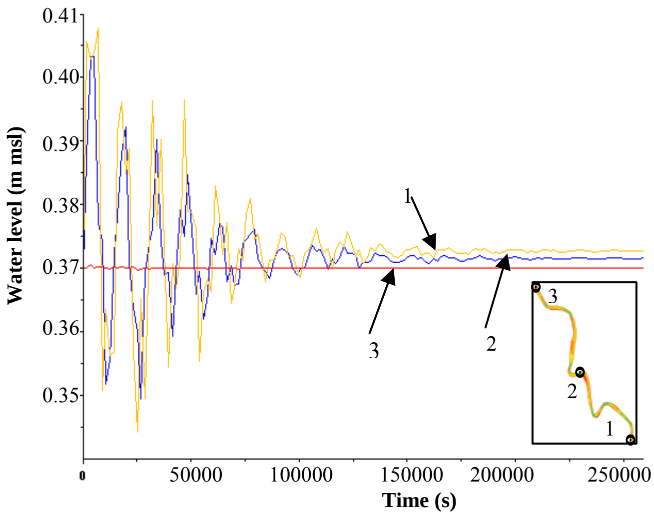

Figure 3: Change of the water level with time at three positions in the domain

The range in the flow velocity fluctuation was higher due to the change in the flow cross section along the reach; however the magnitude of the velocity was very low, the maximum velocity was at the D.S. boundary of about 8 cm/s and the velocity decreases to reach zero near the banks of the river (Figure 4). This slow flow is due to the small discharge in a big flow cross section.

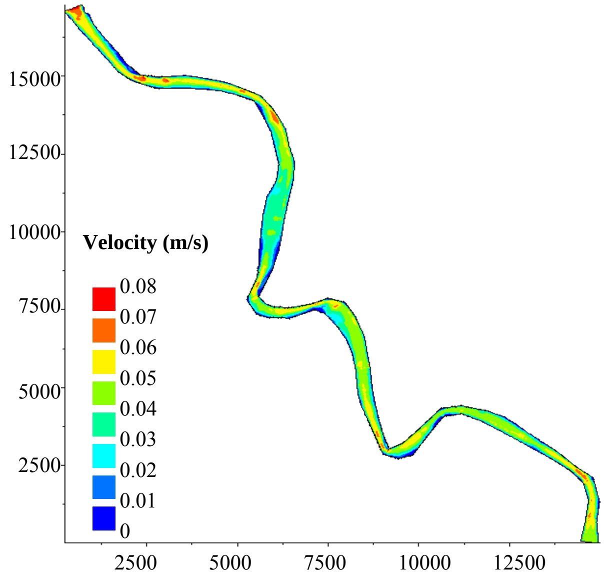

Figure 4: Flow velocity in the whole domain

The meandering of the river in this reach caused some eddies usually after every curvature (Figure 5); however the flow velocity of these eddies is generally very small (about 1cm/s). These eddies in addition to the velocity vector shown in Figure 5 are the reason for the choice of 2-D model instead of 1-D model in this case study.

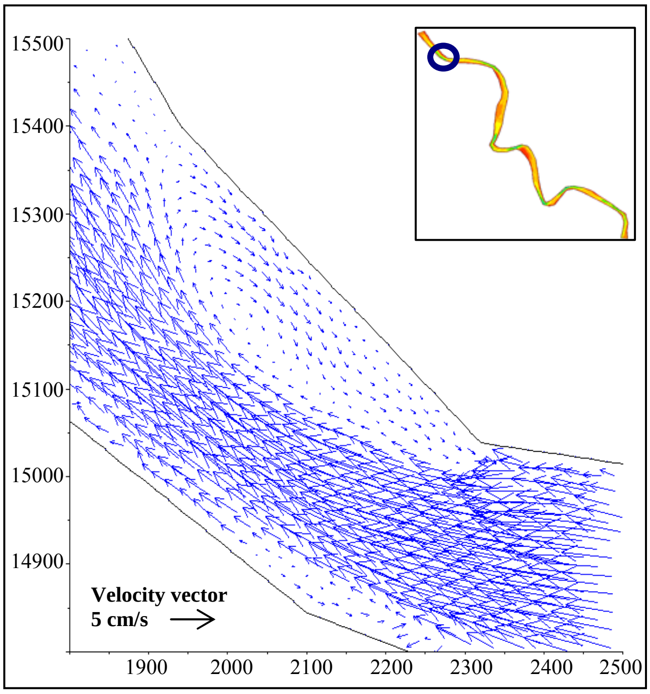

Figure 5: Velocity vector showing eddies at one position in the domain

The fluctuation in the discharge and the sea level during the year affects the water level in the domain and the flow velocity. Changing the water level while fixing the discharge affected the flow velocity as shown in Figure 6; higher velocities were recorded with lower sea level.

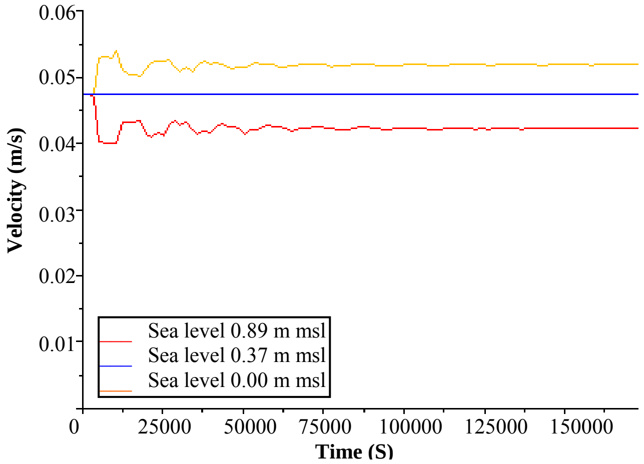

Figure 6: Flow velocity due to changing sea level at the U.S. boundary

Parameter studies

The sensitivity of the model to changes in the friction coefficient and the turbulence viscosity was examined using the average conditions.

Three Manning coefficients (n) were compared: 0.01, 0.022 and 0.03 respectively. The effect of changing friction coefficient on both water level and flow velocity was very small. The water level at the U.S. boundary changed in a range of +2.0 mm and -2.0 mm for “n” of 0.03 and 0.01 respectively when compared to the average case (n = 0.022) (Figure 7). This effect decreases when moving from the U.S to the D.S.

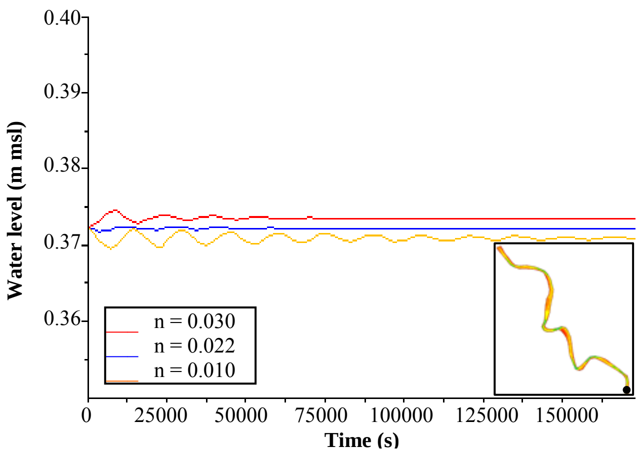

Figure 7: Change of water level due to changing Manning coefficient

The change in the flow velocity was reversely related to the change of the friction coefficient; higher flow velocity occurred for lower Manning coefficient, the change at the D.S boundary was +0.003 and -0.001 m/s for Manning coefficient of 0.01 and 0.03 respectively (Figure 8). This change differs throughout the domain but with the same trend. In addition, bigger fluctuations of the flow velocity until reaching the steady state were noticed in case of smaller friction coefficients because the resistance to the flow is decreased.

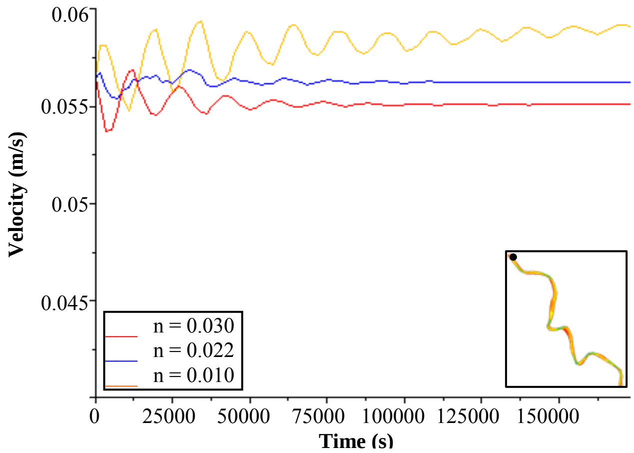

Figure 8: Change of flow velocity due to changing Manning coefficient

The sensitivity of the results for changing turbulent viscosity was investigated by comparing average conditions ($\nu = 0.01\ m^2/s$) to $\nu = 0.001$ and $0.1\ m^2/s$.

The sensitivity was very small (Figure 9 and Figure 10), in both water level and flow velocity. It was noticed also that turbulence viscosity of 0.001 and 0.01 m^2/s gave very similar results.

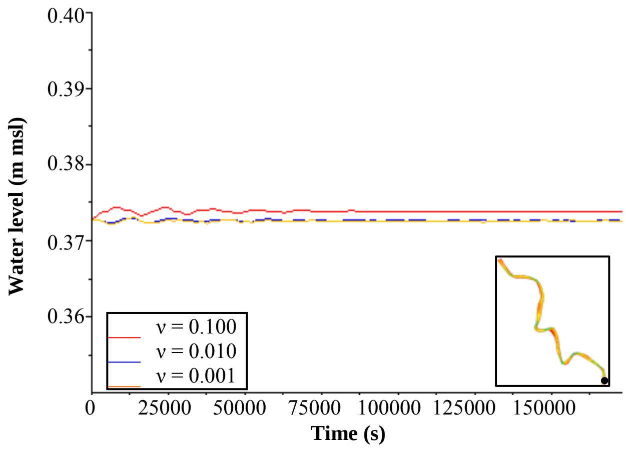

Figure 9: Change of water level due to changing turbulence viscosity at the U.S. side

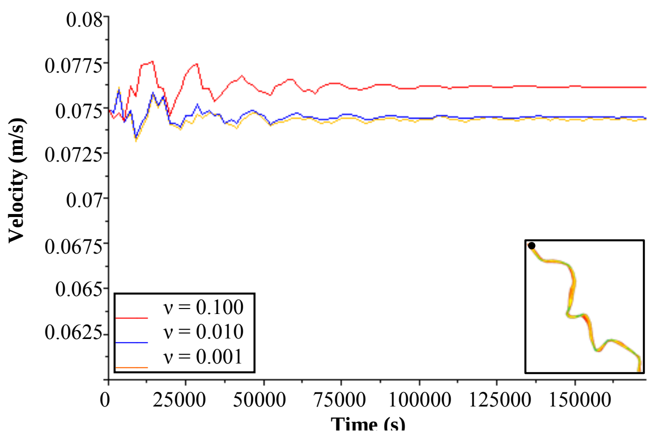

Figure 10: Change of flow velocity due to changing turbulence viscosity at the D.S. side

Salinity transport

The saltwater intrusion into estuaries is usually in a form of salt wedge where a layer of fresh water is flowing outside the river and moving over a layer of saltwater flowing towards the river, this stratification cannot be modeled within a 2-D model. So, another scenario was investigated. A sea storm was assumed when the water level in sea (D.S.) increased by 50cm within 10 hours. The initial salinity was set to zero in the whole domain. A Dirchlet boundary condition for the salinity with 38.5 kg/m^3 was chosen at the sea side.

The saltwater intruded for a distance of about 4.8 km into the river under the average conditions (Figure 11). However, this distance could be bigger than the reality due to the advection impact caused by the sea storm, but it is used here only for comparison purposes. In addition, the salt concentration decreased in upstream direction. The salt concentration depended also on the water depth, as in higher depths lower flow velocities occurred which affected the advection and the diffusion of the salt.

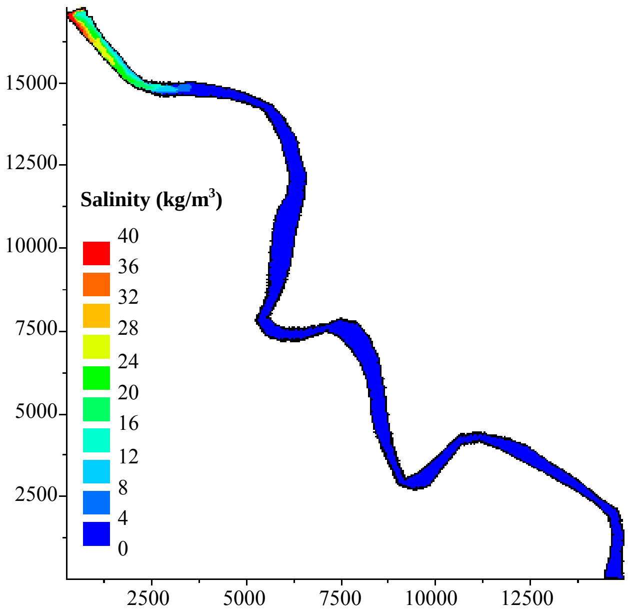

Figure 11: Salinity concentration in the whole domain

Sea level rise

Three scenarios of sea level rise were modeled; those are the increase of sea level by 0.25m, 0.5m and 1.0m respectively. The three scenarios were simulated based on the same storm described in the previous section and under the average discharge in the river.

Comparing the three scenarios to the average conditions revealed that the saltwater intrusion will increase to be about 7.1km, 9.6km and 12.7km for an increase of sea level by 0.25m, 0.5m and 1.0m respectively (Figure 12), so an extra saltwater intrusion of 2.3km, 4.8km and 7.9km respectively occurred. This could affect the irrigation activities in the surrounding area and it could increase the salinity of the agricultural lands in the vicinity of the Nile River.

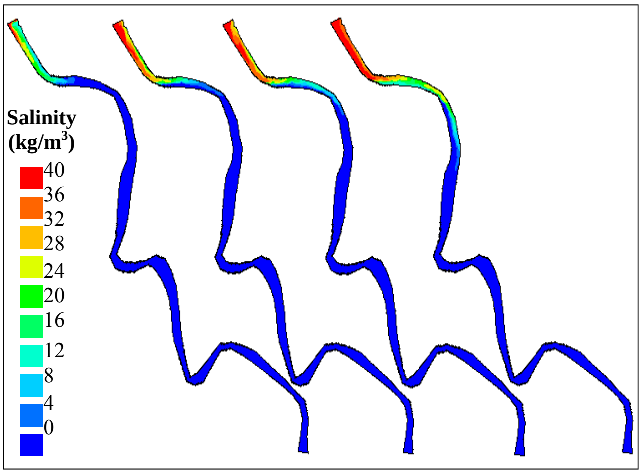

Figure 12: Saltwater intrusion for the sea level rise scenarios compared to the average condition (from the left is the average condition, then cases of sea level increase by 0.25m, 0.5m and 1.0m)

Water managements option and implications on the water budget of Egypt

To bring the system back to the current balance state the river discharge has to be increased; according to the model results the river discharge should be about 150m^3/s, 260m^3/s and 510m^3/s to balance the increase of the sea level by 0.25m, 0.5m and 1.0m respectively.

That means that an additional annual water amount has to be discharged to the sea. This additional amount of water will have bad implications on the total water budget of a country which currently suffers from water shortage problems, as this amount will be considered as a waste.

However, some compromises can be analyzed where the saltwater intrusion can be allowed to increase for a certain distance inside the river to decrease the amount of the additional water that has to be discharged to the sea. This problem becomes more severe in case of a reduction of the Nile flow as a result to the climate change.

Conclusions

In this research a model for the Nile River estuary at Rosetta was setup, the last controlled reach of a length of a bout 35km was modeled using TELEMAC2D modeling system.

For the average conditions of the river flow and the sea level, the water level through the domain had a very small slope close to zero. The flow velocity was very slow (the maximum velocity was about 8 cm/s) and changing through the domain according to the water depth. The meanderings of the river caused the formation of eddies making a 2-D approach necessary. The sensitivity of the model to friction coefficient and turbulence viscosity was very small.

The sea level rise can cause further intrusion for the saltwater inside the river for an idealized storm event, this additional intrusion was 2.3km, 4.8km and 7.9km for an increase of sea level by 0.25m, 0.5m and 1.0m respectively, which could affect the irrigation activities and the soil salinity in the surrounding areas. To maintain the current balance between the saltwater and the fresh water the river flow has to be increased by $67m^3/s$, $177m^3/s$ and $427m^3/s$ for an increase of sea level by 0.25m, 0.5m and 1.0m respectively, so an annual additional discharge is required. This additional discharge will affect the water budget of Egypt where the country suffers from water shortage problems.

2-D model can be used for salinity transport but with certain simplifications and limitations, however 3-D model is better in modeling salinity transport in estuaries to include the stratification impact and the density-driven flow due to the presence of saltwater. So, the use of 3-D model should be considered for further research.

Acknowledgments

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References

Agrawala, S., Moehner, A., El-Raey, M., Conway, D., Aalst, M.V., Hagenstad, M. & Smith, J. (2004). *Development and climate change in Egypt – Focus on coastal resources and the Nile*. Organisation for Economic Co-operation and Development (OECD). http:// www. oecd.org /dataoecd/57/4/33330510.pdf.

Ahmed, A.A., Sersawy, H., Vanacker, V., & Ismail U.H. (2005). Nile River sediment modeling: challenges and opportunities. International Conference of the UNESCO FIT project, Sharm El-Sheikh, Egypt.

El Raey, M. (2010). Impacts and Implications of Climate Change for the Coastal Zones of Egypt. In Michel, D. & Pandy, A. (Editors): Coastal zones and climate change, Report, pp. 31-50. The Henry L. Stimson Center , Washington DC, USA.

Hinkelmann, R. (2005). *Efficient Numerical Methods and Information-Processing Techniques for Modeling Hydro- und Environmental Systems*. Lecture Notes in Applied and Computational Mechanics, Vol. 21, Springer-Verlag, Berlin, Heidelberg.

IPCC, Intergovernmental panel of climate change (2007). *IPCC fourth assessment report, climate change 2007: synthesis report*. http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf.

LNHE, National Hydraulics and Environment Laboratory (2010). *telemac2d user manual*. http://www.opentelemac. org/downloads/MANUALS/TELEMAC2D/telemac2d_user _manual_v6p0.pdf.

Ludwig, F. & Vellinga, P. (2008). Impacts of climate change on water resource management In Egypt and The Netherlands. Report, 42nd Meeting of the Egyptian-Dutch Advisory Panel on Water Management, Den Bosch, the Netherlands. http://www.app-wm.org /liberary/ Download Files. aspx? did=728852&dt=1.

Mahmoud, M. K., El-Balasy, A., & El-ghorab, E. A. (2006). Mathematical model of the sedimentation problem at Rosetta promontory. Tenth International Water Technology Conference, IWTC10 2006, Alexandria, Egypt.

Moussa, A.M., & Aziz M.S. (2007). Nile River sediment transport simulation (case study: Damietta branch). Eleventh International Water Technology Conference, IWTC11 2007 Sharm El-Sheikh, Egypt.

UNFCCC, United Nations Framework Convention on Climate Change (2007). *Climate change: impacts, vulnerabilities, and adaptation in developing countries*. Information services of UNFCCC secretariat, Bonn, Germany.http://unfccc.int/resource/docs/publications/impac ts.pdf.